THE EFFECT OF IRRIGATION SCHEDULING ON THE PERFORMANCE OF YOUNG APPLE TREES IN NEWLY ESTABLISHED ORCHARDS

by
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DECLARATION

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SUMMARY

During a study conducted in a newly established orchard on a gravelly soil in Grabouw, the most effective irrigation schedule for optimum performance, including root growth and root distribution, of young apple trees was determined. In order to be profitable, apple trees in newly established orchards must fill their allocated space as soon as possible. Soil water status and root growth distribution are believed to be major determining factors in achieving such a favourable effect.

Malus domestica 'Bigbucks' (a mutation of 'Corder Gala') with an average size of 1.8 metres grafted on MM109 rootstocks were subjected to three different irrigation cycles from December 2016 to May 2017. Treatment one (T1) was a short irrigation cycle, treatment two (T2) was a medium cycle and treatment three (T3) was a long irrigation cycle. Between December 2016 and May 2017, T1 received *ca.* 10 mm of water every 3 to 4 days, T2 received *ca.* 20 mm water every 7 days and T3 received *ca.* 30 mm water every 14 days. Rainfall to an amount of 153 mm also added to the water supply of the trees.

Physical and chemical properties of the soil were determined, followed by the installation of irrigation equipment, soil water measuring instruments and rhizotrons for studying roots *in situ* several times during the season. Irrigation systems were equipped with controllers that were operated remotely by cell phones and soil water measurements were logged continuously. At the end of the season (May 2017) tree response to irrigation treatments was determined by measuring stem circumference and shoot growth. Root studies using the soil profile wall method was carried out to evaluate final root distribution after the first season.

The evapotranspiration (ET) of each irrigation treatment during the growing season was calculated using the root-zone water balance equation as described by Hillel (2004). The ET at the end of the growing season was 644.3 mm, 580.1 mm and 568.5 mm for T1, T2, and T3, respectively. All three treatments received a sufficient amount of water during the growing season as the lower ET values of T2 and T3 restricted neither vegetative nor root growth of the apple trees.

There was no significant difference between the three treatments in terms of shoot growth and trunk circumference. Rhizotrons were used to determine total root length densities. At the end of the growing season T2 had the highest total root length density, followed by T3 and T1. The use of rhizotrons to study roots *in situ* proved to be successful and cost effective. The rooting index that was determined using the profile wall method showed that soil conditions were more favourable for the two driest treatments, T2 and T3, than T1. These two treatments (T2 and T3) had significantly higher rooting densities throughout the soil profile, grew to deeper soil layers at a greater distance from the tree and had a significantly higher mean amount of roots in the clayey textured subsoil than T1. This finding implies that longer irrigation cycles produced bigger root systems and that such trees will be less prone to drought.

OPSOMMING

Gedurende 'n studie wat in 'n nuutgevestigde boord op 'n gruiserige grond in Grabouw gedoen is, is die mees effektiewe besproeiingskedulering vir die optimale prestasie, insluitende wortelgroei en -verspreiding, vir jong appelbome, bepaal. Appelboome in nuutgevestigde boorde moet so gou as moontlik hulle geallokeerde spasie vul om winsgewend te wees. Die hoeveelheid grondwater en die wortelverspreiding van bome word as belangrike bepalende faktore geag om so ‘n gunstige effek te bewerkstellig.

Drie verskillende besproeiingsiklusse is toegepas op *Malus domestica* 'Bigbucks' ('n mutasie van 'Corder Gala') met ‘n gemiddelde grootte van 1.8 meter wat geënt is op MM109 onderstamme vanaf Desember 2016 tot Mei 2017. Behandeling een (B1) was 'n kort besproeiingsiklus, behandeling twee (B2) 'n medium besproeiingsiklus en behandeling drie (B3) was 'n lang besproeiingsiklus. Vanaf Desember 2016 tot einde Mei 2017 het B1 ongeveer 10 mm water elke 3 tot 4 dae ontvang, B2 het ongeveer 20 mm elke 7 dae ontvang en B3 het ongeveer 30 mm elke 14 dae ontvang. Reënval van 153 mm het ook bygedra tot die watervoorsiening van die bome.

Die fisiese en chemiese eienskappe van die grond is bepaal, gevolg deur die installering van die besproeiingstoerusting, sensors om grondwater te meet en rhizotrons om wortels *in situ* verskeie kere gedurende die seisoen te bestudeer. Die besproeiingstelsel is toegerus met 'n beheerstelsel wat met 'n selfoon aan- en afgeskakel is en grondwatermetings is deurlopend afgelaai. Aan die einde van die seisoen (Mei 2017) is die bome se groei bepaal deur die stamomtrekke en lootgroei van die bome te meet. Wortelstudies, met behulp van die profielwandmetode, is gebruik om die wortelverspreiding na die eerste seisoen te evalueer.

Die evapotranspirasie (ET) gedurende die groeiseisoen van elke besproeiingsbehandeling is bepaal deur die waterbalans-vergelyking van die wortelsone (Hillel, 2004) te gebruik. Die ET aan die einde van die groeiseisoen was 644.3 mm, 580.1 mm en 568.5 mm vir B1, B2, en B3 onderskeidelik. Al drie behandelings het voldoende water ontvang aangesien die laer ET waardes van B2 en B3 nie die vegetatiewe- of wortelgroei van die appelbome beperk het nie.

Daar was geen betekenisvolle verskil tussen die drie behandelings in terme van lootlengte en stam-omtrek nie. Die rhizotrons is gebruik om die totale digtheid van die wortellengte te bepaal. Aan die einde van die groeiseisoen het B2 die hoogste totale wortellengte-digtheid gehad, gevolg deur B3 en B1. Die gebruik van hierdie metode om wortels *in situ* te bestudeer was suksesvol en koste-effektief. Die wortel-indeks, wat bepaal is met behulp van die profielwandmetode, het getoon dat die grondtoestande gunstiger was vir die twee droogste behandelings, B2 en B3, as vir die natter behandeling, B1. Hierdie twee droër behandelings (B2 en B3) se worteldigthede was betekenisvol hoër regdeur die grondprofiel, hul wortels het tot in dieper grondlae en verder vanaf die bome gegroei en hulle het betekenisvol meer wortels in die kleierige ondergrond as B1 gehad. Hierdie bevindinge impliseer dat langer besproeiingsiklusse groter wortelstelsels mee gebring het en dat sulke bome minder vatbaar is tydens droogte toestande.

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LIST OF ABBREVIATIONS AND UNITS

Meaning		Abbreviation/unit
analysis of variance	-	ANOVA
and others (*et alii*)	-	*et al*.
and the rest of (*et cetera*)	-	*etc.*
approximately (*circa*)	-	*ca.*
average evapotranspiration per day	-	ET_c
bulk density	-	P_b
carbon	-	C
cation exchange capacity	-	CEC
centimeter	-	cm
centimole charge per kilogram	-	cmol(+)/kg
correlation coefficient	-	R^2
cubic centimeter	-	cm^3
deciSiemens per metre	-	$dS.m^{-1}$
degrees	-	^{0}
degrees Celsius	-	^0C
delta	-	Δ
easily available water	-	EAW
electrical conductivity of saturated soil extract	-	EC_e
evapotranspiration	-	ET
field capacity	-	FC
for example (*exampli gratia*)	-	*e.g.*
gram	-	g
gram per cubic centimeter	-	$g.cm^{-3}$

hectare	-	ha
hydrogen peroxide	-	H_2O_2
kilometer	-	km
kilogram	-	kg
kilogram per kilogram	-	$kg.kg^{-1}$
kilogram per cubic meter	-	$kg.m^{-3}$
kilopascal	-	kPa
least limiting water range	-	LLWR
least significant difference	-	LSD
mega joules per hour	-	mJ/h
mega Pascal	-	MPa
meter	-	m
meter per second	-	$m.s^{-1}$
micrometer	-	µm
milliliter	-	mL
millimeter	-	mm
millimeter per millimeter	-	$mm.mm^{-1}$
millimeter per squared millimeter	-	$mm.mm^{-2}$
mole per kilogram	-	$mol.kg^{-1}$
nitrogen	-	N
organic material	-	OM
particle density	-	P_s
percentage	-	%
permanent wilting point	-	PWP
phosphorous	-	P
plant available water	-	PAW

porosity	-	f
potassium	-	K
potassium chloride	-	KCl
relative humidity	-	RH
short message service	-	SMS
sodium absorption ratio	-	SAR
soil water retention curve	-	SWRC
square meter	-	m^2
subscriber identity module	-	SIM
sulphur	-	S
temperature	-	T
that is (*id est*)	-	*i.e.*
total root length density	-	TRLD
universal serial bus	-	USB
volumetric water content	-	VWC
water	-	H_2O

CHAPTER 1: GENERAL INTRODUCTION AND PROJECT AIMS

In order to be profitable, apple trees in newly established orchards must fill their allocated space as soon as possible. During the first three years after establishment, rapid root growth of apple trees occur and soil water is a crucial factor determining the type of root development made by young apple trees. South Africa is a dry country with a high evaporation rate and a low mean annual rainfall of only 450 mm (NWRS, 2004). The Western Cape is the biggest apple producing province in South Africa as 76% of the total 24 212 hectares of apple orchards are planted in this province (HORTGRO, 2016). This province, however, has a mean annual rainfall of 348 mm which is well below the mean annual rainfall of South Africa and, due to high mountain ranges in the province, rain is usually erratically distributed (NWRS, 2004). Fortunately the apple growing areas generally have a higher mean annual rainfall than the Western Cape with Grabouw, for example, having a mean annual rainfall of 990 mm (South Africa Explorer, 2017).

In the last 2-3 years, the Western Cape received relatively low rainfall which caused a limited refill of reservoirs and together with an increasing demand for water, the water resources in the province were further limited (CSIR, 2017). It is therefore important to reduce the depletion of water resources and increase the water use efficiency of apple trees without compromising yield and fruit quality. Furthermore, it is important to ensure a deeply established root system as deeper root systems are more tolerant to drought (Brunner *et al.*, 2015).

The objective of this study was therefore to determine the most effective irrigation schedule for the optimum performance, including root growth and root distribution, of young apple trees in newly established orchards on gravelly soils which are wide-spread in apple-growing regions of South Africa. The formulated hypothesis is that a long irrigation cycle will enhance root growth to deeper soil layers compared to short and medium cycle irrigations.

The aims of the project were:

- To monitor and access soil and weather data continuously and apply irrigation treatments remotely with cell phone technology.
- To determine the effect of the different irrigation cycles on the evapotranspiration of apple trees in their first season after planting on a gravelly soil representative of apple growing areas.
- To compare two methods (pressure plate apparatus versus the dew point method) of determining a soil water retention curve (SWRC).
- To develop a cheap and easy method of studying root growth periodicity *in situ*.
- To determine the effect of the different irrigation cycles on root density and root distribution.
- To determine the above-ground vegetative growth response of the apple trees to the three irrigation cycles.

