Improvement of irrigation efficiency in citrus orchards by lowering dripper emitter delivery rate

by

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DECLARATION

I, Christiaan Mauritz Snyman, declare this dissertation, which I hereby submit for the degree M.Sc. (Agric.) Soil Science at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution other tertiary institution.

SIGNATURE:

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ABSTRACT

Most of the world's freshwater is used by the agricultural industry, with irrigation of crops being one of the main uses. In water scarce countries, like South Africa, it is important that this water is used sustainably. Citrus is one of the most irrigated fruit crops in South Africa at around 99 000 ha, making it a very large and important water user. The growth of the industry, 35 000 ha increase since 2014, has placed pressure on current water resources and growers are in search of more efficient irrigation methods to maximise the water at their disposal. Drip irrigation has emerged as a very effective method for the irrigation of citrus and recent advances in drip irrigation technology have reduced emitter delivery rates by 70% compared to conventional drip, in an attempt to increase irrigation efficiency by decreasing drainage and increasing water storage in the rootzone. These systems, commonly referred to as low flow drip (LFD), have been widely adopted in the citrus industry with little research on the effects they have on plant and soil water relations and general irrigation management.

This study therefore attempted to determine the differences between conventional and LFD irrigation systems in both soil and plant water relations. Furthermore, current FAO-56 crop coefficient values were evaluated with two treatments where a 20% and 40% deficit of crop evapotranspiration (ET_c) were applied to test the hypothesis that current crop coefficient values overestimate ET_c for low flow drip systems. This was done by a randomised trial design consisting of five treatments in a mature Mandarin orchard (*Citrus reticulata* cv. 'Nadorcott') where treatment 1 (1.6 l h^{-1}), treatment 2 (2.3 l h^{-1}) and treatment 3 (0.7 l h^{-1}) were irrigated with no deficit and treatment 4 and 5 (0.7 l h^{-1}) were irrigated at -20% and -40% of ET_c respectively. The results indicated that LFD decreased drainage (D) below the root zone and increased water stored in the root zone, which resulted in an increase in transpiration. When soil water content was

evaluated from capacitance probe data the LFD treatments had the highest average water content in the active rootzone, with treatment 3 (0.7 l h^{-1}) at 92% followed by treatment 4 (0.7 l h^{-1} -20%) and 5 (0.7 l h^{-1} -40%) at 88%, the conventional drip followed with treatment 2 (2.3 l h^{-1}) at 87% and finally treatment 1 (1.6 l h^{-1}) at 85%, indicating that LFD stored more water higher in the profile. There were also differences in wetted area between treatments, with treatment 2 (2.3 l h^{-1}) creating the smallest wetted area with an average of 51% of the interpolated area having plant available water (VWC > 0.13 cm^3 cm^{3}) compared to treatments 1 (1.6 l h^{-1}) and 3 (0.7 l h^{-1}) with an average of 56% and 59 % of the total area having plant available water (VWC > 0.13 cm^3 cm^{3}) respectively. There were, however, no differences observed in stomatal conductance (g_s) and both pre-dawn (Ψ_{pd}) and midday stem water potential (Ψ_{smd}) between treatments, with all readings well below the thresholds for stress, indicating that all treatments were well watered at the time of measurements. There were no significant differences in yield and quality between treatments illustrating that LFD is an effective and viable option for citrus irrigation. Furthermore, this also confirms the hypothesis that current FAO-56 values are overestimated for LFD and that it could be reduced between 20-40% with no influence on yield, size and quality in this sub-tropical climate. The final part of this study reviewed irrigation and yield data of Mandarin orchards (*Citrus reticulata* cv. 'Nadorcott') from a wide variety of production areas in South Africa. The main objective was to determine water productivity (WP) benchmark values and to evaluate if there are distinct differences between irrigation methods. No distinct differences were observed between conventional drip and LFD irrigation systems in terms of WP, but there was a noticeable decrease in applied K_c values (season total irrigation ÷ season total ET_o) with a reduction in emitter delivery rate, suggesting improved application efficiency. The findings of this study suggest that irrigation water productivity (WP_i) for 'Nadorcott' in a winter rainfall area is ~ 9.0 kg m^{-3} and ~ 18 kg m^{-3} for summer rainfall areas. When the effective rainfall (P_e) was calculated the summer rainfall regions ranged between 60% -80% and the winter rainfall areas between 40%-60%. These values will ultimately impact the applied K_c, as was the case in this study with much lower applied K_c values realised than recommended in FAO-56 for citrus.

Due the impact of climatic differences on irrigation requirements, a normalised crop water productivity (WP_n) was proposed in this study, which does not only take total water used (TWU) into account but also ET_o and the contribution of rainfall to irrigation. Further research is warranted to gain a deeper understanding of and make meaningful comparisons between summer and winter rainfall regions with regards to WP_c and the contribution or utilization of rainfall.

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LIST OF ABBREVIATIONS AND SYMBOLS

ET – Evapotranspiration

ET_c – Crop Evapotranspiration

ET_o – Reference Evapotranspiration

RDI – Regulated Deficit Irrigation

Ψ_{smd} – Stem water potential

Ψ_{leaf} – Leaf water potential

Ψ_{pd} – Predawn leaf water potential

(T_{leaf}) – Leaf temperature

VPD – Vapour Pressure Deficit

g_s – Stomatal Conductance

E_s – Evaporation from the soil surface

D – Drainage

IE – Irrigation Efficiency

WP_c – Crop Water Productivity

EWP – Economic Water Productivity

WF – Water Footprint

θ – Water Content

TAW – Total Available Water

FC – Field Capacity

PWP – Permanent Wilting Point

RAW – Readily available water

K_c – Crop coefficient

VWC – Volumetric Water Content

S – Soil Water Storage

P_c – Rainfall measurement from under the canopy

AWS – Automatic Weather Station

P_{ci} – Contribution of Rainfall to Irrigation re to ET_o,

K_t – Transpiration Coefficient

K_e – Evaporation Coefficient

P_e – Effective Rainfall

WP_i – Irrigation Water Productivity

TWU – Total Water Use

WHC – Water holding capacity

ρbulk – Bulk density of the soil

K_{cn} – Normalised crop coefficient

WP_n – Normalised Water productivity

CHAPTER 1: GENERAL INTRODUCTION

South Africa is recognized as a water-scarce country with an average annual rainfall of 500 mm. However, there is major intra and inter-annual variation in rainfall, which makes reliable water supply challenging, a key factor for irrigators (Schreiner et al., 2010). From the early 2000s, South Africa was 6% drier compared to the 1970s and the continuous changes in timing, frequency, and quantity of rainfall have been difficult to quantify (Blignaut et al., 2009). The agricultural sector is therefore facing a potential water supply crisis and is faced with difficult decisions regarding the management of valuable water sources (Danckwerts, 2019).

One of the most substantial water usage is crop irrigation, which accounts for approximately 70% of the world's total freshwater consumption (Grafton et al., 2018). With the world population steadily increasing, it is almost certain that a large portion of water currently used by agriculture will be diverted to competing sectors of society (Fereres et al., 2003). With increasing competition between agricultural and non-agricultural users of water, the notion of water conservation and improved water management in the agricultural sector has become a priority. The amount of water available to a grower is finite, and competition often exists between neighbouring irrigators, especially in drought prone areas. Growers that solely rely on irrigation for profitability need to consider, alongside crop production, the cost and availability of water, and potential pollution of resources through over-irrigation.

The portion of water used by a the plant is referred to as the beneficial water use component, and optimising irrigation systems should be aimed at this component (Reinders, 2011). To optimise irrigation systems, it is important to determine what is the responsible usage and quantify the performance of different irrigation systems. In the case of South Africa, a large portion of irrigation water is lost (30-40%) due to inefficiencies from source to crop (Fanadzo and Ncube, 2018). An improvement in efficiency could benefit the agricultural sector immensely.

Although there is a wide variety of irrigated crops in South Africa, citrus production constitutes approximately 50% of the total fruit production, which is planted on approximately 99 000 ha, making it one of the most irrigated crops in the country (FruitSA, 2021). The industry has seen a 26 % increase in hectarage from 2015, resulting in an increase demand for water, which when coupled with severe droughts in many citrus producing areas, has put irrigation schemes under immense pressure. Water scarcity and dry spells are expected to increase in frequency and severity (Jovanovic et al., 2020) and have led many growers to search for more efficient irrigation systems, or methods, that will maximise the water at their disposal in terms of economic return per drop applied.

One of these methods is drip irrigation, which horticulturists have become well acquainted with, as it is widely associated with efficient water application (Fereres et al., 2003). According to Wu and Gitlin (1983), the two main reasons drip irrigation is more efficient than furrow or sprinkler irrigation, and results in improved crop yields, are 1) less water is lost in the application process and water is applied directly to the rootzone of the plant, and 2) drip irrigation applies water extremely uniformly across a field/orchard and facilitates easy application of water (higher irrigation frequency is possible). Conventional drip systems have emitters that supply water at a rate between 2.0 and 8.0 L h^{-1} and has been in use since its invention in the 1960s. In the past decade, advances have been made in drip emitter technology, with discharge rates of <1.0 L h^{-1}, which has been widely referred to as “low flow drip” (LFD). Emitters with an application rate of 0.7 L h^{-1} have become the preferred choice for these systems. Furthermore, it is not only the emitter discharge rate itself that is lowered, but the aim is also to have lower total system delivery. Whilst there are no formal criteria, the maximum system delivery rate for LFD system is typically 4 m^3 ha^{-1} h^{-1} or 0.4 mm h^{-1}. The drawback of most irrigation systems is that the rate at which water is supplied to the rootzone exceeds the rate of transpiration and not all surplus water can be stored in the soil (Batchelor et al., 1996), and therefore the main aim of LFD systems is to better match the hourly transpiration demand without percolating excess water past the rootzone.

In a recent review of strategies, methods, and technologies to reduce non-beneficial consumptive water use on farms by Jovanovic et al. (2020), lowering drip emitter delivery rate was not mentioned, however, drip irrigation in general showed reduced evapotranspiration (ET) compared to surface or sprinkler irrigation mainly due to a reduction in evaporation from the soil surface (E_s). Water application rate has also been identified as a key factor influencing the soil water distribution around the dripper (Assouline, 2002, Brandt et al., 1971, Bresler, 1975), and a decrease in application rate increased the volume of water stored within the root zone, and decreased deep percolation or drainage (Assouline, 2002). The first drip systems aimed at matching transpiration rate, also referred to as micro-drip by some authors, were first adopted in greenhouses, and studies on tomato and sweet corn demonstrated an increase in yield and a decrease in drainage (Koenig, 1997). When comparing LFD to conventional drip systems the main difference observed by Assouline (2002), was that LFD tended to store water closer to the soil surface, with less dynamic changes in water content in the rootzone that resulted in the smallest variance between simulated and potential root water uptake. This coincides with Batchelor et al. (1996), that stated that by lowering the emitter delivery rate to as close as possible to transpiration rate, water will be less likely to drain past the rootzone and may improve irrigation efficiency.

This concept of LFD is one that has been widely adopted in the fruit industry, especially in the citrus industry. There is approximately 11 500 ha of fruit crops on LFD in South Africa, with citrus making up more than 5 000 ha (Vos, 2022). Growers and advisors have reported excellent results with these systems, not only improved vegetative growth and yield, but also with less water applied than the conventional systems. However, with the first LFD system in South Africa installed as recently as 2011, limited research has been done on the possible advantages and disadvantages of these systems, with no formal guidelines on best practice with regards to scheduling and management. Whilst multiple studies have shown drip to be more efficient than furrow or micro-sprinkler irrigation in terms of yield per unit of water (Howell, 2003, Luquet et al., 2005, Fereres et al., 2003), there have been few studies comparing different drip systems with one another. It is therefore of great interest to the agricultural industry to obtain a better understanding of the influence of emitter delivery rate on soil water distribution and drainage, plant water uptake, and irrigation efficiency and management.

1.1 Hypotheses

- A decrease in emitter delivery rate increases capillary action in the soil and results in greater lateral water distribution. This results in less percolation of water passed the root zone, creating a larger wetted volume within the root zone. (Decrease in emitter delivery rate = increased water distribution within the rootzone = decrease in drainage).

- The period over which water is supplied to the rootzone with irrigation is a small fraction of the period over which photosynthesis and transpiration occurs therefore especially in soils with low water holding capacity, LFD can be a useful tool to overcome critical issues.

- Less extreme soil water gradients and lowered tempo of water application on low flow drip systems will result in higher transpiration rates than conventional drip systems.

1.2 Aim

The primary aim of this study was two-fold: firstly, to investigate water distribution patterns in low flow drip irrigation systems and how it can increase irrigation accuracy and secondly, to determine if the current FAO-56 crop coefficient values for citrus are suitable to schedule low flow drip irrigation. Furthermore, the secondary aim was to analyse and integrate weather, irrigation, and yield data obtained from 'Nadorcott' orchards distributed across South Africa, with the purpose of establishing benchmark values for crop water productivity and factors influencing crop water productivity.

1.3 Objectives

- To schedule irrigation on a weekly basis using adjusted FAO-56 crop coefficients, as well as two treatments with 20% and 40% less of crop evapotranspiration (ET_c) requirements.
- To measure and interpolate soil wetting patterns of the different emitter delivery rates.
- To measure pre-dawn, midday stem water potential, and stomatal conductance of trees under different drip delivery rates and irrigation regimes to assess tree physiological performance.
- Measure sap flow of trees subjected to the three application rates to determine if transpiration differs between irrigation systems.
- Determine yield and fruit size of each treatment for each season.

- Collect and compile seasonal irrigation data, yield, rainfall, and reference evapotranspiration (ET_o) data for 'Nadorcott' orchards in various production regions across South Africa.

CHAPTER 2: LITERATURE REVIEW

2.1 Irrigation efficiency

One of the earliest references to irrigation efficiency (IE) was by Beckett et al. (1930) in a study conducted on the water requirements of citrus and avocados in San Diego County California in 1926-27. From early on the term has been used inconsistently and has caused confusion with different meanings to plant physiologists, agronomists, irrigation engineers, and economists (Burt et al., 1997, Nair et al., 2013). The irrigation pioneer O.W. Israelsen defined irrigation efficiency as the ratio of water consumed by a crop to the amount of water diverted from a river or other natural water source into the farm or scheme canals (Israelsen and Wiley, 1950). This basic approach has undergone refinement, for example, Hansen (1960) made the important point that if supplied water is less than the potential use by the plant, efficiency may approach 100%, but the irrigation regime will be poor and crop yield low. He proposed an overall concept of consumptive use efficiency, that might have been a precursor to the concept of beneficial water usage. Subsequently, authors have made refinements or contributions to the concept (Jensen, 1967, Allen et al., 1996, Bos and Nugteren, 1990) but overall Israelsen's original definition of efficiency remains the underlying accounting basis in irrigation (Perry, 2007).

The essence of irrigation performance lies within an irrigation-water balance, where the fate of the water applied is fractioned into a variety of outcomes: how much water reaches the plants, how is the water distributed between each plant, and how much of the water not used is recoverable and/or reaches the ground water? (Burt et al., 1997). There are many possible sources of loss from source to application point for water in an irrigation system (Nair et al., 2013), and therefore an irrigation efficiency, which is a very broad term, can be defined in terms of 1) the irrigation system performance, 2) the uniformity of water application, and 3) the response of the crop to irrigation (Howell, 2003). For each of these three phases, multiple efficiency terms have been defined. Not all the concepts are applicable to drip irrigation and only the most relevant definitions will be discussed further.

1) Irrigation system performance efficiency: This focuses on the efficiencies regarding the transportation of water from source to field.

2) Water conveyance efficiency: This is typically defined as, the ratio between water diverted from the irrigation source (dam, canal, river, etc.) to that reaching the farm or field (Howell, 2003).

$$E_c=100\ \frac{V_f}{V_t} \qquad [1]$$

The conveyance efficiency E_c is expressed as a %, where V_f is the volume of water that reaches the farm or field (m^3), and V_t is the volume of water diverted from the source (m^3).

3) Application efficiency: This concept refers to the required amount of water stored in the root zone to meet the crop requirements versus what was applied. It takes into consideration any application losses to evaporation or seepage from canals or furrows, leaks from sprinkler or drip lines, drainage of water past the root zone, drift of sprinklers or runoff from the soil surface at application (Howell, 2003, Hart and Reynolds, 1965).

$$E_a=100\ \frac{V_s}{V_f} \qquad [2]$$

Where E_a is the application efficiency (%), V_s is the irrigation volume needed by the crop (m^3) and V_f is the volume of water supplied to the farm (m^3).

4) Uniformity of water application: This is a statistical property of the distribution of applied water and is related to the method of irrigation, soil topography, soil infiltration characteristics, and system hydraulic characteristics (pressure, flow

rate, etc.) (Howell, 2003). Many of these concepts are focused on full surface wetting systems and will not be discussed in further detail.

The aforementioned sections have an engineering focus, and all are related to different aspects of irrigation system design. These factors impact irrigation cost, systems, and crop performance in some instances.

5) The response of the crop to irrigation: A comprehensive review on water use indicators by Fernández et al. (2020), suggested that there is no consensus on the suitability and uses of different indicators and views differ between role players. The many definitions of crop response to water can be broadly put into three groups: water use efficiency (WUE), crop water productivity (WP), and economic water productivity (EWP).

The term WUE is mostly used to describe irrigation effectiveness, with a number of different numerators depending on the use, some of which are more applicable to agricultural use of water than others (Fernández et al., 2020, Perry and Bucknall, 2009, Viets, 1962).

$$WUE_c = \frac{ET_c}{I+P} \quad [3]$$

Crop WUE_c is the ratio between the actual crop evapotranspiration ET_c, and the total water applied by irrigation (I) and precipitation (P). The same terminology of crop WUE is also expressed as the ratio between total biomass produced by a crop in a growing season (WUE_p) and the total amount of water consumed by the crop, or crop evapotranspiration (ET_c), in the same period.

$$WUE_p = \frac{Biomass}{ET_c} \quad [4]$$

Fernández et al. (2020), however, does not recommend the use of biomass as indicator as it refers to WUE since from an agronomist perspective the ratio of the total marketable yield obtained to the water used over the growing period (Gregory, 2004, Perry and Bucknall, 2009) is more important, which is better defined in terms of crop water productivity WP_c, introduced first by Molden (1997).

$$WP_c = \frac{\text{yield}}{ET_C} \quad [5]$$

The term productivity refers to inputs used to obtain a product and there is wide consensus that this numerator should be marketable yield (Heydari, 2014, Kijne et al., 2003).To calculate the crop response or economic benefit of irrigation, referred to as the economic irrigation water productivity EWP_i, the ratio between the revenue created by a crop in the growing season and the irrigation water applied (IWU) in the same period is determined (Rodrigues and Pereira, 2009).

$$EWP_i = \frac{\text{profit}}{IWU} \quad [6]$$

Another school of thought is the concept of a water footprint (WF) or alternatively referred to as "virtual water content", that was developed by Hoekstra and Chapagain (2007) to analyse the relationship between the human consumption of the globes freshwater and the appropriation thereof. It is expressed in water volume per unit mass of product (m^3 ton^1) and is broken up into three groups of water footprints, *blue, green,* and *grey.* The *blue* water footprint refers to the volume of water consumed from surface and groundwater sources; the *green* water footprint refers to rainwater consumed and the *grey* water footprint to the amount of freshwater used to assimilate the pollution load associated with the product. A subsequent review by Mekonnen and Hoekstra (2011) estimated the water footprint of 126 crops using data from the period 1996-2005. They found that the global average water footprint for fruit was 967 m^3 t^{-1} and was proportionately made up by 75% green water, 15% blue, and 10% grey. The global average water footprint values for citrus products are summarized in Table 2.1.

Table 2.1 Global average water footprint figures for various citrus types from Mekonnen and Hoekstra (2011).

Product description	Global average water footprint ($m^3\ t^{-1}$)			
	Green	Blue	Grey	Total
Oranges	401	110	49	560
Orange Juice	729	199	90	1018
Tangerines, Mandarins, Clementines	479	118	152	749
Lemons and Limes	532	152	58	742
Grapefruit	367	85	54	506

The WF concept has not been immune to scrutiny, and it has encountered critique. The primary objections to this concept revolve around concerns regarding the accuracy of the calculation methodology. Additionally, it has been argued that, unlike carbon footprints, reducing water consumption at a local level does not necessarily translate into global benefits. Moreover, critics assert that the WF concept may inadvertently promote the notion that all forms of irrigation are wasteful, without adequately considering the essential contextual factors related to regional climate patterns and water availability (Wichelns, 2015, Perry, 2014, Fereres et al., 2017).

Although approaches and definitions differ, broadly speaking water use efficiency, productivity or footprint are all important measures of irrigation performance for an area, which can be a field, farm, basin, irrigation district or entire watershed, and the amount of water required for irrigation. Crop response and yield are not always easy to evaluate or control, but the irrigation system performance and the uniformity of water applied have given rise to many innovations in irrigation technology. One of these advances that changed the landscape of irrigated agriculture is drip irrigation.

2.2 Drip Irrigation

Drip or trickle irrigation refers to a system of small emitters buried or placed on the soil surface that applies water at a controlled or known rate (Cote et al., 2003). Horticulturists and the public have become well acquainted with drip or trickle irrigation, and it is widely associated with efficient water application. The pioneer S. Blass developed the first commercial drip system for agricultural crops at Kibbutz Hatzerim, Israel in the early 1960s. His invention would go on to change the landscape of irrigated horticulture forever (Fereres et al., 2003). A lot of development has since taken place and drip irrigation has been widely promoted as an irrigation method that has improved water use efficiency (Luquet et al., 2005). According to Wu and Gitlin (1983) the two main reasons drip irrigation is more efficient than furrow or sprinkler irrigation, and results in improved crop yields, are 1) less water is lost in the application process and water is applied directly to the root zone of the plant, and 2) drip irrigation applies water extremely uniformly across a field/orchard and facilitates easy application of water (higher irrigation frequency is possible). The irrigation technology pioneer O.W. Israelsen (Israelsen and Wiley, 1950) found that drip irrigation offers numerous advantages, including increased water efficiency, improved crop yield, better nutrient management, weed control, energy savings, soil health promotion, and adaptability to different farming scenarios.

Drip irrigation still commonly consist of emitters delivering between 2.0 to 8.0 L h^{-1}, with the aim of system design to supply the daily water demand of the crop (Assouline, 2002). Typically, the period over which water is supplied to the root zone, even with 2.0 L h^{-1} drippers, is a small fraction of the period over which photosynthesis and transpiration occurs (Batchelor et al., 1996). This has led to the development of low-flow drip (LFD) or micro-drip systems, where application rates are aimed at matching hourly transpiration rates or in other words total application period is equal to the total transpiration period.

Drip irrigation systems are reported to offer the highest water conservation among all irrigation systems including, furrow irrigation, micro sprinkler, and flood irrigation (Brouwer, 1998, Fereres et al., 2003, Howell, 2003, Bryla et al., 2005, Sravani et al., 2020, Wang et al., 2021). The main reason for this improved water conservation is that the wetted zone is limited to approximately 30% of that of other systems and as a result, deep percolation, surface runoff, and evaporation from the soil surface are reduced (Brouwer, 1998, Assouline, 2002, Wang et al., 2020). Drip irrigation also offers greater control over the application of water, fertilization, and pesticides, due to the small amount of water applied on a small surface area. Optimizing operational parameters, such as frequency, duration, and emitter delivery can increase the potential of drip systems to limit losses or inefficient applications (Skaggs et al., 2004, Wu and Gitlin, 1983).

Cote et al. (2003) demonstrated that as water application rate decreases, the wetted area increases, but these authors highlighted the influence of soil hydraulic properties and how this influences soil water distribution from drip systems. Besides soil physical properties, a variety of factors, such as emitter placement (above or below soil surface), emitter discharge rates, irrigation quantity, and frequency, all influence the water distribution from a drip source (Gärdenäs et al., 2005, Wang et al., 2021).

2.3 Principles of soil water availability and distribution under drip irrigation

In contrast to more traditional techniques, like flood or sprinkler irrigation, where full surface wetting takes place and water can be simulated by one dimensional vertical movement, drip irrigation has a three dimensional transient infiltration rate that originates in the region directly around the emitter (Cote et al., 2003). The distribution of the water applied in the soil is mainly influenced by the soil hydraulic properties, like soil texture, organic matter content, soil structure, and compaction (Prasad and Pietrzykowski, 2020, Hillel, 1980). The application rate of water from an emitter will influence the localized wetting pattern beneath the emitter (Burt et al., 1997), and wetted volume directly influences the number of lateral pipes or drip lines required and emitter spacing on each lateral pipe (Reinders et al., 2012). It is important to understand the width and depth dimensions of the wetting pattern in the specific soil when a drip irrigation system is being designed (Burt and Barreras, 2001), as the storage of water in the root zone is limited to the wetted volume created by the emitter. The width of the wetting pattern should correspond to emitter spacing and line spacing, if more than one line is being used, and the depth of the wetting pattern should correspond to the effective rooting depth (Zur, 1996). However, the quantity of water will also influence the wetting pattern, with increased water distribution in both the horizontal and vertical directions as application volume increases (Skaggs et al., 2010, Acar et al., 2009, Reinders et al., 2012). Vertical distribution, however, is not necessarily desired because water moving passed the root zone is wasted and therefore the aim for any irrigation application method should be to maximize the horizontal water movement relative to the vertical to obtain maximum efficiency (Skaggs et al., 2010, Pascual-Seva et al., 2018, Fereres et al., 2003).

There are two conditions under which water movement in soils occur. The first is saturated conditions, which mainly occurs below the water table and in the horizontal plane, with limited flow in the vertical direction. The second condition is unsaturated conditions, which are generally seen as the area above the water table (the vadose zone). Localized zones of saturation can occur after precipitation or irrigation events, but generally, water movement in the unsaturated zone is vertical, although large lateral components can exist (Radcliffe et al., 2002) that are determined by soil water content, which influence capillary forces and can therefore be highly variable under drip irrigation conditions (Skaggs et al., 2010).

The vector describing the slope of the energy distribution within the soil is referred to as the hydraulic gradient. To predict saturated flow, the saturated hydraulic conductivity K_s of a soil is required. Unsaturated flow on the other hand is much more complex and requires the unsaturated hydraulic conductivity K(h) as well as water retention θ(h) functions. Soil texture and structure influence K_s, θ(h) and K(h), and whilst soil texture can easily be determined, soil structure is highly variable and complex to quantify (Radcliffe et al., 2002). Drip irrigation can have a combination of these two flow conditions which make the prediction of wetting patterns challenging.

Hillel (1980) explained that drip irrigation saturates a small part of the soil below the emitter. Soils are saturated when the water content (θ) is equal to the total porosity (ф) of the soil and the air-filled porosity (θ_a) is zero. When all the pores are filled with water and the application rate exceeds the downward movement of water under gravitational potential, ponding will occur on the soil surface. This parameter is important and is referred to as time to ponding (t_p). High emitter delivery rates can cause ponding, which results in water runoff across the soil surface (Bresler, 1978, Brandt et al., 1971, Gärdenäs et al., 2005). Ponding or the lack of infiltration jeopardizes soil water distribution and increases the losses from surface evaporation (Skaggs et al., 2010). Infiltration is therefore a key process because it determines the proportion of water that will enter the soil and what will result in runoff. Infiltration can be described as a wetting front of higher water content moving down the soil profile over time, and infiltration (i) is often expressed as mm h^{-1} (Radcliffe et al., 2002). The shape and abruptness of the wetting front is determined by the pore size distribution within the profile and K(h), with coarse textured soils with a narrow pore size distribution having a more abrupt wetting front and fine textured soils, a much more diffuse wetting front (Radcliffe et al., 2002). The wetting front can also be referred to as the transmission zone and is considered to be the area below or around the saturated zone that is of uniform wetness and still unsaturated (Hillel, 1980). The shape of the wetting pattern (WP) has been described as a truncated-ellipsoid (Figure 2.1) by Elnesr and Alazba (2017) and Andreu et al. (1997) stated that other variables may also influence the spatial distribution of soil water under a drip emitter. These variables include emitter position relative to the active roots, the quantity of irrigation and the frequency at which it is applied, the soil water regime in general and the spatial and temporal changes in soil water content as controlled by root water uptake and leaching.

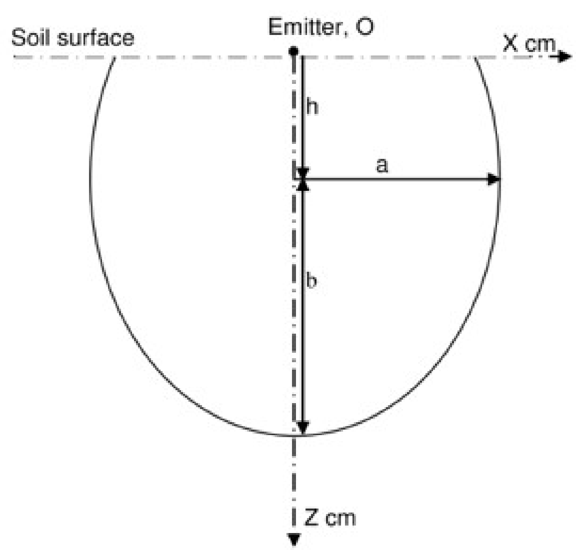

Figure 2.1 Typical truncated ellipsoid wetting pattern under a drip emitter and parameters required for quantifying the two dimensional surface area and volume (Acar et al., 2009).

By using parameters of a half dissected ellipsoid as shown in Figure 2.1, Acar et al. (2009) derived a formula to determine the wetted soil volume.

$$V_{oz} = = \frac{a^2\pi}{3b^2} (b=h)(2b^2-h^2+hb) \qquad [7]$$

Where V_{oz} refers to the wetted soil volume (cm^3), a is half of the maximum lateral wetting front (cm), b is the distance from the vertical point of maximal lateral wetting front advance to the vertical wetting front advance (cm) and h is the distance between point of maximal lateral front advance and soil surface level (cm).

These three-dimensional truncated ellipsoids can be seen as separate "reservoirs" under emitters and to calculate the amount of water required to refill a reservoir, da Silva et al. (2020) proposed the following equation:

$$I_v=(\theta_{fc}-\theta_{actual})\frac{\pi r^2}{e} d \frac{1}{\text{system efficiency factor}} \qquad [8]$$

Where I_v is the irrigation volume required (m^3) to fill the reservoir to FC, θ_{fc} volumetric soil water content at field capacity (pressure head =-1m), θ_{actual} the mean soil water content, r the average diameter of the wetted area, e is the emitter delivery rate ($l\ h^{-1}$), d the rooting depth and the system efficiency factor for drip is considered to be 0.95 (da Silva et al., 2020). The formula used to determine volume by da Silva et al. (2020) might be over simplified when compared to that of Acar et al. (2009).

Soil water content plays an important role in governing the air content and gas exchange of the soil, which in turn affects respiration and growth of roots, microbial activity, and the chemical state of the soil (redox potential) (Hillel, 1980). Accurate determination of θ_{fc} and θ_{actual} is important to understand how depleted these drip "reservoirs" or spheres are but this, however, does not indicate what is available to the plant, as there are many factors influencing plant available water (PAW), as well as a discrepancy in terminology. The water contained in the soil (per unit mass) and the energy state or potential of that water are often referred to as volume wetness and matric potential respectively and are functionally related to each other (Hillel, 1980).

A variety of concepts and terminologies have been presented over the years to describe the different components of soil water dynamics. The available water content (AWC) concept was first described by Veihmeyer and Hendrickson (1927) and is still widely accepted. Available water content or total available water (TAW) can be defined as the amount of water between field capacity (FC) and permanent wilting point (PWP) or wilting point (WP) and is the portion of water available for plant use. This concept is very broad and the availability of water to plants will be affected by the plant, root density, and potential evaporation rate (Minasny and McBratney, 2003, Allen et al., 1998)

The conditions of FC and PWP are determined by an associated matric potential, which is the force that binds water to the surface of the soil particle and what a root must overcome to extract water (Easton, 2021). Minasny and McBratney (2003) refers to integral energy as the amount of energy required to remove an amount of water from the soil. The specific potential energy of water in the soil (Ψt), relates to the water available to plants and can be expressed as the sum of normalised forces acting on the soil water and includes the gravitational-(Ψg) matric-(capillary and adsorptive, (Ψm)), osmotic-(Ψo), and hydrostatic potential (Ψh) (Menne et al., 2022). The term saturation is when matric potential is equal to 0 kPa with FC, depending on texture, being between 0 and -10 kPa (one third of atmospheric tension) (Easton, 2021). The water content at PWP or WP varies with soil texture but has generally been considered to be -1500 kPa for most herbaceous plants. However, plants will experience a substantial amount of stress before reaching PWP and is generally not desired from an agricultural point of view (Zotarelli et al., 2010). The main aim of irrigation is to avoid stress that can be detrimental to crop performance and replenish the soil when the crop specific threshold or refill point (RP) is reached (Figure 2.2).

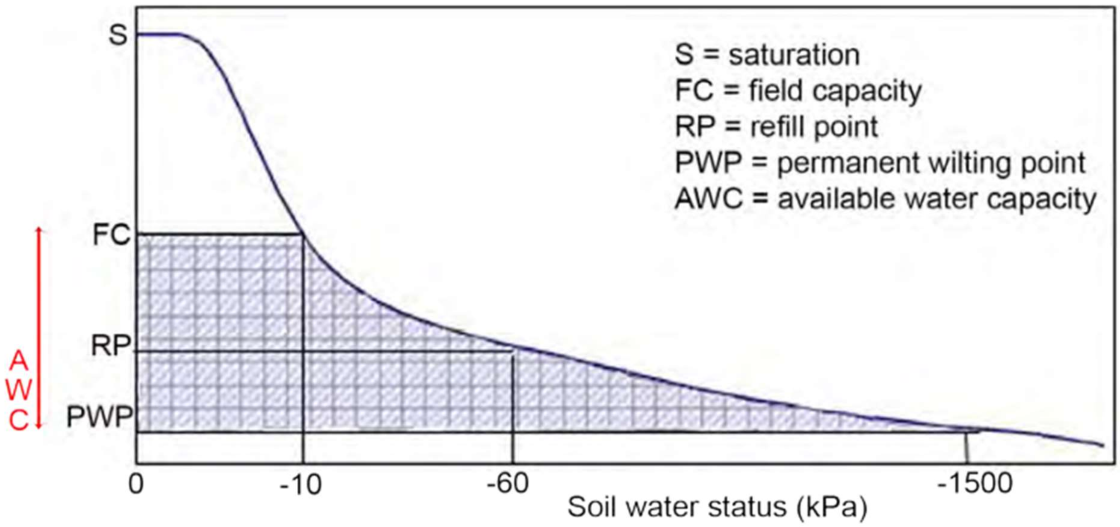

Figure 2.2 Typical soil water tension curve for irrigation management purposes (Metha and Wang, 2004).