CHAPTER 2: LITERATURE REVIEW

2.1 Apple tree roots and root systems

2.1.1 Function of roots and root systems

Apple trees require a root system to deliver a sufficient amount of water and nutrients to the trees in order to anchor them in the soil and to ensure shoot growth (Bengough *et al*., 2005). Roots react to nutrient limitations and stresses such as drought or flooding and are responsible for the synthesis of important compounds such as plant hormones. Plant hormones such as cytokinins, abscisic acid, ethylene and gibberellin are important growth regulators that ensure shoot growth by the process of root-to-shoot signalling. Root systems are therefore essential for the conveyance of growth regulator to shoots to ensure a balanced root-shoot interrelationship (Kramer & Boyer, 1995).

2.1.2 Root growth and phenology

Root growth is a result of cell division, cell enlargement and of pressures that exists due to newly formed cells. The anatomy of roots undergo various changes during root growth that will affect water and nutrient conveyance and absorption (Kramer & Boyer, 1995). Root tips are shielded by a root cap. The apical meristem follows the root cap and this is the area where cell division takes place. Cell elongation will occur in the region following the apical meristem. The root axis governs cell elongation and root tips are pushed forward to extend roots further into the soil. The cell differentiation region is at the rear of the region of cell elongation. In this region cells assume specialized functions and develop specific characteristics during root growth (Hillel, 2004). Roots that are still developing and growing, develop new tissue due to cell differentiation further away from the root tips than roots with a slower growth (Kramer & Boyer, 1995).

One can distinguish between two types of root growth: root growth in length or root growth in girth. The absorbing surface of the root system will increase when the absorbing roots grow in length. Longer roots, however, will result in the formation of

roots (Kolesnikov, 1971). Water and nutrient supply and an improved stability to the plants will increase when the conducting roots grow in thickness. An increase in root diameter occurs due to secondary root growth as a result of cambial activity (Kramer & Boyer, 1995).

Branching of roots (root development from the new roots) can be characterized by their length, direction, amount or their branching angle. Two types of branching patterns exist, namely herringbone and dichotomous. The herringbone pattern will develop branching roots from the horizontal roots while the dichotomous pattern will have branching roots growing from the horizontal and vertical roots in all directions. Root branching is highly dependent on the local environment in which they grow, for example soil moisture, temperature and tortuosity. (Smit *et al.*, 2000). Branched roots are able to penetrate superficial soils more easily compared to horizontal and vertical roots (Atkinson & Wilson, 1980).

Root growth periodicity can be affected by different factors, but is mostly dependant on the species (Atkinson, 1980). Furthermore, environmental factors such as soil moisture and soil temperature will influence the seasonal growth patterns of apple tree roots (Lyr & Hoffman, 1967). Root growth periodicity will also differ in bearing trees compared to non-bearing trees (Atkinson, 1980). As our study focussed on non-bearing apple trees, the root growth periodicity of non-bearing trees will be discussed.

Root growth starts towards the end of autumn and the beginning of winter when the branches of the tree become dormant (Kolesnikov, 1971) and soil temperature is warm enough (6.2 ^{0}C or higher) (Rogers, 1939). Rapid root growth occurs during spring and stops when bud break occurs. After bud break, nutrients and energy are no longer used by the roots but rather by the shoots and leaves. During the summer, little or no root growth occurs as water and nutrients are only used by the leaves. Thereafter leaf-fall in autumn and tree dormancy in winter will stimulate root growth (Kolesnikov, 1971).

2.1.3 Root distribution

Root distribution refers to the existence of roots in a specific position on a grid, rather than the orientation of the roots. Therefore, when the root distribution of trees are

studied, root length or the mass thereof as a function of factors such as position between neighbouring plants, soil depth and distance from the stem must be of concern and when measuring the root distribution, roots of more than one plant must be included (Lynch, 1995).

Roots can be grouped into vertical and horizontal roots, because of their distribution. Vertical roots grow vertically downwards into the soil along soil cracks and earthworm holes. These roots can reach depths from two to ten metres or deeper. They are usually the roots that are responsible for the conveyance of nutrients and water and they are also able to obtain trace elements from the deeper soil horizons. The vertical roots also ensure anchorage of trees. Vertical roots are also more likely to be the active roots because of their ability to penetrate the deeper soil horizons compared to those closer to the surface. The horizontal roots are distributed parallel to the soil surface where valuable nutrients accumulate in large quantities and microbiological processes are most active. These roots grow to depths of 30 to 100 centimetres or more (Kolesnikov, 1971).

The lateral spread and depth of roots are both dependant on the environment in which the trees grow and heredity of the tree. The root spread and distribution of trees of various species growing in the same deep, well-aerated soil can vary significantly. This will also be true for the root distribution of trees of similar species grown under different conditions and environments – their root distribution can also vary significantly. Although the distribution of roots is a result of both heredity and of the environment, roots in general will always grow in the direction of optimal soil water. The amount of water that is available to trees, however, will depend on the soil volume that the roots occupy. Trees with a deeper root system will be more tolerant of drought than trees with a shallow root system, because a deeper rooting system will create a larger absorbing area for roots and the roots are therefore more likely to have contact with more moist areas in the soil. High root densities can, however, also have a negative effect on trees as high root densities can lead to an increase in the competition for water and nutrient uptake between neighbouring plants. The competition for water and nutrients between the roots will result in a decrease of root length density, because the uptake per unit of root surface will become smaller (Kramer & Boyer, 1995).

2.1.4 Factors affecting root growth and distribution

The root growth of apple trees is mainly affected by environmental factors such as physical, chemical and biological factors and also competition with other plants (Kramer & Boyer, 1995). In research done by Weaver and Cramer (1932) they stated that “although the root habits of a tree are governed, first of all, by the hereditary growth characters of the species, they are often quite as much the product of environment”.

2.1.4.1 Physical factors

The physical properties of soil can influence root growth both directly and indirectly. Root growth will be influenced directly through restricting root penetration and indirectly by affecting the water content and aeration of the soil (Kramer & Boyer, 1995). Restricted root penetration can be a result of soil compaction and soil temperatures when these factors are not optimal for root growth while the water content and aeration of the soil will be influenced by the texture and structure of the soil.

2.1.4.1.1 Soil compaction

Soil compaction is a physical process where the soil consolidates under unsaturated conditions due to an applied force that is great enough to destroy aggregates (Wolkowski & Lowery, 2008). Compaction particularly reduces the volume and continuity of large pores (Mitchell & Berry, 2001). Roots tips are usually thicker than most soil pores (Lipiec & Hatano, 2003) and are unable to reduce their diameters in order to penetrate pores narrower than the diameter of their root caps (Wiersum, 1957). Therefore, if roots attempt to grow through a compacted soil they must be able to open the pores by exerting a large enough pressure to overcome the mechanical strength of the soil. This will cause roots to experience mechanical impendance that will eventually have an indirect effect on the physiology of the shoots (Franco *et al.*, 2011).

Hardpan layers of natural occurrence and tillage pans as a result of tillage operations can restrict root growth and root development. The nature of soil governs the whole appearance of the root system. More roots will be found in loose soils than in

compact soils and therefore deep tillage before planting is necessary to remove restricting layers and to benefit plant growth in compacted soils (Unger & Kaspar, 1993).

2.1.4.1.2 Soil temperature

The optimum soil temperature for apple tree root growth is between 7.2 ºC and 20.5 ºC (Kolesnikov, 1971). Low soil temperatures (temperatures between 1.7 ºC and 7 ºC) as well as very high soil temperatures (temperatures between 35 ºC and 40 ºC) will inhibit the root growth of apple trees. At low soil temperatures, hydraulic conductance will decrease (Bolger *et al.*, 1992) and the uptake of nutrients and water by the root system will be reduced, which will affect the functioning of root systems. Branching will also decrease if root growth occurs at low soil temperatures (Nielson, 1974). Furthermore, low soil temperatures will result in more brown roots and a lower shoot to root ratio (Franco *et al.*, 2011). At high soil temperatures, however, branching will increase. Root growth will increase as temperature increase, but high soil temperatures can affect the enzymatic activity of root systems negatively (Nielsen, 1974).

Seasonal changes and daily fluctuations in soil temperature can also have a remarkable influence on the development and growth of apple tree root systems. Seasonal changes are dependent on the phenological stage of the tree (Kaspar & Bland, 1992). The soil temperature will generally increase early in spring and decrease towards winter. As soil temperatures increase and consequently dry the soil, downward root growth to deeper soil layers will occur (if no irrigation is applied) (McMichael & Burke, 1998). Daily temperature fluctuations will influence the morphological structure of roots and it will also have an influence on the metabolism and functioning of roots (Kaspar & Bland, 1992). The morphological changes in root growth will affect branching, dry mass and root length (Nielsen, 1974).

Seasonal changes and daily fluctuations in soil temperature can also have a remarkable influence on the development and growth of root systems. These seasonal changes are, however, dependant on the phenological stage of the tree and the duration of the temperature change. Temperature fluctuations will influence the morphological structure of roots and it will also have an influence on the

metabolism and functioning of roots (Kaspar & Bland, 1992). The morphological changes in root growth will affect branching, dry mass and root length (Nielsen, 1974).

2.1.4.1.3 Soil texture and structure

Soil varying significantly in texture will affect root growth to different extents. For example, clay soils with poor drainage being subjected to hypoxia (oxygen deficiency) will limit root growth while a well-drained sandy loam soil will be more favourable for root growth (Bengough *et al.*, 2005). Thus, the texture and structure of a soil will have an influence on the water holding capacity of the soil which can affect root growth.

The bulk density of a soil will be affected by its structure, *i.e.* the degree of compaction or how loose the soil is (Hillel, 2004). Increases in soil strength occur for an extensive range of soil textures when soils dry in a range of matric potentials between -5 kPa and -1500 kPa. Large strength increases are mainly noticeable in hard-setting soils over a wide range of soil textures, from sandy to clayey. These soils tend to collapse to an massive structure and make cultivation difficult and limit root growth (Mullins *et al.*, 1987).

Bulk density is also affected by the soils ability to swell or shrink. The swelling and shrinkage characteristics of a soil will be reliant on both the water- and clay content that is present in the soil (Hillel, 2004). In a study done by Chaudhari *et al.* (2013) they found that the sand content within a soil will have a greater effect on soil bulk density than other soil properties and stated that sandy soils will most likely have a higher bulk density than clayey soils. It is therefore evident that the bulk density of a soil will greatly be influenced by the texture of the soil. Growth-limiting bulk densities are used to determine whether root growth of apple trees will be restricted or not and because of the direct relationship of soil texture on soil bulk density, it is important to take the soil texture into consideration when estimating the growth-limiting bulk density for apple trees (Daddow & Warrington, 1983).

2.1.4.1.4 Soil water

Soil water can either enhance or diminish root growth. In a soil dryer than the permanent wilting percentage, water and mineral absorption will be inhibited and this will reduce root growth. On the other hand, an excess of soil water will cause an oxygen deficiency which also leads to a decrease in root growth (Kramer & Boyer, 1995).

Water is one of the main metabolic agents in the life of plants as it is a source of hydrogen atoms which plants need to photosynthesize and it is also a product of respiration. Water losses due to transpiration as a result of a vapour pressure gradient that exists between the dry atmosphere and the generally water-saturated tissue of the leaves of plants, can complicate the water supply to plants for survival. In order to manage soil-plant-water relations, a comprehensive model must be used to understand the complicated inherent functioning of the interactions and mechanisms involved during root growth (Hillel, 2004). Huck and Hillel (1983) described two sets of processes based on their fundamental mechanisms to comprehend the relationship between root activity and canopy growth. The first process they considered was the movement of carbon through the plant system. During photosynthesis, carbon enters the plant in the form of CO_2. Soluble carbohydrates that is produced during photosynthesis, is necessary for both root and shoot growth. The allocation of the energy reserves to ensure root- and shoot growth is highly dependent on the transient conditions. For example, when the plant is completely hydrated, shoot growth will occur. During water stress situations, however, shoots will react to the water limitations first as it is directly exposed to the atmosphere, while the roots will be able to maintain hydration and turgor as it is closer to the water source (Hillel, 2004). The second set of processes Huck and Hillel (1983) considered was the water flow through the soil-plant complex. Considering plant tissue having a small water-storage capacity compared to water losses through transpiration, it is important for new roots to be directly exposed to moist soil where water is available. Roots will constantly grow to moist regions to sustain water losses through transpiration (Hillel, 2004).

Root growth patterns are not easily understood as the soil water potential constantly changes in the field which cause significant variation in the soil water content throughout the soil profile. As a result of these changes, factors that limit root growth will also change over time (Bengough *et al.*, 2005). Dexter (2004) introduced the *S*-theory where *S* is a physical soil parameter that defines the suitability for root growth of a specific soil structure and which measures the microstructure of soils. The *S*-value can easily be determined with the use of a logarithmic soil water retention curve (SWRC) that is obtained by plotting the water potential against the gravimetric water content ($kg.kg^{-1}$). The *S*-value will be the equivalent of the point of inflection of the slope of the SWRC. Although the *S*-theory is a suitable measure for defining the physical quality of a soil, the physical stresses that can influence a growing crop on a daily basis are not identified in this theory (Dexter, 2004). The Least Limiting Water Range (LLWR) introduced by Da Silva *et al.* (1994) may be a more suitable approach to consider the exact factors that limit root growth of a growing crop during its growing season as one is able to estimate the LLWR several times during the growing season for each soil horizon at various locations (Bengough *et al.*, 2005). Da Silva *et al.* (1994) defined the LLWR as the range in soil water content in which factors that can limit plant growth are minimal, *i.e.* where root growth are not extremely limited by physical factors such as aeration, mechanical resistance and limitations associated with matric pressures.

Roots grow towards moist regions in the soil, because new roots have an immature vascular system that depends on water availability in the surrounding area. Therefore, root distribution is dependent on the way water is distributed within a soil profile (Hillel, 2004).

2.1.4.1.5 Soil aeration

In soils that lack sufficient non-capillary pore spaces, poor soil aeration and insufficient oxygen will limit root growth. An oxygen deficiency in soil is a result of different factors affecting the aeration of the soil. These factors include incorrect soil management such as compaction and over-irrigation. An excess of water in the soil due to over-irrigation, excessive rainfall or flooding will cause an oxygen deficiency in soils if the drainage is inadequate. In sandy and fine-textured soils, aeration seldom becomes a problem (Huang & NeSmith, 1999).

Good gas exchange between the pore spaces of the soil and the aboveground air is necessary to ensure that a soil is well aerated. A decreased gas exchange rate due to an increase in water content which causes an extremely low air-filled soil porosity, can limit root growth to a great extent (Kramer & Boyer, 1995).

The establishment of young trees in soils with a low aeration status will be inferior due to inhibitory effects on processes such as root elongation, hormone synthesis, water and nutrient uptake, respiratory capacity, proliferation, carbohydrate accumulation and viability which are all necessary for the survival of plants (Huang & NeSmith, 1999).

2.1.4.2 Chemical factors

2.1.4.2.1 Soil pH

Soil pH is measured according to a logarithm scale and is an indication of the alkalinity or acidity of soil. The optimal soil pH_{KCl} for crop growth is between 5.5 and 6.5. Essential plant nutrients are obtained from the soil when it is dissolved in the soil solution. In acid soils (soil pH in the range of 4.5 to 6.5), most of the nutrients and minerals are more soluble than in alkaline soils. In soils that are extremely acidic (soil pH in the range of 4 to 5), high concentrations of soluble iron, manganese, boron, copper, zinc and aluminium can cause toxicity that will limit plant growth. Although phosphorus is never readily soluble in the soil, it is mostly available in a pH range of 5.5 to 7.5.

In high acidity soils which are commonly found in the apple growing regions in the Western Cape (Wooldridge *et al.*, 1995), soil organic matter decomposition by bacteria is slowed down which will reduce plant-available nitrogen (N), sulphur (S) and phosphorus (P). A calcium deficiency may also occur at low soil pH, especially when the CEC of the soil is also very low. Low pH soils with low organic matter content will have poor tilth and are poorly aggregated. In order to prevent limited root growth, crops should not be cultivated in low pH soils without application of a suitable ameliorant to lower the acidity. Lime can be used to raise soil pH when necessary (Fernández & Hoeft, 2009).

2.1.4.2.2 Soil salinity

Saline soils, which are mostly found in the Eastern- and Northern Cape of South Africa (De Villiers *et al.*, 2003), contain a detrimental amount (conductivity of the saturation extract ≥ 2 dS/m) of neutral soluble salts that will negatively affect the growth of most crops. These soluble salts are the sulphates and chlorides of magnesium, sodium and calcium. A substantial amount of gypsum ($CaSO_4$, $2H_2O$) can be present in many saline soils, but sodium and chloride are by far the most dominant ions in highly saline soils.

Soils that are leached with salt water will disperse and lower air and water permeability and it will also increase soil pH. This is the case in many heavy clay soils. Water availability to plants will be less in saline soils, because an increase in the salt concentration will cause a decrease in the osmotic potential of the soil. Depending on the degree of salinity, saline soils will cause poor crop yields and uneven growth. Excessive absorption of salt ions may be toxic to the plants and the absorption of other essential plant nutrients will be limited (Abrol *et al.*, 1988).

2.1.4.2.3 Toxic elements

The most common elements found in soils that can be toxic to plants are lead, copper and aluminium. An excess of oxygen can also be toxic and limit root growth as it effect enzymatic systems that are necessary for root growth (Kramer & Boyer, 1995).

2.1.4.3 Biological factors

A diverse population of bacteria and fungi in soils are beneficial when present, because it can suppress root diseases (Berg, 2009). For example, the presence of arbuscular mycorrhizal fungi will ensure that trees tolerate abiotic stresses such as soil salinity and drought. These abiotic stresses can be overcome as the arbuscular mycorrhizal fungi are able to change abscisic acid levels in the xylem sap and increase root hydraulic conductivity; extra-radical hyphae will enhance nutrient and water uptake and roots will have a higher root surface (Franco *et al.*, 2011). In contrast, soil-inhabiting nematodes can limit root growth when they feed on the root cells (Kramer & Boyer, 1995).

2.1.4.4 Competition with other plants

Root systems usually decrease in size when they are grown in competition with other plants as water availability to trees decrease when competing crops also demand water for survival (Kramer & Boyer, 1995). Tworkoski and Glenn (2008) determined the response of apple trees to ground covers crops and they found that apple trees grown with cover crops with shallow and fewer roots photosynthesized significantly more than those grown with cover crops that had deeper rooting systems.

Root growth of trees is limited when there is more than one crop present, because the crops compete for water and these available nutrients (especially nitrogen) and water will easily be depleted. Toxic substances can be released during the decomposition of competitive plants which will also limit root growth (Kramer & Boyer, 1995).

The root systems of trees in an orchard will be smaller the closer the planting distance, because of the competition between the trees (Tworkoski & Glenn, 2008).

2.1.5 Methods to study roots

Root studies ensure an understanding of the role the root system plays in a plant's morphological, biochemical, physiological and anatomical life. It is also useful to understand the interrelationship between root growth and above-ground growth of the plant and it promotes an understanding of the participation of root growth in nutrient uptake, fruiting and photosynthesis. The main aim of root studies is to develop different soil and plant management systems to ensure a high annual yield.

Root studies can be a difficult task due to the inaccessibility of roots, root longevity, extreme soil variations, different plant management systems and the great diversity of plants. It can further be complicated by the necessity of studying only some aspects of the roots or studying the whole plant. Different methods to study roots exist as a solution to these problems and it is therefore important to carefully choose the correct technique that will be the most practicable and best suited for the purpose of the investigation (Kolesnikov, 1971).

Although several techniques and methods exist to study roots, only two methods were used during this study. These two methods are the profile wall method and a

modified version of the glass wall method. These two methods will be discussed. Other methods to study roots is discussed by Kolesnikov (1971) and Böhm (1979).

2.1.5.1 Profile wall method

The profile wall method consists of digging a trench a certain distance from the trunk with a specific length, width and depth. The depth to which the trench is excavated is normally as deep as the maximum length to which the horizontal roots grow. After the trench is excavated, the trench wall is cleaned. A clean trench wall helps the researcher to inspect the spread of the roots and to measure root diameters. It is also helpful to identify the different horizons within the soil profile (Kolesnikov, 1971). When the trench is clean, a frame with a square grid (5 × 5 cm or 10 × 10 cm) is placed against the profile wall. The grid assists the researcher (Böhm, 1979) to mark and record roots according to depth of penetration and thickness onto a plan (with a desired scale). The plan illustrates the root distribution in the different horizons and can be used to estimate the amount of roots present within the trench, which is useful for comparing root growth under different soil conditions (Kolesnikov, 1971).