Allen et al. (1998) applied a practical approach to irrigation scheduling in the FAO 56 guidelines and describes soil water availability with the following terminologies and equations:

$$TAW=1000\ (\theta_{FC}-\theta_{WP})\ Z_r \qquad [9]$$

Where TAW refers to the total available soil water in the root zone (mm), θ_{FC} to field capacity ($m^3\ m^{-3}$), which is the amount of water that remains after saturation and free drainage has taken place, θ_{WP} soil water content where the crop can no longer extract water or wilting point ($m^3\ m^{-3}$) and Z_r the rooting depth (m). The TAW is influenced by soil type (Figure 2.3) and the rooting depth and ultimately represents the amount of water the plant theoretically can extract from the root zone.

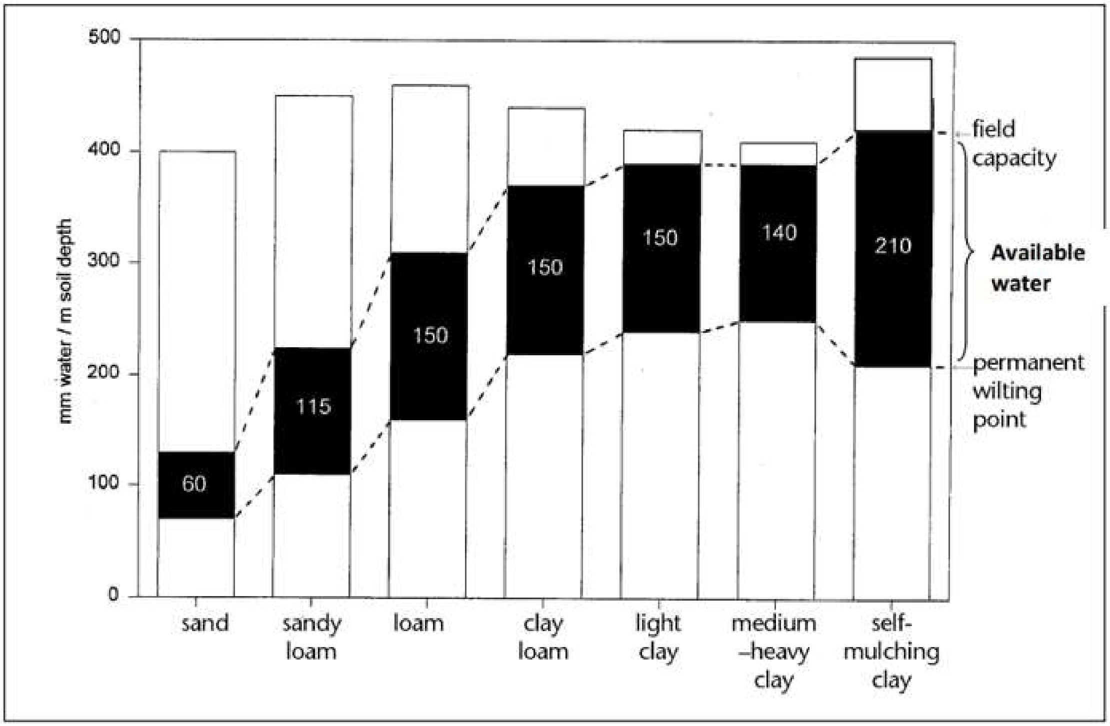

Figure 2.3 The thresholds for field capacity, permanent wilting point and available water content per soil texture class (mm m^{-1}) (Cotching, 2011).

The fraction of AWC that a crop can extract from the root zone before experiencing stress is referred to as readily available water (RAW).

$$RAW = p\ AWC \qquad [10]$$

Where p refers to the fraction of AWC that can be depleted from the rootzone before water stress occurs (reduction in evapotranspiration (ET_c)) and has a range of between 0 and 1. Values for p are a function of the evaporative power of the atmosphere and are listed the FAO 56 guidelines (Table 2.2). A value of 0.50 is commonly used for many crops although climatic adjustments can be made (Allen et al., 1998). The principle of RAW and applying it to different soil types and crops forms the basis of irrigation scheduling. However, the type of irrigation system used will influence the irrigation management and in the case of drip irrigation the main difference between systems is the application rate and the wetted area created.

Table 2.2 Ranges of maximum effective rooting depth (Zr) and soil water depletion fraction for no stress (p) for Citrus (Allen et al., 1998).

Crop	**Maximum rooting depth (m)**	**Depletion Fraction (for ET ~ 5 mm/day) p**
Citrus – 70% Canopy	1.2-1.5	0.5
Citrus – 50% Canopy	1.1-1.5	0.5
Citrus – 20% Canopy	0.8-1.1	0.5

2.4 Drip emitter delivery rate and management practices

The main goal or principle of drip irrigation or any irrigation for that matter is the frequent replenishment of water lost by ET_c (Andreu et al., 1997). Drip irrigation allows for frequent irrigations of small volumes, where crop demand can be supplied daily. There are a variety of emitter delivery rates used commercially in drip irrigation and studies have shown that water application rate is a key factor influencing the soil water regime around the dripper (Assouline, 2002, Brandt et al., 1971, Bresler, 1975), and in combination with soil texture has the most significant impact on wetting patterns (Cote et al., 2003). These studies showed that water distribution in general was greater on silt/clay soils than on sandy soils and the wetted radius increased with a decrease in discharge rate from the emitter.

Skaggs et al. (2010) performed a series of simulations with a variety of emitter delivery rates and application sequences. These authors found that pulsing or short frequent applications of drip irrigation had a maximum of 13% influence on water distribution. Similar findings by Cote et al. (2003) indicated that pulsing slightly increased the wetted radius. Selim et al. (2013) investigated the influence of irrigation scheduling and initial water content (θ_i) on soil water distribution and found that in sandy soils the wetted area was larger under daily irrigations, but higher water content values occurred in the root zone under alternate day irrigation. Furthermore (θ_i) showed an insignificant effect on the wetted pattern and the effects of (θ_i) was not noticeable after a few irrigations.

In summary, these studies show that apart from soil hydraulic characteristics, emitter delivery rate does influence the distribution of water in the soil and that a larger wetted volume can be expected with lowering delivery rate. However, the influence of (θ_i) and application methods like pulsing or continuous irrigation on soil water distribution is suggested by most authors to be minimal. These factors above describe the most important factors to manage the soil water status but to schedule irrigation accurately it is also important to understand the water requirement and water relations of the crop in question. This will aid in determining thresholds and an irrigation strategy that is suited to the specific crop's needs and phenology.

2.5 Water use of Citrus

Citrus originated in drier monsoon areas of Asia and have generally not performed well in very humid tropics, hence most of the commercial production areas are located at latitudes greater than 20°N and 20°S, but less than 45°N and 35°S, and from sea level up to 600–750 m above seas level, with semi-arid, Mediterranean and humid sub-tropical climatic regions being the main three production zones (Talon et al., 2020, Carr, 2012).

It is important to estimate accurate water requirements for citrus orchards to ensure optimal production with minimal wastage of water, however, to define the optimal water requirement for any given plant species in a given location is difficult since it is determined by various factors, which include (1) whole plant transpiration (T), (2) soil texture, (3) ambient humidity, (4) water quality, and (5) plant characteristics (Talon et al., 2020). Variations among species, varieties, rootstock-scion combinations, and the interaction of each of these factors to their environment have made it extremely difficult to determine the water use of citrus (Talon et al., 2020, Pérez-Pérez et al., 2008). Mandarins (*Citrus reticulata*) specifically have exhibited more anisohydric behaviour compared to other citrus varieties (Romero-Trigueros et al., 2021), which correlated with findings of Vahrmeijer et al. (2018) that measured the highest total daily transpiration in Mandarins, compared to Valencia's (*Citrus sinensis*) and Grapefruit (*Citrus paradisi*) of similar canopy size.

Water usage in orchards, often referred to as ET_c, can be broken down into two components, namely E_s and T. Fereres et al. (2012) described these components as related, although they are influenced by different factors. In well-watered systems, ET_c was predominantly driven by the absorption of solar radiation energy. However, aside from environmental variables like air temperature (T_a), solar radiation (R_s), and vapor pressure deficit (VPD), the rate at which E_s occurs is also affected by the frequency of rainfall and irrigation. On the other hand, T is additionally influenced by factors related to the crop itself, such as canopy size, leaf area, and stomatal conductance (Allen et al., 1998). It is generally acknowledged that the low stomatal/canopy conductance in Citrus spp. limits their water usage compared to other crops, as noted by Shalhevet and Levy (1990). Research indicates that citrus trees exhibit higher hydraulic resistance in the root-to-leaf pathway compared to many other crops, and when faced with high atmospheric demand, these trees may struggle to supply enough water to their leaves, even when soil water is adequate (Marin and Angelocci, 2011, Villalobos et al., 2009).

Many attempts have been made to quantify the minimum amount of water that can be applied to citrus at specific growth stages through regulated deficit irrigation (RDI) trials and experiments but no consensus has emerged (Ballester et al., 2014, Chartzoulakis et al., 1999, García-Tejero et al., 2010b, Hutton and Loveys, 2011, Pérez-Pérez et al., 2008). Furthermore, it is difficult to do RDI or water usage trials in high rainfall regions in the subtropics, where low VPD and excessive water availability for extended periods create scenarios where no deficit can be induced, and crop water demand is low. Dryland citrus production is found in many of these high rainfall areas (e.g. Uruguay, Brazil, and Florida) but the advantages of irrigation during critical periods has been proven which indicates that in certain periods water has a significant impact on yield in citrus (Goñi and Otero, 2009, Petillo and Sánchez, 2004).

However, there is a point that irrigation becomes non-beneficial, as Petillo and Sánchez (2004) found that increasing irrigation to 150% ET_c led to more vegetative growth but did not enhance yield, which suggests that the relationship between yield and irrigation is not linear. Where rainfall is not sufficient for dryland production the scheduling of irrigation (between rainfall events) is important for the maximization of available water resources. Effective rainfall is challenging to calculate with many variables between areas and crop species impacting the fate of rainwater. In the case of citrus, the interception of rainfall by tree canopies is an important factor that needs to be accounted for when calculating effective rainfall and can range between 35%-50% (Fares et al., 2008). (Obreza and Pitts, 2002) proposed the following effective rainfall calculation.

$$ER = P_{net} - R - DR \qquad [11]$$

Where P_{net} (mm) is the net precipitation reaching the ground surface after canopy interception, R (mm) is the runoff, and DR (mm) is the deep drainage of water that percolates beyond the root zone. Only the portion of rainfall that is used to meet the ET_c needs are deemed effective (USDA, 1970). However, T rate follows a seasonal pattern with the highest rates occurring in summer and the lowest in winter (Vahrmeijer et al., 2012), and therefore the season in which rainfall occurs also has an impact on the contribution of rainfall towards T. No research was found differentiating rainfall contribution based on seasonality of rain.

A number of studies collectively affirm the importance of irrigation in enhancing citrus yield, they also highlight the variability in water requirements based on geographical location, cultivar type, and specific growth stages. Furthermore, it is difficult to transfer measurements and estimations based on different methods and techniques and done under different environmental conditions to other citrus orchards and the variation of some of the findings are summarised in Table 2.3.

Table 2.3 Summary of water usage figures for mature citrus reported in literature through the measurement of either evapotranspiration (ET) or only transpiration (T). These studies were done in a variety of climatic regions, cultivars, and tree spacings (trees per hectare). Where data was not reported it is noted with (NR).

Citrus Type	**Trees per ha**	**Location**	**Technique**	**Component measured**	**Ave water use**	**Max water use**	**Reference**
Citrus	NR	Sundays River Valley, RSA	Lysimeter	ET	NR	6.1mm day^{-1}	Green and Moreshet (1979)
Citrus	NR	Florida, USA	Water balance	ET	3.3mm day^{-1}	5.0 mm day^{-1}	Rogers et al. (1983)
Clementine	432	Spain	Lysimeter	ET, soil evaporation	≈ 1mm day^{-1}	≈ 2.3mm day^{-1}	Castel et al. (1987)
Clementine	400	Southern Italy	Sap Flow	T	4 mm day^{-1} (100l.day^{-1})	8 mm day^{-1} (200l.day^{-1})	Rana et al. (2005)
Navel Orange	299	Calif.USA	Energy Balance	ET		0.8 mm h^{-1} (26.8 l h^{-1})	Consoli et al. (2006)
Navel Orange	284	Calif.USA	Energy Balance	ET		0.9 mm h^{-1} (31.7 l h^{-1})	Consoli et al. (2006)
Limes	179	Brazil	Sap flow	T	0.6 mm day^{-1} (winter) 2.5 mm day^{-1} (summer	4.6 mm day^{-1}	Marin et al. (2019)

Valencia Orange	800	WC, RSA	Sap Flow	T	2.2 mm day^{-1}	4.0 mm day^{-1}	Vahrmeijer et al. (2018)
Afourer Mandarin	1000	WC, RSA	Sap Flow	T	1.79 mm day^{-1}	3.61 mm day^{-1}	Vahrmeijer et al. (2018)
Valencia orange	389	Nelspruit, RSA	Water balance	ET	2 mm day^{-1} (winter) 5.2 mm day^{-1} (summer)		Mostert (1999)

2.6 Crop coefficients of Citrus

The historic FAO Paper No. 24 introduced the two-step crop coefficient-reference ET (K_c-ET_{ref}) procedure internationally in 1977. This practical approach revolutionized the estimation of crop water requirements. FAO-56 by Allen et al. (1998) built upon this foundation to further enhance and refine the methodology. The method is based on the Penman-Monteith equation which provides a reference evapotranspiration (ET_o) which is an indication of the evaporative demand and a K_c that encompasses all the factors related to plant hydraulic resistance, from the evaporating surfaces to the soil, and the resistance of water vapor diffusion from these surfaces into the atmosphere. Rogers et al. (1983) proposed that there are several factors contributing to variations in K_c. These factors include 1) variety and/or rootstock, 2) tree spacing, 3) canopy height, 4) ground cover, 5) tillage, 6) leaf area index (LAI), 7) method for estimating reference evapotranspiration, 8) microclimate, 9) irrigation method and frequency, and 10) method of measuring ET_c. When assuming that ET_o adequately encompasses most of the fluctuations attributed to weather and climate, the K_c can be seen as transferable, especially in agricultural crops where vegetation tends to exhibit greater uniformity compared to natural vegetation with regards to canopy size, spacing, and plant health (Allen and Pereira, 2009). However, some authors suggest that the linear relationship between ET of a short grass surface and rough clustered canopy of certain tree crops, like citrus, does not always hold true and therefore K_c values may not be readily transferable between different climatic zones and orchard management practices (Taylor et al., 2015, Testi et al., 2004, Annandale and Stockle, 1994). It is therefore understandable that a wide range of K_c values have been reported for mature citrus orchards in different climatic regions ranging from 0.6 to 1.2 (Hoffman et al., 1980, Rogers et al., 1983, Castel et al., 1987, Allen et al., 1998, Snyder and O'Connell, 2007), with differences in intra-seasonal variation as well (Figure 2.4).

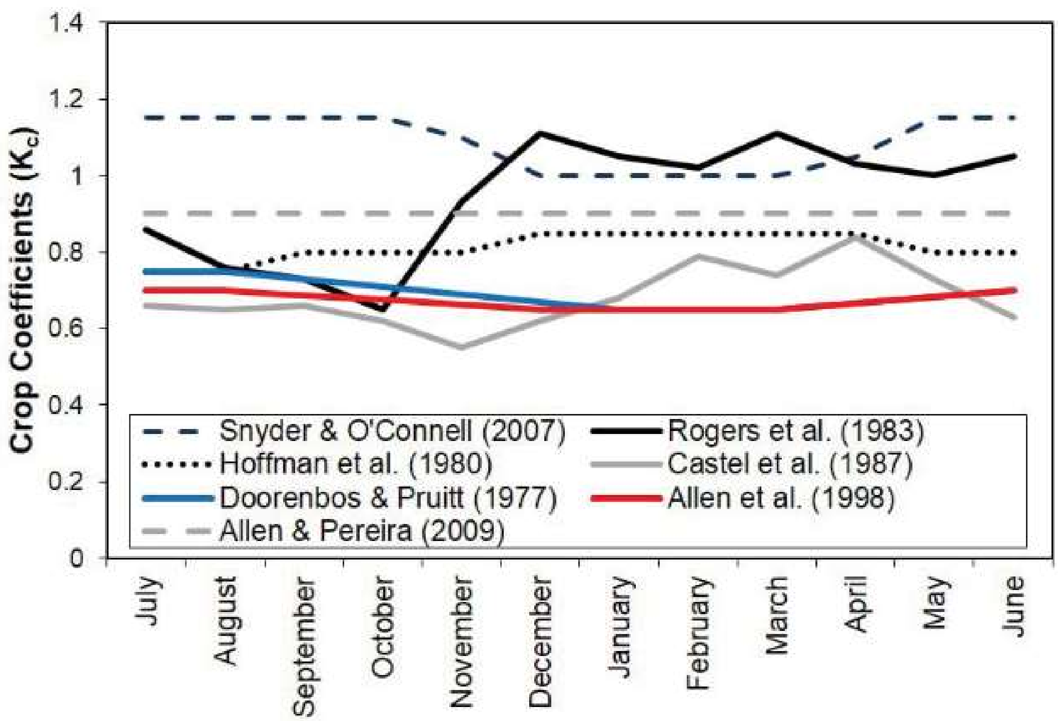

Figure 2.4 Published crop coefficients for citrus compiled by Vahrmeijer et al. (2018).

To obtain precise estimates of water consumption for citrus using crop coefficients, it is often necessary to reduce the coefficient during the hottest period of the year when VPD rises (Taylor et al., 2015) and in FAO-56 guidelines, Allen et al. (1998) accounted for the impact of stomatal closure on transpiration rates during periods of high potential evaporation by adjusting the mid-season K_c value down from 0.75 to 0.70 in an orchard with 70% crop cover. Additionally, for humid and sub-humid climates, the listed K_c

values were recommended to be increased by 0.1 to 0.2. A more comprehensive procedure have since been proposed by Allen and Pereira (2009) where a reduction factor (F_r) is estimated from mean stomatal resistance.

A practical method to determine or develop a set of K_c values for a specific crop in an area is with the use of a soil water budget or soil water balance (SWB) (Farahani et al., 2008, Castel et al., 1987). Where ET_c can be estimated as follows:

$$ET_{c-meas}=P+I-D-R-\Delta S \qquad [12]$$

Where denotes measured ET_c, P represents rainfall, I refer to irrigation applied, D ET_{c-meas} is deep percolation or drainage below the rootzone, R is water runoff from the surface and lost to the plant and ΔS the change in soil water profile storage. All these variables are represented in units of mm water. The water balance method is deemed not the best choice for drip irrigated orchards according to Rana et al. (2005) and Testi et al. (2006) due to the discontinuous nature of the crop and difficulties associated with determining drainage and soil water content, however, K_c values still ought to be decreased in cases where water stress-resistant cultivars are employed, when cultivation incorporates plastic or organic mulch, soil enhancements, plastic tunnels, or other technologies that affect ET_c (Pereira et al., 2021) as in the case of drip irrigation, where R is negligible (Castel et al., 1987).

Many adjustments have been proposed to better adapt K_c values for citrus under specific conditions like local climate (Allen et al., 1998), fractional canopy cover and height (Allen et al., 1998, Allen and Pereira, 2009, Rallo et al., 2021), ground cover (Villalobos et al., 2009) and stomatal behaviour (Taylor et al., 2015), but little research have been done to relate K_c values to different irrigation systems and methodologies. With new advances in irrigation like low flow drip that is reported to have lower water usage than conventional irrigation systems, the question arises how should the current K_c values need to be adapted for more efficient systems in terms of K_t and K_e respectively?

CHAPTER 3: MATERIALS AND METHODS

3.1 Description of experimental site.

The study was conducted in a commercial orchard located 13 km north-east of Nelspruit, Mpumalanga Province (GPS-Coordinates: -25.426430°S 31.107073°E) from June 2021 to July 2023. The area is situated in the summer rainfall region of South Africa, with most of the precipitation occurring in mid-summer (January-February). The climate is mild and considered to be Cwb according to Köppen-Geiger climate classification with an average annual precipitation of 934 mm. (https://en.climate-data.org)

Figure 3.1 Positioning of the trial site within the commercial orchard.

The orchard was planted in 2006 with 'Nadorcott' mandarin (*Citrus reticulata)* grafted on 'Carizzo' Citrange rootstocks, at a spacing of 5.5 m x 2 m, totalling 909 trees per ha. The canopy was maintained at a height of 3.5 m and width of 3 m, with a hedgerow forming over time. The trees were planted on ridges (0.3 m in height) at an orientation of 30° West of North. The soil texture class was sandy loam with 6% clay, 11% silt, and 83% sand, which generally is considered a texture class with a low WHC. The orchard was originally irrigated with a double line of 1.6 L h^{-1} x 1 m pressure compensated drip irrigation system (Netafim, Uniram) which equals 3636 emitters per ha. Irrigation scheduling was done with AquaCheck sub-surface capacitance probes (AquaCheck Soil Moisture Management, Durbanville, South Africa). Scheduling was performed through a combination of field observations with a soil auger, probe trends, and theoretical volumes based on historical crop coefficient (K_c) and reference evapotranspiration (ET_o) values. These values were compared weekly and adjustments were made when both field observations and probes showed soil water content was outside the set norms for the phenological period (either too wet or dry), any discrepancies between field observation and probe data had to be investigated in field with profile holes. Therefore, the theoretical schedule only formed the initial plan and volumes could be either increased or decreased based on soil monitoring tools. Irrigation frequency was typically daily but could be twice a day in peak demand periods.

Other management practices included occasional mechanical hedging in December, as part of summer pruning and fruit thinning, where crop load had to be managed. Grass in the work row was mowed frequently, and no weeds or cover crop were present on the ridge. The orchard received an annual application of approximately 170-20-170 kg ha^{-1} of N, P, and K respectively, with fertilizer application starting in July, peaking in September, and ending in February.

A randomised trial design was laid out with five treatments and four replications of each treatment. Each replication consisted of ten trees, of which the three trees in the centre were used for measurements, ignoring the four "edge" trees on either side (Figure 3.2).

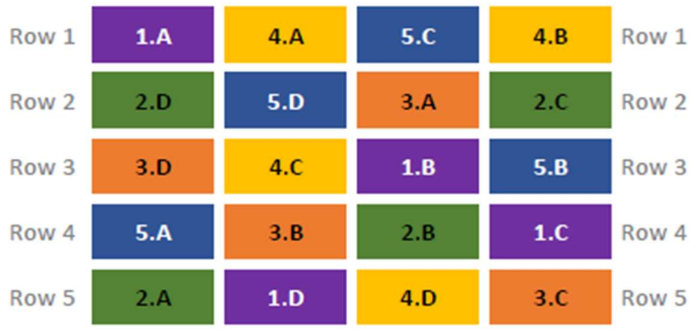

Figure 3.2 The randomised trial layout design for the different irrigation systems and different application volumes. Each replicate is indicated by letters A to D.

The treatments varied in:

1) Emitter delivery rates where treatments 1 and 2 were the "conventional" drip or industry standard and treatment 3 being the low flow drip (LFD) with an emitter delivery rate of less than 1 l h^{-1} and application rate of less than 4 m^3 ha^{-1} h^{-1} (Table 3.1).

2) Quantity of water applied with treatments 1-3 receiving 100% of crop evapotranspiration (ET_c) and treatments 4 and 5 receiving 20% and 40% less of ET_c respectively.

Table 3.1 Details of each treatment with regards to water regime, number of driplines, emitter delivery rate (L h^{-1}), emitter spacing (m), and system application rate (m^3 ha^{-1} h^{-1}).

Treatment no.	Water Regime	Drip lines	Emitter delivery rate (L h^{-1})	Emitter spacing (m)	System application rate ($m^3 ha^{-1}$ h^{-1})
1	ET_c	2	1.6	1.0	5.82
2	ET_c	2	2.3	1.0	8.36
3	ET_c	2	0.7	1.0	2.55
4	ET_c-20%	2	0.7	1.0	2.55
5	ET_c-40%	2	0.7	1.0	2.55

Treatments were programmed accordingly with a controller. (Netafim NMC Junior, Hatzerim, Israel). Irrigation was scheduled for treatments 1 to 3 using the same set of crop coefficients (K_c), resulting in each treatment being irrigated with the same volume of water, treatments 4 and 5 were irrigated with 20% and 40% less respectively. Crop evapotranspiration ET_c was estimated as:

$$ET_c = ET_o \, K_c \quad [1]$$

K_c values were used to relate ET_o values to ET_c and have been widely adopted by the agricultural community. The FAO-56 guidelines recommended K_c values for mature citrus trees with a ground cover of 70% range from 0.65 to 0.75 (Allen et al., 1998).These values were adjusted according to equation 2, where values for citrus without ground cover at 70% canopy coverage were used, where $K_{C\ ini}$; $K_{C\ mid}$; $K_{C\ end}$ values were 0.70, 0.65, and 0.70 respectively.

$$K_{C\ mid} = K_{c\ mid}\ (tab) + [0.04(u_2-2) - 0.004(RHmin-45)\left(\frac{h}{3}\right)^3 \quad [2]$$

The adjustment accounts for situations when minimum relative humidity (RH min) is less than 45% or when windspeed (u_2) is lower than 2 m s^{-1}. The weather data used to determine RH min and u_2 was from an automatic weather station within 100 m of the study site. The data set consisted of 7 years of hourly data, (**iLeaf,** integrated weather data interpretation software (http://www.**ileaf**.co.za/). All K_c values in Table 3.2 are for drip irrigated orchards with canopy volume providing 70% shaded cover. Months have been adjusted to southern hemisphere phenological dates.

Table 3.2 Adjusted FAO-56 monthly crop coefficient (K_c) values for the study area.

Month	Phenological Stage	FAO K_c Values (Allen et al., 1998)	Adjusted FAO K_c Values (Allen et al., 1998)
January	Cell enlargement	0.65	0.55
February	Cell enlargement	0.65	0.54
March	Cell enlargement	0.65	0.55
April	Colour break-Fruit maturation	0.66	0.55
May	Fruit maturation	0.68	0.58
June	Harvest	0.69	0.61
July	Harvest- Bud swell	0.70	0.67
August	Bud break-Pre bloom	0.70	0.67
September	Full bloom	0.69	0.66
October	Fruit set-Cell division	0.67	0.63
November	Fruit set- November drop	0.66	0.59
December	Cell enlargement	0.65	0.55

Daily ET_o was calculated using the FAO-56 Penman-Monteith equation (Allen et al., 1998) from weather data obtained from an automatic weather station (AWS) serviced by **iLeaf,** integrated weather data interpretation software (http://www.**ileaf**.co.za/). The AWS was located within 100 m of the orchards on an open stretch of mown lawn. The weather parameters recorded were windspeed, solar radiation, temperature, relative humidity, and rainfall. An additional tipping bucket rain gauge was installed beneath the canopy (Model TR-525I, Texas Electronics, Dallas, USA) in the centre of the ridge to determine canopy interception. For irrigation scheduling weekly ET_o forecasts from **iLeaf** were used to set up irrigation schedules. The weekly ET_c calculated for each treatment, was divided into equal daily irrigations which commenced at 06:00 am for all treatments and switched off accordingly. In treatment 4 and 5 irrigation volumes were reduced by 20% and 40% respectively. Scheduling for the week was done on Mondays, but due to changing forecasts schedules were later amended to every 4 days, based on updated forecasts.

3.2 Irrigation scheduling and quantification

To measure soil water content and to aid in irrigation scheduling, each treatment had an 80 cm AquaCheck sub-surface capacitance probe (AquaCheck Soil Moisture Management, Durbanville, South Africa). This was used to evaluate the irrigation regimes and to aid in the scheduling between rainfall events, where extraction should occur before irrigation commences again. Each treatment was irrigated from a separate 5000 L storage tank with fertilizer pre-mixed with fresh water i.e. stock solution. A flow meter (Model SF Fertilizer Meter, Netafim, Israel) was fixed at each tank to measure the total amount of water given to each treatment. Each treatment received the same amount of N-P-K in total, but at varying EC concentrations due to different amounts of water being applied, specifically to treatments 4 and 5. Fertilizers used were liquid ammonium nitrate (21% N), liquid calcium nitrate (15%N,18%Ca), and water-soluble potassium sulphate (42% K).

3.3 Soil water dynamics

3.3.1 Soil water distribution

To determine soil water distribution under the different emitter deliveries Teros-10 volumetric soil water sensors (Meter, Pullman, WA, USA) were placed in a grid design as illustrated in Table 3.3 in treatments 1, 2 and 3. These sensors were logged at an hourly interval using an AM16/32 B multiplexer and a CR1000 logger (Campbell Scientific Ltd, Logan, Utah, USA).

Table 3.3 Summary of Teros 10 volumetric soil moisture sensor placement coordinates. (0;0) represents the emitter. Distances are in cm.

Sensor	(X; Y)	Sensor	(X; Y)	Sensor	(X; Y)	Sensor	(X; Y)
1	(0; -10)	**6**	(15; -10)	**11**	(30; -10)	**16**	(45; -10)
2	(0; -20)	**7**	(15; -20)	**12**	(30; -20)	**17**	(45; -20)
3	(0; -30)	**8**	(15; -30)	**13**	(30; -30)	**18**	(45; -30)
4	(0; -40)	**9**	(15; -40)	**14**	(30; -40)	**19**	(45; -40)
5	(0; -60)	**10**	(15; -60)	**15**	(30; -60)	**20**	(45; -60)

3.3.2 Interpolation of volumetric content

Hourly readings of Teros 10 grid data were used to interpolate and illustrate soil water distribution under a dripper. Symmetry of the wetting pattern around the dripper was assumed, and values were "mirrored" for interpolation using Surfer® (Golden software). The method of interpolation used was Kriging. The vertical boundary (y-axis of interpolation area) was set at 60 cm below the soil surface and the horizontal boundaries (x-axis of interpolation area) 50 cm either side of the emitter. All interpolated values fell within the measured value range. The interpolated area was equal to 6000 cm^2 and with the aid of the measurement feature in Surfer®, the surface area between contours could be determined. The wetted area (cm^2) was represented by values of VWC > 0.13 cm^3 cm^{-3} and the area representing the readily available water (RAW) where values of VWC = 0.17- 0.21 cm^3 cm^{-3}.

3.3.3 Soil water balance

Volumetric water content θ readings were used to determine the total amount of water stored (S) in the root zone (mm). The four sensors readings at each depth or layer (x=0, 15, 30 and 45 cm from the dripper) were averaged to provide five readings. The thickness of the 10cm and 60 cm sensor's layer were 15 cm respectively with the

20cm, 30cm and 40cm layers being 10cm thick each, this total to 60cm over which S was calculated.

$$S= \sum_{i}^{n} \theta \times \Delta Z \qquad [3]$$

where S represents soil water storage (mm), *n* is the number of soil layers and ΔZ the thickness of each layer. These readings were compared with one another daily to create a soil water balance, the time of readings used was 05:00 am, when plant water uptake and drainage was complete from the previous day. It was also just prior to when the day's irrigation commenced. The water balance was calculated as proposed by Morgan et al. (2006)

$$ETc=- \Delta S+ I+P_c-D \qquad [4]$$

Where ET_c represents crop evapotranspiration, *I* effective irrigation from emitter (mm) l h^{-1} per m^2, P_c rainfall measurement from under the canopy (mm), D drainage and ΔS change in storage over two consecutive days at 05:00 am. The water balance and ΔS that was calculated represents a single emitter (Figure 3.3).

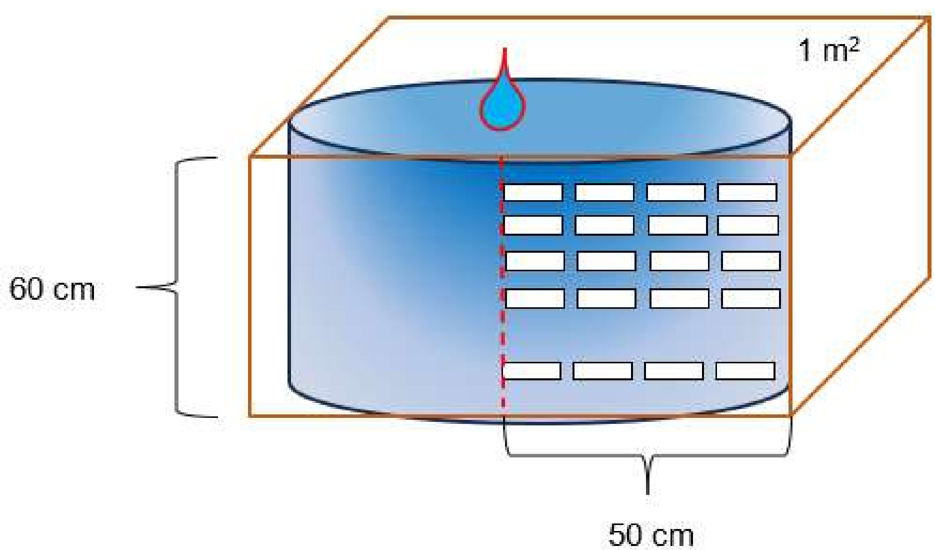

Figure 3.3 Schematic representation of the wetted volume for a single emitter considered for water balance calculations.

3.3.4 Soil matric potential (Ψsoil)

To determine the soil matric potential in the root zone, two dielectric water potential-based sensors (TEROS 21, Meter Pullman, WA, USA) were placed at 20 and 40 cm in treatments 1, 2, and 3. The proximity of the sensors to the emitter were aimed to simulate the capacitance probe placement (15-20 cm) and was done intentionally to compare values with a commercial irrigation scheduling tool. These values can also be compared to sensors 7 & 9 (at 20 cm and 40 cm depth and 15 cm distance from the dripper) of the Teros 10 volumetric sensors since matric potential and volumetric water content are related to one another.