The traditional profile wall method was accepted in 1932 when an intensive root study on orchards trees were done by Oskamp and Batjer at the New York Agricultural Experimental Station and is still used by researchers today (Smart *et al.*, 2006). This method not only enables researchers to study the root system of trees, but it can also be used to determine the density of the absorbing roots as this method makes it possible to record roots within the soil profile with a diameter as small as 1 mm. This method to study roots is also cheap and allows the researcher to investigate a vast area to obtain convincing results (Kolesnikov, 1971). This method, however, can be time-consuming and labour intensive (that can be expensive). As this method is a destructive method to study roots, soil variability can be increased and a large amount of fine roots are lost after the soil is excavated (Atkinson, 1980).

2.1.5.2 Glass wall method

The glass wall method enables a researcher to observe roots through glass panels that are placed against the soil. This method was first introduced by Sachs in 1865 where he observed roots in its natural condition by placing glass panels either

horizontally, vertically or inclined against any root in the soil (Kolesnikov, 1971). According to Böhm (1979), glass walls are generally installed vertically to prevent the breakage of the glass and also to minimize the difference in rooting density in the bulk soil to that observed through the glass.

To install a glass wall, soil must be excavated to create a trench and the trench wall must be smoothed. Glass plates, or Plexiglass, are then placed against the smoothed trench wall while ensuring good contact between the soil and the observation window. This observation window is also called a rhizotron. In our study, we used Perspex to create an observation window. It is essential to create decent contact between the observation window and the soil in order to prevent the modification of the environmental conditions under which roots grow and also to prevent water seepage into the air spaces and condensation on the window. After the observation windows have been installed it must be covered with a wooden or plastic plate in order to prevent light to reach the roots (Böhm, 1979).

With the glass wall method, roots can be observed and recorded qualitatively, semi-quantitatively and quantitatively. Qualitative data is obtained when root characteristics such as root colour, branching and the direction of root growth is described. When a frequency scale is used to visually estimate rooting intensity, semi-quantitative data can be obtained. Quantitative data can be obtained in various ways which include the determination of root characteristics such as root length, root development and distribution, rooting intensity and density and detailed examination of roots with the use of photographs. Root length can be determined with the use of an opisometer when roots are mapped on a grid or transparent foil. During the vegetation period of a plant, it is possible to get information about the root development and distribution. This can be done by counting the root intersections *in situ*. A grid system of 5 × 5 cm is used and each root that crosses a line must be recorded. This enables the researcher to determine the root length by using an equation explained by Böhm (1979). The rooting intensity can be determined by dividing the root length (in centimetres) which is visible per square centimetre by the surface area in which the roots were observed. Rooting density, which is the cm root length per cm^3 soil volume, can be calculated if the soil volume of the rhizotron is known and if it is compared with volumetric samples. Volumetric samples must be taken from the bulk soil near the window where roots are observed. Lastly,

photographs can be taken of the roots through the observation window. These photographs can be used to distinguish white roots from the dark soil and recordings of roots can be made from these photographs (Böhm, 1979). In our study, we used a scanner to capture root images.

The glass wall method has some limitations like changes in soil conditions that can influence root growth and the limited observation field. Changes in soil conditions include temperature and gas exchange fluctuations and light which might reach roots. In addition to the small observation area, roots can grow away from the observation window after formation which can complicate root recordings. On the other hand this method makes it possible to observe roots very close to normal conditions, because after it is installed, glass panels can stay in the ground for long periods of time without disturbing the soil. This also enables the researcher to understand the plant's life cycle as roots can be studied during different periods of vegetation and be related to the above-ground growth and yield (Kolesnikov, 1971).

2.2 Effect of irrigation scheduling on apple tree root growth

2.2.1 Irrigation scheduling

Irrigation is the artificial supply of water to a soil profile to replenish the root zone in order to avoid drought and to ensure crop growth, but it also increases food production to feed an expanding population. Although rainfall can contribute to the water supply of crops, it is not always evenly distributed during a season and can be highly variable during years. Therefore irrigation is necessary to multiply crops and to increase yields. High quality yields can be produced profitably when irrigation systems are well-managed (Hillel, 2004). Irrigation scheduling, *i.e.* when and how much water to apply, is important to manage the available water for irrigation efficiently in order to decrease water losses (through transpiration and evaporation) and increase both vegetative and root growth (Tanner & Sinclair, 1983).

2.2.2 Methods to schedule irrigation

Depending on the irrigation system that is available and the objectives of the irrigator, it is important to choose the correct irrigation scheduling approach in order to schedule irrigation successfully. Different irrigation approaches exist in order to

schedule irrigation. These approaches are based on measurements, *i.e.* soil based measuring techniques, plant based measuring techniques and atmospheric based measuring techniques (Jones, 2004).

2.2.2.1 Soil based measurements

Soil water measurements can be conducted by measuring both the potential of soil water and the amount of water present in the soil. The oldest method to determine water content is the gravimetric method. The method entails the weighing of the moist soil, drying the soil at 105 ºC and determining the oven dry mass of the soil. These weights are then used to calculate the amount of water in the soil (Hillel, 2004). This method is still the norm against which other methods are calibrated.

Gypsum blocks and ceramic based sensors are both solid matric equilibration methods to determine soil water content. Gypsum blocks responds to changes in the surrounding soil and measure the electrical resistance. The electrical resistance is used to determine the water content of the soil, as electrical resistance is proportional to water content. The soil water potential can be determined indirectly with the use of a soil water retention curve.

The heat dissipation sensor is a ceramic based sensor consisting of a ceramic cylinder that contains a heater and thermocouple. Thermal conductivity is used to determine the moisture content of the ceramic. This is made possible through measuring temperature change. The temperature change is then plotted against log time to determine the moisture content of the ceramic. The moisture characteristic of the ceramic disc is used to convert moisture content into water potential (Campbell, 2015).

Tensiometers for measuring soil water potential was developed early in the 1930's (Richards & Neal, 1937) while neutron probes to measure soil water content only became available in the 1950's (Gardner & Kirkham, 1952). Tensiometers measure soil water content indirectly. They measure the matric potential of the soil which is subsequently converted to water content with the use of a soil water retention curve. Tensiometers measure matric potential based on differences in soil water retention. Neutron probes measure soil water content. The instrument consists of a radio-active source (that emits fast neutrons) as well as a detector of moderated neutrons.

When the probe is lowered into the soil, fast neutrons are emitted in all directions while moderated neutrons are reflected back to the detector and counted. Water is especially effective in moderating the fast neutrons. Neutron probes must be calibrated for each specific soil (Hillel, 2004). New types of equipment to measure soil water content are still being developed today in order to make irrigation scheduling more user-friendly, for example capacitance meters which are smaller and readily automated. Capacitance meters usually consist of a pair of electrodes that are installed in the soil. The soil acts as the dielectric medium. The dielectric permittivity of the soil is determined by measuring the charge time of the capacitor (Charlesworth, 2005).

When scheduling irrigation based on soil water measurements, not only does one know when to irrigate, but also how much water to apply when the crop is irrigated. There are many commercial systems available that make it possible and easy to use this irrigation scheduling approach (Jones, 2004).

2.2.2.2 Plant based measurements

Plant based measurements to schedule irrigation include measurements of both plant physiological response and water status of plant tissue (Jones, 2004). Plant based measurements can indicate the timing of irrigation, but it does not give an indication on how much water to apply. Scholander-type pressure chambers to measure leaf-water potential are widely used in South Africa as a plant-based measuring technique to schedule irrigation and this is also the method that receives the most attention of all the plant-based measuring techniques. This method gives the best results when used at pre-dawn under normal conditions, but when conditions are exceptionally hot and dry during pre-dawn when leaf-water potential measurements are taken, the measurements can be unreliable (Annandale *et al.*, 2011). Never the less, the time for leave water potential measurements has been standardized to be determined pre-dawn when the water potential in the plant is in equilibrium with the water potential in the soil.

Although other plant-based measurements to schedule irrigation exists, *e.g.* visible wilting of plants, stomatal conductance, hyperspectral imaging of plants and the

growth rate of plants (Jones, 2004), none of these methods are developed in South Africa to use as a practical method of scheduling irrigation (Annandale *et al.*, 2011).

2.2.2.3 Atmospheric based measurements

In South Africa many commercial farmers have used the Class A-evaporation pan method where they made use of crop factors and evaporation pan data to schedule irrigation. This method is still being used amongst some commercial farmers (Stevens *et al.*, 2005). This method, however, proved to have serious limitations as it is dependent on climate and estimations of crop evaporation that can be inaccurate due to the use of constant values (Van Zyl *et al.*, 1989).

The Penman-Monteith equation is used to calculate the evaporation of crops with the use of climate data such as temperature, wind speed, radiation and humidity (Hillel, 2004). Today this equation is used to schedule irrigation successfully as automated weather stations give detailed weather data that can be used as input data to estimate crop water requirements (Annandale *et al.*, 2011).

2.2.3 Water requirement of apple trees

Optimal soil water content for apple trees is not easily defined as the water requirements of apple trees will vary between different cultivars and rootstocks, as well as between the combinations of the two. Some guidelines on soil water extraction levels' effect on apple tree growth and growth stages, during which irrigation must be applied, do however exist and will be discussed.

2.2.3.1 Soil water extraction levels

The optimal amounts of water for crops cover a wide range of soil water contents from field capacity (between -2 and -8 kPa) to permanent wilting point (-1500 kPa). Root growth of apple trees will be restricted when water levels are outside these limits as water contents above field capacity will limit aeration and water content levels below permanent wilting point will restrict root growth as roots will not be able to withdraw water from soil (Kirkham, 2014).

Soil water contents between field capacity and water content values in the range of -40 kPa and -60 kPa will be easily available to trees and the trees will not be under

stress. Water contents between the last-mentioned range and -200 kPa will be less available to the trees as it is strongly held by the soil, but tree damage will only start to develop at water content values between -200 kPa and -1500 kPa. The best quality and yield will be produced allowing a water extraction level of 50% of plant available water (PAW). At a water extraction level of 75% of PAW a decrease in vegetative growth and fruit size will occur and at 90% depletion of PAW there will be large economic losses (Boland *et al.*, 2002).

2.2.3.2 Soil water at different growth stages

Apple trees undergo five critical growth stages and it is important to know which growth stages are most susceptible to water availability in order to design an irrigation system to optimise the amount of irrigation applied during the season (Boland *et al.*, 2002). The five critical growth stages of apple trees are illustrated in Figure 2.1 (Figure 2.1 is adapted from Boland *et al.*, 2002).

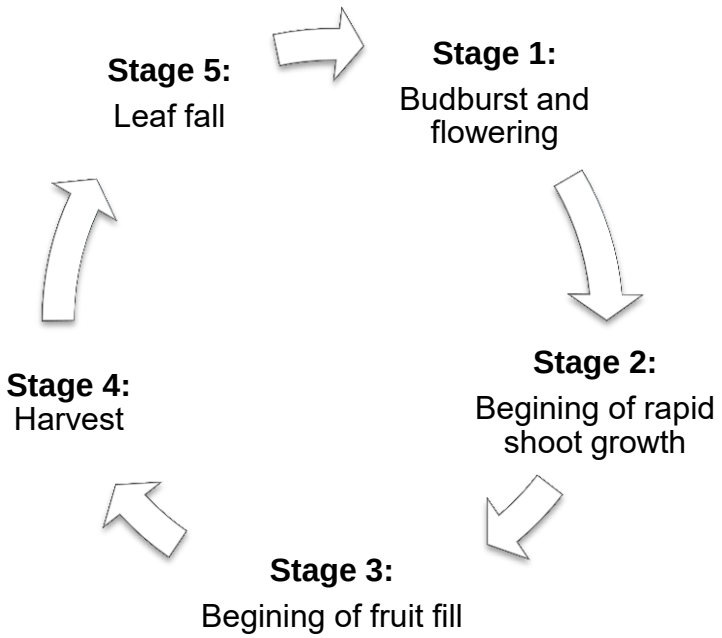

Figure 2.1: The growth cycle of apple trees

Fruit enlargement depends largely on cell division and formation which take place during stage one while fruit size will increase rapidly during stage three due to cell enlargement, which is driven by water uptake into the cell. It is therefore critical that soil water must be readily available for apple trees during stage one and stage three

and irrigation during these stages is critical. During stage two, adequate water must be provided because of steady fruit growth and the division of fruit cells. Rapid growth of spring roots also occurs during stage two and it is therefore important to manage irrigation water effectively to enhance the growth of these roots. During harvest the amount of water irrigated can be reduced as cell enlargement decreases at this stage. There must, however, be a sufficient amount of water in the soil once the fruits are removed, because root growth occurs and nutrients are taken up and stored in the trees. During stage five, no irrigation water is required in the Western Cape apple producing regions as the trees enter dormancy and rainfall is usually adequate, but at the end of this stage it is important to monitor soil water to determine when irrigation must be applied for the following growing season (Rendell McGuckian Consulting Group, 2013). In other areas with lower rainfall during this period, for example the Eastern Free State, irrigation water will have to be applied for both the apple trees and cover crops in the orchard.

During stage two and stage three, apple trees undergo constant growth and the application of irrigation water during these stages is important to maintain constant fruit growth (Rendell McGuckian Consulting Group, 2013). Water deficit during these stages may decrease fruit growth and reduce fruit size (Ebel *et al.*, 1993). It will be optimal if the water content is easily available to the trees during these stages in order to maintain a constant fruit growth (Boland *et al.*, 2002). However, because roots grow towards the moist regions in the soil, (Hillel, 2004) it is important to consider both the fruit- and root growth of apple trees when scheduling irrigation to improve/manipulate the root growth as fruit- and root growth are dependent on one another. Therefore irrigation must be scheduled to reach the specific goal of the orchard, whether it is good quality, high fruit yields or deep-developed and well-distributed root systems.

2.2.4 Root growth response to irrigation

The soil water content distribution throughout the soil profile will influence the water uptake by roots. Green and Clothier (1999) proved that 70% of the water uptake by apple tree roots occurred in the 0-400 mm soil depth layer when the surface soil water was distributed uniformly. Under these uniformly distributed soil water condition, 70% of the tree's fine roots were located in the 0-400 mm depth layer. The

water uptake by roots changed when partial irrigation was applied with roots taking up twice as much water at the wetted part of the soil profile. They concluded that water uptake by the roots of apple trees is more dependent on the availability of water near the surface rather than the distribution of fine roots through the soil profile. Their results indicated that roots prefer to grow toward moist regions. Similar results were found in research done by Koumanov *et al.* (2006) and Sokalska *et al.* (2009).

Koumanov *et al.* (2006) stated that the roots of almond trees will extract soil water easily from soil layers where there are optimal amounts of water. They also stated that the way in which roots withdraw soil water is greatly dependent on the amount of water which is available throughout the soil profile. Sokalska *et al.* (2009) stated that mature apple tree roots withdraw soil water easily close to the tree trunk where water is readily available. Eventually when water is depleted close to the tree trunk, roots will grow to areas with more available soil water after the depletion of soil water close to the tree trunk (Sokalska *et al.*, 2009).

Irrigation will greatly influence the root system architecture of apple trees as apple trees are able to adjust to the root zone water balance. A phenomenon termed “hydraulic lift” is a mechanism plant roots use to transfer soil water from deeper, wetter soil layer to dry layers near the soil surface. This mechanism enables plant roots to redistribute soil water. This is an important characteristic used by roots in order to facilitate root growth, especially when it is most necessary in dry soils to resist drought conditions (Burgess *et al.*, 1998).

Roots will penetrate deeper soil layers when the depth to which the soil is irrigated, increases (Cullen *et al.*, 1972). Sokalska *et al.* (2009) proved that intensive irrigation will cause a shallow rooting system with an asymmetric root distribution while a uniform root distribution were obtained when less irrigation water was applied more economically, *i.e.* when less frequent irrigations were applied. When soil profiles are deeply wetted less frequently, the soil profile will be allowed to dry out from the surface and roots will adapt to the changes in soil water content by penetrating into the deeper and wetter soil layers.

2.2.5 Irrigation strategies to improve root distribution

As discussed above, it is possible for roots to penetrate deeper soil layers when irrigation is applied correctly. Even when only limited water resources are available, but managed properly, it will be possible to manipulate root growth without causing fruit production to decrease (Tim Cummins & Associates, 1998).

As previously mentioned, it is important that adequate soil water is available during cell division in order to ensure high quality fruit yields. It is therefore important to apply irrigation water strategically during times when it is most necessary. Roots will grow to favourable soil layers (Ruiz-Sánchez *et al.*, 2005) and it is therefore possible to manipulate apple roots to grow to deeper soil layers.

Several authors have reported different peaks of active root growth (Atkinson, 1980). Peaks vary due to the age of apple trees and also due to the rootstock/scion combination (Li *et al.*, 2013). Rybakov and Dzavakjanc (1967) observed three peaks in active roots growth in one-year-old apple trees. Rogers & Head (1969) reported two flushes of active roots growth in mature apple trees with the first flush is in late spring, during or immediately after bloom, the second flush late in summer or the beginning of autumn, just after harvest. Atkinson (1980) also confirmed a second flush in fall when shoots are no longer growing. New studies done by Lötze (2016), however, suggest that root growth flushes in bearing apple trees are similar, irrespective of the type of soil or the scion. She found one main peak of root growth in bearing apple trees in the winter with a smaller peak in the summer. She emphasized that root growth in bearing trees differ from non-bearing apple trees as the white root growth in the non-bearing apple trees were not consistent during the winter, but they did, however, produce roots in different quantities during the growing season. During active root growth, roots will compete with aboveground growth for carbohydrates (Priestley *et al.*, 1976), but vigorous root- and shoot growth rarely occur simultaneously (Atkinson & Wilson, 1980) and roots are therefore an important source for accumulated carbohydrates (Atkinson, 1980).

Volschenk (2013) showed in her study that water deficit after harvest did not affect the yield and that fruit size was not reduced in the subsequent season. She further concluded that a 75% depletion of PAW throughout the season produced favourable

fruit quality. These results showed that in order to save water, it is possible to stress apple trees to some extent during the second flush of active root growth without decreasing fruit quality and yield. During the first flush of active root growth it is not desirable to put trees under extreme stress, because stress conditions during the first flush can eventually reduce cell enlargement. Consequently this will reduce fruit size and quality. Volschenk (2013) proved that 50% depletion of PAW during cell enlargement can still ensure acceptable fruit quality. These results showed that the soil can reach water potentials between -20 and -70 kPa before irrigation has to be applied. These findings are, however, on bearing apple trees. In non-bearing apple trees, cell enlargement of fruit are not to be expected and it may even be possible to stress trees below a water potential of -70 kPa, but excessive stress must be avoided as a reduction in vegetative growth will be detrimental to the long term profitability of the orchard.

2.3 Soil water retention

Soil water retention is the relationship between the potential- and amount of soil water. This relationship can be graphically plotted in order to create a soil water retention curve (SWRC). The soil water content will affect various mechanical- and physical soil properties. Mechanical properties include soil strength, plasticity, penetrability, compactibility and consistency while physical soil properties refers to the pore-size distribution of soil, soil porosity and bulk density. Furthermore, water content can affect root respiration as it governs the gas exchange and air content of the soil. Soil water potential refers to the condition of soil water and is an indication of its free energy per unit mass (Hillel, 2004). Soil water potential will influence various processes such as water evaporation, redistribution, infiltration, microbial activity and plant water uptake (Bittelli & Flury, 2009).

A SWRC can be used to determine the plant available water (Bittelli & Flury, 2009), the water holding capacity of the soil (Gupta & Larson, 1979) and the water flow within the soil. When the plant available water within a soil is known, crop water requirements can be estimated and irrigation scheduling can be managed (Bittelli & Flury, 2009). The estimation of crop water requirements will ensure a desirable balance between the water and air within the root zones of crops which will in return optimize the growth of the crop while irrigation scheduling is important to produce

high yields without reducing the quality of the crop (McMullen, 2000). Irrigation scheduling can be improved when the water holding capacity of a soil, along with its energy status, is known (Howell, 2004). The quantification of soil water flow is of great use in agricultural applications such as the computation of irrigation volumes and fertilization. This can be done by solving the Richards' equation. The SWRC is an input parameter which can be used to solve this equation in order to model soil water transport (Solone *et al.*, 2012).

Different laboratory (Klute, 1986) and field methods (Bruce & Luxmoore, 1986) can be used to determine soil water potential and soil water content in order to generate a SWRC. During this study the aim was to compare two laboratory techniques for determining a SWRC. These two methods are the pressure plate apparatus and the WP4C dew point potential meter. At very low water potentials, the pressure plate apparatus becomes less reliable while the dew point potential meter becomes more reliable (Solone *et al.*, 2012). These two methods were therefore tested to conclude whether it will be possible and accurate to use these two techniques in combination to obtain a SWRC.

2.3.1 Pressure plate apparatus

The pressure plate apparatus was first introduced by L.A. Richards in the 1930s (Richards, 1948) and is still commonly used to determine the SWRC of soils (Dane & Hopmans, 2002). This method is a liquid equilibration method (Solone *et al.*, 2012). The pressure plate apparatus measures soil water potential between 100 kPa and 1500 kPa suctions. The apparatus consists of a pressure chamber, a porous ceramic plate and a pressure supply system (Klute, 1986).