3.3.5 Soil physical properties

Soil samples were taken at 20, 40 and 60 cm from a profile hole in the ridge between trees and sent in for texture analysis at an accredited laboratory (Labserve, Nelspruit, South Africa) (Table 3.4). An estimated water content at field capacity (-10 kPa) and wilting point (-100 kPa) was provided from the laboratory derived from a database of South African soils, which is their intellectual property and therefore the formula was not provided. Soil bulk density (*ρbulk*) was determined through physical sampling of undisturbed soil cores using a core sampler of a known volume. Samples were oven dried at 105 ˚C for 24 hours after which they were weighed again to determine (*ρbulk*).

Table 3.4 Physical soil analysis of the study area for samples taken at 0-20 cm; 20-40cm and 40-60 cm, indicating the 5 texture classes (%), stone fraction per volume basis ,volumetric water content in % at -10 kPa and -100 kPa, water holding capacity (WHC) mm/m and bulk density ρbulk (kg m^{-3}).

Depth	**Clay**	**Silt**	**Sand**	**Fine sand**	**Medium sand**	**Coarse sand**	**Stone (v/v)**	**-10 kPa**	**-100 kPa**	**WHC**	**ρbulk**
(cm)	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**mm/m**	**(kg m^{-3})**
0-20	6	11	83	38	24	22	6	22	12	98	
20-40	6	11	83	38	24	21	4	22	12	101	1517
40-60	6	7	87	42	24	21	3	21	11	102	

To validate or confirm the estimations of field capacity (FC), readily available water (RAW) and permanent wilting point (PWP) provided by Labserve and to determine VWC at other soil matric potentials a soil water characteristic curve was created using the Teros 21 sensor measurements of Ψ_{soil} and the corresponding VWC data from Teros 10 sensors (20cm). Water was withheld for a period for the soil to dry out and the hourly readings of both Ψ_{soil} and VWC were compared and with the aid of R software, *soilwater* package described by de Sousa et al. (2020) a characteristic curve was fitted based on the Van Genuchten (1980) equation in Figure 3.4. These values were compared with values in Table 3.4 and an average was used where there were multiple values (Table 3.5).

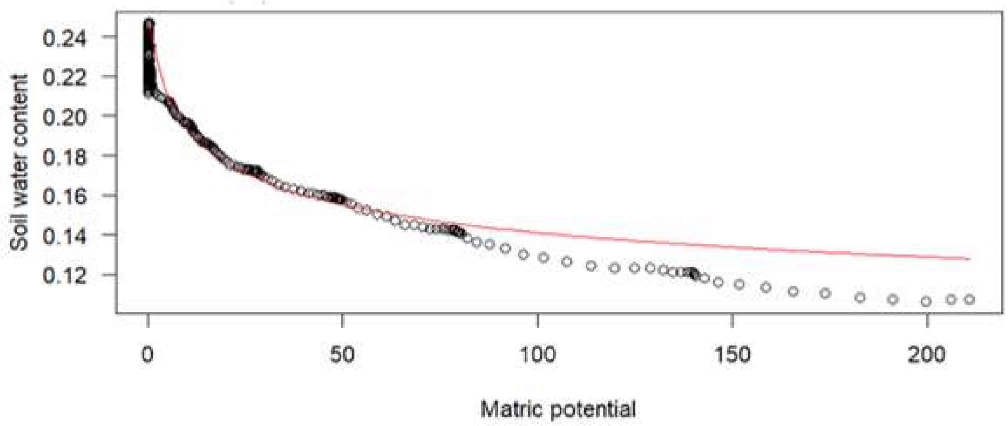

Figure 3.4 Soil water characteristic curve where volumetric soil water content ϴ (cm^3 cm^{-3}) (VWC) were plotted against soil matric potential (Ψsoil) (-kPa) with a fit line produced by R software- soilwater package.

Table 3.5 Values for soil matric potential (Ψ-soil) (-kPa) and corresponding volumetric water content ϴ (cm^3 cm^{-3}) as determined by R software- soilwater package and laboratory analysis. NA indicate where values where not provided.

(Ψ-soil) Soil matric potential (-kPa)	VWC ϴ (cm^3 cm^{-3}) R-*soilwater*	VWC ϴ (cm^3 cm^{-3}) Laboratory analysis	VWC ϴ (cm^3 cm^{-3}) Final averaged
-10KPA (Field capacity)	0.19	0.22	0.21
-30KPA (Readily available water)	0.17	NA	0.17
-60KPA	0.15	NA	0.15
-100KPA (Permanent wilting point)	0.14	0.12	0.13

3.3.6 In field volumetric water content sampling

Gravimetric water content was determined by taking samples in the same grid pattern as described in Table 3.3 and was done both parallel and perpendicular to the tree row to test the assumption of symmetry of the wetting pattern. Samples were weighed immediately after sampling (m_{wet}) then oven dried at 105 ˚C for 24 hours after which they were weighed again (m_{dry}) to determine gravimetric water content (θ_g) as described by Hillel (1980).

$$\theta_g = \frac{m_{water}}{m_{soil}} = \frac{m_{wet} - m_{dry}}{m_{dry}} \quad [5]$$

Soil bulk density ($\rho bulk$) was then used to calculate volumetric water (θ_v) for these samples, which is the volume of liquid per volume of soil.

$$\theta_v = \frac{Volume_{water}}{Volume_{soil}} = \frac{\theta_g * \rho_{soil}}{\rho_{water}} \quad [6]$$

The data was also interpolated with Surfer® and compared with Teros-10 data.

3.3.7 Quantification of drainage (D)

To determine drainage a passive wick lysimeter (Meter Drain Gauge G3®, Pullman, WA, USA) was installed in treatments 1, 2, and 3 at 40 cm, which was below the root zone. The passive wick lysimeter works by diverting downward-flowing infiltrated water into a collection reservoir and converting it to a mm reading. A Hydros 21 sensor (Meter Pullman, WA, USA) within the drain gauge was used to measure water depth, temperature, and electrical conductivity (EC). A Teros-10 volumetric soil water sensor (Meter, Pullman, WA, USA) was placed near the drain gauge at 60 cm depth to monitor when water moves past the root zone and drainage should be expected. These sensors were logged on an hourly basis using a ZL6 datalogger (Meter Pullman, WA, USA).

3.4 Ecophysiological measurements

3.4.1 Transpiration

The heat ratio method of the heat pulse velocity technique as described by Burgess et al. (2001) and (Taylor et al., 2015) was used to determine transpiration on six trees (two each from treatments 1, 2, 3, and 5) with more or less the same sized canopy.

In each tree trunk, four sets of custom-made heat pulse probes were carefully inserted at different depths (15, 20, 30, and 40 mm). This was done to consider the variation in sap flux within the conducting sapwood across the radius of the trunk. Each probe set consisted of two Type T thermocouples (made of copper and constantan) enclosed in polytetrafluoroethylene (PFTE) tubing with an outer diameter of 2.0 mm. The thermocouples were placed at equal distances (0.475 cm) both upstream and downstream of the heater probe, which was inserted into a brass collar measuring 2.5 mm. These probe sets were inserted between the rootstock and the scion, below the lowest branch, and were evenly spaced around the trunk. Care was taken to randomly arrange the probes and avoid any irregularities or abnormalities in the trunk. The heat pulse velocity (V_h) in cm h^{-1} for each probe set was calculated following Marshall (1958) as:

$$V_h = \frac{k}{x} \ln\left(\frac{v_1}{v_2}\right) * 3600 \qquad [7]$$

where k is the thermal diffusivity of green (fresh) wood (assigned a value of 2.5 x 10^{-3} cm^2 s^{-1} (Marshall, 1958)), x is distance in cm between the heater and either the upper or lower thermocouple, v_1 and v_2 are increases in temperature after the heat pulse is released (from initial temperatures) as measured by the upstream and downstream thermocouples and 3600 converts seconds to hours. Heat pulse velocities were measured and logged on an hourly basis using a CR1000 data logger and an AM16/32B multiplexer (Campbell Scientific Ltd, Logan, Utah, USA). Conversion of heat pulse velocities to sap flux densities, taking into account wounding, were performed according to Burgess et al. (2001). Wounding corrections were performed by using wounding coefficients *b, c*, and *d* obtained from a numerical model developed by Burgess et al. (2001) using the following equation:

$$V_c=bV_h+cV_h^2+dV_h^3 \qquad [8]$$

where V_c is the corrected heat pulse velocity. The functions describing the correction coefficients in relation to wound width (w) were as follows:

$$b=6.6155w^2+3.332w+0.9236 \qquad [9]$$

$$c=-0.149w^2+0.0381w-0.003 \qquad [10]$$

$$d=0.0335w^2-0.0095w+0.0008 \qquad [11]$$

The wound width was assumed to be equal to 0.44 cm based on the analysis of wounding in citrus by (Vahrmeijer et al., 2018).

The presence of heartwood was determined by taking wood cores with an incremental borer. These core samples were stained using safranin, with unstained areas being marked as non-conducting wood. Other wood characteristics, including sapwood moisture content (m_c) and density (ρ_b) were determined from additional core samples taken during the measurement period. Following the determination of m_c and ρ_b, sap velocity (V_s) was calculated from the corrected heat pulse velocity using the equation suggested by Marshall (1958) that was later modified by Barrett *et al*. (1995):

$$V_s=\frac{V_s\rho_b(c_w+m_c c_s)}{\rho_s c_s} \qquad [12]$$

where c_w and c_s are specific heat capacity of the wood matrix (1200 J kg^{-1}°C^{-1} at 20 °C (Becker and Edwards, 1999) and sap (water, 4182 J kg^{-1}°C^{-1}) at 20 °C (Lide, 1992), respectively, and ρ_s is the density of water (1000 kg m^{-3}). Volumetric flow for individual probes was calculated as the product of V_s and its cross-sectional area of conducting sapwood. Whole stem flux (Q) was calculated by means of a weighted average of heat pulse velocity with depth (Equation 11), as applied by Hatton *et al*. (1990).

$$Q=\pi\left[r_1^2*v_1+\left(r_2^2-r_1^2\right)*v_2+\left(r_3^2-r_2^2\right)*v_3+\left(r_4^2-r_3^2\right)*v_4\right] \quad [13]$$

where v_x is the heat pulse velocity measured by sensor x, placed between radii r_{x-1} and r_x. Integrated volumetric sap flow of the individual trees (l day^{-1}) was converted to transpiration (mm day^{-1}) using the ground area allocated to each tree in the orchard i.e. 11 m^2.

3.4.2 Stem and leaf water potential measurements

The most critical time for water application in the study area is August-October (Bud break-fruit set) where stress is not desired and accurate irrigation is critical. It was during this period that most of the water potential measurements were conducted. The absence of rain was important to ensure the values obtained were a reflection only of irrigation applied, however, the trial was conducted over two seasons with frequent rainfall events.

Pre-dawn water potential (ψ_{pd}) and midday stem water potential (ψ_{stem}) measurements were performed when rain was absent and clear skies and warm conditions prevailed. Pre-dawn (ψ_{pd}) measurements were done on three leaves close to the main stem of the three central trees (1 leaf per tree) of each replicate of each treatment. This totalled 60 leaves per round of measurements. Midday (ψ_{stem}) measurements were done on the same central tree as ψ_{pd} measurements by covering three similar leaves with aluminium foil covered bags one hour prior to solar noon. All measurements were done using a Scholander pressure chamber (Model 600, PMS Instrument Company, Albany, OR, USA).

3.4.3 Stomatal conductance

During the same periods when leaf water potential measurements were taken, stomatal conductance (g_s) mmol m^{-2} s^{-1}, were measured using a Li-600 porometer and fluorometer (Li Cor, Lincoln, Nebraska, USA) on the same trees as the water potential measurements, on three similar sun exposed leaves on the hour every hour when all visible moisture had evaporated from the foliage.

3.5 Yield analysis: quantity, size, and internal quality per treatment

Yield (kg $tree^{-1}$) from the three centre trees of each treatment were determined individually (including fruit count and size) for the season prior to the trial starting (2020-21) and the subsequent two season of the trial 2021/22 and 2022/23. Fruit quality characteristics were analysed from each sample tree (10 fruits per tree) of each replication of each treatment only for the 2022/23 season. This includes juice content, total soluble solids content (TSS); titratable acidity (TA); and colour. This was done by a quality control laboratory of a commercial citrus packhouse.

CHAPTER 4: SOIL WATER DYNAMICS UNDER DIFFERENT DRIP EMITTER DELIVERY RATES

4.1 Introduction

Drip irrigation is an efficient method of water application in agriculture, wherein water is applied directly to the root zone of plants in small, frequent doses (Brouwer, 1998, Fereres et al., 2003, Howell, 2003, Bryla et al., 2005). Soil water distribution under drip irrigation involves various factors that influence the movement and distribution of water within the soil profile, these factors include soil hydraulic properties, which are influenced by soil texture, organic matter content, soil structure and compaction

(Prasad and Pietrzykowski, 2020, Hillel, 1980). Besides the soil physical properties, other factors such as emitter placement (above or below the soil surface), emitter discharge rates and irrigation quantity and frequency, all influence the water distribution from a drip source (Gärdenäs et al., 2005).

Generally, water movement in the unsaturated zone (above the water table) is considered to be vertical, although large lateral components can exist (Radcliffe et al., 2002), with soil hydraulic properties and water content having the biggest influence on soil capillary forces that determine lateral water movement (Skaggs et al., 2010). Many studies have shown though that a decrease in application rate also results in an increase in the wetted volume around the dripper, in terms of horizontal to vertical spreading (Cote et al., 2003, Burt et al., 1997, Skaggs et al., 2010). Thus, by lowering emitter delivery rate and creating a larger wetted volume, deep percolation can potentially be decreased. This can potentially increase plant water uptake because of more water being available to the roots, due to a larger portion of the rootzone being wetted. It is important to understand that drip irrigation creates three-dimensional spheres or "reservoirs" and the shape of the wetting pattern (WP) has been described as a truncated-ellipsoid by (Elnesr and Alazba, 2017). The water content in these reservoirs can range from saturated conditions just below the emitter to permanent wilting point (PWP) around the edge or border of the sphere. (Hillel, 1980) and as a result it is much more difficult to determine plant available water (PAW) in the root zone of drip irrigated crops compared to full surface wetting.

Data presented in this chapter aims to illustrate how dripper application rate influences the amount of water stored in the root zone and how this corresponds to the crop water demand and usage over various time scales. This will ultimately test the hypothesis that the current FAO 56 crop coefficient (K_c) values are overestimated for low flow drip (LFD) systems.

4.2 Materials and methods

The materials and methods for this chapter are described in **Chapter 3.**

4.3 Results

4.3.1 Irrigation data

Despite the high rainfall and therefore periods of no irrigation, there were critical periods where rainfall was low (flowering & fruit set) in both the 2021/22 and 2022/23 seasons and irrigation was applied to meet crop evapotranspiration (ET_c) requirements. Total irrigation applied was lower in 2021/22 compared to 2022/23 (Table 4.1) even though the ET_o was similar at 1051 mm and 1063 mm respectively and higher rainfall was experienced in 2022/23 with 882 mm compared to 765 mm in 2021/22. This is mainly due to the quantity and distribution of rainfall, with smaller rainfall events evenly distributed across the summer and autumn months (October-May) in 2021/22, compared to the 2022/23 season when exceptionally high rainfall occurred in February, and the late summer and autumn period was dry (March-June) (

Figure ***4.1***).

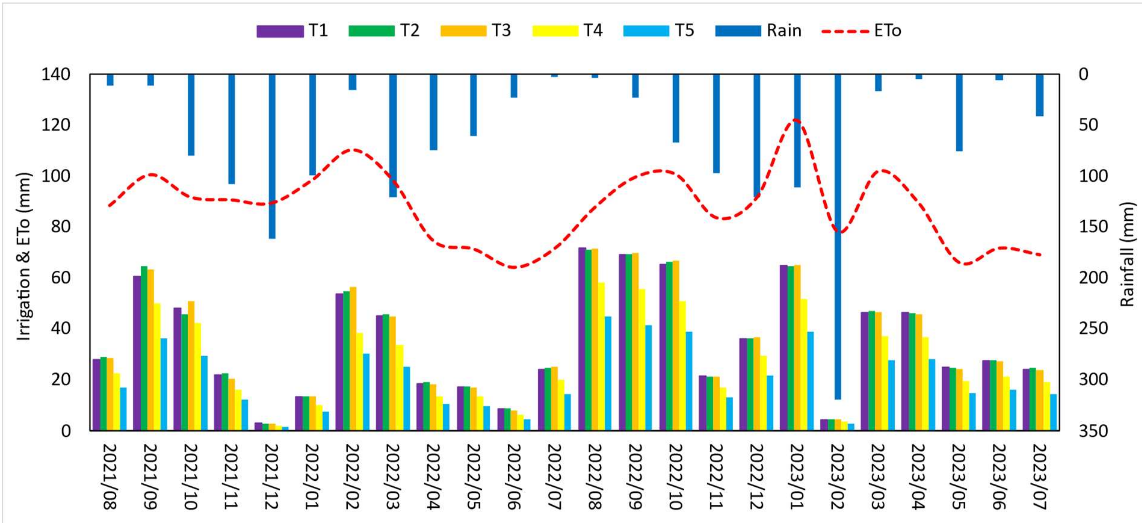

Figure 4.1 Monthly applied irrigation volumes (mm) for treatment 1 (1.6 l h^{-1}), treatment 2 (2.3 l h^{-1}), treatment 3 (0.7 l h^{-1}), treatment 4 (0.7 l h^{-1}, ET_c- 20%), and treatment 5 (0.7 l h^{-1}, ET_c- 40%), rainfall (mm), and reference evapotranspiration (ET_o) (mm) from August 2021 to July 2023.

Rainfall therefore supplemented crop water requirement more in the 2021/22 season compared to the 2022/23 season. To quantify the portion of precipitation falling on the root zone a tipping bucket rain gauge was placed under the canopy at a height of 40 cm (P_c). These values were recorded hourly and compared with the AWS readings (P) and applied irrigation (I) (Figure 4.2). The portion of rainfall reaching the surface beneath the canopy (P_c /P) was 66% and 65% for seasons 2021/22 and 2022/23 respectively. There are, however, other factors that weren't considered when determining effective rainfall, such as stem flow, runoff, and antecedent soil water content and thus it should be considered as an effective rainfall ratio. For both seasons rainfall started to accumulate considerably from November and plateaued off in June.

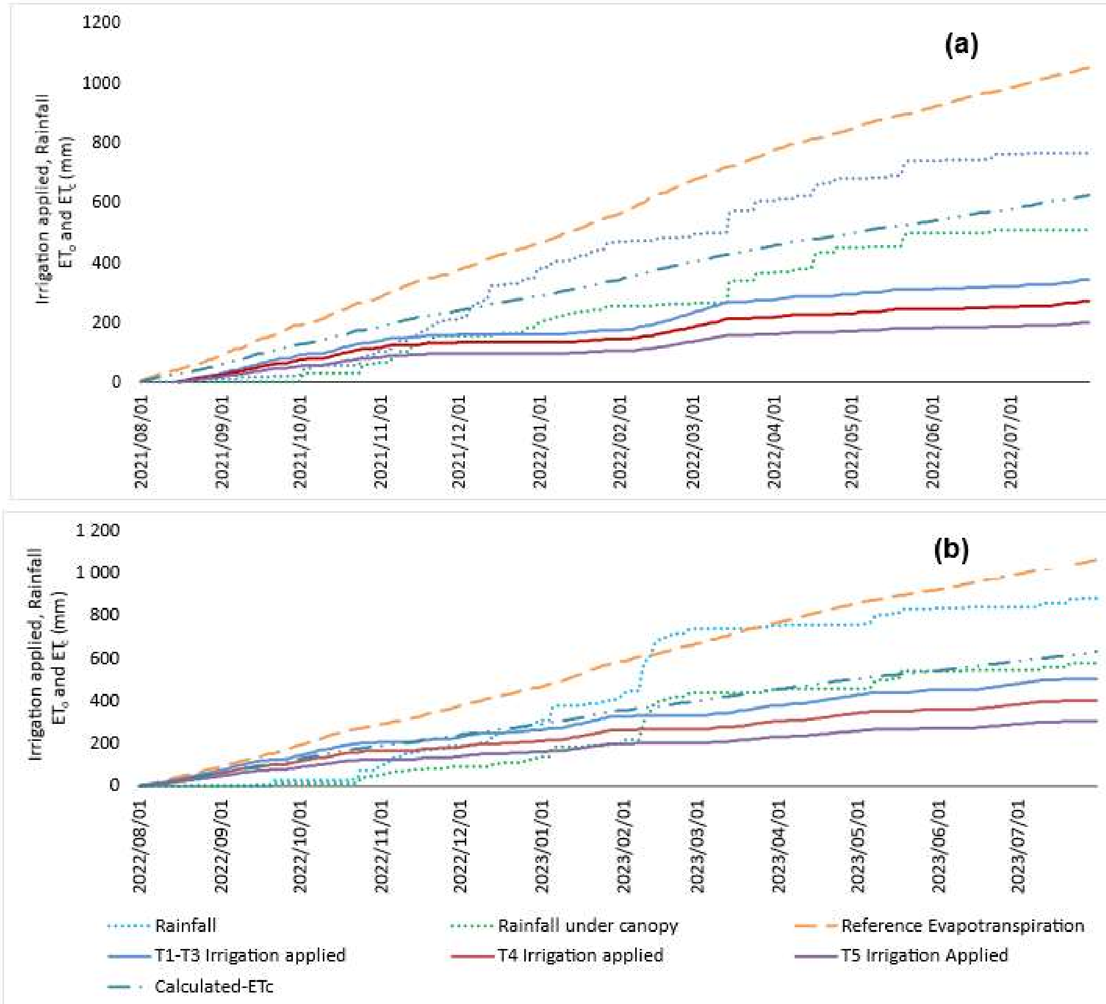

Figure 4.2 Cumulative values for reference evapotranspiration (ET_o) mm, rainfall (mm), rainfall measured under the canopy (mm), calculated crop evapotranspiration (ET_c) from adjusted FAO-56 crop coefficients (K_c), and irrigation applied (mm) for treatment 1 (1.6 l h^{-1}), treatment 2 (2.3 l h^{-1}), treatment 3 (0.7 l h^{-1}), treatment 4 (0.7 l h^{-1}, ET_c- 20%), and treatment 5 (0.7 l h^{-1}, ET_c- 40%) for the (a) 2021-22 season and (b) 2022-23 season.

If one considers P_c as a closer reflection of effective rain, the cumulative total does not exceed ET_c and ideally the irrigation applied should only supplement P_c and the total applied crop coefficient (K_c) should equal the theoretical K_c, as outlined in material and methods.

$$\text{Total } K_c = \frac{P_c + I}{ET_o} \quad [1]$$

Where P_c is the total rainfall under the canopy (mm), I total irrigation (mm) and ET_o is the total reference evapotranspiration. The season in this study ran from August to July. These values for the August 2020 to July 2023 period are summarized in Table 4.1. The theoretical required ET_c was calculated from adjusted K_c values from FAO-56 (section 3.2) and actual ET_o values recorded at the AWS. For the fully irrigated treatments (1-3) the total ET_c was 624 mm and 630 mm for 2021/22 and 2022/23 seasons respectively.

Table 4.1 Irrigation (I), rainfall (P), rainfall under the canopy (P_c), reference evapotranspiration (ET_o), rainfall contribution to irrigation P_{ci} (%), applied crop coefficient (K_c) (Applied K_c= I/ET_o), and total crop coefficient (K_c)(Total K_c= (P_c+ I)/ ET_o) summary for the treatments over a two-season period (August 2020 – July 2023).

Treatment	Season	*I* (mm)	*P* (mm)	P_c (mm)	ET_o (mm)	Applied K_c I/ ET_o	Total K_c P_c+ *I* /ET_o	P_{ci} (%) rainfall contribution to irrigation
T 1	2021/22	343	765	508	1051	0.33	0.81	60%
	2022/23	504	882	579	1063	0.47	1.02	53%
T 2	2021/22	350	765	508	1051	0.33	0.82	60%
	2022/23	506	882	579	1063	0.47	1.02	53%
T 3	2021/22	351	765	508	1051	0.33	0.82	60%
	2022/23	505	882	579	1063	0.47	1.02	53%
T 4	2021/22	271	765	508	1051	0.26	0.74	65%
	2022/23	402	882	579	1063	0.38	0.92	59%
T 5	2021/22	200	765	508	1051	0.19	0.67	72%
	2022/23	304	882	579	1063	0.29	0.83	66%

The total water applied (P+I) for the 2021/22 season was 1018 mm, however, when rainfall under the canopy was considered (P_c + I), the total water applied was significantly lower with a total of 851 mm. These values for the 2022/23 season were much higher with 1386 mm for P+I and 1083 mm for P_c + I. Although ET_c was much lower than the amount of rainfall reaching the rootzone (P_c), not all the rainfall received can be stored in the soil and utilized by trees and the need for supplementary irrigation was determined by soil water monitoring (capacitance probes). Irrigation scheduling was aimed at utilising rainfall optimally and only to commence irrigation again when the readily available water (RAW) of the rootzone was depleted. To normalise irrigation and rainfall values across seasons and to calculate the contribution of rainfall to irrigation (P_{ci}) with regards to ET_o, the applied K_c was expressed as a percentage of the total K_c.

$$P_{ci}(\%)=\left(1-\left(\frac{\text{Applied } K_c}{\text{Total } K_c}\right)\right)\times 100 \qquad [2]$$

The higher the percentage, the greater the utilization of rainfall for crop water requirements. Total K_c values for all treatments were higher in 2022/23 compared to 2021/22, which can be attributed to the less effective rainfall of 53% compared to 60% in the two seasons respectively. Due to the deficit applied to treatments 4 and 5, the contribution of rainfall to irrigation was much higher, and thus the reliance or utilisation of rainfall much greater.

4.3.2 Soil water response to irrigation

Irrigation for all the treatments was scheduled the same, with irrigation starting daily at 06:00 am and switching off according to the application rate and irrigation volume for each treatment, which depended on the calculated ET_c. The aim was not to keep the soil water within a certain range but rather to schedule according to the ET_c requirement and monitor the soil water and plant response because of the different rates of water delivery and deficit levels (treatments 4 & 5). The capacitance probes installed in each treatment were, however, useful in aiding scheduling between rain events, with the aim of allowing 30-40% extraction before irrigation was restarted. A capacitance soil water sensor measures soil water by assessing the change in capacitance caused by variations in the dielectric constant of the soil. These values are relative, and probes need to be calibrated for irrigation scheduling based on trends. In the context of probe graphs, field capacity (FC) represents 100% of relative water content and the refill point where readily available water (RAW) is depleted is generally accepted to be at 70% of field capacity for drip irrigation. This may differ between different probe management software interfaces.

Capacitance probes, especially with drip irrigation, are sensitive to 1) probe placement and positioning, and 2) the movement of the emitter and disturbances to the probe or soil surface around the probe. Probes do, however, still provide valuable data in terms of general soil water trends and the soil water responses to rain and irrigation (depth of wetting and drainage or extraction). For the duration of the trial, all the treatments were between FC and 70% RAW in the rootzone (Figure 4.3a) except for March and May 2023 when profiles were dried out after excessive rainfall and the commencement of irrigation was perhaps too late. The variation in soil water content in the buffer zone, the area below the active root zone, between treatments and across the two seasons is much more pronounced, however, the daily variation within a treatment showed lower variability (Figure 4.3b). Water from the higher delivery rate emitters more regularly reached the buffer zone compared to that of the LFD treatment, with average water content in the buffer zone for the duration of the trial for treatments 1 and 2 at 91% and 89% respectively, compared to treatment 3 at 84% (Figure 4.4). All these treatments received the same amount of water. For the deficit treatments 4 and 5, the average water content in the buffer zone was 83% and 79% respectively. When considering only the active rootzone, treatment 3 (0.7 l h^{-1}) had the highest average water content at 92% followed by treatment 4 (0.7 l h^{-1} -20%) and 5 (0.7 l h^{-1} -40%) at 88%, with treatment 2 (2.3 l h^{-1}) at 87% and finally treatment 1 (1.6 l h^{-1}) at 85%. The data from capacitance probes are valuable to provide inputs on general trends, but absolute values can be misleading and should be analysed in relation to other soil water measurement instrumentation.

Capacitance probes provide insight into only a small portion of the soil, and especially with drip irrigation, where individual reservoirs exist with varying water content within the reservoir, correct placement of capacitance probes is challenging, and the influence of positioning relative to the dripper will influence the data generated. These values are thus difficult to transfer between sites and experiments.

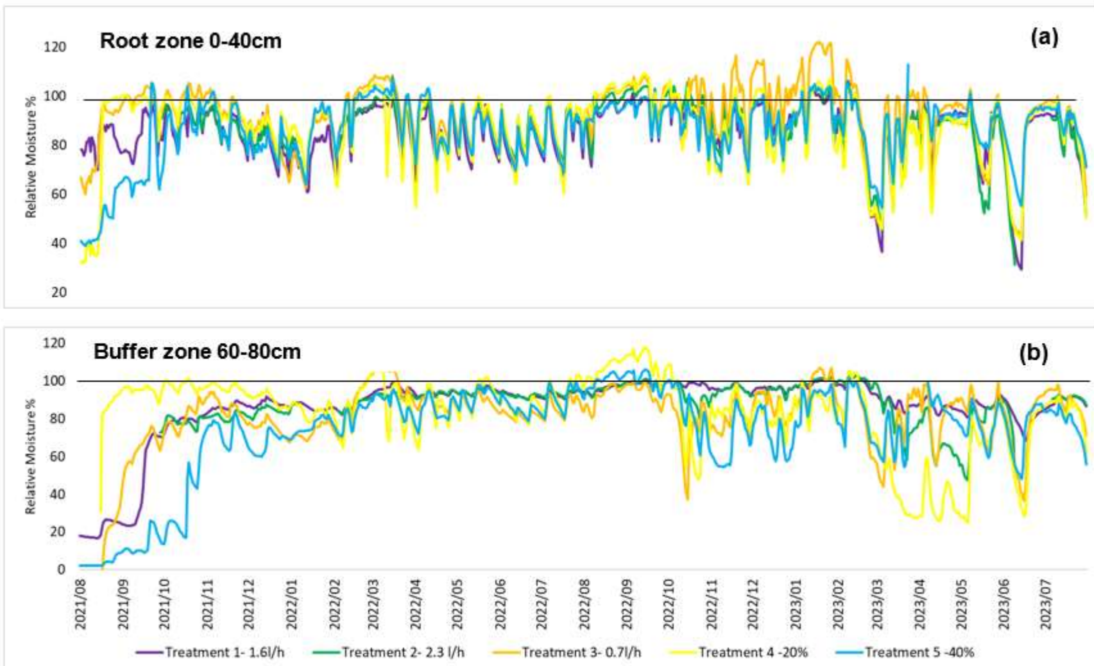

Figure 4.3 Daily average soil water data from Aquacheck capacitance probes for treatment 1 (1.6 l h^{-1}), treatment 2 (2.3 l h^{-1}), treatment 3 (0.7 l h^{-1}), treatment 4 (0.7 l h^{-1}, ET_c- 20%) and treatment 5 (0.7 l h^{-1}, ET_c- 40%) for the period August 2021-July 2023, for the (a) active root zone 0-40cm and (b) the buffer zone 60-80 cm. The line at 100% represents field capacity.

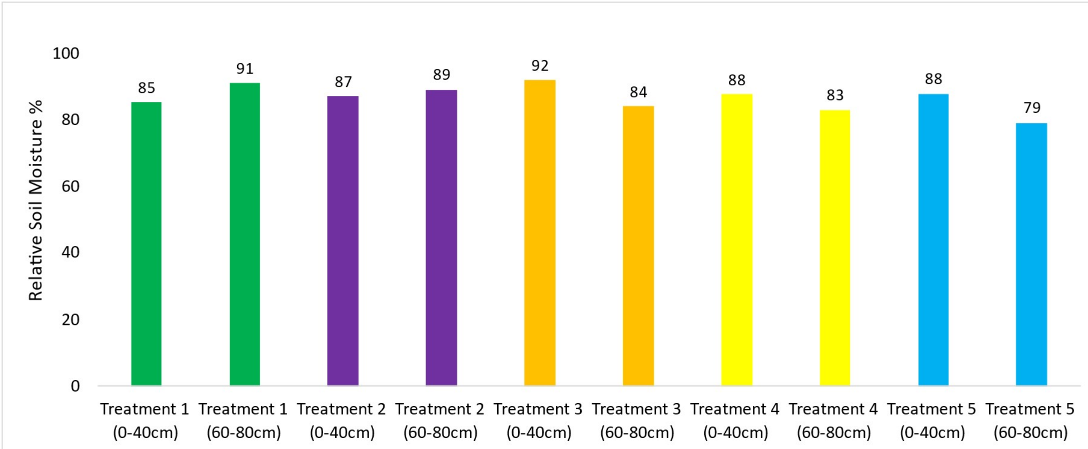

Figure 4.4 Average relative soil water content from Aquacheck capacitance probes for treatment 1 (1.6 l h^{-1}), treatment 2 (2.3 l h^{-1}), treatment 3 (0.7 l h^{-1}), treatment 4 (0.7 l h^{-1}, ET_c-20%) and treatment 5 (0.7 l h^{-1}, ET_c- 40%) for the period September 2021-July 2023 for the active root zone (0-40cm) and buffer zone (60-80cm) respectively.

4.3.3 Soil water storage

Periods where irrigation was the only water supplied (with no rainfall), were chosen to estimate the total amount of water stored in the root zone in treatments 1, 2, and 3 receiving 100% of ET_c. To determine the change in soil water storage (ΔS) subsequent day readings of total storage of the profile (0-60cm) at 05:00 am were compared. At this time, it was assumed that all water uptake by the tree and free drainage had taken place, and it was just prior to the next irrigation event commencing at 06:00 am. There were few periods where no rainfall occurred, and these periods rarely lasted more than 3 weeks. Large rainfall events contributed to soil water storage and sufficient drying-out time was required after these events to avoid saturated conditions and to allow trees to utilize rainfall until RAW had been depleted.

At the start of the period shown in Figure 4.5, total soil water storage in all three treatments were very similar to one another with no difference between them. From 2021/10/11 to 2022/10/18 daily irrigation applied was 7.45 mm per emitter or 2.7 mm ha ^{1}.

Soil water storage increased for all 3 treatments over this period with treatment 3 showing the largest increase. A malfunctioning pump on treatment 2 on 2021/10/18 halted irrigation prematurely and a decrease in storage was observed for this day. The schedule was adjusted downwards according to the ET_o forecast to 5.4 mm per emitter or 1.99 mm ha^{-1} daily from 2021/10/19 to 2021/10/24, after which rain occurred and irrigation was halted. The sudden drop in actual ET_o values from 17/10/2021 to 19/10/2021 could perhaps have contributed to the subsequent increase in storage, especially in treatment 3, as ET_c was overestimated. Throughout the trial ET_o forecast accuracy was challenging with predictions generally overestimating actual ET_o.

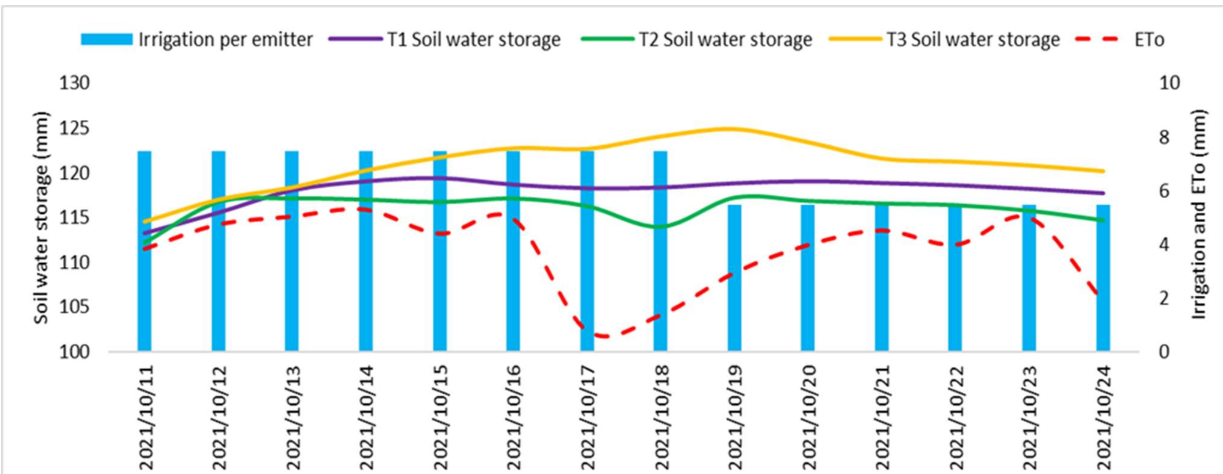

Figure 4.5 Daily average profile water storage (0-60cm) at 05:00 am for treatment 1 (1.6 l h^{-1}), treatment 2 (2.3 l h^{-1}), treatment 3 (0.7 l h^{-1}), irrigation applied per emitter (mm), and daily reference evapotranspiration (ET_o) (mm) for the period 2021/10/11 to 2021/10/24.

Irrigation was scheduled on a weekly basis, and applied K_c was calculated over the same period (Figure 4.6). The applied K_c value for the period 2021/10/11 to 2021/10/17 was 0.67 and a total increase in profile soil water storage of 5.09 mm, 4.08 mm, and 8.11 mm was measured for treatments 1, 2, and 3 respectively. The downward adjustment in irrigation volume from 19 – 24 October 2021 resulted in a decrease in soil water storage in this period, with an applied K_c value of 0.54 and a total decrease in soil water storage of 1.12 mm, 2.53 mm, and 4.68 mm for treatments 1,2 and 3 respectively. The average K_c for the entire period was 0.64 with a total increase in soil water storage of 4.53 mm, 2.50 mm, and 5.63 mm for treatments 1,2, and 3 respectively. Data collected from the drain gauge installed at a depth of 40 cm, indicate the amount of water (mm) that moved past the active root zone (0-40 cm), where 80% of the roots were concentrated. An emitter was placed directly above the drain gauge position, but a portion of water may still have moved passed the cylinder. Treatment 3 had the lowest drainage, with a total of 2.1 mm, followed by treatment 2 with 5.2 mm and treatment 1 with double the amount of drainage at 10.4 mm collected over the period. Important to note that this is not directly correlated to soil water storage in Figure 4.5 since storage was calculated over 60 cm.

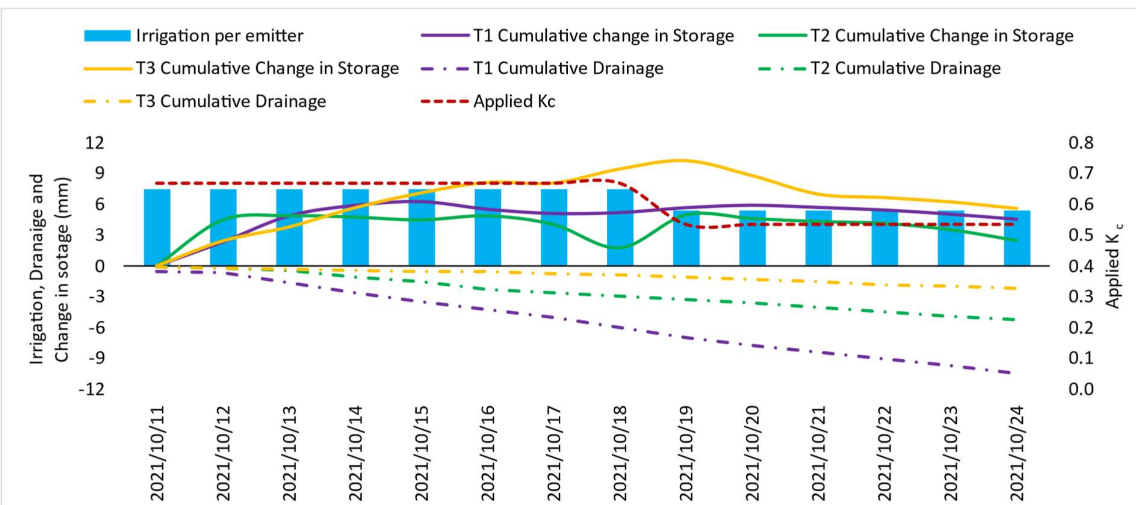

Figure 4.6 Daily applied irrigation per emitter (mm), cumulative change in soil water storage (ΔS) (mm) and cumulative drainage (D) (mm) for treatment 1 (1.6 l h^{-1}), treatment 2 (2.3 l h^{-1}), treatment 3 (0.7 l h^{-1}), and the average applied crop coefficient (K_c) for the period 2021/10/11 to 2021/10/24.

The daily change in storage in Figure 4.7, Illustrates how soil water storage changes over the course of a day with regards to the hourly irrigation applied (mm) and ET_o

(mm). A period where irrigation volumes did not vary and ET_o was constant (2021/10/10 - 2021/10/17) was used to calculate average hourly readings for all parameters involved. The biggest variation or change in soil water storage was in treatment 2, followed by treatment 1 and then treatment 3, which maintained the most constant soil water storage over the course of a day. This illustrates that the higher the emitter delivery rate, the greater the change in soil water storage as result of an irrigation application, with both the maximum and minimum storage values being influenced by delivery rate.

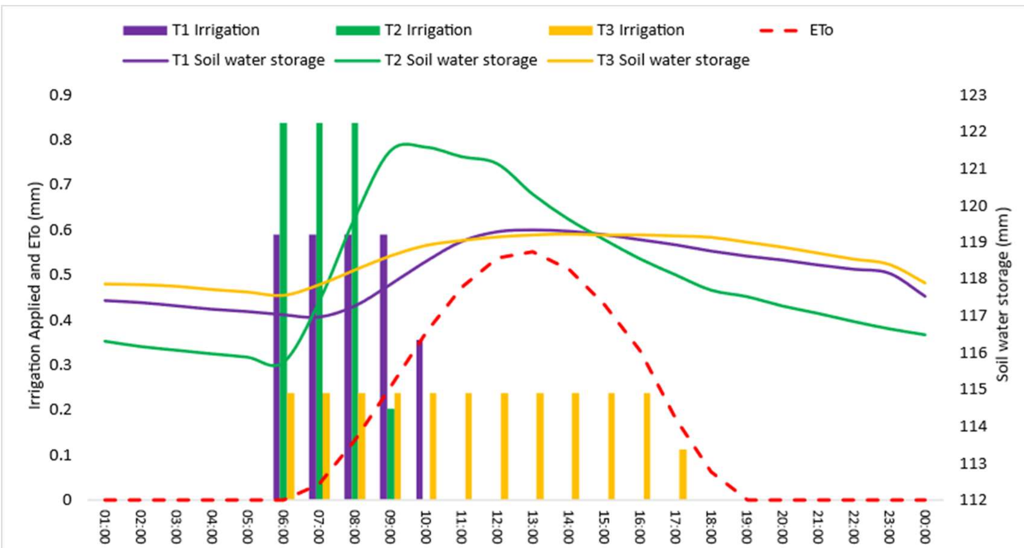

Figure 4.7 Average hourly irrigation applied (mm) for treatment 1 (1.6 l h^{-1}), treatment 2 (2.3 l h^{-1}), treatment 3 (0.7 l h^{-1}), evapotranspiration (ET_o) (mm) and soil water storage (mm) for 10/10/2021 to 17/10/2021.

In the 2022/23 season irrigation resumed after system maintenance (end of July) when soil profiles dried out slightly. Treatment 2 had the lowest soil water storage at 105 mm at the start of the period 2022/08/11-2022/09/05 compared to treatments 1 and 3 at ~ 113mm (Figure 4.8). The irrigation schedule started initially with 6.55 mm per emitter or 2.4 mm ha^{-1} scheduled daily. From 2022/08/17 irrigation volumes were increased to 7.6 mm per emitter or 2.7 mm ha^{-1} for the rest of the period in Figure 4.8. The average ET_o for the period was 3.2 mm per day, with 2022/08/19 and 2022/08/30 having exceptionally low ET_o values of 1.6 mm and 0.8 mm respectively. Soil water storage increased in all 3 treatments over this period with all 3 treatments ending with the same soil water storage of ~120 mm.

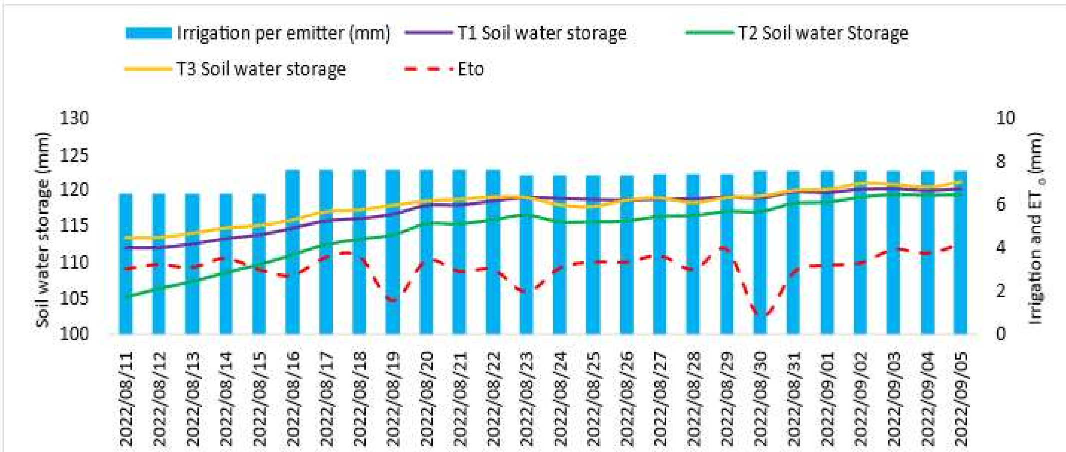

Figure 4.8 Daily average profile water storage (0-60cm) at 05:00 am for treatment 1 (1.6 l h^{-1}), treatment 2 (2.3 l h^{-1}), treatment 3 (0.7 l h^{-1}), irrigation applied per emitter (mm), and daily reference evapotranspiration ET_o (mm) for the period 2022/08/11 to 2021/09/05.

The increase in soil water storage in the August 2022 period is evident in Figure 4.9 where treatment 2 had the largest increase over the period with a total of 14.23 mm or an average of 0.54 mm per day. Treatments 1 and 3 had a total increase of ~ 8 mm or 0.3 mm per day. This contradicts findings during October 2021 (Figure 4.6) where the largest increase in storage was found in treatment 3 and the lowest increase in treatment 2. The theoretical or targeted K_c for this period was 0.67, the actual applied K_c was initially 0.73 from 2022/08/11-15 after which the irrigation volume was increased, based on ET_o forecasts, resulting in the applied K_c being 0.86 for the remainder of this period, notably higher than the target K_c. Data collected from the drain gauge (Figure 4.9) showed that treatment 3 (0.7 l h^{-1}) had almost no drainage with a total of 0.52 mm over the period, followed by treatment 1 (1.6 l h^{-1}) with 6.97 mm and the highest drainage measured in treatment 2 (2.3 l h^{-1}) with 10.4 mm collected over the period. It is important to note that drainage was collected at 40cm, whilst storage was calculated over 60 cm, and that these two figures were directly correlated to one another.

The average hourly storage for the period 2022/08/30- 2022/09/05 (Figure 4.10) yielded similar results to the October 2021 period (Figure 4.7), with treatment 2 (2.3 l h^{-1}) again displaying the biggest difference between daily maximum and minimum soil water storage, however, unlike in October 2021 (Figure 4.7) treatment 3 (0.7 l h^{-1}) followed and then treatment 1 (1.6 l h^{-1}) with the smallest change in soil water storage. The minimum soil water storage values for treatment 3 were again the highest of all three treatments, as also observed in October 2021 (Figure 4.7).

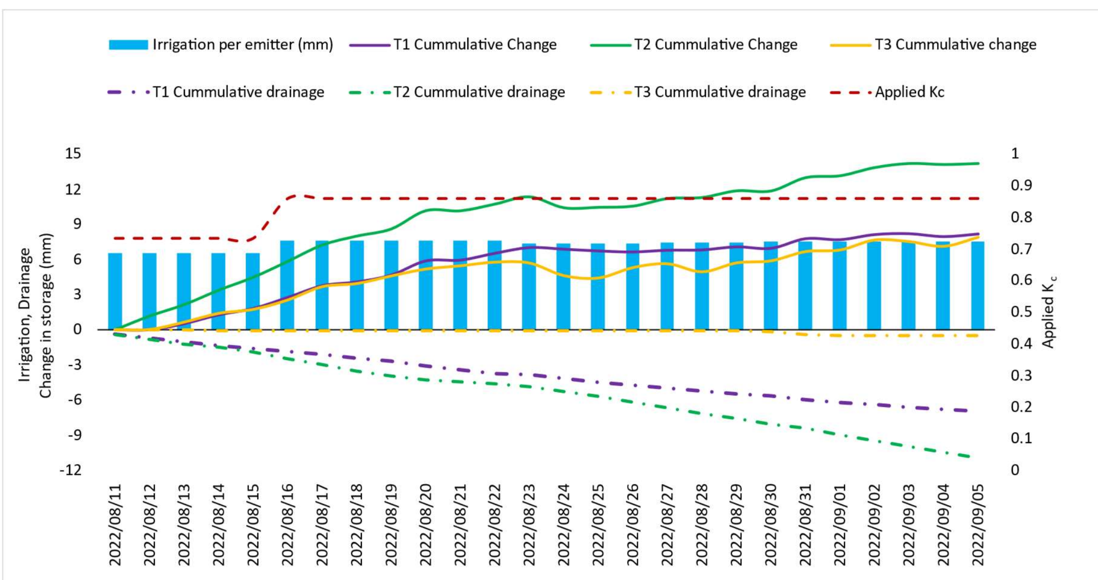

Figure 4.9 Daily applied irrigation per emitter (mm), cumulative change in soil water storage (mm) for treatment 1 (1.6 l h^{-1}), treatment 2 (2.3 l h^{-1}), treatment 3 (0.7 l h^{-1}), and the average applied crop coefficient (K_c) for the period 2022/08/11 to 2022/09/05.

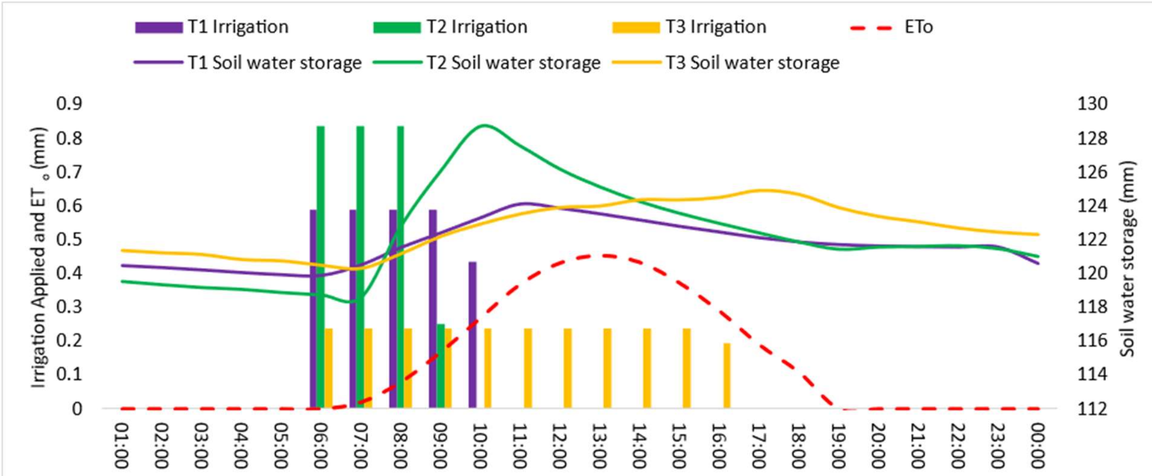

Figure 4.10 Average hourly irrigation applied (mm) for treatments 1 (1.6 l h^{-1}), treatment 2 (2.3 l h^{-1}), treatment 3 (0.7 l h^{-1}), reference evapotranspiration (ET_o) (mm), and soil water storage (mm) for the period 2022/08/30 to 2022/09/05.

The final period that was evaluated was from 2023/04/11 to 2023/04/26 (Figure 4.11) where the soil profiles were overall drier compared to the periods in October 2021 (Figer 4.5) and August 2022 (Figure 4.8). As with the October 2021 period (Figure 4.5) initial soil water storage was the same for all 3 treatments ~ 86 mm, after which soil water storage remained relatively constant for the duration of this period. Initially, irrigation applied per day was 4.8 mm per emitter or 1.8 mm ha^{-1}, whereafter on 2023/04/15 it increased to 5.7 mm per emitter or 2 mm ha^{-1}. The average ET_o over this period was 3.1 mm per day, with consistent values, apart from 2023/04/15 with an ET_o of 1.5mm.

The largest increase in soil water storage was observed in treatment 3 (Figure 4.12), with a total increase of 8 mm compared to 0.5 mm and 1.7 mm for treatments 1 and 2 respectively. This agrees well with data from the October period (Figure 4.6). The theoretical or target K_c for this period was 0.55, the applied K_c from 2023/04/11 to 2023/04/16 was 0.57, which was very close to the target. On 2023/04/17 the irrigation schedule was adjusted, and the K_c increased to 0.64 on 2023/04/17 and again to 0.73

on 2023/04/23. The average K_c for the entire period was 0.63, which was slightly higher than the targeted 0.55.

The average hourly storage for the period 2023/04/11- 2022/04/26 (Figure 4.13) showed similar results to the October 2021 period (Figure 4.7), with treatment 2 (2.3 l h^{-1}) again having the biggest difference between daily maximum and minimum soil water storage, followed by treatment 2 (1.6 l h^{-1}), with treatment 3 (0.7 l h^{-1}) showing the smallest change in soil water storage. As in the previous periods, the minimum soil water storage values for treatment 3 were again the highest of all three treatments, however, unlike the previous periods the maximum soil water storage values for all treatments were much closer to one another, with maximum treatment 2 values only slightly higher than treatment 3.

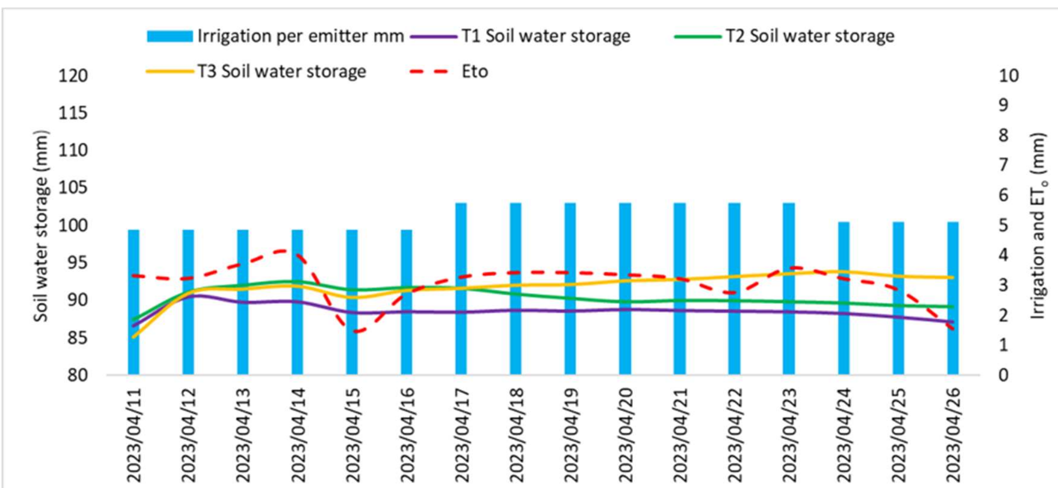

Figure 4.11 Daily average profile water storage (0-60cm) at 05:00 am for treatment 1 (1.6 l h^{-1}), treatment 2 (2.3 l h^{-1}), treatment 3 (0.7 l h^{-1}), irrigation applied per emitter (mm), and daily reference evapotranspiration ET_o (mm) for the period 2023/04/11 to 2023/04/26.

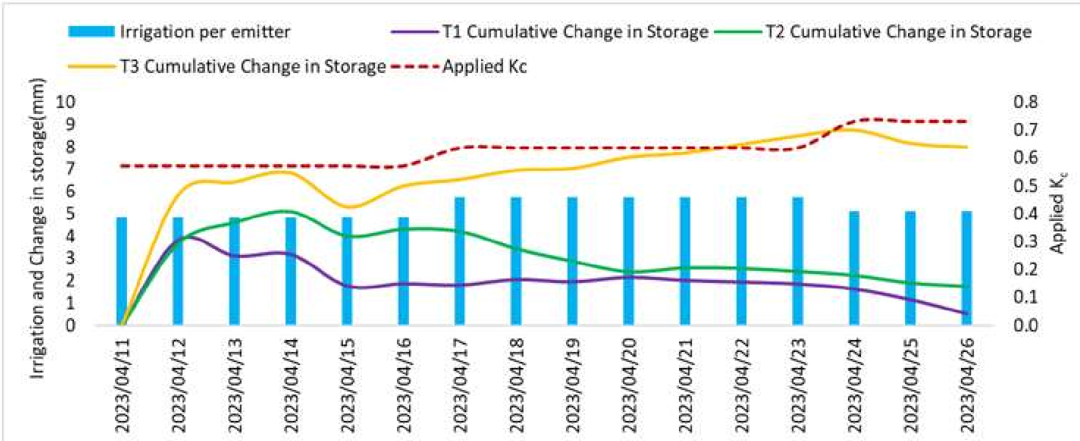

Figure 4.12 Daily applied irrigation per emitter (mm), cumulative change in soil water storage (mm) for treatment 1 (1.6 l h^{-1}), treatment 2 (2.3 l h^{-1}), treatment 3 (0.7 l h^{-1}), and the average applied crop coefficient (K_c) for the period 2023/04/11 to 2023/04/26.

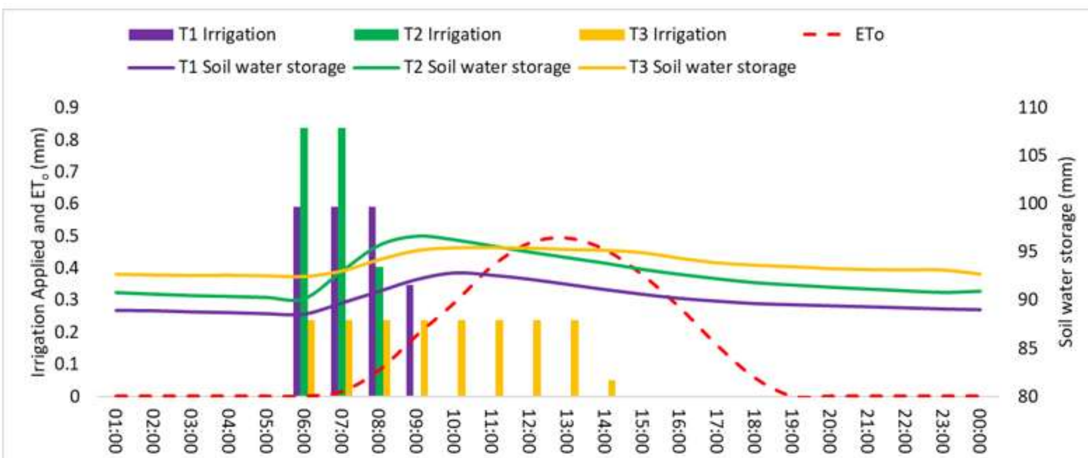

Figure 4.13 Average hourly readings for irrigation applied (mm) for treatment 1 (1.6 l h^{-1}), treatment 2 (2.3 l h^{-1}), treatment 3 (0.7 l h^{-1}), evapotranspiration (ET_o) (mm), and soil water storage (mm) for the period 2023/04/17 to 2023/04/23.

4.3.4 Soil water distribution

From the preceding section, it was evident that the amount of water stored in the designated rootzone (0-60cm) varied with emitter delivery rate. Volumetric soil water content (VWC) (Θ) and soil water storage (S) (mm) are interconnected, but the primary distinction lies in the fact that soil water storage is associated with a particular depth or soil layer (Z), while volumetric measurements can be taken at specific points. Consequently, when assessing VWC from each Teros 10 sensor individually, valuable insights were gained into how water was distributed within a specific reservoir, in relation to the emitter's position. To better understand the variation within the reservoir and how it changes over time, the Teros 10 sensor data was interpolated with the aid of Surfer® (Golden software), using the Kriging interpolation method (Figure 4.14). This was done by averaging the daily VWC for treatments 1,2 and 3 for the 2021-22 season (Figure 4.14 a, b, and c) and the 2022-23 season (Figure 4.14 d, e, and f). There was no clear pattern of water distribution present between treatments 1, 2, and 3, however, there are similarities between seasons for wetting pattern for each treatment. In treatment 1 there was a widening of the wetted area from 40-50 cm depth that had a high VWC close to FC ~ 0.21 cm^3 cm^{3}, and higher in both seasons (Figure 4.14 a and c). There was another zone of high VWC that was present just below the emitter at a depth of 10 cm, which ranged between saturation and FC. A similar zone of high VWC was present in treatments 2 and 3. In treatment 2 (Figure 4.14 b and d) it was present between 30 cm and 60 cm, but in treatment 3 it was concentrated between 0 and 30 cm (Figure 4.14 c) but did reach 60 cm (Figure 4.14 f). The interpolated surface area represents the cross-sectional area under a single emitter up to a depth of 60cm, which is the designated rooting depth and where the deepest Teros-10 sensors were placed, this equated to 6000 cm^2 (100 cm x 60 cm). The term wetted area in this study refers to the area where VWC > 0.13 cm^{3} cm^{-3} which represents permanent wilting point (PWP) and is regarded as the lower limit of plant available water (PAW) and therefore any value higher can be utilised by the plant. For the 2021/22 season, VWC for the entire interpolated area was on average higher than PWP (0.13 cm^{3} cm ^{3}), however, the portion of the area where water was readily available (0.17-0.21 cm^{3} cm ^{3}) differed between treatments, with treatment 2 having the lowest average area of RAW at 50%, followed by treatment 3 at 62%, with treatment 1 with having the largest area of RAW at 68%. The following season (2022/23) the average wetted area decreased for treatments 1 and 3 to 92% and 86% respectively with treatment 2 remaining at 100%, the opposite was observed when comparing area of RAW with treatment 3 having the largest area of RAW at 45% followed by treatment 1 at 44% with treatment 2 having the smallest area of RAW at 49%. The values in Table 4.2 and Figure 4.14 are averages for the entire season and do not distinguish between rainfall and irrigation. It is important to distinguish between the effect of irrigation on VWC and rainfall and how VWC changes seasonally.

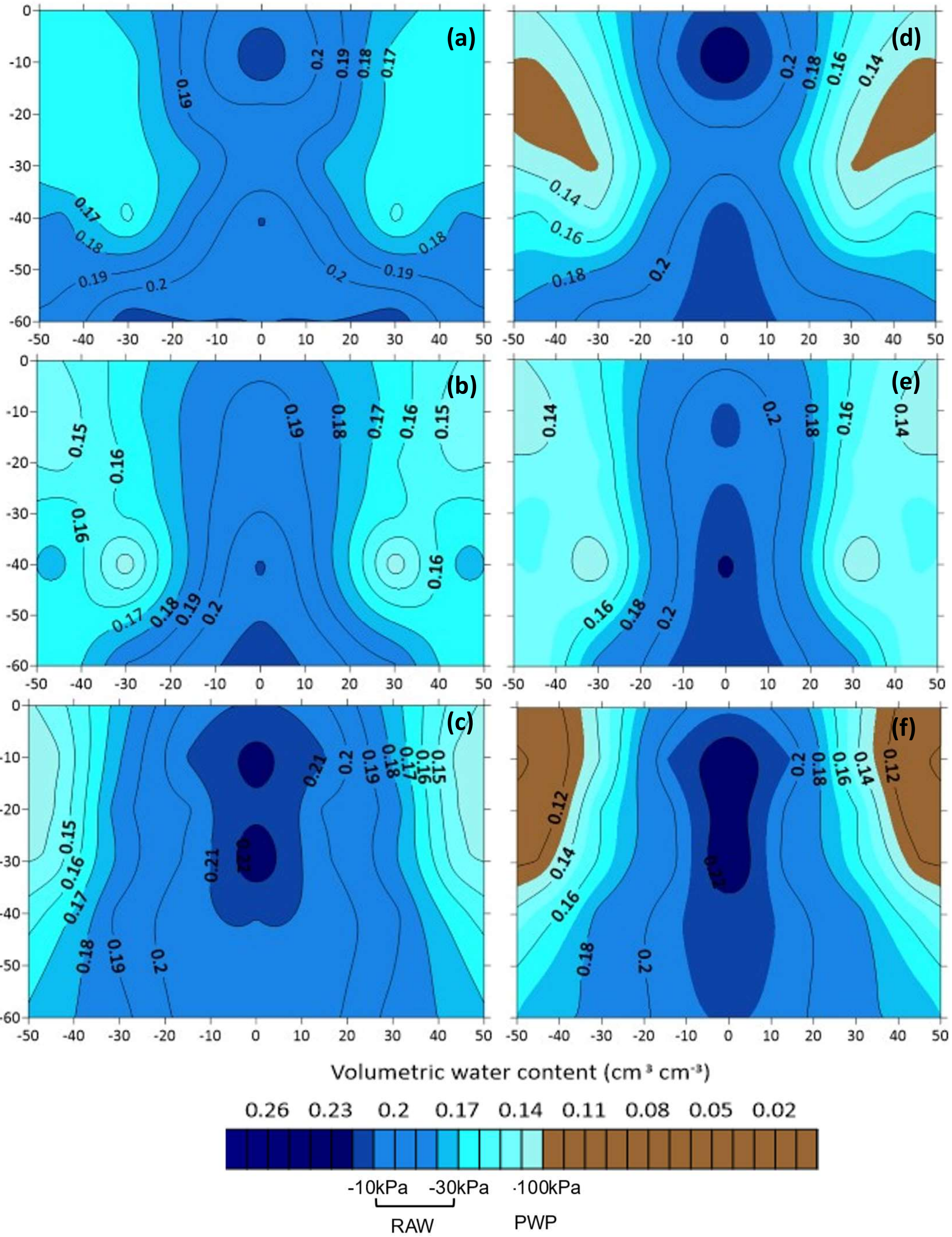

Figure 4.14 Interpolated daily average volumetric water content values (cm^3 cm^{-3}) using Surfer® from Teros 10-Sensors placed in a grid format. The data presented is for the 2021-22 season (a) treatment 1 (1.6 l h^{-1}), (b) treatment 2 (2.3 l h^{-1}) and (c) treatment 3 (0.7 l h^{-1}) and 2022-23 season (d) treatment 1 (1.6 l h^{-1}), (e) treatment 2 (2.3 l h^{-1}) and (f) treatment 3 (0.7 l h^{-1}). Season period is from August to July. RAW refers to readily available water.

Table 4.2 The average wetted area (cm^2) determined by Surfer® where volumetric water content (VWC) was > 0.13 cm^3 cm^{3} and the area of readily available water (RAW) (cm^2) where VWC = 0.17-0.21 cm^3 cm^{3} for treatment 1 (1.6 l h^{-1}), treatment 2 (2.3 l h^{-1}) and treatment 3 (0.7 l h^{-1}), for the 2021/22 and 2022/23 seasons.

Treatment	Season	Total Interpolated Surface (cm^2)	Wetted Area (cm^2) (VWC > 0.13 cm^3 cm^{-3})	Wetted % of Total Area	RAW Area (cm^2) (VWC =0.17-0.21 cm^3 cm^{-3})	RAW % of Total Area
T1	2021/22	6000	6000	100%	4056	68%
T2		6000	6000	100%	3019	50%
T3		6000	6000	100%	3733	62%
T1	2022/23	6000	5514	92%	2655	44%
T2		6000	6000	100%	2317	39%
T3		6000	5151	86%	2673	45%

In order to achieve this the average VWC of all four sensors in the (x-plane) (0 cm ,15 cm ,30 cm,45 cm) at each depth (y-plane) (10 cm, 20 cm, 30 cm, 40 cm and 60 cm) was determined (Figure 4.15) for the 2021-22 and 2022-23 seasons. This data was divided into spring and summer (September – February), that represents the rain season or period of high rainfall (Figure 4.15a and c) and autumn and winter (March-August) that represents the dry season or low rainfall period (Figure 4.15b and d). This was done to illustrate the influence of rain on VWC in the reservoir and to show the influence of irrigation in the absence of rainfall or only during light rainfall events.