2.3.1.1 Principle of the method

The pressure supply system must consist of a special high-pressure, low-capacity compressor that can be regulated in a range from 100 to 1600 kPa if frequent measurements are to be made. For this method of determining soil water retention, it is recommended to use undisturbed soil samples. In soils that contain a significant amount of stones (any material larger than 2 mm) it can become rather difficult to obtain a representative sample of the bulk soil. In these cases the data obtained

from the disturbed soil (material smaller than 2 mm) must be corrected for the presence of stones as the stony soil holds less water than the soil without stones.

Undisturbed or disturbed soil samples that are packed into retainer rings are placed onto the ceramic plate. The ceramic plate with the soil samples must be wetted by placing the ceramic plate with samples on it in water to a level just below the top of the samples. The soil samples within the pressure plate apparatus are brought to a specific water potential. The exact water potential is obtained by exerting pressure onto the soil sample. Due to the applied pressure, excess water within the soil sample is forced to flow through a porous ceramic plate. Eventually the sample reaches equilibrium, *i.e.* when there is no more out flow of water, and the water potential of the soil sample will be equal to the pressure applied. The gravimetric water content of the sample can then be calculated by removing the sample from the pressure plate and oven-drying it. The volumetric water content of the sample can be determined with the use of the calculated gravimetric water content and the bulk density of the sample. Bulk density can easily be determined with the use of the dry sample mass and the volume of the ring. These measurements are used to create a SWRC when different pressures are applied to the soil samples in the pressure plate (Klute, 1986).

2.3.1.2 Disadvantages of the method

The main disadvantage of the pressure plate method is the extremely long time it takes to determine a SWRC. Furthermore, this method may give unreliable results at low water potentials and a low unsaturated hydraulic conductivity can cause errors when water retention is determined. At small values of unsaturated hydraulic conductivity, samples will require longer equilibration times which can be time-consuming and eventually can cause a lack of equilibration (Gee *et al.*, 2002). Campbell (1985) stated that coarse-textured soils are more susceptible to incomplete equilibration due to a low unsaturated hydraulic conductivity in the pressure plate apparatus at different matric potentials. He also stated that a low hydraulic conductivity that exists within the soil sample, due to the dewatering of a thin layer at the bottom of the sample, can prevent further drainage of the sample and consequently equilibrium will not be reached.

Soil shrinkage, which can occur after the desaturation of the sample, can cause a loss of hydraulic contact between the ceramic plate and the sample. This will cause incomplete drainage and no equilibrium will be reached. Drainage can also be hindered due to blocked pores in the ceramic plate. Blockage of pores can be a result of soil dispersion, biological growth or colloidal material (Cresswell *et al.*, 2008).

Hillel (2004) stated that soil texture and structure strongly influence soil-moisture retention, especially in the low-suction range, and it is therefore recommended to use undisturbed soil samples. Hence, if disturbed soil samples are used, the water retention determinations will be inaccurate. In a study done by Cresswell *et. al.*, (2008) where they evaluated the accuracy of the pressure plate apparatus at matric potentials of -500 and -1500 kPa, they suggested the use of disturbed soil samples as it improved drainage and the contact with the porous ceramic plate which ensured better results.

2.3.2 Dew point potential meter

The dew point potential meter (water potential meter) is a vapour pressure equilibration method that is based on the dew point technique. This technique entails the determination of the relative humidity of air above a soil sample in a closed chamber. In this study the WP4C Dew Point Potentiameter (Decagon Devices, 2015a) was used to obtain water potential readings in the range of -0.1 MPa to -300 MPa. The WP4C is able to deliver accurate water potential readings in this range.

2.3.2.1 Principle of the method

Before the water potential of a soil sample is measured with the WP4C, it must first be calibrated with 0.5 molar KCl. For the use of this method it is necessary to use disturbed soil samples, *i.e.* soil fractions that are smaller than 2 mm. The soil samples must be air-dried and then wetted to desired water content. This can be done in plastic containers or glass jars that can be closed. The samples must be allowed to equilibrate in the closed containers or jars.

A subsample is then taken from the jars or containers and transferred to a WP4C sample cup and placed into the sealed chamber. The sealed chamber contains a

mirror and a thermoelectric (Peltier) cooler to control the mirror temperature. The mirror is used to determine when dew starts to form. A photoelectric cell is used to determine the exact point at which condensation starts to appear on the mirror. A beam of light that is directed to the mirror will reflect into a photo detector. When dew starts to form on the mirror, the photo detector will sense the change in reflectance and the thermocouple records the temperature on the mirror. Constant redistribution of air within the chamber is ensured with an internal fan. This redistribution of air reduces the sample equilibration time. The temperature within the chamber is measured for both the sample surface and the dew point with a thermo-electrical module. When a reading is finished, the water potential and temperature of the sample are presented on the screen (Decagon Devices, 2015a).

After readings have been taken it is possible to determine the gravimetric water content of the sample (Gubiani *et al.*, 2013).

2.3.2.2 Disadvantages of the method

A disadvantage of this method explained by Campbell and Norman (1998) is that measurements become less reliable at higher values of water potential (*i.e.* near saturation). The unreliability is due to the exponential form of the Kelvin's equation that is used to determine the total suction of the soil sample through deriving the water potential from the relative humidity. The relative humidity is dependent on the resolution of temperature and according to the Kelvin's equation, small changes in relative humidity at 20 °C can result in significant changes in water potential. This statement is confirmed by Decagon Devices (2015a) where they state that the WP4C has an accuracy of 1% from -5 MPa to -300 MPa while a ±0.05 MPa accuracy can be expected in the range of 0 to -5 MPa. This mean the WP4C will be less reliable as the water potential values increase.

Another disadvantage of the method described by Campbell *et al.* (2007) is a lack of thermodynamic equilibrium between the soil sample and the sample chamber. The lack of thermodynamic equilibration leads to faulty readings or in some cases no reading at all.

2.3.3 Other methods to determine a SWRC

As stated previously, various other methods exist to determine a SWRC curve. The principle of some of these methods will be discussed briefly.

2.3.3.1 Suction tables

The use of suction tables entails that the water retention is determined through drainage at low suctions (<1 bar). Different apparatus exists to determine water retention based on this method (Klute, 1986). An example of such an instrument is tension-plates that are connected together in which a soil sample is equilibrated using a matric suction value that is known. The soil air must be kept at atmospheric pressure and a hanging water column control the pressure difference across the plate (Hillel, 2004). A relatively large number of cores can be tested at once and the systems are built to work in a suction mode (Klute, 1986).

2.3.3.2 Thermocouple psychrometry

Thermocouple psychrometry is measurements of both hygrometry and psychrometry *i.e.* the water potential of a soil sample can be measured through determining either the dew-point temperature or the wet-bulb temperature depression of the soil sample. The temperature depression is then associated with the relative humidity by the use of the Kelvin equation. To perform measurements, a soil sample is placed in a closed chamber. The liquid within the sample will evaporate until the partial pressure of the vapour is equal to the vapour pressure of the liquid. When the liquid starts to evaporate, the humidity in the chamber starts to rise. With an increase in humidity, the vapour condenses into liquid at a rate that is equal to the evaporation. At this point the system is in equilibrium, because there will be no further change in humidity. At equilibrium, the partial pressure of the vapour in the air is measured with a psychrometer. With the use of the Kelvin equation, a definite relation exists between the water potential of the sample and the relative vapour pressure above the sample and therefore the water potential of the soil sample can be measured directly (Kirkham, 2014). Different equipment exists to determine water retention with psychrometers and is explained in detail by Rawlins and Campbell (1986).

2.3.3.3 Filter paper method

With this technique, soil matric suction is measured indirectly with the use of a previous established calibration curve (Bicalho *et al.*, 2007). A soil sample is placed in a ring in such a way that the upper surface of the sample is flat and level with the top of the ring. The initially dry filter paper is then placed on the ring in order to establish good contact with the soil sample (De Almeida *et al.*, 2015). The filter paper will gradually be wetted due to the water movement from the soil to the filter paper. Flow of water will stop when equilibrium is reached and at this point the soil and the filter paper will have the same suction values. After equilibrium has been reached, one can determine the gravimetric water content of the filter paper and the gravimetric water content can then be converted to suction with the use of the calibration curve (Bicalho *et al.*, 2007). The calibration curve can be obtained by following the same procedure as done with the soil sample, but instead of the soil sample a salt solution of a known molality in distilled water must be used. The suction of the filter paper is then calculated from the relative humidity of the air above the solution (ASTM, 2003).

2.3.3.4 Electrical resistance

An electrical resistance sensor measures water potential and consists of a standard matrix that is calibrated with the soil solution under such conditions that both solutes and water are exchanged (Campbell & Gee, 1986). A pair of electrodes is immersed in the standard porous matrix such as fibre glass, nylon or gypsum. These porous materials, usually in the form of a block, are easily placed in the soil. When the blocks are placed into the soil it will equilibrate with the matric suction of the soil water (Hillel, 2004) and a measurement is made when the matric potential of the porous block is equal to the potential of the soil solution. The porous blocks are calibrated against soil wetness in order to determine a relationship between electrical resistance and water potential of the soil. The matric potential of the sensor can then be inferred with the use of this relationship (Campbell & Gee, 1986).

2.3.3.5 Field methods

The determination of a SWRC in field requires a lot of equipment and it is also very time consuming. The variability of soil characterization and the fact that

determinations of water content-potential are done on a small area is other factors that complicate the determination of a SWRC in field. Therefore, when a SWRC is going to be determined in field, certain questions should be answered before the initiation of such an activity to ensure that the data obtained will be satisfactory (Bruce & Luxmoore, 1986).

An instrument which can be used in field to determine a SWRC is a tensiometer. Tensiometers offer a liquid equilibration method that provides an *in situ* indication of soil matric potential. The instrument consists of a permeable porous ceramic cup which is connected to a manometer through a tube. These parts are all filled with water. A soil's suction is measured by placing the ceramic cup in the desired soil. At this stage, the water inside the tensiometer is at atmospheric pressure and comes into hydraulic contact with the sub-atmospheric soil water. According to the second law of thermodynamics, the water inside the tensiometer will have a natural tendency to equilibrate with the soil water. The pressure within the tensiometer will fall below atmospheric pressure due to the soil water that exercises suction and a certain amount of water will be drawn out from the airtight tensiometer. The manometer indicates this sub pressure (Hillel, 2004). A major limitation of this method is the range in which the instrument measures. Measurements can only be made between 0 – 80 kPa since the cups for field use have a bubbling pressure of 100 kPa (Lal & Shukla, 2004). Recently, high suction tensiometers that can measure up to 200 kPa have been developed (Toll *et al.*, 2015).