In both the 2021-22 and 2022-23 seasons there was a difference in VWC between the high rainfall period and the low rainfall period, which is expected considering the frequency of rainfall events that replenished or supplemented the VWC in the reservoirs. In both seasons the standard deviation is greater at 0-30 cm in the profile compared to 40-60 cm, which suggests most changes in soil water content occurred in this zone due to irrigation events, rainfall, root uptake and evaporation. In Figure

4.15 a and c, that represents the period of high rainfall (September-February), treatment 3 (LFD) had the lowest average VWC at 60 cm followed by treatment 2 and then 1. Similarly, in Figure 4.15 b and d, the low rainfall period (March-August), treatment 1 had the highest average VWC, followed by treatment 3 and treatment 2 with similar values. The standard deviation in Figure 4.15 b and c suggests there could be significant differences between treatment 1 compared to treatments 2 and 3 at 60 cm depth.

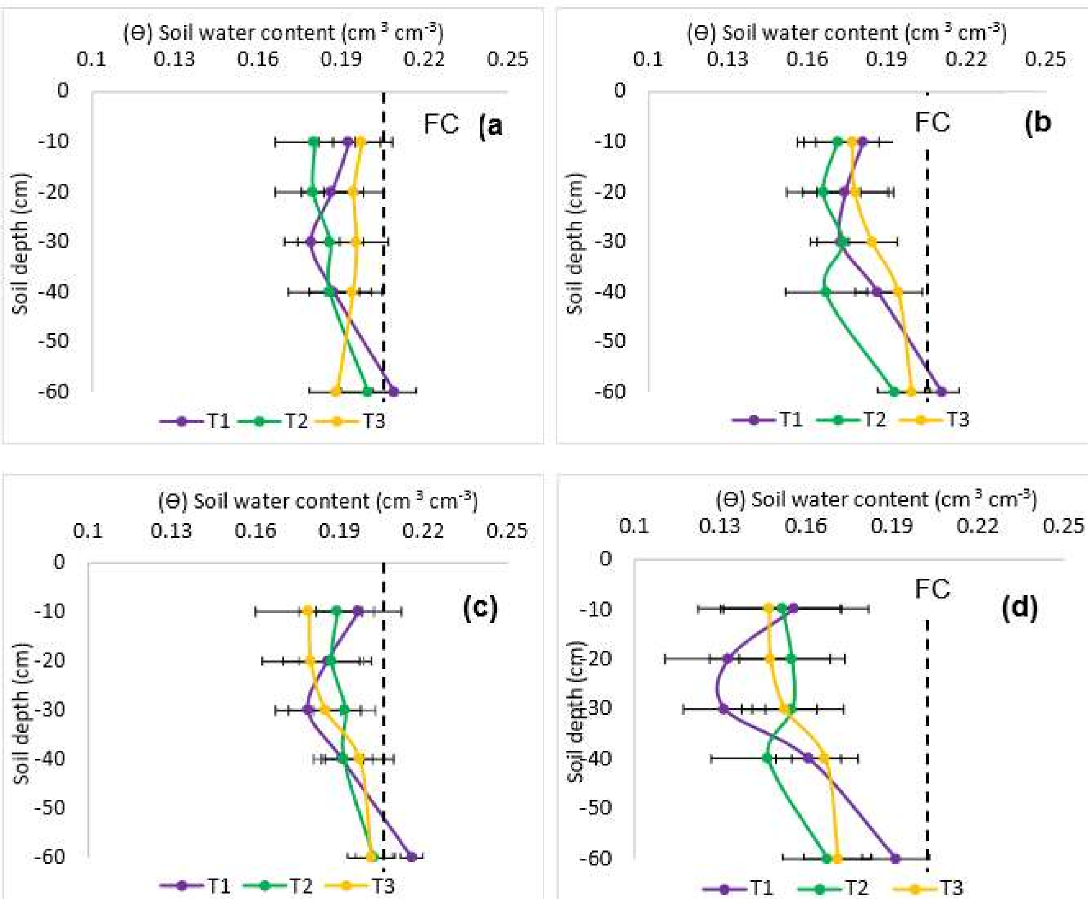

Figure 4.15 Average volumetric water content Θ (cm^{-3} cm^{-3}) at various depths (cm) for treatment 1 (1.6 l h^{-1}), treatment 2 (2.3 l h^{-1}) and treatment 3 (0.7 l h^{-1}) for the 2021-22 and 2022-23 seasons for the high rainfall period (a) and (c) (September-February) and low rainfall period (b) and (d) (March-August). Field capacity (FC) is indicated with a dashed line (FC= 0.21 cm^3 cm^{-3}); standard deviation is indicated with error bars.

The average VWC of each Teros 10 sensor in the x-plane – horizontal distance from the emitter and y-plane - vertical distance from the emitter was calculated along with the average VWC for the profile (Figure 4.16) for the period 2021/10/11-2021/10/24. The sensors were directly below the emitter at x = 0 cm (green line) and in treatments 1, 2, and 3 this was where the highest VWC was measured. As horizontal distance from the emitter increased (x-plane), there was an overall decrease in VWC. This can be clearly observed in Figure 4.16 c, with Figure 4.16 a and b showing a similar trend but having some variation, especially between the 30 cm and 45 cm plane. There is a clear increase in VWC with depth in treatments 1 and 2, which is on contrast to the decrease in VWC with depth observed in treatment 3. At each of the respective distances from the emitter in treatment 3, the 60 cm depth had the lowest VWC compared to treatments 1 and 2, where the highest VWC was observed at 60 cm. When considering the average VWC in the active rootzone (0-40 cm), the highest average was observed in treatment 3 at 0.21 $cm^3\ cm^{-3}$, with both treatment 1 and treatment 2 having an average of 0.19 $cm^3\ cm^{-3}$. In all three treatments the sensors 15 cm from the emitter resembled the profile averages the closest.

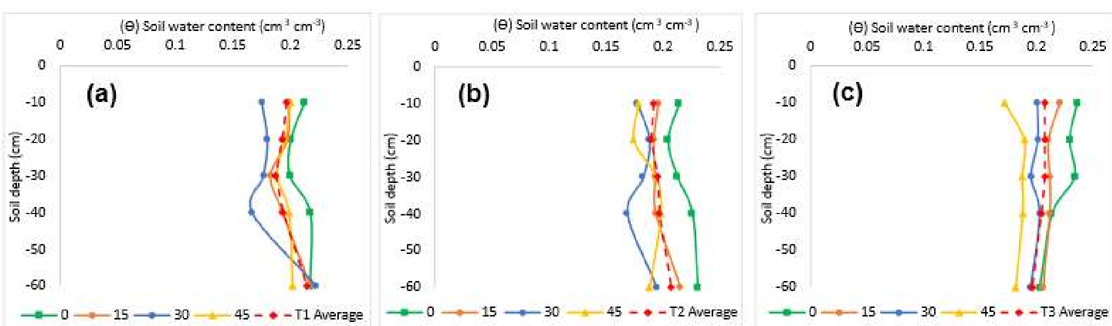

Figure 4.16 The average volumetric water content (Ө) $(cm^{-3}\ cm^{-3})$ for (a) treatment 1 (1.6 l h^{-1}), (b) treatment 2 (2.3 l h^{-1}) and (c) treatment 3 (0.7 l h^{-1}), at various distances from the emitter, x-plane, (0 cm, 15 cm, 30 cm, and 45 cm) at different soil depths (cm), y-plane, with the profile average being indicated in dashed red line. For the period 2021/10/11-2021/10/24.

Data for the period 2022/08/11 – 2022/09/05 is presented in Figure 4.17 and a similar trend was observed, with a decrease in VWC with an increase in horizontal distance (x- plane) from the emitter. This was most noticeable at 45 cm from the emitter in treatment 3 (Figure 4.17c). An increase in VWC with depth is again clearly visible in treatment 1, but VWC changed very little with depth in treatments 2 and 3, apart from the 45 cm line in treatment 3, where there was a large increase in VWC down the profile. The average VWC content in this period is not as closely related to the 15cm line as in the October scenario, but rather somewhere between 15cm and 30cm. Again, the highest overall average VWC in the active rootzone was in treatment 3 at 0.20 cm^{3} cm^{-3} with both treatment 1 and treatment 2 having an average of 0.19 cm^{-3}.

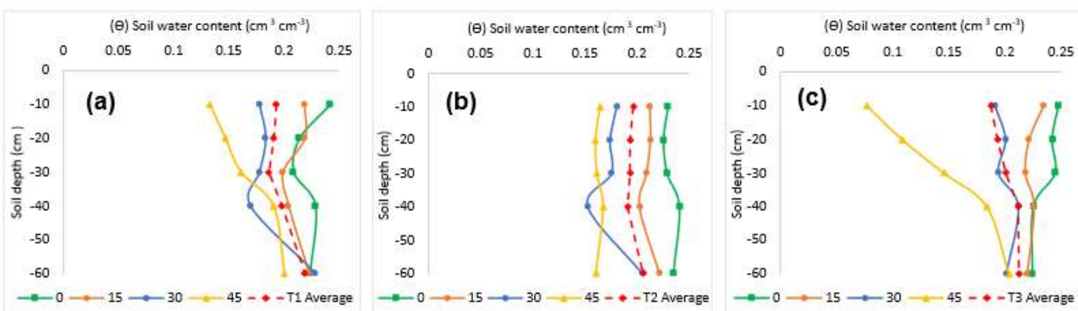

Figure 4.17 The average volumetric water content (ϴ) (cm^{-3} cm^{-3}) for (a) treatments 1 (1.6 l h^{-1}), (b) treatment 2 (2.3 l h^{-1}) and (c) treatment 3 (0.7 l h^{-1}), at various distances from the emitter, x-plane, (0 cm, 15 cm, 30 cm and 45 cm) at different soil depths (cm) ,y-plane, with the profile average being indicated in dashed red line. For the period 2022/08/11-2022/09/05.

The final period that was investigated was 2023/04/11-2023/04/26 (Figure 4.18). Once again, a decrease in VWC was observed with an increase in horizontal distance from the emitter, with much clearer differences in VWC observed between distances from the emitted in the x-plane. In both treatments 1 and 2 the variance from 45 cm to 0 cm is much more pronounced than treatment 3, with the latter again having the highest VWC average through the profile (0-60cm) at 0.19 cm^{3} cm^{-3}. As with the August period, the average VWC line is not clearly represented by the 15 cm line, but rather between the 15 cm and 30 cm lines for treatments 1, 2 and 3.

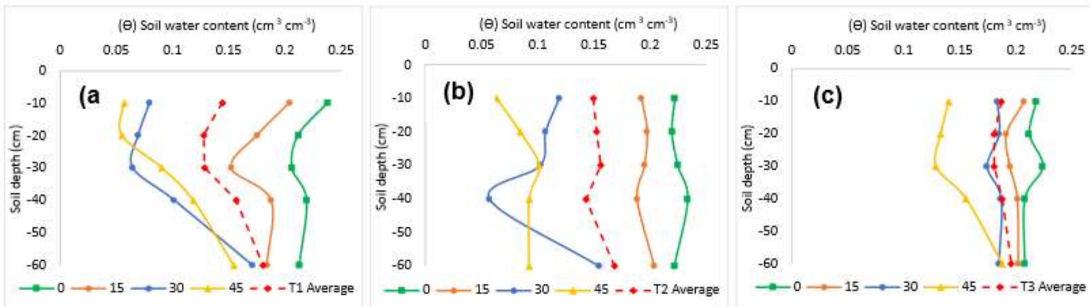

Figure 4.18 The average volumetric water content (Ө) (cm^{-3} cm^{-3}) for (a) treatment 1 (1.6 l h^{-1}), (b) treatment 2 (2.3 l h^{-1}) and (c) treatment 3 (0.7 l h^{-1}), at various distances from the emitter, x-plane, (0 cm, 15 cm, 30 cm and 45 cm) at different soil depths (cm), y-plane, with the profile average being indicated in dashed red line. For the period 2023/04/11-2022/04/26.

To better understand the variation within the reservoir and how it changes over time, the Teros 10 sensor data was interpolated with the aid of Surfer® (Golden software), using the Kriging interpolation method. The data for the period 2023/04/17-2022/04/23 (Figure 4.13) was selected as this was the driest period of all the data evaluated with a prolonged absence of rain and constant irrigation being applied. Data was interpolated at 06:00 am, just prior to irrigation starting, then at 10:00 am, 14:00 and finally at 18:00. Each treatment received 5.7 L of water, from 06:00 am with treatment 1 irrigating for 3h 33m, treatment 2 for 2h 28m and treatment 3 for 8h 08m (Figure 4.19).

The shape of the wetted area of Figure 4.19a is different to that of Figure 4.19b and c with an increase in width from 45 cm and deeper, creating a continuous wet zone. In all three treatments a saturated zone is present in the x=0 plane, which is directly below the emitter. In all three treatments the saturated zone's area increases after 06:00 am, when irrigation commences and moves down in the profile over time reaching the deepest point at 18:00. It is important to note that water will continue to move through the evening under gravity when little plant extraction or evaporation takes place. The rate at which the saturated zone moved through the profile differed between treatments with treatment 2 (2.3 l h^{-1}) having the deepest saturated zone, where water moved beyond the measured range of the profile (70 cm), followed by treatment 1 (1.6 l h^{-1}) that had two distinct areas of saturation, the deepest part reaching 70 cm and finally treatment 3 (0.7 l h^{-1}), where the saturated zone remained fairly concentrated between 20 cm-40 cm with the deepest point reaching 60 cm.

The average wetted area (cm^2) for each time interval for the period 2023/04/17-2022/04/23 was measured with Surfer® and summarised in Table 4.3. The interpolated surface area represents the cross-sectional area under a single emitter up to a depth of 60cm, which is the designated rooting depth and where the deepest Teros-10 sensors were placed, this equates to 6000 cm^2 (100cm x 60cm). The change in wetted area over time in all three treatments was minimal with a total daily change of 1%. There were, however, differences in wetted area between treatments, with treatment 2 (2.3 l h^{-1}) creating the smallest wetted area with an average of 51% of the area having plant available water (VWC > 0.13 cm^3 cm ^{3}) compared to treatments 1 (1.6 l h^{-1}) and 3 (0.7 l h^{-1}) with an average of 56% and 59 % of the total area having plant available water (VWC > 0.13 cm^3 cm ^{3}) respectively. These figures can also be a representation of the soil moisture gradient where better water distribution led to less extreme gradients between saturation and PWP and increase in RAW. Therefore treatment 3 had the least extreme gradient of VWC within the area under the dripper followed by treatment 1 and then treatment 2.

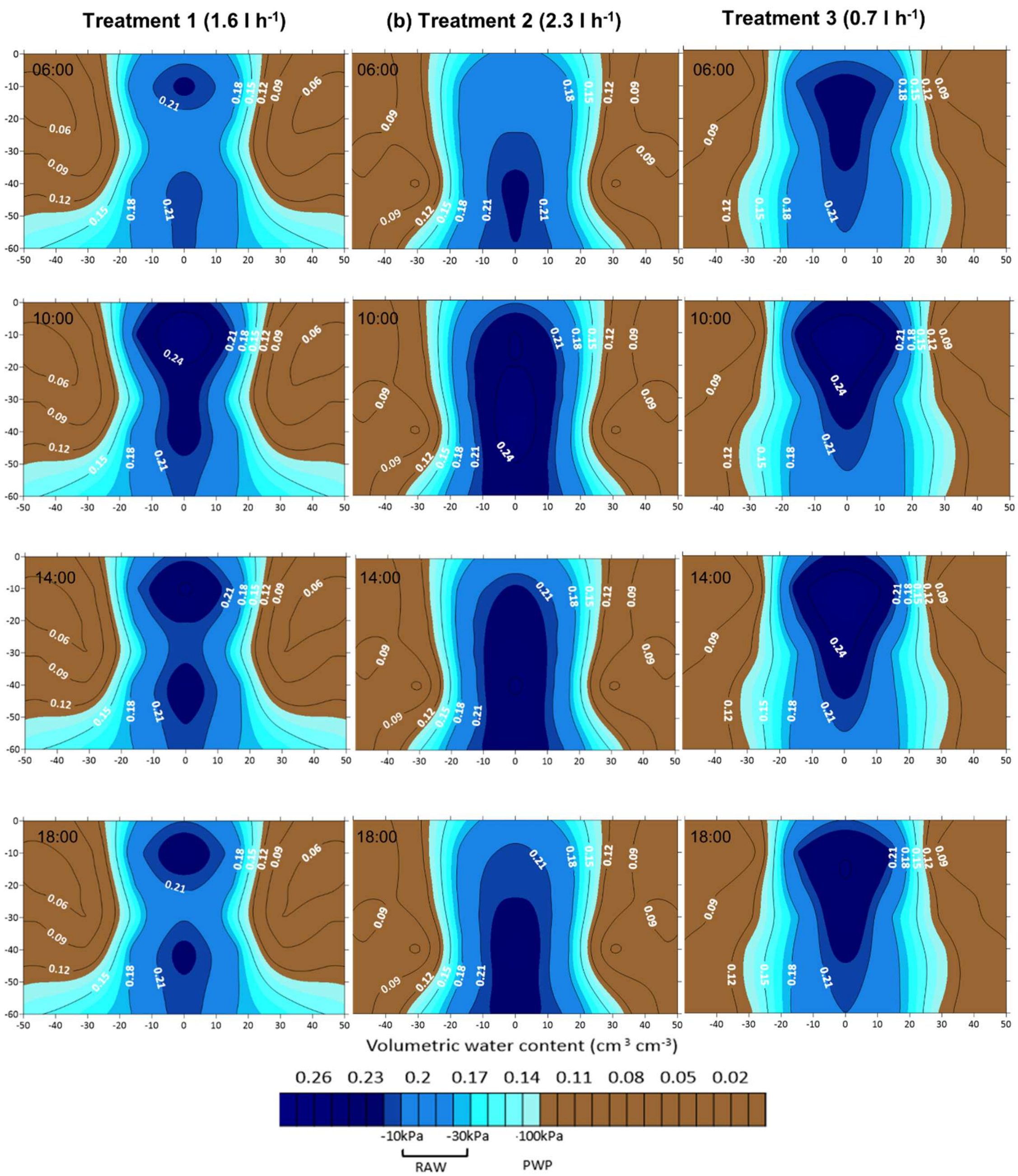

Figure 4.19 Interpolated volumetric water content values (cm^3 cm^{-3}) using Surfer® for the period 2023/04/17-2022/04/23 from Teros 10-Sensors placed in a grid format. The data is for (a) treatment 1 (1.6 l h^{-1}), (b) treatment 2 (2.3 l h^{-1}) and (c) treatment 3 (0.7 l h^{-1}), at 06:00 am, 10:00 am, 14:00 am and 18:00 labelled respectively.

Table 4.3 The average wetted area (cm^2) determined by Surfer® where volumetric water content (VWC) was > 0.13 $cm^3\ cm^{-3}$ and the area of readily available water (RAW) (cm^2) where VWC = 0.17-0.21 $cm^3\ cm^{-3}$ for treatment 1 (1.6 l h^{-1}), treatment 2 (2.3 l h^{-1}) and treatment 3 (0.7 l h^{-1}), at 06:00 am, 10:00 am, 14:00 am and 18:00 for the period 2023/04/17-2022/04/23.

TREATMENT	TIME	TOTAL INTERPOLATED SURFACE (CM^2)	WETTED AREA (CM^2) (VWC > 0.13 $CM^3\ CM^{-3}$)	WETTED % OF TOTAL AREA	RAW AREA (CM^2) (VWC =0.17-0.21 $CM^3\ CM^{-3}$)	RAW % OF TOTAL AREA
T1	06:00	6000	3380	56%	1603	27%
T2	06:00	6000	3077	51%	1621	27%
T3	06:00	6000	3373	56%	1460	24%
T1	10:00	6000	3413	57%	1054	18%
T2	10:00	6000	3140	52%	869	14%
T3	10:00	6000	3420	57%	1257	21%
T1	14:00	6000	3359	56%	1117	19%
T2	14:00	6000	3110	52%	1022	17%
T3	14:00	6000	3352	56%	1134	19%
T1	18:00	6000	3326	55%	1367	23%
T2	18:00	6000	3077	51%	1183	20%
T3	18:00	6000	3917	65%	1535	26%

4.3.5 Transpiration

Daily transpiration data was collected to determine if irrigation application rate had an influence on plant water uptake. The average fractional canopy cover of the measured trees was 0.71 ± 0.07 and can be considered representative of the orchard and comparable with one another. The daily transpiration data (mm $tree^{-1}$) for the period 2021/10/11 - 2021/10/24 was used since soil water storage was already investigated for this period (Figure 4.5 and Figure 4.6), there was no rainfall, and the applied irrigation and K_c was managed according to the target values. The daily transpiration and ET_o values are plotted together (Figure 4.20) to illustrate the influence that ET_o has on transpiration. A trend can be observed between ET_o and transpiration, with a clear decrease in transpiration from 17/10/2021-18/10/2021 when ET_o decreased to 0.77 mm and 1.36 mm for those respective days. Over the course of this period treatment 1 (1.6 l h^{-1}) had the lowest total transpiration with a total of 23.7 mm $tree^{-1}$ that equates to a daily average of 1.69 mm $tree^{-1}$. This was followed by treatment 2 (2.3 l h^{-1}) with a total of 27.7 mm $tree^{-1}$ and a daily average of 2.0 mm $tree^{-1}$, with the highest being treatment 3, with a total of 30.60 mm $tree^{-1}$ and a daily average of 2.19 mm $tree^{-1}$. Treatment 3 had consistently the highest daily transpiration apart from only three days where treatment 2 had the highest transpiration values, with treatment 1 consistently having the lowest values.

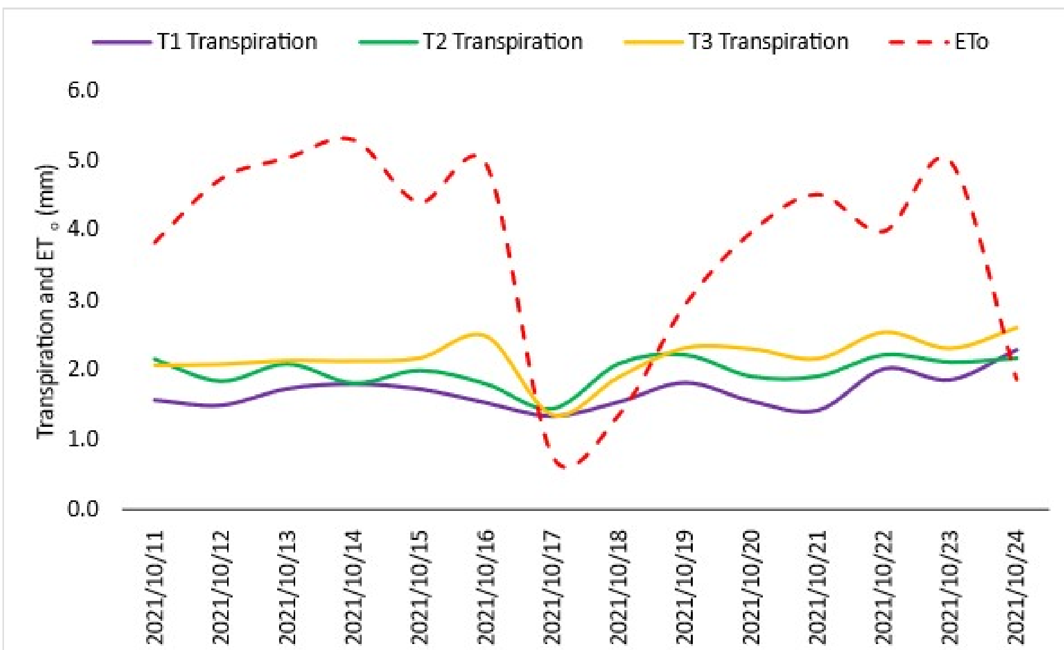

Figure 4.20 Daily transpiration (mm $tree^{-1}$) vs reference evapotranspiration (ET_o) (mm) data for treatment 1 (1.6 l h^{-1}), treatment 2 (2.3 l h^{-1}) and treatment 3 (0.7 l h^{-1}) for the period 2021/10/11 -2021/10/20. Dashed lines represent polynomial trend line (2nd degree of freedom).

The data in Figure 4.21 showed the relationship between daily transpiration (T) and ET_o for treatments 1, 2, and 3 and represents the transpiration coefficient (K_t) where:

$$K_t = \frac{\text{Transpiration (T)}}{ET_o} \qquad [3]$$

Treatment 3 (0.7 l h^{-1}) had the highest daily average K_t of 0.61 and a $r^2 = 0.498$, this was followed by treatment with a daily average K_t of 0.57 and $r^2 = 0.490$ with treatment 1 having the lowest daily average K_t of 0.49 and a $r^2 = 0.095$. The low r^2 value of treatment 1 indicated that there could be other factors, besides ET_o, which had an influence on transpiration. For treatments 1 and 3 ~ 50% of the variance in transpiration could be attributed to ET_o.

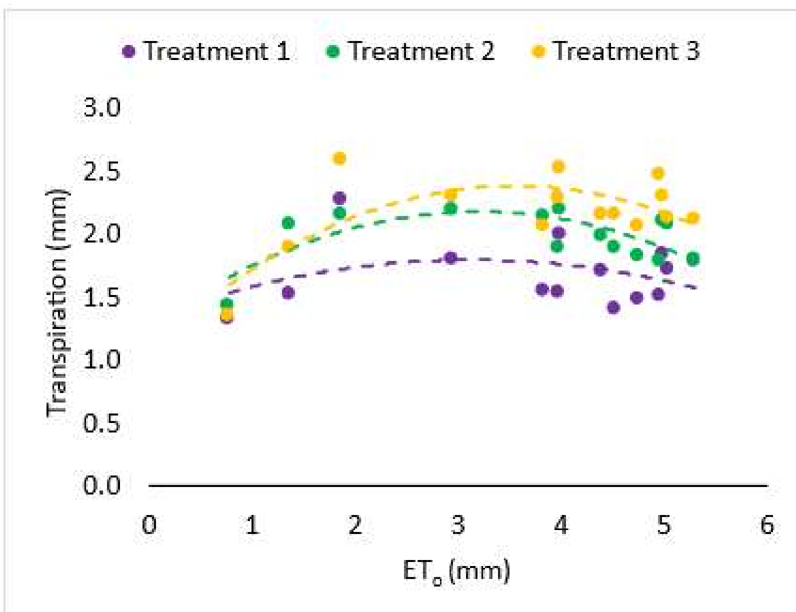

Figure 4.21 Daily transpiration (mm tree^{-1}) vs reference evapotranspiration (ET_o) (mm) data for treatment 1 (1.6 l h^{-1}), treatment 2 (2.3 l h^{-1}) and treatment 3 (0.7 l h^{-1}) for the period 2021/10/11-2021/10/20.

CHAPTER 5: PHYSIOLOGICAL RESPONSE OF CITRUS TO LOW EMITTER DELIVERY RATE DRIP IRRIGATION

5.1 Introduction

Variations among species, varieties, rootstock-scion combinations, and the interaction of each of these factors with different environments, impacts the water requirements of citrus orchards (Talon et al., 2020). Several studies have investigated aspects of the water relations of citrus, with many focused on physiological responses to water stress or regulated deficit irrigation (RDI) (García-Tejero et al., 2010a, Chartzoulakis et al., 1999, Ballester et al., 2014, Morgan et al., 2006). In contrast to various other crops, the low stomatal or canopy conductance of *Citrus* spp. places a limit on maximum transpiration rates, thereby reducing seasonal water use of citrus relative to other crops having higher canopy conductance's. There have only been modest advancements in accurately determining the precise water needs of citrus under different environmental conditions (Carr, 2012). As a result, irrigation scheduling based on the full evapotranspiration (ET_c) requirements of the crop are not always sufficiently accurate.

This can have consequences for crop performance and overall water productivity of citrus orchards. There are multiple physiological responses to both over and under irrigation, which differ based on the intensity and frequency of these conditions and is a function of the irrigation method or system. Different wetting patterns and application rates may impact plant water relations and can provide valuable information on the efficacy of different irrigation systems. The response of citrus to low flow drip (LFD) has not been well researched, however, it is hypothesized that because these systems create larger wetted areas with more readily available water, they can lead to improved plant water relations. It is therefore important to monitor different physiological responses when evaluating and comparing different irrigation systems and regimes, as they provide context as to whether not only the quantity of water applied was adequate, but if the rate at which it was applied had an influence. Importantly, these responses should be evaluated in conjunction with soil water content and weather conditions.

5.2 Physiological response to under irrigation or water stress

5.2.1 Shoot growth and leaf abscission

Citrus has distinct growth flushes, which are initiated by the availability of water in tropical climates or a rise in temperature in subtropical and Mediterranean climates. These flushes in summer and autumn can be delayed by water stress (Jones et al., 1985). Severe stress, as indicated by a pre-dawn leaf water potential of -2.75 MPa, resulted in leaf abscission as a result of the formation of two main abscission zones 1) at the base of the petiole under moderate stress 2) abscission can occur between the lamina and the petiole in periods of severe stress (Kriedemann and Barrs, 1981, Ribeiro and Machado, 2007). This allows the distinction between normal leaf abscission and that triggered by a water stress.

5.2.2 Stomatal conductance and leaf water potential

Stomatal conductance in *Citrus* spp. is highest mid-morning between 09:00 and 10:30 am, after this period when the vapour pressure deficit (VPD) approaches values of > 1.5 kPa stomatal conductance (g_s) declines (Ribeiro and Machado, 2007). It is not only VPD that contributes to the control of g_s, as Brakke and Allen (1995) confirmed that when soil water was not readily available, the reduction in g_s occurred earlier in the day, than when solely driven by high VPD. This is supported by Talon et al. (2020) who reported that at a constant VPD, the photosynthetic response of mature and young citrus leaves, measured as g_s, was moderately reduced at a soil water deficit of -30 kPa, with a severe reduction at -50 kPa.

Leaf water potential (Ψ_{leaf}) is also sensitive to VPD (Kriedemann and Barrs, 1981) and stomatal closure can result in higher values of leaf water potential (LWP) but generally trees grown under limited soil water availability have lower leaf water potential compared to trees in soils with a high water availability (Jones et al., 1985). Values for Ψ_{leaf} for citrus species are reported to range between -1.0 MPa and -2.5 MPa in the early afternoon depending on the water content of the soil, whilst predawn stem water potentials can be as high as -0.20 MPa in well-watered trees (Jones et al., 1985, Ribeiro and Machado, 2007). Sdoodee and Somjun (2008) found that Ψ_{leaf} and midday stem water potential (Ψ_{stem}) correlated strongly to soil water availability and that a decrease in soil water resulted in a decrease in Ψ_{leaf} and Ψ_{stem}. It is important to note that the sap flow of the scion and Ψ_{leaf} may be influenced by the rootstock and needs to be taken into consideration when values are compared between different trees or orchards (Carr, 2012).

5.2.3 Yield, quality, and fruit size

Yield is not only influenced by the current and previous season's water status but the effects may be cumulative and slow to develop (Doorenbos and Kassam, 1979, Shalhevet and Levy, 1990). An important component that determines yield is fruit size and an improvement in fruit size due to full irrigation has been found to be in the order of 6-7 kg fresh fruit m^{-3} applied with the most critical periods being phases 1 and 2 of fruit growth, whilst stress during phase 3 has little impact on yield (Goñi and Otero, 2009, Petillo and Sánchez, 2004). To avoid a reduction in fruit size Carr (2012) suggested that Ψ_{stem} should not drop below -1.3 MPa. It is, however, not only fruit size that contributes to yield in response to irrigation, but also the total number of fruit that reaches maturity Chartzoulakis et al. (1999), where water stress during flowering can reduce fruit set and during phase I can increase late fruit drop Doorenbos and Kassam (1979). Whilst fruit size is determined in phases 1 and 2, fruit quality is mainly determined in phase 3 of fruit growth where water availability influences juice content, total soluble solids (TSS), and total acidity (TA,) with an increase in these parameters observed when deficit irrigation is applied (García-Tejero et al., 2010a, Peng and Rabe, 1998, Shalhevet and Levy, 1990, Ballester et al., 2014).

5.2.4 Plant response to over irrigation or saturated conditions

Over-irrigation refers to the condition where more water is supplied to the plant than is required for optimal growth and development. The abiotic stress caused by over-irrigation is due to sub-optimal soil aeration or lack of oxygen and the unavailability and leaching of mobile nutrients (Atay et al., 2017, Hillel, 1980, Fiebig and Dodd, 2016). Prolonged saturated conditions have a negative impact on citrus yield and fruit size, furthermore, it can result in a complex of root rot diseases caused mainly by *Phytophtora* spp. This further affects the roots ability to absorb nutrients and water and ultimately causes slow decline or death (Cacciola and Lio, 2008, Atay et al., 2017).

The aim of this chapter was to explore whether various application rates of drip irrigation systems lead to distinct physiological responses and furthermore to assess the impact of different water regimes on yield, fruit size, and quality.

5.3 Materials and Methods

Detailed materials and methods are presented in **Chapter 3**

5.4 Results

5.4.1 Weather Variables

It is imperative to gain a comprehensive understanding of the meteorological factors that potentially impact both the physiological responses of citrus trees and their water use. When analyzing the meteorological parameters throughout the two citrus production seasons, spanning from August to July, it is evident that total rainfall for the 2021/22 and 2022/23 seasons were comparable, totaling 765 mm and 882 mm, respectively. However, a marked distinction arises in terms of their temporal distribution. In the 2021/22 season, a conventional summer precipitation pattern prevailed, characterized by evenly distributed rainfall from October through May, except for an abnormally dry February. In contrast, during the 2022/23 season, nearly half of the total annual precipitation, constituting 49%, occurred within a condensed timeframe spanning just two months, January, and February 2023. Notably, in February 2023 alone 318 mm was recorded. Consequently, although higher rainfall was experienced in the 2022/23 season, the intensity and concentrated distribution of the rainfall, meant that it was probably less effective as compared to the evenly distributed precipitation pattern in the 2021/22 season (Figure 5.1 B).

The average daily temperatures were quite similar between the two seasons, with an average daily temperature of 19.3 °C in the 2021/22 season and a slightly higher 20.2 °C in the 2022/23 season (Figure 5.1 A). The maximum daily temperature in both seasons was recorded in October at 39.1 °C and 39.3 °C for the 2021/22 and 2022/23 seasons respectively. These conditions, however, were not prolonged and the high temperatures were only experienced on a single day. Mean daily solar radiation values were also very similar, with 14.55 MJ m^{-2} day^{-1} recorded in the 2021/22 season and 14.42 MJ m^{-2} day^{-1} in the 2022/23 season (Figure 5.1 D). While the total reference evapotranspiration (ET_o) values were similar for both seasons, at 1051 mm for 2021/22 and 1063 mm for 2022/23, there were notable differences in monthly trends, which closely mirrored rainfall distribution. In the 2021/22 season, January had a significantly lower ET_o of 99 mm compared to the 122 mm in the 2022/23 season.

Conversely, in February 2021 ET_o was 110 mm which was higher than the 78 mm recorded in February 2023 (Figure 5.1 C). Finally, the vapour pressure deficit (VPD) for the two seasons was very similar with an average of 0.84 kPa and 0.94 kPa for the 2021/22 and 2022/23 seasons respectively. The maximum values in both seasons were recorded in September with the 2021/22 season reaching a slightly higher daily peak at 2.31 kPa compared to 1.97 kPa in the 2022/23 season. (Figure 5.1 E). It is evident that the overall patterns of weather parameters in Figure 5.1 were similar across the two seasons. Apart from a few extreme rainfall events, which influenced applied irrigation volumes, the data from the two seasons are similar enough to allow comparison of results across both seasons.

Periods where no significant rainfall occurred for at least two weeks were targeted for water potential measurements to ensure that the only variable impacting soil water content of the treatments was the irrigation application rate and quantity of water applied. Furthermore, for measurements of ψ_{stem} overcast and cool conditions were avoided. In this study there were no significant differences in ψ_{pd} between treatments at each measurement date despite differences in application rate (Treatments 1-3) and quantity of water applied (Treatments 4 and 5) (Figure 5.2). Furthermore no treatment experienced stress at predawn as proposed by Kriedemann and Barrs (1981) at -0.5 MPa. There were, however, significant differences between the different measurement dates ($P<0.0001$).

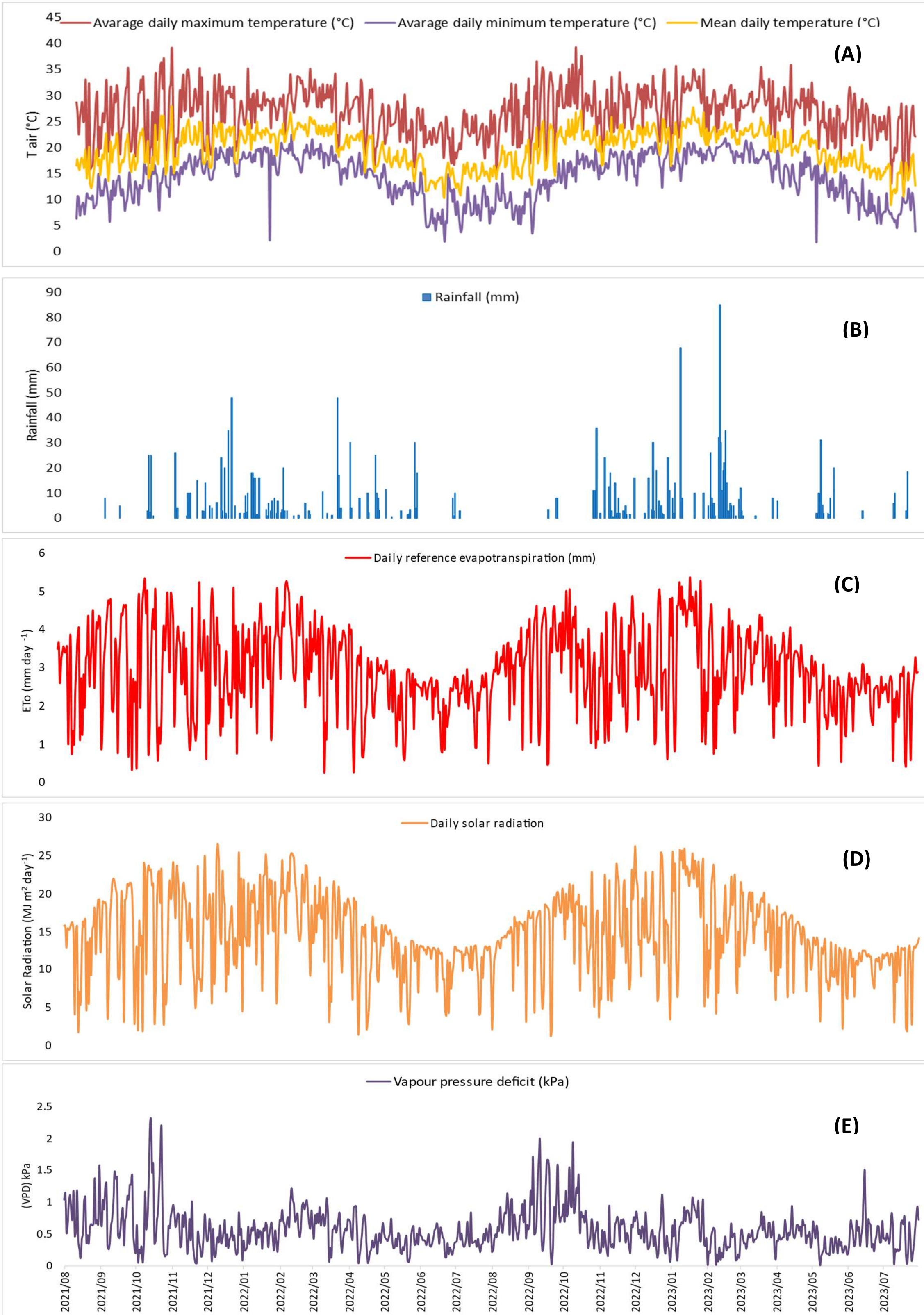

Figure 5.1 (A) Maximum, minimum and mean air temperature (Tair) (°C), (B) total daily rainfall (mm), (C) daily reference evapotranspiration (ET_o) (mm day ^{1}), (D) daily solar radiation (MJ m^{-2} day^{-1}) and (E) vapour pressure deficit (kPa). Data is from 1 August 2021 to 31 July 2023.

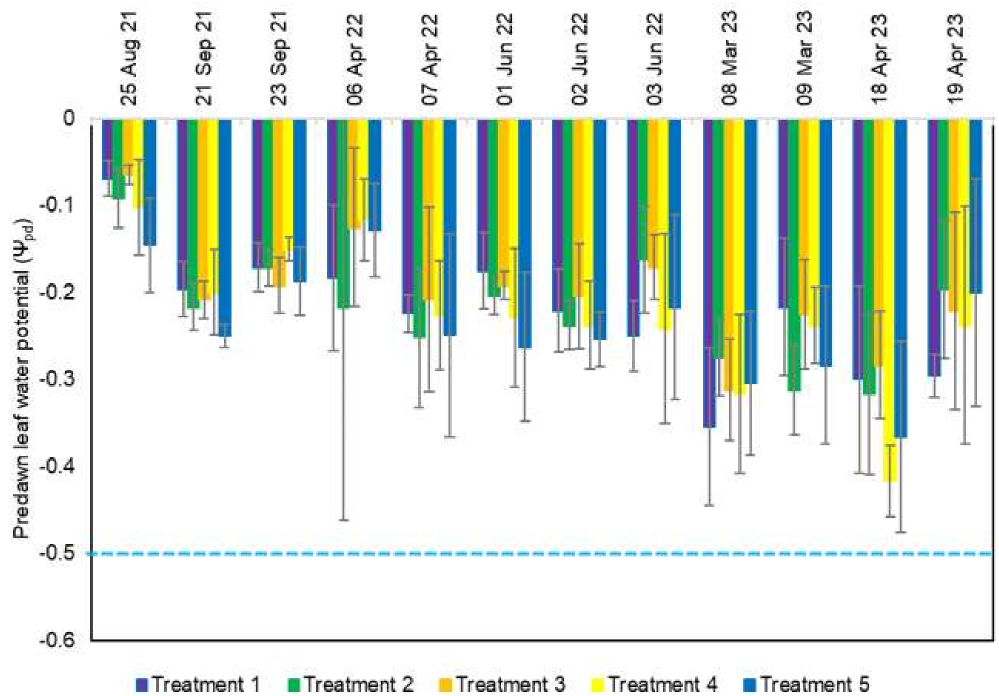

Figure 5.2 Pre-dawn leaf water potential (MPa) of treatment 1 (1.6 l h^{-1}), treatment 2 (2.3 l h^{-1}), treatment 3 (0.7 l h^{-1}), treatment 4 (0.7 l h^{-1}, ET_c- 20%) and treatment 5 (0.7 l h^{-1}, ET_c- 40%) over the duration of the trial. The blue dashed line is where stress starts to occur as proposed by (Kriedemann and Barrs, 1981). A two-way ANOVA was done on each individual date with no significant differences between treatments (Tukey's (HSD) test p>0.05)).

The average profile volumetric water content (VWC) of all 20 of the Teros 10 sensors at 05:00 am on the day of water potential measurements were compared to the corresponding ψ_{pd} measurements (Figure 5.3). Whilst clear differences between treatments are difficult to discern, there was a positive correlation between VWC and ψ_{pd} ($p < 0.0001$), with ψ_{pd} increasing as VWC content increased.

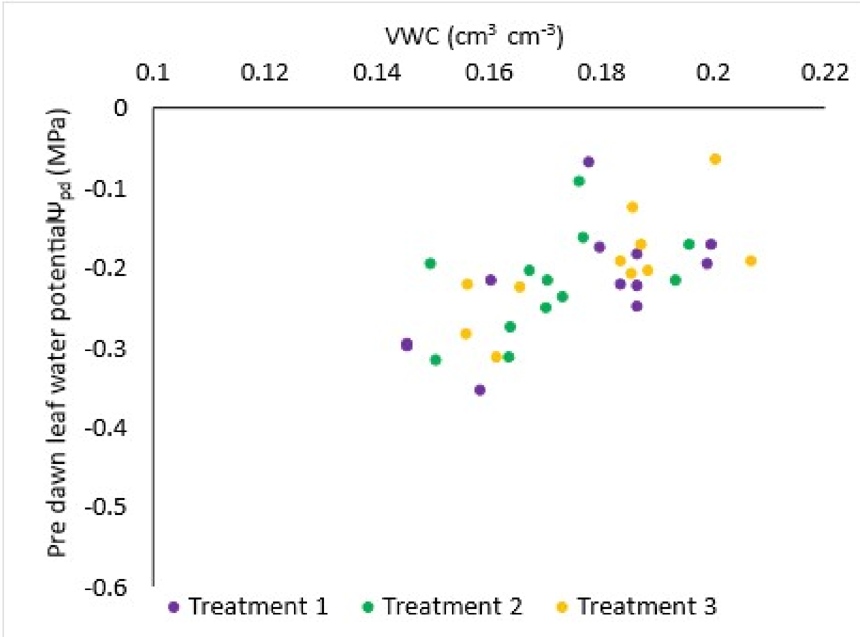

Figure 5.3 The relationship between predawn leaf water potential (ψ_{pd}) (MPa)and average volumetric soil water content (VWC) (m^{-3} m^{-3}) for treatments 1 (1.6 l h^{-1}), treatment 2 (2.3 l h^{-1}) and treatment 3 (0.7 l h^{-1}), over the course of the two seasons during rain free periods ($p< 0.001$) with a Pearson correlation value of ($r = 0.612$).

5.4.2 Midday stem water potential (ψ_{stem})

Measurements of (ψ_{stem}) were taken on the same day as the ψ_{pd} measurements, if weather conditions allowed (no overcast conditions), to determine if there were different responses to the application method and quantity of water applied (Figure 5.4). There were no significant differences observed between treatments on any of the measurement dates (Tukey's (HSD) test $p>0.05$).

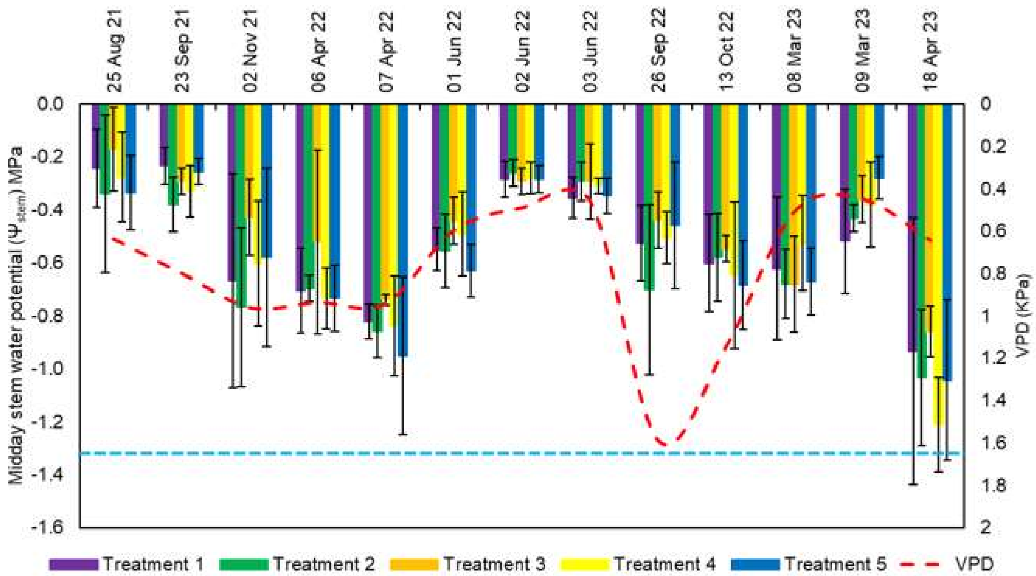

Figure 5.4 Midday stem water potential (MPa) of treatment 1 (1.6 l h^{-1}), treatment 2 (2.3 l h^{-1}), treatment 3 (0.7 l h^{-1}), treatment 4 (0.7 l h^{-1}, ET_c- 20%) and treatment 5 (0.7 l h^{-1}, ET_c- 40%) over the duration of the trial compared to vapour pressure deficit (VPD) (kPa) on the day of measurement. A two way ANOVA was done on each individual date with no significant differences between treatments (Tukey's (HSD) test p>0.05)) Lez-Altozano and Castel (1999) proposed that that the threshold for stress for ψ_{stem} is -1.3 MPa (blue dash line) for citrus.

5.4.3 Stomatal conductance

The impact of emitter delivery rate and deficit irrigation on stomatal conductance (g_s) was evaluated during periods where no rainfall occurred within at least two weeks and irrigation was fully operational. Measurements started in the morning varied between 08:00 and 10:00 depending on the time it took for leaves to dry sufficiently because of dew. Diurnal measurements were done on these selected dates, and hourly data for 2022/04/06 is presented in Figure 5.5. Conditions for transpiration were good with a recorded maximum temperature of 32 °C with a maximum VPD of 0.935 kPa and 12.2 recorded sun hours with little clouds present. There was however a lot of variation in hourly readings, as indicated by the standard deviation, with no clear trend between treatments. However, g_s tended to be highest in the morning from 09:00 to 11:00, after which it decreased and remained fairly constant from 14:00 up until the last measurement at 17:00. The highest reading was recorded for treatment 3 (0.7 l h^{-1}) at 13:00 with a reading of 144 mmol m^{-2} s^{-1} and the lowest reading was recorded the same time for treatment 5 (0.7 l h^{-1} ET_c- 40%) with a reading of 23 mmol m^{-2} s^{-1}.

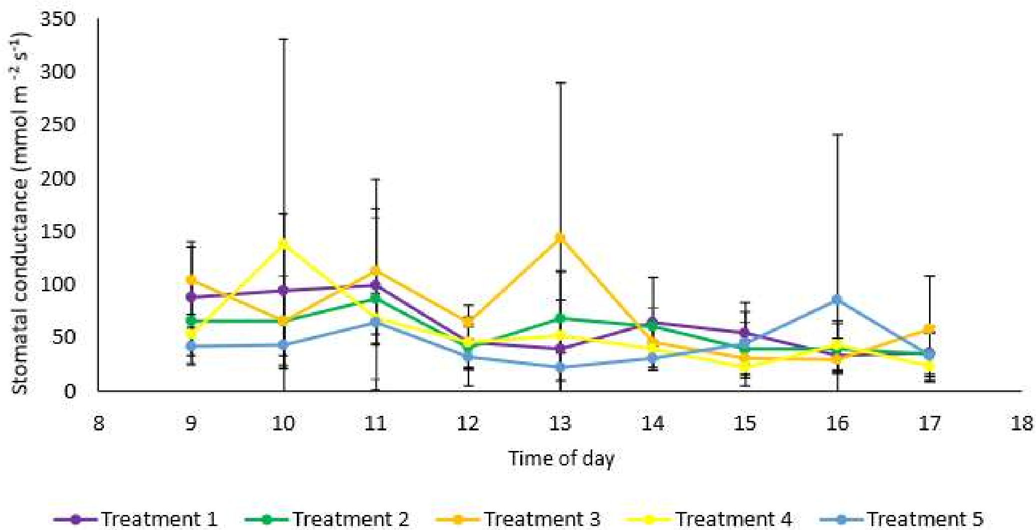

Figure 5.5 Hourly stomatal conductance (g_s, mmol m^{-2} s^{-1}) on 2022/04/06 for treatment 1 (1.6 l h^{-1}), treatment 2 (2.3 l h^{-1}), treatment 3 (0.7 l h^{-1}), treatment 4 (0.7 l h^{-1}, ET_c- 20%) and treatment 5 (0.7 l h^{-1}, ET_c- 40%). Error bars indicate standard deviation.

To evaluate all the measurement dates over the duration of the trial the measurements between 10:00 am-12:00 pm were used to determine an average g_s per treatment for each date (Figure 5.6), as this was consistently the highest g_s for all treatments, with the highest number of measurements taken during this period. Although large variations can be observed within sampling dates for the different treatments, there were no significant differences between treatments. The average g_s for all the treatments ranged between 26-34 mmol m^{-2} s^{-1}, except for 06/04/2022 and 07/04/2022 where the average g_s for the treatments was between 64 mmol m^{-2} s^{-1} and 71 mmol m^{-2} s^{-1}.

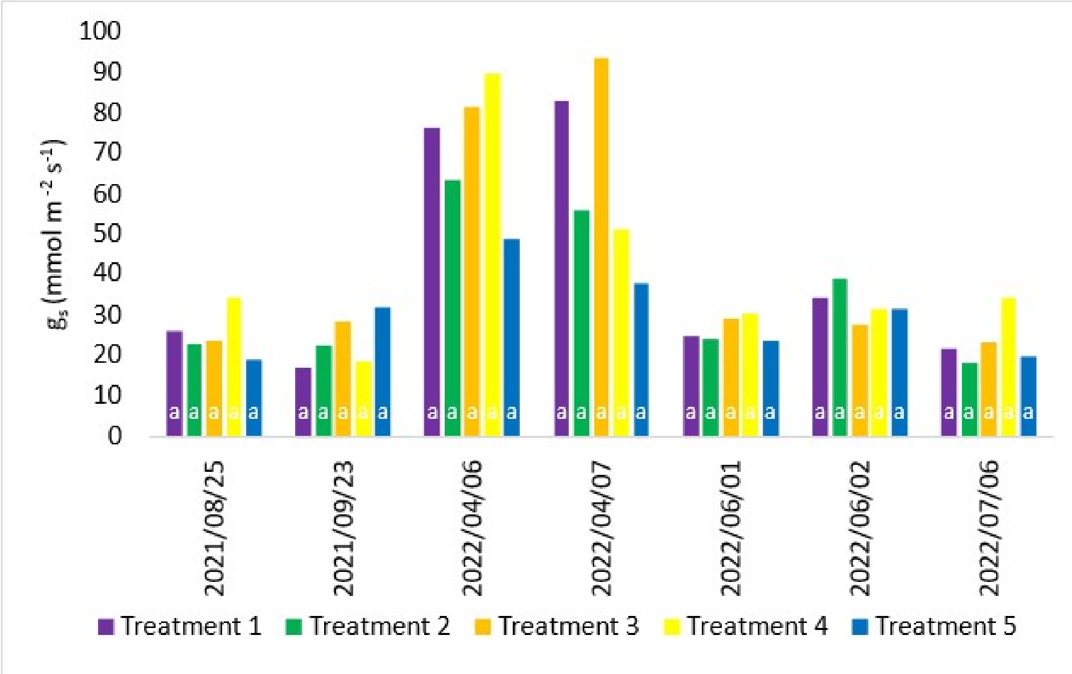

Figure 5.6 Average stomatal conductance (g_s mmol m^{-2} s-^{1}) between 10:00 am and 12:00 pm for treatment 1 (1.6 l h^{-1}), treatment 2 (2.3 l h^{-1}), treatment 3 (0.7 l h^{-1}), treatment 4 (0.7 l h^{-1}, ET_c- 20%) and treatment 5 (0.7 l h^{-1}, ET_c- 40%) over the duration of the trial. A two-way ANOVA was done on each individual date, mean values with the same letters are not significantly different from each other (Tukey's (HSD) test p>0.05).

5.4.4 Yield and Size

The first yield assessment in 2021 was done prior to the commencement of the trial, to serve as a baseline value, due to the alternate bearing tendency of 'Nadorcott' mandarin orchards on the farm. The yield for treatments 1-5 were 79 t ha^{-1}, 75 t ha^{-1}, 83 t ha^{-1}, 87 t ha^{-1}, and 80 t ha^{-1} respectively with no significant differences between the treatments indicating that the chosen trees were uniform at the start in terms of yield, making comparisons later in the trial feasible. Marketable yield refers to fruit with an economic value, this fruit should be in season with sufficient colour, internal quality, and within the desired size range (50-86 mm diameter) for packing or juicing. The grading of fruit on blemishes and other quality standards will influence the economic return of the fruit, these standards are set by the Perishable Product Export Control Board (PPECB). All fruit sent to the packhouse was either sold as packed fresh fruit or sent for juice.

The trial commenced on 1 August 2021 and the yield that followed this season was an "off" year, with a very light crop which averaged 7 t ha^{-1} across the 5 treatments with no significant differences between treatments (Figure 5.7). The return crop, however, in 2022 was an "on" year, with a much higher yield than 2021 of 116 t ha^{-1} across the 5 treatments with no significant differences between any of the treatments. Within each season there were no distinct impacts of the irrigation application method (treatments 1-3) or irrigation quantity (treatments 4 & 5) on total marketable yield.

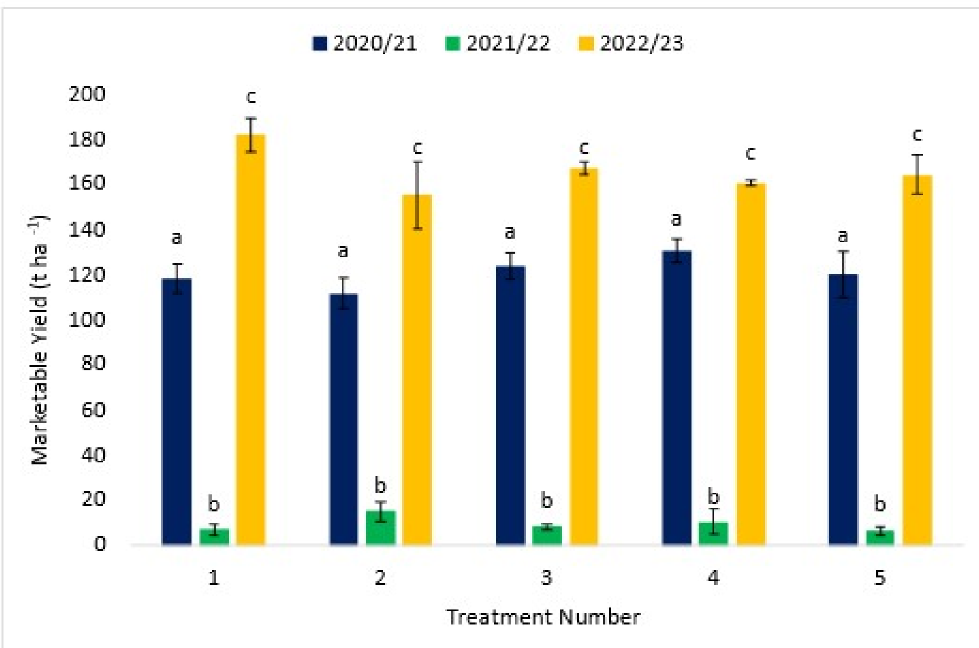

Figure 5.7 Marketable yield (t ha ^{1}) for treatment 1 (1.6 l h^{-1}), treatment 2 (2.3 l h^{-1}), treatment 3 (0.7 l h^{-1}), treatment 4 (0.7 l h^{-1}, ET$_c$- 20%) and treatment 5 (0.7 l h^{-1}, ET$_c$- 40%) for the 2020/21, 2021/22 and 2022/23 seasons. Statistical analysis was done using a two way – ANOVA, values with the same letters are not significantly different from each other (Fisher's (LSD) test p>0.05).

5.4.5 Fruit size

A random sample of 200 fruit was collected from the harvested fruit from each treatment and sized with a caliper. The average fruit size per treatment was determined in mm (Figure 5.8). The 2021 harvest had the smallest fruit size; however, this was prior to the commencement of the trial and the differences between treatments were small, which suggests the trees at the trial site were comparable prior to the imposition of treatments. Fruit size increased following the start of the trial, with an average fruit size of 66 mm and 67 mm for the 2022 and 2023 harvests respectively, compared to 62 mm in 2021. For the 2022 harvest fruit size was similar between treatments, however, for the 2023 harvest, fruit from treatment 3 were larger than all the other treatments, with an average fruit size of 70 mm. No statistical analysis could be performed since the fruit were combined from all the individual trees after picking and only one sample was taken from each treatment. This is acknowledged as a shortcoming in the sampling strategy.

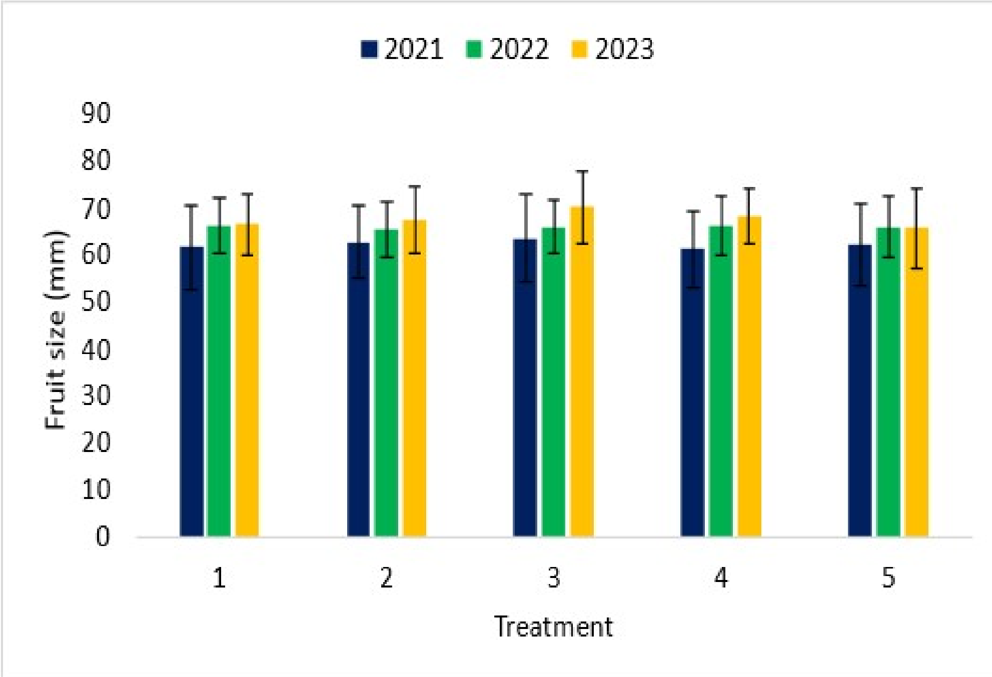

Figure 5.8 Average fruit size (mm) for treatment 1 (1.6 l h^{-1}), treatment 2 (2.3 l h^{-1}), treatment 3 (0.7 l h^{-1}), treatment 4 (0.7 l h^{-1}, ET_c- 20%) and treatment 5 (0.7 l h^{-1}, ET_c- 40%) for the 2020/21, 2021/22 and 2022/23 seasons. Error bars indicate standard deviation.

5.4.6 Internal quality

At harvest 12 fruit of the same size (count 1) were analysed from a combined sample per treatment and as a result, no statistical analysis could be performed. This analysis was only done for the 2023 harvest. Total soluble solids (TSS, measured as Brix) and acidity were very similar between all the treatments. The TSS ranged from 10.3% in treatment 5 to 11.1% in treatment 4, with an average over all five treatments of 10.8%, all above the minimum export standard of 9.0%. Less variation between treatments was observed for acidity, with treatment 2 having the lowest acid content of 0.67% and treatment 3 the highest at 0.75%. The overall average of all five treatments was 0.7%, which was above the minimum export standard of 0.65%.

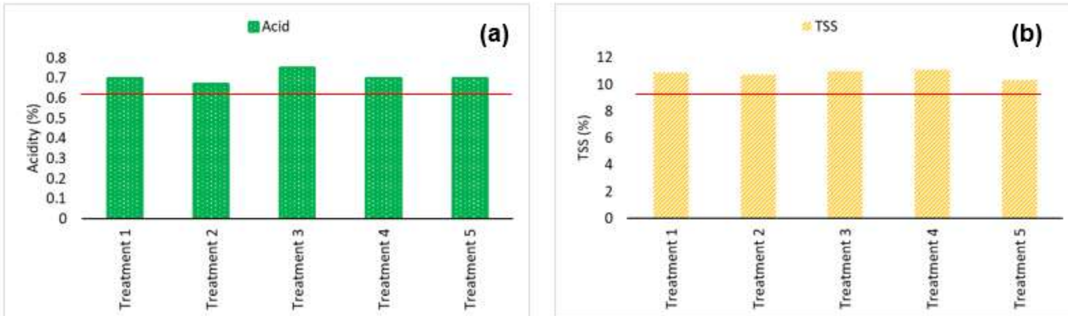

Figure 5.9 Internal quality results for treatment 1 (1.6 l h^{-1}), treatment 2 (2.3 l h^{-1}), treatment 3 (0.7 l h^{-1}), treatment 4 (0.7 l h^{-1}, ET_c- 20%) and treatment 5 (0.7 l h^{-1}, ET_c- 40%) for (a) acidity (%) and (b) TSS (%) for the 2023 season. The red line indicates the minimum export standards for South African mandarins (PPECB).

5.5 Discussion

It has been well documented that high temperatures (> 38 °C) and low humidity can reduce fruit set, which can be exacerbated under soil water deficits (Talon et al., 2020). The period during which the study was conducted can be considered favorable for citrus production with no significant events like hail, frost, or heat waves that could have compromised fruit set and trees were well watered in periods where rain was absent as described in Chapter 4 of the results.

Excessive and prolonged rain during the peak water demand period (spring and summer) negated the effect of the irrigation treatments for extended periods of time, which made the timing of physiological measurements to determine potential differences in treatments challenging. The plant can refill xylem and other tissues with water when transpiration rates are low, which typically occurs overnight. This process will continue until there is no longer a water potential gradient present and equilibrium is reached between the plant and the soil, usually just prior to dawn (Jones, 2004). Therefore one can assume that when ψ_{pd} is highly negative it is due to inadequate replenishment of water and that soil water potential is highly negative, therefore ψ_{pd} is an accurate indicator of plant water status (Chone et al., 2001). There were no significant differences between treatments with regards to ψ_{pd}, suggesting all treatments, were well watered during the time of measurements and that emitter application rate and a 20% and 40% deficit had no influence on ψ_{pd}. The fact that the deficit treatments did not show any difference to the fully irrigated treatments, one can assume that surplus water was available at the time of measurements, which can be due to soil water storage from prior rain events or that the irrigation applied was more than adequate due to over estimation of K_c values.

It was noted by Dzikiti et al. (2010) that ψ_{pd} is not as sensitive an indicator for mild stress compared to that of ψ_{stem} and Lez-Altozano and Castel (1999) proposed a ψ_{stem} threshold for stress in mandarins of -1.3 MPa. All ψ_{stem} measurements in this study were well below the threshold for stress. This suggests that the application rate (treatment 1-3) and the quantity of water supplied (treatment 4-5) was sufficient. Although measurements can't discern between an oversupply and sufficient water, it does, however, show that low flow drip had no negative impact on plant water relations in this regard and performed on par with conventional drip systems.

Romero-Trigueros et al. (2021) found that g_s was a good indicator for plant water status and a strong negative correlation existed between g_s and a decrease in soil water content or with an increase in VPD. The results in this study show variation in g_s across measurement periods but no significant difference between treatments on any occasion. The seasonal variation in g_s is consistent with findings of Ribeiro and Machado (2007) which showed that soil water content and VPD in subtropical conditions are the most important factors affecting citrus water relations. The VPD on measurement dates ranged between 0.4 kPa and 1.6 kPa, together with the seasonal changes in soil water content described in Chapter 4, could explain the large variation in g_s observed in this study. There is a perception in the industry that by lowering application rates to supply water over a longer period will in turn cause stomata to stay open for longer, this hypothesis could not be confirmed in this study with no significant difference in g_s between application rates observed on the measurement dates, however, limited data was available under favourable or comparable weather conditions. No g_s threshold for stress was found in available literature for 'Nadorcott' or Mandarins but since no significant differences were found between treatments in this study, with specific reference to the 20% and 40% deficit treatments, it is unlikely that any treatment was stressed during measurement periods, confirming the ψ_{pd} and ψ_{stem} results.