2.3.4 Comparative studies between different methods

Solone *et al.* (2012) stated that the unreliability of the pressure plate apparatus raised several questions and therefore comparative studies between the pressure plate apparatus and alternative methods are necessary.

Madsen *et al.*, (1986) did a comparative study between thermocouple psychrometers and the pressure plate apparatus. They found that pressure plate measurements gave higher water potentials than those measured with a thermocouple psychrometer. Richards and Ogata (1961) also compared psychrometry and the pressure plate apparatus, but only found similar results between the two techniques when back flow of water from the pressure plate apparatus into the sample was

prevented through detaching the sample from the membrane before releasing the applied pressure. Gee *et al.* (2002) also did a comparative study between pressure plates and thermocouple psychrometry and estimated that soil water potentials at permanent wilting point (± -1500 kPa) may not reach equilibrium when using the pressure plate apparatus. They therefore suggested that alternative methods such as dew point meters and thermocouple psychrometry must be used to determine water potentials at low suctions (Bittelli & Flury, 2009).

Toll *et al.* (2015) used high capacity tensiometers to make measurements for a SWRC. They compared their results with those obtained by chilled mirror hygrometers, filter paper tests and pressure plate measurements. Reasonable consensus in the higher suction range (1000 – 10 000 kPa) were found in tests done through the filter paper method and the dew point hygrometer method. Differences were found between measurements made by the tensiometer and the pressure plate. They contributed these differences to different volumetric responses. There was less volume change of the samples when the pressure plates were used, because of the different shrinkage paths. Tests done with the pressure plates showed higher gravimetric water contents and a lower degree of saturation than measurements made with the tensiometers. They emphasised that their results demonstrated the importance of obtaining volumetric measurements when a SWRC is determined.

Bittelli and Flury (2009) compared the pressure plate apparatus and the dew point technique and found pronounced differences between the two methods, especially at potentials less than -10 m H_2O (-100 kPa). They found that the pressure plate apparatus constantly gave higher water content values than the dew point technique at the same water potential. They therefore concluded that the plant-available water was underestimated when the pressure plate apparatus was used, because of the overestimation of soil water content at permanent wilting point. Their study was, however, only done on a soil with a silt loam texture. Solone *et al.* (2012) studied the effect that errors in SWRC can have on the soil water balance on soils with different textural properties. They showed that limitations for measuring the SWRC with the pressure plate apparatus were mainly in fine textured soils and proposed that the pressure plate apparatus should not be used for these soils and that one should rather use alternative methods, such as the dew point technique.

CHAPTER 3: MATERIALS AND METHODS

3.1 Experimental site

3.1.1 Site selection

An experimental site, representative of gravelly soils, was selected in one of South Africa's main apple growing areas. Gravelly soils are wide-spread in the apple growing regions of South Africa and it was therefore important to choose a site accordingly. The experimental site was selected in Grabouw, Western Cape, on the Oak Valley Estate (34°09'17.6"S 19°02'45.4"E) in the Elgin valley, which is in the Overberg region. The former use of the selected experimental site was for the cultivation of apples.

The Elgin valley is separated from the sea by a narrow range of mountains with altitudes ranging from 300 metres to 600 metres above sea level. These conditions create a cool climate which is essential for the production of deciduous fruits. Oak Valley Estate has 350 hectares under fruit production, which makes it one of the largest deciduous fruit production units in South Africa. Apples are planted on 280 of these 350 hectares of fruit ("Oak Valley Estate," 2017).

Grabouw has a Mediterranean-type climate with an annual rainfall of about 990 mm. The highest rainfall is usually during June (long term mean of 168 mm) and the lowest rainfall in February (22 mm). February is also the warmest month with an average maximum temperature of 24.8 ºC. July is the coldest month with an average minimum night temperature of 6.4 ºC (South Africa Explorer, 2017).

3.1.2 Soil description and classification

Before planting of the field trial, five profile pits were dug to a depth of 1200 mm on the experimental site to describe and classify the soil as well as to determine the soil uniformity. These five profile pits were evenly distributed over the entire experimental site. Since the land was already deep delved and ridged at that stage, profile pits were positioned perpendicular to the ridges in such a way that it showed a cross section of the ridges.

Soil descriptions included depth of the different soil horizons, colour, mottles, structure and an estimation of texture. The soil was then classified into a form and family according to the South African Soil Classification System (Soil Classification Working Group, 1991).

3.1.3 Soil sampling

Soil samples for chemical and physical analyses were taken in each of the five profile pits at four depth increments namely 0-300 mm (A), 300-600 mm (B), 600-900 mm (C) and 900-1200 mm (D). Care was taken to include stones and gravel in the samples in order to make them fully representative of the soil. Each sample weighed approximately 3.6 kg.

All soil analyses were done on the soil samples of each profile pit at the four depth increments as described above, unless specified otherwise.

3.2 Experimental orchard

3.2.1 Treatments

The treatments consisted of three different irrigation cycles. Each treatment was replicated (R) five times, thus there were 15 experimental plots in total. The first treatment (T1) was a short irrigation cycle, the second treatment (T2) was a medium irrigation cycle and the third treatment (T3) was a long irrigation cycle.

The irrigation treatments were as follows:

T1: Twice a week, 10 mm per irrigation

T2: Once a week, 20 mm per irrigation

T3: Once every two weeks, 30 mm per irrigation

3.2.2 Layout

The experimental orchard formed part of a bigger orchard on the Oak Valley Estate. A randomized block design was used for the experimental layout.

Each experimental plot contained fifteen data trees (three rows of five trees) with two border rows of trees in between plots. There were also two border tree rows between plots (Figure 3.1) except for the first five experimental plots on the east side that only had one border tree row.

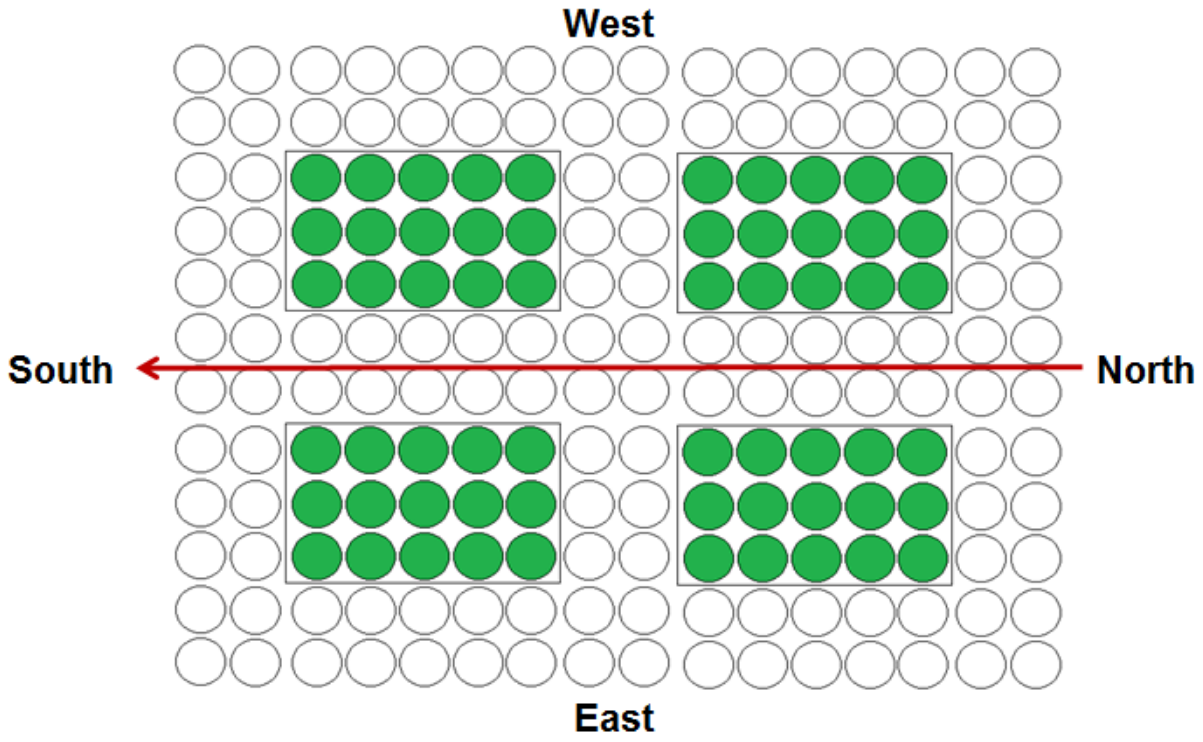

Figure 3.1: Layout of four irrigation plots; the green circles (in blocks) represent the experimental trees while the clear circles represent the border trees; the red arrow indicate that trees were planted in a north-south row direction.

3.2.3 Planting

Before planting, the soil was deep delved to a depth in the range of 1000-1100 mm. The soil was ridged to a height of 0.45 m (Figure 3.2) down-hill in a north-south direction and covered with plastic to fumigate the soil.

Malus domestica 'Bigbucks' (a mutation of 'Corder Gala') with an average size of 1.8 metres were planted according to the farm's standard practices on 10 October 2016. The trees were grafted on MM109 rootstocks. One-year-old *Malus domestica* 'Golden Delicious' and *Malus domestica* 'Fuji Suprema' trees, both grafted on MM109 rootstocks, were planted as pollinators. Trees were planted on the ridges in

a north-south row direction and spaced 1.5 m × 4 m (Figure 3.3). Pollinators were planted in the first experimental row from the east side (*i.e.* the first border row in the experimental orchard had no pollinators) with the first border tree (at the top of the experimental orchard, *i.e.* at the north side) being a pollinator, followed by two 'Bigbucks' trees and then another pollinator was planted. Every third tree in that row was a pollinator. Here after pollinators were planted in every third row and followed the same sequence as described. There was one pollinator in each experimental plot.

A vertical trellis system (Figure 3.4) was used to support trees to the solaxe system. With the solaxe system the trees consist of a strong central leader with 18 to 22 bearing branches that are spread around the main stem (Lauri & Lespinasse, 2000). Apart from the structural branches, the central leader was kept free of any other growth to allow light to penetrate to the middle of the tree. Approximately one month after the establishment of the trees leader (in their first leaf), toothpicks were used to bend the branches at an angle of 90 degrees to the central. In their second leaf branches will be bent below horizontal. In bearing apple trees, this slow their growth and make them reproductive (SA Orchards, 2014).