To investigate the hypothesis that LFD had no negative effect on yield compared to conventional drip irrigation, it was important to first establish that prior to the commencement of the trial all trees had similar yields. A very high yield in the season prior to the commencement of the trial had a major impact on the 2021/22 yield and resulted in an "off year". Alternate bearing is common for 'Nadorcott' mandarin and is caused by excessive fruit load in "on" years that hinders summer vegetative shoot growth, leading to reduced flowering and an "off" year. This is mainly because fruit acts as a significant carbohydrate sink, disrupting the equilibrium between vegetative shoot development and root growth through constrained carbohydrate distribution to the roots (Stander et al., 2018). There were no significant differences in yield between treatments over the two seasons and therefore irrigation application rate, nor a 20% and 40% deficit, had an influence on yield. This confirms the hypothesis set out that the same yields can be achieved with LFD systems as with conventional drip and that this could be achieved with less water. Similar findings were made in studies by Assouline (2002) and Koenig (1997) that showed no increase in yield with lowered application rate but did show that irrigation requirement decreased due to increased soil water storage

Fruit size did increase over the duration of the trial but was not statistically significantly different between treatments. There was also no correlation between yield and fruit size, with the two “on” years (2021 and 2023) having the smallest and largest fruit size respectively. Citrus fruit size can be affected during phase II of fruit development and can therefore be used to indicate if stress occurred in that period. It is important to note that compensatory fruit growth can take place if water returns to adequate levels up to three months prior to harvest Ginestar and Castel (1996) and Carr (2012) which would have likely happened in this summer rainfall environment. The internal quality of citrus is influenced by the plant water status in phase III of fruit development and can be improved by a mild deficit or decreased by over-irrigation (Peng and Rabe (1998) it is therefore a very important factor that determines if the fruit harvested has an economic value. Internal quality was only sampled in the final season and no statistical analysis was performed, however, there were no differences in acidity and brix (TSS). All treatments were within the South African minimum export standards and therefore there are no differences in economic value of the fruit between the five treatments.

5.6 Conclusion and recommendations

Based on the findings that there were no differences in yield, fruit size, and internal quality between treatments it can be assumed that there was no significant water stress in any of the treatments during phases I, II, or III of fruit development (Romero et al., 2006, Ginestar and Castel, 1996, Lez-Altozano and Castel, 1999, Peng and Rabe, 1998). Therefore, emitter application rate and 20% and 40% deficit had no influence on crop performance. The adjusted FAO-56 crop coefficient (K_c) values used to schedule irrigation in this study supplied water at adequate levels with no physiological stress or any adverse effects observed with regard to yield, quality, and size, despite a 20% and 40% reduction of the K_c values. This confirms the hypothesis that current FAO 56 K_c values are not suited for LFD systems, but further investigation is required on the exact amount of overestimation of the current values for both LFD and conventional drip systems. K_c, comprising K_t for transpiration and K_e for evaporation, faces challenges in regional transferability Taylor et al. (2015). Despite the generic citrus value in the current FAO-56 Kc values, the absence of species differentiation, especially for Mandarins (*Citrus reticulata*) with unique water relations or K_t Romero-Trigueros et al. (2021), indicates the need for species-specific or even cultivar-specific K_c values. Notably, variations in K_t among species and K_e among irrigation methods and planting systems, especially in combined systems like LFD, necessitate a reassessment of existing K_t values. It is important to note that irrigation was only scheduled continuously for a maximum of 3-4 weeks at a time and the influence of rain should not be ignored in this trial and that without the frequent replenishment of soil water, the influence of deficit treatments could have appeared more significantly. Caution should be taken when with LFD systems when continuous irrigation is done for extended periods as waterlogging might occur, as with any irrigation system, soil moisture should be monitored, and irrigation halted when moisture levels increase day to day.

CHAPTER 6: WATER PRODUCTIVITY OF 'NADORCOTT' MANDARIN ORCHARDS IN SOUTH AFRICA: A CASE STUDY

6.1 Introduction

Water, often the limiting factor for development and production, is not an infinite resource for most farmers, and the adverse effects of climate change threaten irrigated agriculture, necessitating sustainable water use for producers to survive (Nikolaou et al., 2020). To manage water optimally for irrigation purposes requires a comprehensive understanding of the crop water requirement and what factors influence productivity. There are various factors that determine the water requirement for a citrus orchard which are: (1) whole plant transpiration, (2) soil texture, (3) ambient humidity, (4) water quality, and (5) species, variety, and rootstock-scion combination (Talon et al., 2020). To satisfy the water requirement, most producers rely on irrigation where rainfall (frequency and quantity) and climate are the biggest determining factors for irrigation requirements. To determine the irrigation requirement many producers rely on the FAO56 crop coefficient approach which is powerful in that it combines evapotranspiration (ET_o), which reflects atmospheric conditions, with a crop coefficient (K_c), which considers crop changes. The approach operates on the assumption of a constant ratio between ET_o and crop evapotranspiration (ET_c), provided that the K_c remains constant. ET_o is widely used in agriculture to estimate water demand and represents the evapotranspiration (ET) from a hypothetical well-watered short grass surface, the equation used to calculate ET_o is referred to as the Penman-Monteith equation, uses a combination of variables such as temperature, humidity, wind speed, and solar radiation.

Mostert (1999) reported that the contribution of rainfall to irrigation in a summer rainfall area can range between 33% to 44% and that high rainfall areas in the subtropics create complex scenarios with low VPD and excessive water availability for extended periods, where not all rainfall can be utilised by the crop. Rainfall is unpredictable and, as with other climatic factors, are out of a producer's control. However, what is in a producer's control is the irrigation method or system they use and the scheduling of irrigation. Therefore, to achieve high crop water productivity (WP_c) or water use efficiency (WUE) producers need to have an accurate estimation of a plant's ET_c and apply water via the most efficient irrigation system and in the most efficient manner (Martínez-Gimeno et al., 2020).

Several studies have investigated certain aspects of water relations of citrus, with many focused on physiological responses to water stress or regulated deficit irrigation (RDI) (García-Tejero et al., 2010a, Chartzoulakis et al., 1999, Ballester et al., 2014, Morgan et al., 2006). Studies on crop response to RDI are invaluable, especially to growers with limited water resources, however, the question remains, how much water is required to produce a unit mass of citrus? and how does it differ between production areas and irrigation systems?

The concept of a water footprint (WF), or alternatively referred to as "virtual water content", was developed by Hoekstra and Chapagain (2007) to analyse the relationship between the human consumption of the globes freshwater and the appropriation thereof. It is expressed in water volume per unit mass of product (m^3 ton^{-1}) and is broken up into three groups of water footprints, *blue, green,* and *grey.* The *blue* water footprint refers to the volume of water consumed from surface and groundwater sources; the *green* water footprint refers to rainwater consumed and the *grey* water footprint to the amount of freshwater used to assimilate the pollution load associated with the product. Essentially, although the WF concept aimed to offer a comprehensive perspective on water usage, its tendency to oversimplify, rely on standardised methods, overlook local contexts, and inadequately account for water dynamics make it an imperfect and potentially misleading instrument for the purpose of managing water resources effectively (Fereres et al., 2017).

From an agronomist's standpoint, water use efficiency (WUE) can be defined as the proportion of the total marketable yield achieved in relation to the water utilized throughout the growing period (Gregory, 2004, Perry and Bucknall, 2009) and this is better defined in terms of crop water productivity WP_c , introduced first by Molden (1997) and reviewed by Fernández et al. (2020).

$$WP_c = \frac{\text{Marketable yield (kg ha}^{-1})}{\text{TWU (m}^3 \text{ ha}^{-1})} \quad [1]$$

Where units for WP_c are kg m^{-3}, marketable yield is the portion of biomass sold for profit, for example, the fruit of a citrus tree (kg ha^{-1}), and TWU is the total amount of water used in the growing season that would be irrigation (I) (mm), and effective rainfall P_e (mm) (Equation 2). Bearing in mind that effective rainfall can be difficult to quantify.

$$TWU = I + P_e \quad [2]$$

Especially in high rainfall regions, WP_c will be low, however, not all precipitation might be effective, and this will overshadow the influence of irrigation on yield and compare poorly to low rainfall areas, where TWU is less. Therefore Rodrigues and Pereira (2009) proposed the use of irrigation water productivity WP_i which is the ratio between the marketable yield and irrigation applied (IWU) over a growing season, this is also frequently referred to as irrigation water use efficiency (IWUE).

$$WP_i = \frac{\text{Marketable yield}}{\text{IWU}} \quad [3]$$

The limitation of this equation is that the effect of rain on crop performance, which might be significant in certain phenological periods, is ignored. Jamshidi et al. (2020) found that evapotranspiration water productivity (WP_{ET}) is inversely correlated with irrigation level and that the intersection point between relative yield and WP_{ET} can be regarded as the equilibrium point between yield and optimal irrigation savings (Figure 6.1). Values were made relative by setting the maximum yield and WP_{ET} to 1, this was done to compare yields and WP_{ET} with one another.

This information is invaluable to growers and the broader industry as it shows the potential losses in yield if water is restricted, but also where additional water becomes non-beneficial in terms of yield. The results in Figure 6.1 are based on data from the same region and field with the same irrigation system. To compare water productivity (WP_{ET} or WP_c) values between production regions is extremely difficult mainly due to differences in ET_o and rainfall quantity and distribution, which results in arid climates generally having a lower water productivity compared to humid climates due to their higher ET_o and ET and therefore a higher irrigation requirement. Fereres et al. (2017) argued that ratios like WP_{ET} , WP_c and WF are too simple to drive decision-making and to compare regions that differ in crop evapotranspiration (ET_c) will only make sense if a procedure is developed to normalize with ET_o.

The aim of this chapter was to compare the yield, irrigation, and rainfall data of different 'Nadorcott' mandarin orchards in various production regions and to identify trends between the different production areas in terms of WP_c, rainfall contribution to irrigation, and applied crop coefficient (K_c) values, which is seasonal applied irrigation volume divided by ET_o. Furthermore, factors influencing WP_c that are within a producer's control like irrigation type and hail/shade netting were identified. Finally, the possibility of a normalised water productivity index or score (WP_n) that will enable one to compare different production regions with different climatic conditions to one another was investigated.

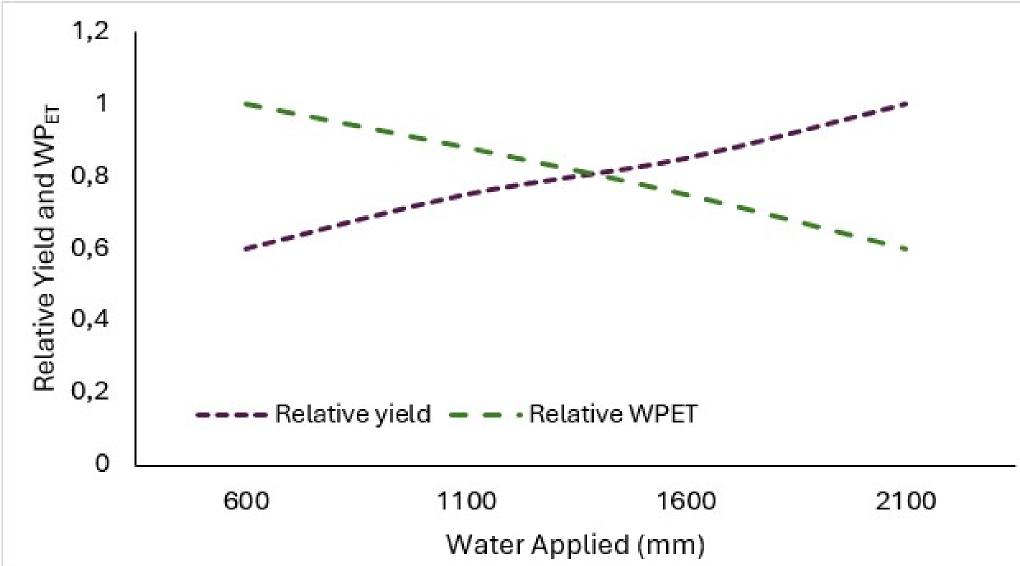

Figure 6.1 Relative values of evapotranspiration water productivity (WP_{ET}) and yield resulting from varying irrigation amounts applied in the same field (Jamshidi et al., 2020).

6.2 Materials and Methods

To determine crop water productivity WP_c, historic data from a variety of orchards in different production regions of the same variety, 'Nadorcott' mandarin (*Citrus reticulata*) were compared. Data to be analysed include irrigation water applied, rainfall, weather data (ET_o), and yield. These orchards have a variety of irrigation systems, conventional drip (emitter delivery > 1.0 l h^{-1}), low flow drip (LFD) (emitter delivery < 1.0 l h^{-1}), and micro-irrigation, with a variety of spacings and delivery rates. Furthermore, some orchards were under shade/hail netting.

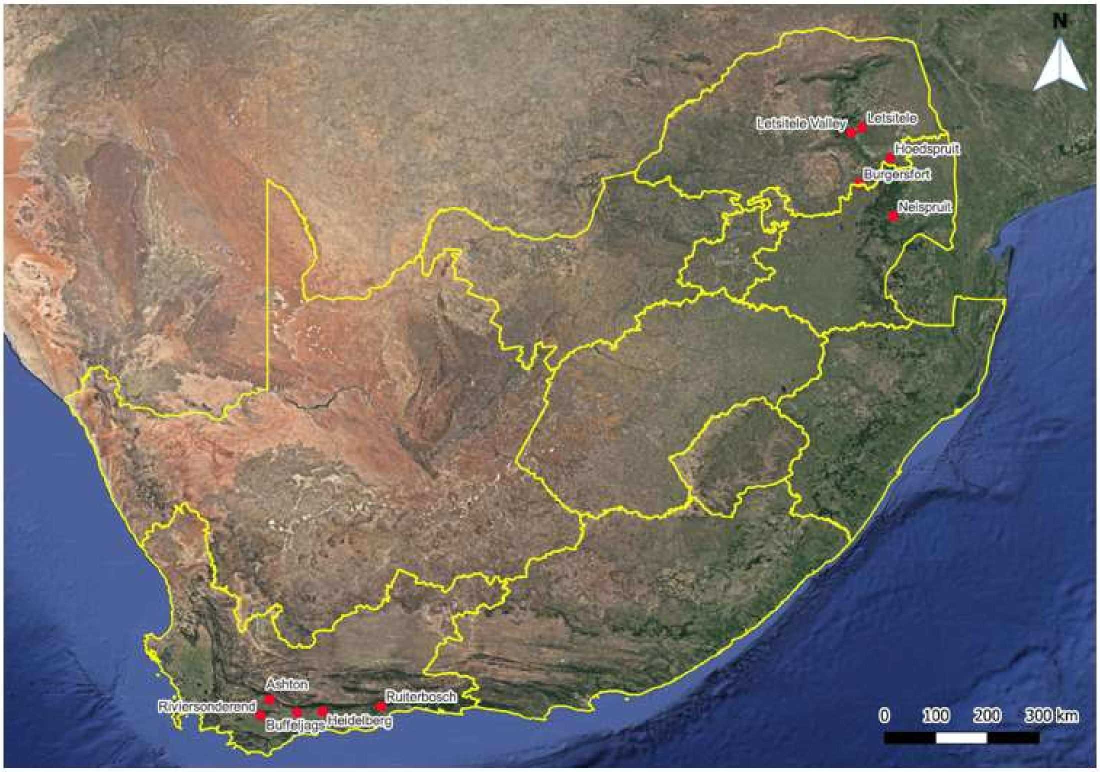

Figure 6.2 Map of South Africa with the locations of the production areas included in the data set.

The outcome of this study was to provide:

1) Water productivity benchmarks (WP_{c},) in terms of water applied per unit mass of fruit produced for different production regions and irrigation systems (m^3 kg^{-1})
2) An alternative method of determining effective rainfall (P_{ci}) and determine the contribution of rainfall to irrigation for summer and winter rainfall areas respectively.
3) Derived seasonal K_c values per region and irrigation system.
4) A method to normalise WP_c values (WP_n) so that comparisons can be made between different regions more accurately.

An orchard represents the smallest data point for which 1) yield and 2) irrigation volume applied are recorded. On average orchards in the data set reach full production in year 6 and therefore all calculations relating to irrigation applied, effective rainfall, WP_c and WP_n were performed on full bearing orchards.

Table 6.1 A summary of the irrigation type used in hectares and number of orchards in each production area for the 'Nadorcott' orchards included in the case study.

	Hectares and (number of orchards) under each irrigation type			
Area	**Conventional Drip (Delivery rate: ≥ 1 l h^{-1})**	**Low flow Drip (Delivery rate: ≤ 1 l h^{-1})**	**Micro-Sprinkler**	**Area Total (Ha)**
Ashton	47 (14)	87 (31)		**134 (45)**
Burgersfort	181 (76)	60 (29)		**241 (105)**
Hoedspruit		51 (18)		**51 (18)**
Letsitele	53 (21)			**53 (21)**
Letsitele Valley		59 (24)		**59 (24)**
Nelspruit	110 (57)	64 (19)		**174 (76)**
Riviersonderend		84 (36)		**84 (36)**
Ruiterbosch		7 (5)		**7 (5)**
Buffeljags			40 (21)	**40 (21)**
Heidelberg	16 (6)		63 (21)	**79 (27)**
Irrigation Type total	**408 (174)**	**412 (162)**	**102 (42)**	**923 (378)**

6.3 Results and discussion

The orchards in the data set vary in a variety of factors however, despite these variations, orchard management was consistent and adhered to established industry standards. For irrigation scheduling, this included using tools such as weather forecasts, reference evapotranspiration (ET_o) and crop coefficient (K_c) values, capacitance probes, and tensiometers to guide irrigation decisions. Furthermore, irrigation volumes were adjusted according to canopy size and K_c values according to the respective phenological stage. In cases where multiple weather stations were present on a farm, the data was averaged to represent the farm's overall weather conditions. The climate in each area is distinct, with notable differences among them. Two primary groups or regions were identified in the dataset based on rainfall patterns, these regions are winter rainfall and summer rainfall (Table 6.2). The most significant difference within these two groups is the amount of rainfall received, with Nelspruit and the Letsitele Valley experiencing the highest rainfall in the summer rainfall region, and Ashton the lowest in the winter region. This variation in rainfall also influenced ET_o, with higher rainfall areas typically showing lower seasonal ET_o values, although these factors might not necessarily be exclusively linked. Both ET_o and rainfall directly impact irrigation practices, as ET_o indicates the atmospheric evaporative demand and therefore the potential water use of the crop, while rainfall contributes as a water source for the crop.

There is seasonal variation in each area with regard to ET_o and rainfall, which will affect the irrigation requirement from one season to the next. Additionally, canopy size plays a crucial role in determining water demand, where ET_c is anticipated to rise annually until the canopy reaches its maximum volume, which can differ from one orchard to another. In this dataset, since the canopy volume of the orchards wasn't measured annually the age of the orchard was utilized to categorize and determine the average irrigation volumes for each season (Table 6.3). Further sub-regional groups were also identified based on information in (Table 6.2), where areas with similar ET_o were classified relatively to one another as warm (ET_o > 1200 mm), moderate (ET_o =1100 -1200 mm), or cool (ET_o < 1100 mm), and the same for rainfall with high (>800 mm), moderate (400-800 mm), or low (0-400 mm) rainfall categories. These combinations resulted in four sub-regions namely warm-moderate summer rainfall, moderate-high summer rainfall, warm-low winter rainfall, and cool-moderate winter rainfall.

Orchards less than 3 years old had comparable annual irrigation volumes, averaging 191 mm ± 40 mm across various locations (Table 6.3). In the <3 years age group, Hoedspruit reported the lowest average annual irrigation at 137 mm (single orchard in this grouping), while Burgersfort had the highest at 221 mm± 74 mm. Notably, both these areas are situated in the same warm-moderate summer rainfall sub-region. However, in orchards aged 3-6 years, the differences in irrigation become more pronounced. Ashton stands out as the highest with an average annual irrigation of 641 mm± 78 mm, whereas areas with moderate-high summer rainfall had the lowest average of 244 mm ± 35 mm. Since not all age groups are represented in each area, aggregating the data into sub-regional levels offers a clearer picture, as illustrated in (Table 6.3) The winter rainfall region exhibited higher annual irrigation rates compared to the summer rainfall region. Consistent with expectations, the sub-regions experiencing the highest rainfall and lowest ET_o (indicating relatively cooler conditions) had the lowest annual irrigation requirements.

Table 6.2 Summary of the annual reference evapotranspiration (ET_o) (mm) and rainfall (mm) for the areas in the data set for the 2020-2023 seasons.

	Region	ET_o (mm)				Rainfall (mm)			
	Season	**2020/21**	**2021/22**	**2022/23**	**Average**	**2020/21**	**2021/22**	**2022/23**	**Average**
Summer Rainfall	**Burgersfort**	1370	1279	1327	**1325**	525	604	703	**611**
	Hoedspruit	1403	1309	1411	**1374**	673	564	712	**650**
	Letsitele	1226	1114	1402	**1247**	661	542	580	**594**
	Letsitele Valley	1095	1049	1187	**1110**	950	924	881	**918**
	Nelspruit	1231	1028	1051	**1103**	839	737	890	**822**
Winter Rainfall	**Ashton**	1309	1232	1078	**1206**	236	293	396	**308**
	Rivier-sonderend	1143	1045	1026	**1071**	870	632	780	**761**
	Ruiterbosch	1035	1078	1016	**1043**	644	714	801	**720**
	Buffeljags	859	983	1115	**986**	676	576	519	**590**
	Heidelberg	973	969	970	**971**	718	520	624	**621**

Table 6.3 Annual applied irrigation (mm) per region, sub region, and area for the 2021-23 seasons grouped by orchard age in years. NA - no orchard in that age grouping. Standard deviation indicated with ± where calculated.

Region	Sub region	Area	Average annual irrigation (mm) Orchard age (years)				
			<3	(3-6]	(6-9]	(9-12]	12<
Summer Rainfall	Warm-moderate summer rainfall	Burgersfort	221±74	309±37	337±31	366±26	419±150
		Hoedspruit	137	457±44	390	NA	NA
		Letsitele	NA	397±86	306±29	445	379±95
	Moderate-high summer rainfall	Letsitele Valley	NA	206±1	216±7	252±66	342±38
		Nelspruit	187±33	248±36	278±63	238±58	211±36
Winter Rainfall	Warm low winter rainfall	Ashton	193±96	641±78	634±47	NA	NA
	Cool-moderate winter rainfall	Riviersonderend	208±34	325	NA	NA	NA
		Ruiterbosch	181±3	266±105	NA	NA	NA
		Buffeljags	NA	333	421±120	468±155	481±166
		Heidelberg	NA	345±90	472±100	501±126	NA

To calculate WP_c for an orchard or area, the yield (t ha^{1}) is required with the respective applied irrigation (I) and effective rainfall (P_e). To truly determine the effectiveness of rainfall one needs to take into consideration the rate and amount of rain, antecedent soil water content, topography, and phenological period. Not all the aforementioned information was available and even with all this information available, there is little consensus on the variety of proposed methods to calculate effective rainfall. It was therefore decided to follow a more simplistic approach where the contribution of rainfall to crop water requirements relative to ET_o served as a measure of effectiveness. This illustrated the amount of irrigation required despite the rainfall that occurred, all within context of ET_o. From (Figure 6.3) it is evident that applied irrigation volumes increased up to year 6, after which changes in irrigation volumes were minimal with age, as orchards reach full canopy volume. It was therefore decided that only orchards 6 years and older would be used to determine effective rainfall since they have reached a maximum canopy size and therefore maximum water requirement. Young orchards may provide a skewed reflection of rainfall contribution due to their low water use.

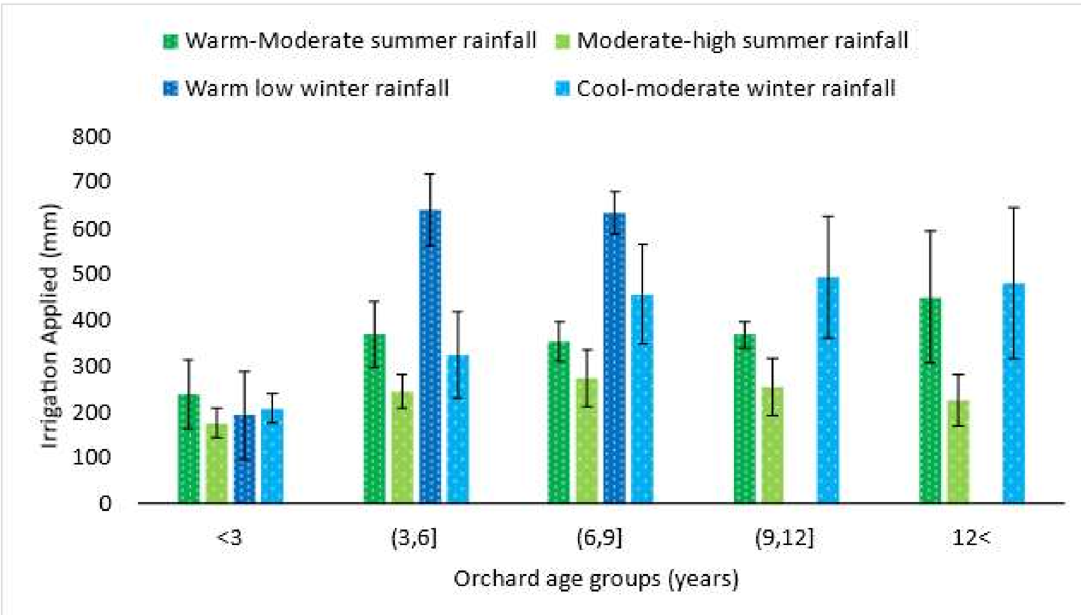

Figure 6.3 Average annual irrigation applied (mm) for the 2021-23 season per age group grouped on a sub-regional level. Error bars indicate standard deviation.

By assuming irrigation was applied to meet demand and stressed conditions did not occur (see description of irrigation scheduling above), a variety of derived K_c values were determined, which followed the rationale of traditional K_c values where it is the ratio to determine crop water demand from ET_o. In this context, the total K_c represents the ratio between the total water applied or supplied to an orchard and ET_o over a season.

$$\text{Total } K_c = \frac{\text{Season I (mm)} + \text{Season P (mm)}}{\text{Season } ET_o \text{ (mm)}} \qquad [4]$$

Where season I refers to the total amount of irrigation applied over a season (mm), season P to the total rainfall (mm), and season ET_o (mm) to the total reference evapotranspiration over the same period. The applied K_c which represents only the ratio of irrigation volumes to ET_o does not illustrate the seasonal variation of an actual K_c for citrus but does give an indication of the amount of irrigation required for a season in a specific area.

$$\text{Applied } K_c = \frac{\text{Season I (mm)}}{\text{Season } ET_o \text{ (mm)}} \quad [5]$$

This allows the calculation of the contribution or effectiveness of rainfall to the total water demand or irrigation (P_{ci}), since it was assumed that irrigation was applied equal to crop water demand based on the scheduling tools described in materials and methods. Therefore P_{ci} , represents the effective rain, when irrigation was not required, and can be expressed as a ratio or converted to a percentage as follows:

$$P_{ci}(\%) = \left(1 - \left(\frac{\text{Applied } K_c}{\text{Total } K_c} \right) \right) \times 100 \quad [6]$$

This data (Table 6.4) represents the average of the three respective seasons (2020-2023). From the data, it is evident that the higher the annual rainfall and the lower the ET_o the greater the total K_c, as can be observed in the moderate-high summer rainfall and cool-moderate winter rainfall sub-regions with an average K_c value of 1.02 and 1.10 respectively. This is much greater when compared to the two warm sub-regions with an average of 0.79 for the warm summer rainfall and 0.90 for the warm winter rainfall sub-regions respectively. However, when comparing applied K_c values, the summer rainfall regions applied considerably less water than the winter rainfall regions with an average applied K_c of 0.27 in the summer rainfall regions and 0.51 in the winter rainfall regions. The timing and quantity of rainfall is reflected in the contribution of rain to irrigation and only the portion of rainfall utilised by the plant to meet ET_c requirements was deemed to be effective (Fares et al., 2008). In this data set (Table 6.4) the largest contribution of rainfall to irrigation was 78% from the moderate-high summer rainfall sub-region, followed by the warm moderate summer rainfall sub-region at 62%. Although different approaches were used these values (Table 6.4) are much higher than reported by Mostert (1999) for Nelspruit (moderate-high summer rainfall sub-region), which was estimated to be between 33%- 44% and Cruse et al. (1982) for the Rio-Grande valley, similar to the warm moderate summer rainfall sub-region, where rainfall contributed 50% to irrigation. The lowest contribution was observed in the warm-low winter rainfall sub-region with an average contribution of 37%, followed by the cool-moderate winter rainfall region at 57%. These values correspond with the study by Taïbi (2022) in the Mediterranean citrus growing regions of North Africa, where rainfall contributed 40%-50% of the total water demand of citrus in the area. Overall, the rainfall in the summer rainfall region contributed more to ET_c than rainfall in the winter rainfall region, which is due to the fact that little to no rainfall occurs in the peak water demand period (summer) and that as previously stated rainfall can only be deemed effective when its used for evapotranspiration (Cerdà et al., 2009).

Table 6.4 Average total and applied crop coefficient (K_c) values for orchards 6 years and older for the 2020-23 seasons. I refer to irrigation (mm), P to rainfall (mm), ET_o to reference evapotranspiration and P_{ci} the contribution of rainfall to total water applied (%) in terms of ET_o. Data was grouped by region, sub-region, and area.

Region	Sub region	Area	Total K_c $(I+P)/ET_o$	Applied K_c (I/ET_o)	P_{ci}
Summer Rainfall	Warm-moderate summer rainfall	Burgersfort	0.77	0.30	61%
		Hoedspruit	0.78	0.28	65%
		Letsitele	0.78	0.30	61%
	Moderate-high summer rainfall	Letsitele Valley	1.06	0.24	78%
		Nelspruit	0.96	0.21	78%
Winter Rainfall	Warm low winter rainfall	Ashton	0.90	0.57	37%
	Cool-moderate winter rainfall	Buffeljags	1.06	0.46	57%
		Heidelberg	1.14	0.50	56%

The final requirement to determine WP_c is yield, which is influenced by multiple factors, including tree age, planting density, netting, alternate bearing tendencies or general seasonality, and fruit quantity and size. Yield in this study was expressed as (t ha ^{1}) and only represents fruit with an economic value that was sent to the packhouse and recorded in the database, where out-of-season fruit and fruit culled on the farm as waste was excluded and not recorded. Figure 6.4 shows that 'Nadorcott' trees are precocious and start to set fruit from as early as 2 years of age, with a rapid increase in yield year on year up to year 5, after which trees are in full bearing and no further increase is observed. The average yield for mature orchards in this data set was 54-ton ha^{-1}. It is important to note the great variation in yield over time reflecting, among other factors, the alternate bearing nature of this cultivar (Figure 6.4).

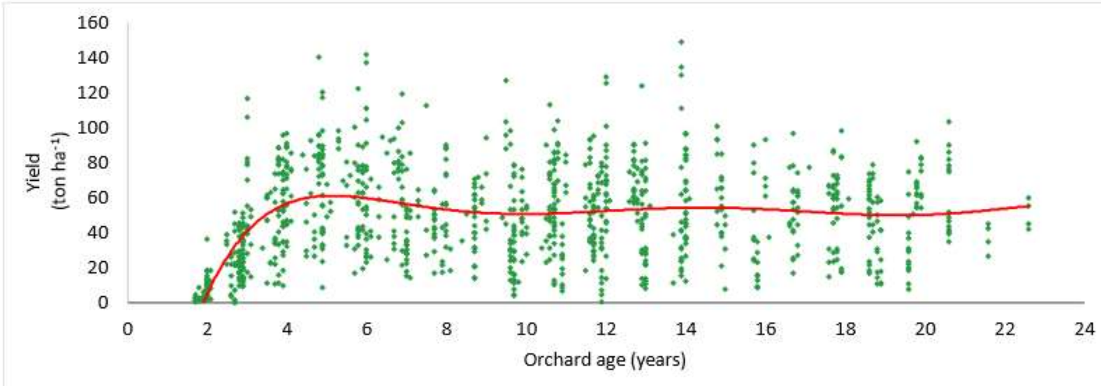

Figure 6.4 Yield (t ha^{-1}) for orchards of varying ages for the 2020-23 seasons. All the orchards included in the data set are presented. The red line represents the trend line (6th degree polynomial).

When comparing the yield data between regions (Table 6.5), the summer rainfall regions had a much higher average yield in each of the 5 age categories with age < 3 years averaging 29 ± 25 t ha^{-1} in the summer rainfall region compared to 19 ± 9 t ha^{-1} in the winter rainfall region, ages (3-6] years 55 ± 25 t ha^{-1} compared to 34 ± 17 t ha^{-1}; (6,9] years 61 ± 25 t ha^{-1}, compared to 44 ± 19 t ha^{-1}; ages (9,12] 57 t ± 26 t ha^{-1}, compared to 44 ± 24 t ha^{-1} and ages 12 < 58 ± 25 t ha^{-1}, compared to 47 ± 23 t ha^{-1} in the winter rainfall regions.

Table 6.5 Average yield (ton ha ^{1}) per region, sub region and area for the 2021-23 seasons, grouped by orchard age in years. NA; no orchard in that age grouping.

Region	Sub region	Area	Yield (ton ha ^{1}) Orchard age (years) <3	(3-6]	(6-9]	(9-12]	12<
Summer Rainfall	Warm-moderate summer rainfall	Burgersfort	28±26	60±23	48±17	74±22	55±24
		Hoedspruit	25±3	80±16	78±16	NA	NA
		Letsitele	NA	35±13	59±21	43	51±17
	Moderate-high summer rainfall	Letsitele Valley	NA	39±11	55±27	58±21	73±13
		Nelspruit	35±8	62±28	65±29	52±28	51±30
Winter Rainfall	Warm low winter rainfall	Ashton	19±10	59±14	44±18	NA	NA
	Cool-moderate winter rainfall	Riviersonderend	14±7	15±6	NA	NA	NA
		Ruiterbosch	24±2	30±12	NA	NA	NA
		Buffeljags	NA	30±4	43±21	45±25	47±23
		Heidelberg	NA	35±13	45±18	43±24	NA

If one firstly considers only yield versus irrigation (WP_i) a clear distinction can be made between regions, with WP_i values being ~ 50% more in the summer rainfall region within each respective age group (Figure 6.5). The average across all age groups for the summer rainfall region was 18.3 kg m^{-3} ± 10.6 kg m^{-3} and 9.6 kg m^{-3} ± 4.6 kg m^{-3} for the winter rainfall region. Kirda et al. (2007) found similar WP_i values for mandarins (*Citrus reticulata*) with values that ranged from 4.1 kg m^{-3} to 11.7 kg m^{-3} in a Mediterranean climate with an average annual rainfall of 650 mm. When compared to other citrus varieties (*Citrus sinensis*) the values from this study were much higher than other comparable sub-tropical climates (summer rainfall) with WP_i values of 3.9 kg m^{-3} to 5.5 kg m^{-3} (Mostert, 1999, Panigrahi and Srivastava, 2017) and Mediterranean climates (winter rainfall) of 3.5 kg m^{-3} to 5.6 kg m^{-3} (Chartzoulakis et al., 1999). Poveda-Bautista et al. (2021) published a wide range of WP_c values for 'Navelinas' (*Citrus sinensis*) in the Valencia region, Spain that are comparable with the findings of this study with WP_c values of 5.0 kg m^{-3} to 19.0 kg m^{-3}. Overall limited research is available from comparable climatic regions and varieties to benchmark with the findings of this study.

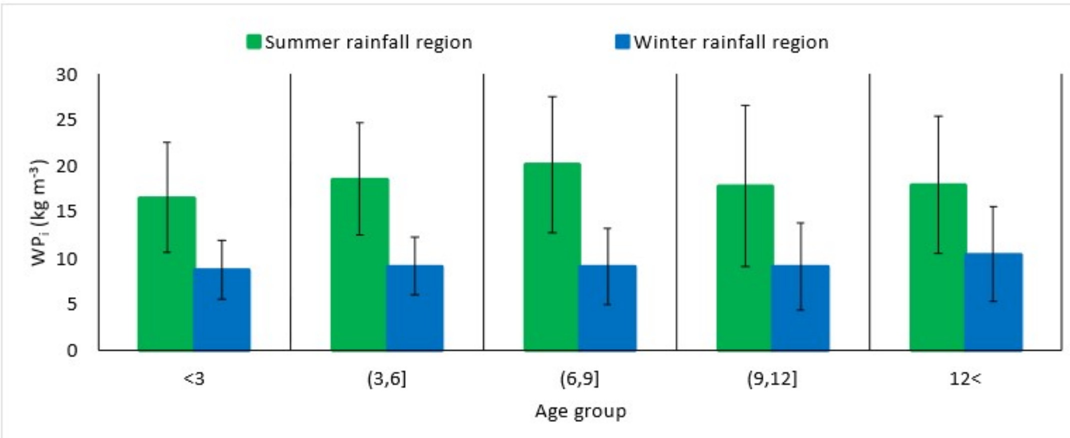

Figure 6.5 Average irrigation water productivity WP_i (kg m^{-3}) per age group and per region for the 2020-2023 seasons. Error bars indicate standard deviation.

The factors influencing WP_c are yield, irrigation applied, and effective rain. Effective rainfall was estimated from equation 6 by multiplying the annual rainfall with P_{ci}. Therefore, P_e in equation 2 was calculated as follows:

$$P_e = P \times P_{ci} \qquad [7]$$

Where P refers to annual rainfall (mm), and P_{Ci} the contribution of rainfall to irrigation (%). When comparing WP_c values across regions (Figure 6.6), young orchards (< 3 years) have low WP_c figures averaging 3.0 kg m^{-3} for the winter rainfall regions and 4.0 kg m^{-3} for the summer rainfall regions. From age 6 years and older these figures remain constant with an average of 5.6 kg m^{-3} for the winter rainfall region and 7.0 kg m^{-3} for the summer rainfall region. Excluding orchards younger than 6 years, the Hoedspruit area had the highest average WP_c with 9.8 kg m^{-3} followed by Burgersfort with an average of 8.0 kg m^{-3}. The area with the lowest average WP_c was Heidelberg with 5.3 kg m^{-3}.

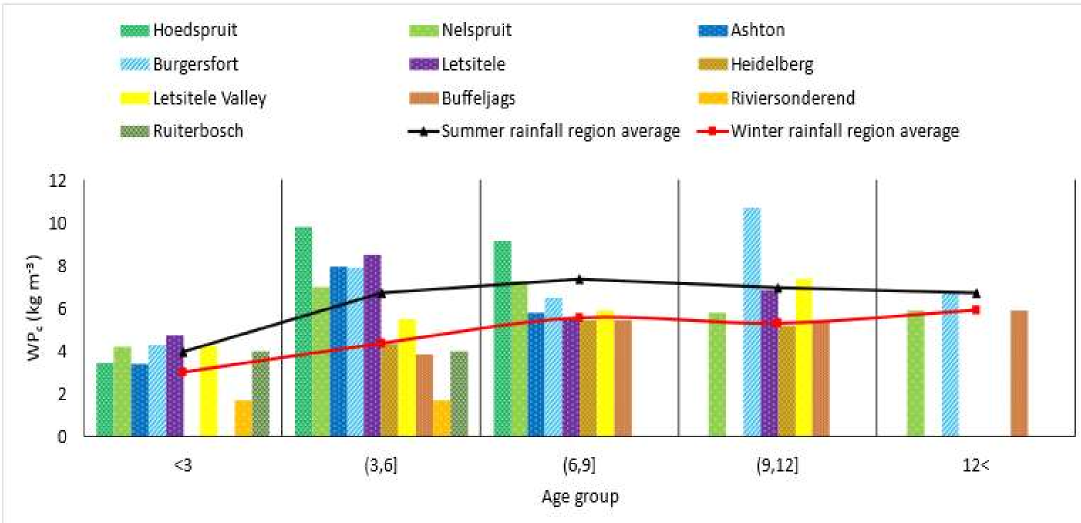

Figure 6.6 Average crop water productivity WP_c (kg m^{-3}) per age group and per area for the 2020-23 seasons. Regional averages are represented by solid black (summer rainfall region) and red lines (winter rainfall region).

From (Figure 6.6) it is evident that there were differences in WP_c between climatic regions. This could be due to yield differences, which a producer can control only to a certain extent, because there are inherent differences between regions, such as growing degree days, maximum temperatures, and vapour pressure deficit, that influence fruit set and size and ultimately yield. This makes some areas more productive for certain varieties (Talon et al., 2020, Chelong and Sdoodee, 2013, Chartzoulakis et al., 1999).

The other variable that influences WP_c is TWU or more specifically the amount of supplementary irrigation applied, since rainfall can't be controlled by the grower. The quantity of water applied will be determined by the ET_o of the area, however, it is also influenced by the effectivity of the irrigation system and the management thereof, which is usually based on soil water monitoring. Where irrigation systems are ineffective more water would have to be applied to replace depleted soil water. To evaluate the influence of irrigation type on TWU and K_c, Table 6.6 summarises the average yield (t ha^{-1}), applied K_c and WP_c (kg m^{-3}) for orchards in full production (6 years and older) according to the different irrigation systems used in each sub region for seasons 2021 - 2023.

Table 6.6 Average yield (t ha^{-1}) applied crop coefficient (K_c) and WP_c (kg m^{-3}) for orchards 6 years and older for the 2021-23 seasons. I refer to irrigation (mm), ET_o to reference evapotranspiration, TWU to total water use, and P_e to effective rainfall (mm). Conventional drip refers to dripper emitter delivery rate of >1 l h^{-1}, low flow drip refers to dripper emitter delivery rate of <1 l h^{-1} and micro sprinkler includes all micro sprinkler systems. Data was grouped by region, sub region, irrigation type and area. Standard deviation is indicated by ±.

Region	Sub region	Irrigation Type	Area	Yield (ton ha^{-1})	Applied K_c (I/ET_o)	TWU (mm) ($I+P_e$)	WP_c (kg m^{-3})
Summer Rainfall	Warm-Moderate summer rainfall	Conventional Drip	Letsitele	51±17	0.30±0.05	747±66	6.9±2.4
			Burgersfort	62±24	0.25±0.02	739±60	8.4±3.4
		Low flow drip	Burgersfort	51±24	0.43±0.1	882±141	5.8±2.8
			Hoedspruit	78±24	0.28±0.08	850±0	9.1±1.8
	Moderate-high summer rainfall	Conventional Drip	Nelspruit	52±30	0.22±0.05	876±73	5.9±3.8
		Low flow drip	Letsitele Valley	61±20	0.24±0.05	982±15	6.2±2.1
Winter Rainfall	Warm low winter rainfall	Conventional Drip	Ashton	44±18	0.57±0.07	758±71	5.7±2.1
	Cool-moderate winter rainfall	Conventional Drip	Heidelberg	41±24	0.39±0.05	744±66	5.5±3.0
		Micro-sprinkler	Heidelberg	44±22	0.52±0.12	851±109	5.3±2.6
			Buffeljags	45±23	0.46±0.12	795±85	5.6±2.7

The variation in yield becomes apparent when comparing different climatic regions rather than irrigation types (Table 6.6). It has been reported that climatic factors like rainfall, temperature, and evaporation influence yield in citrus (Downton and Miller, 1993, Tubiello et al., 2002) , and therefore differences in yield are to be expected with a variety of climatic regions in the data set. Although not included in this data set, there are known differences in growing degree days between regions, which could be another contributing factor impacting yield, where Chelong and Sdoodee (2013) showed that growing degree days had a significant impact on yield mainly due to an increase in fruit size. The significant standard deviation within each region suggests that factors beyond just irrigation type and regional climate have notable impacts on yield (Table 6.6). These factors include rootstock, tree nutritional status, and production practices like pruning and thinning (Talon et al., 2020, Stander et al., 2018, Martínez-Cuenca et al., 2016, Dubey and Sharma, 2016).

Regarding the applied K_c values, it's only meaningful to compare systems within each sub-region due to variations in rainfall effectiveness, which impacts the irrigation requirements to meet crop ET. In general, conventional drip and low flow drip (LFD) systems exhibited similar performance (Table 6.6). In the warm-moderate summer rainfall region, conventional drip had the lowest applied K_c value of 0.28± 0.08, while LFD was slightly higher at 0.35± 0.05. In the moderate-high summer rainfall sub-region, LFD and conventional drip resulted in similar applied K_c values of 0.24± 0.06 and 0.22± 0.06, respectively. The only sub-region with micro-sprinkler was the cool-moderate winter rainfall sub-region, where micro-sprinkler had a considerably higher applied K_c value of 0.52± 0.12 compared to 0.39± 0.05 for conventional drip. A wide range of K_c values have been reported for mature citrus orchards in different climatic regions ranging from 0.6 to 1.2 (Hoffman et al., 1980, Rogers et al., 1983, Castel et al., 1987, Allen et al., 1998, Snyder and O'Connell, 2007) , although not all these values were determined with the same methodology they are in general much higher than what was determined in this study for all irrigation systems. The difference between drip irrigation and micro-sprinkler K_c values may be due to a function of K_e and not necessarily K_t.

When comparing TWU values, there was little differences between areas and irrigation systems, especially when taking the standard deviation into account. However, the one area where significant differences may have been present was between the micro-irrigated and drip irrigated orchards in Heidelberg, where the average water applied for drip orchards was 744 mm± 66 mm compared to the micro irrigation orchards average of 851 mm± 109 mm. This was consistent with findings in other studies where TWU under drip irrigation was less than for micro - sprinklers (Brouwer, 1998, Fereres et al., 2003, Howell, 2003, Bryla et al., 2005, Chartzoulakis et al., 1999, Danckwerts, 2019).

A similar trend to the applied K_c was observed when comparing irrigation systems in terms of WP_c, where in the warm-moderate summer rainfall sub region WP_c values for conventional drip and LFD compared closely with an average of 7.7 kg m^{-3} and 7.5 kg m^{-3} respectively (Table 6.6). In the moderate-high summer rainfall region LFD had a slightly higher average WP_c at 6.2 kg m^{-3} compared to conventional drip at 5.9 kg m^{-3}. In the winter rainfall regions, the only comparison in irrigation systems was possible in the cool-moderate region, where conventional drip had a slightly higher average WP_c of 5.5 kg m^{-3} compared to micro sprinklers at 5.3 kg m^{-3}. When only considering absolute values, the highest WP_c was 9.1 kg m^{-3} on an LFD system in Hoedspruit, with the lowest being Heidelberg on micro-sprinkler with a WP_c of 5.3 kg m^{-3}. There is little comparative data available for WP_c on 'Nadorcott' or other Mandarins (*Citrus reticulata*). A study by Kirda et al. (2007) on (*Citrus reticulata*) 'Marisol' found irrigation water use effectivity (IWUE) , where effective rain was not included, to range between 4 kg m^{-3} and 11 kg m^{-3} for a winter rainfall area, with an average annual rainfall between 450-750 mm. Considering the efficacy of rainfall in the moderate winter rainfall area (Table 6.4) these IWUE values can be converted to WP_c and would equate to 3.4 kg m^{-3} to 6.4 kg m^{-3}, that would be comparable with data in Table 6.6.

It is important to note that within each irrigation system type there are also variations in delivery rates, and not all low flow, drip or micro-sprinkler systems were equal in their respective groups. Figure 6.7 Illustrates the variety in irrigation system delivery rates (mm h^{-1}). Drip delivery rates ranged from 0.23 mm h^{-1} to 1.3 mm h^{-1} and micro sprinkler > 2 mm h^{-1}. There was an increase in K_c with an increase in delivery rate (R^2 = 0.47) (Figure 6.7a). Conversely there was a decrease in WP_c with an increase in system delivery rate, but system delivery rate only explained a very small proportion of the variation in WP_c, as indicated by a much lower R^2 value (0.058) (Figure 6.7b). Studies by Koenig (1997) , Selim et al. (2013) and Cote et al. (2003) found that a decrease in emitter delivery rate limits deep drainage, with more water available in the rootzone, resulting in an increase in the effectivity of the irrigation system. A shortcoming of the data set is that there are many more orchards with low delivery rates (< 1 mm h^{-1}) than orchards with other irrigation system and ideally the data set should have had an even distribution of irrigation systems across regions to truly compare the influence of emitter delivery rate on applied K_c and WP_c. All new developments by the farms in the data set have been on drip irrigation with the most recent developments (from 2018) moving towards LFD < 4.0 mm h^{-1}.

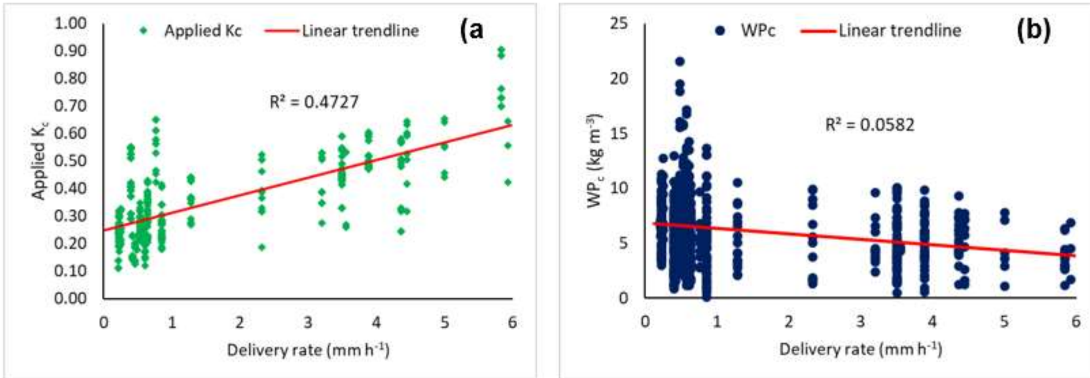

Figure 6.7 Comparison between (a) applied crop coefficient (K_c) and (b) crop water productivity-WP_c (kg m^{-3}) and irrigation system delivery rate (mm h^{-1}) for orchards 6 years and older for the 2020-2023 seasons.

Finally, another distinguishing factor between orchards, besides region and irrigation system, is that some orchards were under shade net, and this may have influenced WP_c, either by impacting yield or the irrigation applied because of a change in water use and microclimate. Unfortunately, both open and netted orchards were not found in every region to allow for a comprehensive comparison. The areas where there were both open and netted orchards 6 years and older are presented in Table 6.7. For the Burgersfort area there were no clear difference in open or netted orchards in terms of yield, applied K_c or WP_c. For Letsitele both yield and WP_c were higher in open orchards, however, the applied K_c, which is directly linked to irrigation volumes was lower under net. The netted orchards in the Nelspruit region had a slightly higher yield and lower applied K_c, which resulted in a higher WP_c for the netted orchards with notably a lower standard deviation, as compared to orchards without nets. Many studies have shown that shade netting can increase water productivity by lowering transpiration demand through a decrease in VPD and an unchanged or improved yield due to improved carbon assimilation rates (Prins, 2018, Jifon and Syvertsen, 2003).

Table 6.7 Average yield (t ha^{-1}) applied crop coefficient (K_c) and water productivity (WP_c, kg m^{-3}) for orchards 6 years and older for the 2020-23 seasons, I refers to irrigation (mm), ET_o to reference evapotranspiration, conventional drip refers to dripper emitter delivery rate of (>1 l h^{-1}), Orchards were grouped by area and if they were netted or open. Standard deviation is indicated by ±.

Area	Netted	Irrigation type	Yield (ton ha^{-1})	Applied K_c (I/ET_o)	WP_c kg m^{-3}
Burgersfort	Open	Conventional Drip	61±11	0.25±0.02	8.2±1.5
	Netted	Conventional Drip	62±27	0.26±0.03	8.4±3.8
Letsitele	Open	Conventional Drip	55±17	0.31±0.05	7.3±2.4
	Netted	Conventional Drip	40±12	0.27±0.06	5.6±1.7
Nelspruit	Open	Conventional Drip	52±30	0.22±0.05	5.1±3.5
	Netted	Conventional Drip	53±32	0.17±0.05	5.9±3.3

A drawback of WP_c is that it uses absolute values of irrigation and does not consider the atmospheric evaporative demand of an area, which should be considered as areas with a higher ET_o will have a correspondingly higher crop ET requiring more irrigation to maintain productivity. As a result, WP_c will be lower despite yield being equal. To determine the efficiency of irrigation in relation to atmospheric evaporative demand and to incorporate the effective rainfall contribution (P_e) to the total water requirements of the crop, a normalised K_c (K_{cn}) was calculated as follow:

$$K_{cn} = \frac{I + P_e}{ET_o} \quad [8]$$

where K_{cn} refers to a normalised crop coefficient based on I, irrigation applied (mm), ET_o and P_e effective rainfall (mm) [equation 8]. The aim of calculating a K_{cn} was to consider the irrigated volume and the utilisation of rainfall in context of the atmospheric evaporative demand, as indicated by ET_o. To determine how productive irrigation applications were in an area and season, a normalised water productivity score was calculated as follows:

$$WP_n = \frac{Yield}{K_{cn}} \qquad [9]$$

Where WP_n is a score or index (considered to be dimensionless) for water productivity. To illustrate the difference between WP_c and WP_n, the yield of all three seasons in the data set was made to be equal to the long-term average which is 54 t ha^{-1} (Table 6.4). This was done to remove yield as a variable and highlight the influence of only irrigation and effective rainfall on the two respective water productivity indicators and the effect of normalising for local climate and inter-season variation using ET_o.

Since WP_c only takes absolute values of TWU and yield into consideration, the WP_c values become closely matched when yield is kept constant (Figure 6.8a), with the most productive regions being Letsitele and Ashton, followed by Burgersfort then Buffeljags, Heidelberg, Hoedspruit, and Nelspruit and finally the Letsitele valley. When considering WP_n (Figure 6.8b), the ranking of productivity between areas differed to that of WP_c (Figure 6.8a), with Burgersfort being the most productive followed Hoedspruit and Letsitele then Ashton, with Nelspruit and Buffeljags having similar values with Heidelberg being slightly lower and finally the Letsitele Valley being the least productive. When comparing the order of the areas between WP_c (Figure 6.8a) and WP_n (Figure 6.8b), it was evident that there were different outcomes between WP_c and WP_n with the most significant change in rankings being between Ashton moving from 2nd to 4th and Hoedspruit moving from 6th to joint 2nd. Furthermore, all the other areas moved position with no area retaining its place between WP_c and WP_n apart from Letsitele valley remaining 8th in both scenarios.

As expected, the WP_c ranking follows the exact trend of the TWU, where the higher the TWU the lower the WP_c (Figure 6.8a). This is not the case for WP_n, where ET_o is used to normalise the total water applied relative to atmospheric evaporative demand (Figure 6.8b). Therefore, areas that require more water are not penalised, as is the case for a normal WP_c calculation (Figure 6.8a). When P_e is excluded from TWU and only irrigation is considered, with the difference between TWU and irrigation being P_e essentially, the complexity of rainfall contribution becomes clear. From this data one can see that there are areas like Nelspruit and Letsitele Valley with low applied irrigation and WP_c values which were mainly due to the high rainfall of the area. In terms of irrigation potential these areas can produce the most fruit with the least amount of irrigation water (normal rainfall) and it can therefore be argued that these are the most productive areas. To accurately determine rainfall contribution and water productivity for high rainfall areas remains challenging for both WP_c and WP_n indicators.

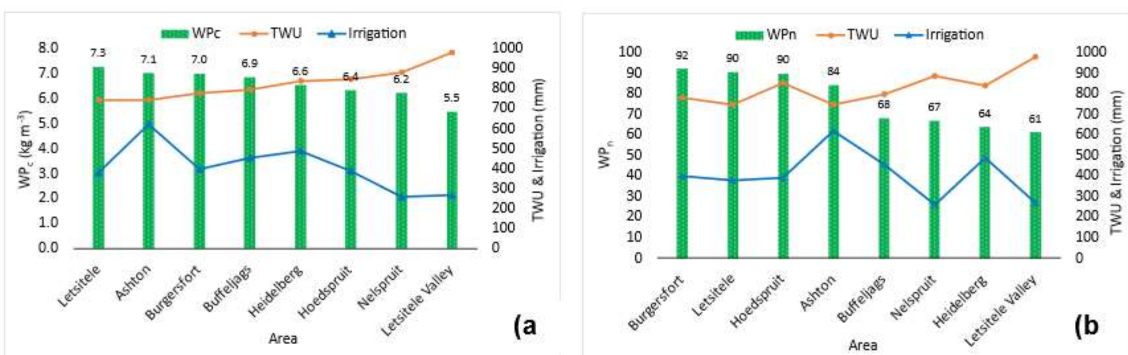

Figure 6.8 Average (a) crop water productivity -WP_c (kg m^{-3}) and (b) normalised crop water productivity WP_n, for mature orchards (>6 years) for the 2020-23 seasons. Yield was made equal to 54 t ha^{-1} (long term average) for all blocks. Total water use (TWU) that represents irrigation and effective rainfall (mm) is indicated on the secondary y-axis. Data in each respective graph is arranged from most productive to least productive (left to right).

When applying WP_c and WP_n to the actual yield data of seasons 2021-23 for orchards in full production (> 6 years) the influence of yield between areas become evident (Figure 6.9). The higher-yielding summer rainfall region is the most productive for both

WP_c (Figure 6.9a) and WP_n (Figure 6.9b), with the ranking of all the areas being the same in both figures. A similar trend in terms of water use efficiency (WUE, kg m^{-3}) was observed by Vahrmeijer et al. (2018) where the summer rainfall areas had overall higher average WUE compared to the winter rainfall areas. Vahrmeijer et al. (2018) found values of 5.4 kg m^{-3} to 7.9 kg m^{-3} for 'Nadorcott' Mandarins in the winter rainfall area, which is comparable but on the higher end of values in (Figure 6.9a) for the winter rainfall region. It is important to note that only transpiration was considered in this study and that different denominators would result in different absolute values. When comparing data in Figure 6.8 with Figure 6.9, the productivity of areas according to WP_n in both cases remained similar except for Letsitele Valley moving from 8th to 4th, and Ashton from 4th to 6th, whereas the order of areas according to WP_c changed completely. One can argue that WP_n is less sensitive to the influence of absolute TWU values and that it is a more accurate water productivity indicator than WP_c by taking the environmental demand into consideration. It can be especially useful to compare water productivity between areas within a specific rainfall region, but with different ET_o. Since there was still a clear divide between rainfall regions for WP_n further research is required to normalise fully between summer and winter rainfall regions.

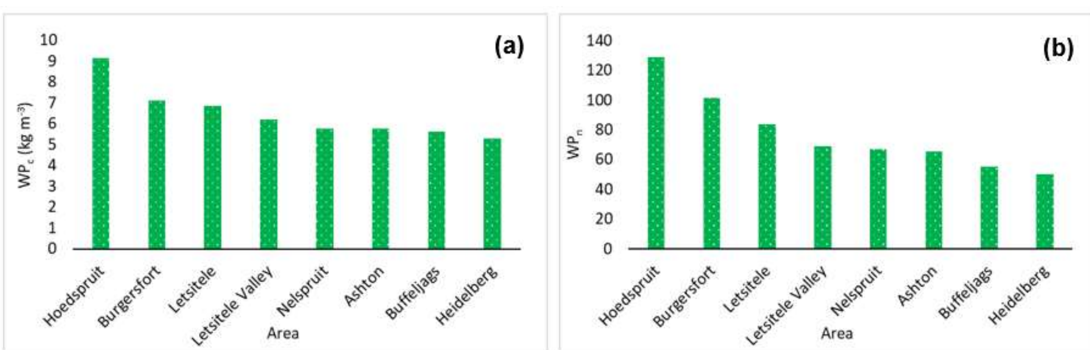

Figure 6.9 Average (a) crop water productivity -WP_c (kg m^{-3}) and (b) normalised crop water productivity WP_n, for mature orchards (>6 years) for the 2020-23 seasons using actual yield. Data in each respective graph is arranged from most productive to least productive (left to right).

6.4 Conclusion

This study focused on evaluating the water productivity of 'Nadorcott' Mandarin (*Citrus reticulata*) orchards in South Africa. The study provided valuable insights into the sustainable management of water resources within the context of citrus cultivation. Through a comprehensive analysis, the study unveiled the complex interactions among various factors influencing water productivity, including tree age, weather fluctuations, shade net usage, and irrigation system. It is worth noting that certain factors, such as soil type, rootstock selection, and planting densities, which could potentially impact water productivity, due to their influence on yield and water use, were not considered in this study. The most noteworthy observation was that summer rainfall regions exhibited lower seasonal applied irrigation and crop coefficient (K_c) values compared to winter rainfall regions. This was attributed to the fact that rainfall in the winter rainfall region occurs during a period of low evaporative demand and could not be utilised for transpiration as much as rain that occurred in summer during the peak evaporative demand period. The study introduced a simplified method for calculating effective rainfall contribution (P_e) by using ET_o, offering clear insights into the necessity for supplementary irrigation in different areas to meet crop water requirements.

The research findings indicated that overall crop yield and crop water productivity (WP_c) were higher in summer rainfall regions, with the warm-moderate summer rainfall sub-region having the highest WP_c in this study. Although no distinct differences were observed between conventional drip and low-flow drip (LFD) irrigation systems in terms of WP_c, there was a noticeable decrease in applied K_c values with a reduction in emitter delivery rate, suggesting improved application efficiency. Results in Chapter 4 indicated that when compared to conventional drip irrigation LFD showed a decrease in drainage with more water being stored in the root zone that is potentially available for uptake. All irrigation blocks in this data set were monitored by capacitance probes, field observations and tensiometers to ensure irrigation was resumed timeously and to optimally utilise rainfall. Therefore, the differences in soil water dynamics under LFD could have resulted in soil monitoring tools indicating adequate soil water content levels in the rootzone for longer periods, in turn resulting in less water being applied. When comparing conventional drip to micro irrigation, significant differences were noted in applied irrigation, but none with regards to WP_c due the large variation in yield within the data set. The difference in K_c values again may be a result of accurate soil water monitoring where systems such as micro-irrigation, that have large K_e component due to a larger wetted area, required more water to maintain adequate soil water content levels in the rootzone compared to conventional drip and LFD. The fact that no difference in yield was observed when irrigation systems were compared indicate that water was unlikely to be a limiting factor and that all orchards, regardless of irrigation system used, were scheduled optimally. Orchards utilizing shade nets exhibited the lowest applied K_c values, yet there were no significant differences in yield and WP_c. This is mainly a result of lower evaporative demand due to lower solar radiation and wind under the net structures resulting in less water being scheduled and applied. It is worth mentioning that the utilization of net structures for fruit production is increasing due to an increase in the grade of fruit that is packed (more class 1 cartons), as a result of fewer blemishes and sunburn, together with the exclusion of hail in areas where it is prevalent. Orchards under net would therefore have a higher economic water productivity (EWP). However, economic return was not included in this study and could be the topic for future research.

A limitation of the two indicators WP_c and WP_i is that they do not consider the climate of the of an area, as represented by ET_o, or P_e in the case of WP_i. Therefore, it is recommended that WP_i, should only be used to compare orchards or farms with one another where P_e can be considered equal, but not between areas where rainfall patterns and quantities differ. For this purpose, WP_c would provide a more accurate indication of water productivity, however, only where ET_o demand is equal or similar. To compare areas in different climatic regions with one another a normalised productivity indicator was proposed WP_n, which aimed to objectively compare areas with one another, based on their own unique climatic conditions (ET_o and rainfall). The findings of this study suggest that WP_i for 'Nadorcott' in a winter rainfall area is ~ 9.0 kg m^{-3} and ~ 18 kg m^{-3} for summer rainfall areas. These values can serve as a guideline or benchmark for growers but would be subject to accurate irrigation monitoring in regions comparable to those used in this study. These values would not necessarily be transferable to other citrus species or cultivars since there are differences in yield potential and water relations between species. For summer rainfall regions P_e ranged between 60% -80% and 40%-60% in winter rainfall areas, these values are important when setting up water budgets and will ultimately impact the applied K_c, as was the case in this study with much lower applied K_c values realised than recommended in FAO-56 for citrus. This was because rainfall was taken into account in the applied K_c values, and K_c values are impacted by the various irrigation systems due to differences in wetting patterns and therefore evaporation.

When comparing WP_n and WP_c, using an average yield, there was a noticeable difference in how the areas were ranked, where WP_c merely followed TWU from lowest to highest, but WP_n did not follow this pattern. From this one can argue that the area that applied the least amount of water compared to the environmental demand, utilised the water, both irrigation and rain, the most efficiently. Both indicators seem to favour summer rainfall areas as the most productive, which again highlights the importance of accurately determining the contribution of rainfall, especially in areas where rainfall occurs in periods of low demand (winter rainfall regions) or areas where there is a complete oversupply of water by rain (high rainfall regions) and a large portion of that water does not contribute to transpiration. Further research is warranted to gain a deeper understanding of and make meaningful comparisons between summer and winter rainfall regions with regards to WP_c and the contribution or utilization of rainfall.

The study's methodologies, encompassing the analysis of historical yield and data, irrigation systems, and weather patterns, provide a robust framework for assessing water productivity. The establishment of water productivity benchmarks and seasonal crop coefficients, along with methods for effective rainfall determination, can be instrumental in guiding water management practices and setting goals for growers on what is achievable in their respective regions and what measures they can take (for example drip irrigation or shade net) to change their water usage without compromising yield.

CHAPTER 7: GENERAL DISCUSSION AND CONCLUSIONS

The weather conditions, specifically the variations in rainfall distribution and intensity, played a crucial role in determining the irrigation requirements and management of irrigation scheduling throughout the two seasons of the study. An important finding was that more rain did not equate to less irrigation and intense and poorly distributed rainfall could not be fully utilized by the crop. Rainfall interception by a mature citrus canopy was found to be ~ 35% and should be taken into consideration when effective rainfall is calculated. This study proposed methodology to determine the contribution of rainfall to irrigation (P_{ci}) with reference to the areas atmospheric demand (as represented by reference evapotranspiration (ET_o)), which provided a measure of the need for supplementary irrigation in an area. In the summer rainfall areas P_{ci} ranged between 60-78% whilst it was 37%-57% in winter rainfall areas. These values are important to incorporate into grower water budgets to ensure one does not over or under rely on rainfall.

The influence of rainfall was evident in the analysis of water productivity data for 'Nadorcott' orchards that revealed there are significant differences in applied water quantities between winter and summer rainfall regions, with the latter being able to rely heavily on rainfall to supplement irrigation. This was evident when seasonal crop coefficient (K_c) values were calculated for summer and winter rainfall regions by dividing season total irrigation with total season ET_o. These values ranged between 0.2 -0.3 for the summer rainfall region and 0.4-0.6 for the winter rainfall region. These values are much lower than average values reported in FAO-56 which ranges between 0.65-0.70 (unadjusted). Furthermore, there was a decrease in applied K_c values with a decrease in emitter delivery rate, with micro irrigation having higher total water use (TWU) figures as compared to drip. The use of shade netting resulted in lower applied

K_c values and growers should consider the changes in atmospheric evaporative demand beneath these structures when scheduling irrigation. There was, however, no significant difference observed in yield between irrigation systems with only normal intra seasonal variation observed.

The use of crop water productivity (WP_c) lacks the necessary nuances of rainfall and ET_o to objectively compare and indicate different regions productivity and a normalised water productivity indicator WP_n was proposed. Both indicators suggest that summer rainfall regions are the most productive, emphasizing the need to accurately assess rainfall's impact, especially in winter rainfall areas with low demand or high rainfall where water exceeds transpiration needs. Further research is needed to better understand and compare the water productivity in summer and winter rainfall regions.

The main objective of this study was to determine the influence of emitter delivery rate on irrigation efficiency and if there are any benefits in using LFD systems as it have become increasingly popular among citrus growers in South Africa. The improvement in irrigation efficiency of LFD systems is anchored in the hypothesis that lowering emitter delivery rates will increase capillary action resulting in greater lateral distribution of water and less vertical movement or drainage. This was found to be true, whereby the drainage observed in the LFD treatments, exemplified by treatment 3 (0.7 $l\ h^{-1}$), was less than the conventional drip systems resulting in water being stored higher in the profile. One could argue that drainage in high delivery systems can be avoided through short interval (pulse) irrigations, but this would require intensive management which is often not practical in large commercial setups. Not only was water stored higher in the profile, but it was also more readily available with a smaller portion of the wetted area being either saturated, or below PWP. The more homogenous water distribution could result in higher the potential water uptake as established by Robles et al. (2023) and Fernandes et al. (2021) and as hypothesized was also the case in this study where LFD had the highest daily transpiration rate especially in periods of higher demand.

In terms of yield, internal quality, and size there were no difference among all treatments, including the 20% and 40% deficit treatments which might suggest a degree of over irrigation. However, it is important to note that the evaluation of LFD and conventional drip together with adjusted FAO-56 K_c values proved challenging with frequent rain and a general overestimation of ET_o values from the weather forecasting model used. This highlights the need for accurate ET_o forecast and that irrigation scheduling based on these values should not exceed 2-3 days in advance under South African conditions. Nonetheless, the K_c values achieved were close to the target values set out and soil water content measured by capacitance and volumetric sensors indicated more than adequate levels which suggest that the adjusted FAO-56 K_c values are overestimated for LFD and as hypothesized need to be adapted for more efficient systems and the application of precision irrigation strategies.

All these findings suggest that LFD is an effective way of irrigating citrus with no compromise in yield or quality. The lower risk of drainage and larger wetted areas created by LFD systems make it easy to manage and maintain good plant water relations with less water.

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