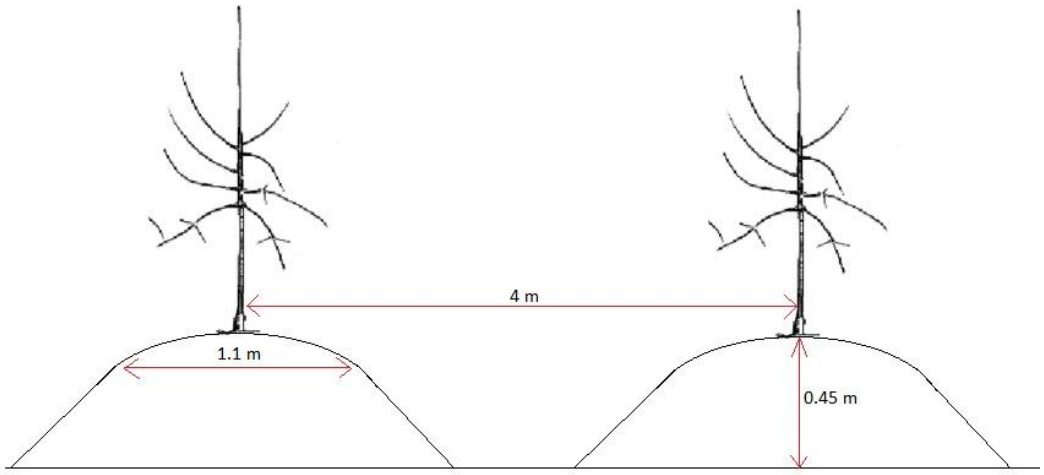

Figure 3.2: Dimensions of ridges and between-row spacing of trees.

Figure 3.3: The Bigbucks apple trees planted on ridges in a north-south row direction and spaced 1.5 m × 4 m.

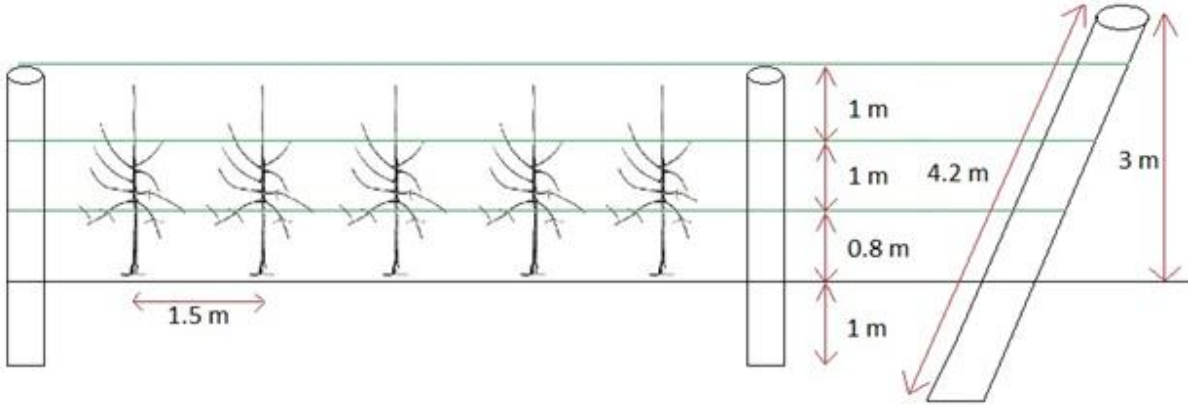

Figure 3.4: Trellis system on which trees were trained; the green lines represent wires.

3.2.4 Standard practices after planting

After the trees were planted, the stems of the trees were painted with polyvinyl acetate (PVA) paint. This was done to protect the trees against herbicides. The paint also contained copper to prevent snails from getting into the tree. Herbicides were used to control weeds when necessary.

The trees were fertilized manually with Turbo 31 (50-65% ammonium nitrate, 15-20% potassium chloride and 7-10% superphosphate) once every two weeks. Each tree received 50 grams of fertilizer which were evenly distributed around the stems of the trees. Care was taken during the distribution of the fertilizer to avoid contact between the stem and fertilizer.

3.3 Irrigation system

The irrigation system for the field trail was designed by Louis du Plessis from Aquasphere Agriculture (Vyeboom). Water was permanently under gravimetric pressure and available to irrigate when necessary. The water was filtered through an Amaid 80 mm plastic filter. The system was designed in such a way that each experimental plot and each treatment can be irrigated either separately, or simultaneously. Hydraulic valves were used to control water flow to the treatments and ball valves to irrigate the plots separately, when necessary.

Water meters (ARAD Multi-Jet water meters, Netafrim, Cape Town, South Africa) registered the total amount of irrigation water for each treatment. These water meters registered every 10 litres of water. Furthermore, small in-line flow meters (Liquid flow meter, Micro Robotics, Stellenbosch, South Africa) were used in T1 repetition two, four and five (T1R2, T2R4, T1R5), T2 repetition one, two and four (T2R1, T2R2, T2R4) and T3 repetition two, three and four (T3R2, T3R3, T3R4) to calculate the amount of water that was applied during irrigation. The flow meters were installed in the middle row of each treatment plot and measured the flow of seven micro-sprinklers. Both the water meters and the flow meters were connected to the data logger (3-Channel Vibrating-Wire Datalogger, Campbell Scientific, Somerset West, South Africa) (as described in point 3.6) which registered the amount of water that was applied during irrigation.

Each of the three main water meters was calibrated by recording the initial amount of water registered on the water meter (WM_i), allowing water to flow through the meter for eight minutes and recording the amount of water registered on the water meter again (WM_f) when the irrigation was switched off. The amount of water which flowed through the water meter during the eight minutes when the irrigation system was switched on was determined by subtracting WM_f from WM_i. These amounts were

then compared to the amounts registered by the data logger to determine if there were any differences in the amount of water indicated on the water meter itself and that registered by the data logger.

Each in-line flow meter that was installed was calibrated using seven buckets and measuring cylinders. A bucket was placed under each micro sprinkler in the same row where the flow meter was installed and the irrigation for that particular plot was switched on for 5 to 10 minutes. Dripping of water was allowed to stop completely after the irrigation was switched off before the amount of water that flowed through each sprinkler was determined using measuring cylinders. Subsequently the total amount of water that flowed through all seven sprinklers was calculated. This calibration method was repeated for all nine flow meters that were installed. The amount of water measured, was compared to the amount of water that was registered by the data logger in order to determine if there was any difference between the two. Finally a calibration curve was obtained by plotting the actual amount of water that was measured (Y-axis) against the amount of water registered by the data logger (X-axis). The equation of the regression line was used to determine the actual amount of water applied during irrigation.

Lateral irrigation pipes were fastened on the first wire of the trellis system (0.8 m above the soil surface) and Eintal micro sprinklers hung downwards from the pipe. The micro sprinklers were located in the middle between two trees. Each micro sprinkler wetted an area of 2.545 m^2.

An electronic control system (GSM Commander, Polygon Technologies, Cape Town, South Africa) was used to automatize the irrigation system. This control unit contained a SIM card which made it possible to connect to cellular networks. A cell phone was used to communicate to the GSM commander when irrigations had to be switched on or off.

3.4 Soil chemical properties

Samples from each of the five profile pits at the four depth increments (as described previously) were pooled to four composite sample, one sample for each depth increment. These composite soil samples were analysed for $pH_{(KCl)}$, electrical

conductivity (EC), basic cations, Bray II phosphorus (P) and titratable acidity by Bemlab (Pty) Ltd, South Africa.

3.5 Soil physical properties

3.5.1 Particle-size analysis (soil texture)

The pipette method as described by Gee and Bauder (1986) was used to determine the texture of the soil for each profile pit at depth increments A to D. The particle size of all four depth increments for the five profile pits were analysed in triplicate, *i.e.* a total of 60 samples were analysed. Disturbed sieved soil (<2 mm) samples with a mass of 40 g were used for analysis.

The weighed soil samples for analysis were placed in 800 mL beakers and organic matter (OM) was removed from the samples by adding 5 mL of 30% (by volume) hydrogen peroxide (H_2O_2) solution to the samples. Samples were heated to 90°C and more H_2O_2 was added when the reaction subsided. The samples were treated with H_2O_2 until all of the OM was destroyed. Excess peroxide was removed by heating the samples for an hour after the final addition of H_2O_2. The samples were then oven-dried and weighed to determine the amount of OM contained in each sample.

The dry samples were dispersed by adding 10 cm^3 Calgon (35.7 g sodium hexameta phosphate ($(NaPO_4)_6$) and 7.9 g sodium carbonate (Na_2CO_3) in 1 dm^3 water) solution and distilled water to each sample and mixing it for 10 minutes using a laboratory mixer. After the dispersal of the samples the sand was separated from the silt and clay by pouring the suspension through a 53 µm sieve into a one litre sedimentation cylinder. The sand (which accumulated on the sieve) was washed thoroughly with distilled water, transferred to a weighing dish, dried at 105 ºC and weighed. The dried sand was transferred to a nest of sieves arranged from top to bottom with decreasing sizes in the following order: 0.5 mm, 0.25 mm, 0.106 mm, 0.053 mm and pan. A sieve shaker was used to shake the sieves for 10 minutes after which each sand fraction was weighed.

The cylinders that contained the silt and clay fractions were filled with distilled water to the one litre mark. The suspensions were left to stand several hours to equilibrate

at room temperature. After equilibration the suspensions were agitated with a hand stirrer in an up-down motion for 30 seconds. The time when stirring was completed was recorded. After the appropriate time interval (4 minutes and 20 seconds) the clay and silt fraction was determined by carefully lowering a Lowy pipette into the suspension to a depth of 10 cm. A 25 mL sample was withdrawn and discharged into a beaker. The pipette was rinsed with distilled water and the rinsed water was added to the beaker. The beaker (containing the silt and clay suspension with water) was dried at 105 ºC, which allowed the water to evaporate. The beaker was cooled in a desiccator and weighed.

The clay and silt suspension was left to stand for the appropriate time interval (7 hours and 13 minutes) and the clay fraction was determined in the same way the clay and silt fraction was determined.

The following masses were used to determine the percentage sand, silt and clay that the soil contained:

A_a = mass (g) pipetted fine silt and clay

A_b = mass (g) pipetted clay

A_c = mass correction for Calgon (0.011 g)

A_d = mass (g) sand fraction on sieve

A_e = mass (g) oven dry soil after OM was removed

The calculations were done as follow:

$$\text{Percentage sand fraction} = \frac{A_d \times 100}{A_e}$$

$$\text{Percentage fine silt and clay } (A_f) = \frac{(A_a - A_c) \times 1000 \times 100}{A_e \times 25}$$

$$\text{Percentage clay } (A_g) = \frac{(A_b - A_c) \times 1000 \times 100}{A_e \times 25}$$

$$\text{Percentage fine silt} = A_f - A_g$$

$$\text{Percentage coarse silt} = 100 - \text{sum of sand fractions} - A_f$$

The texture triangle (Hillel, 2004) was used to determine the nominal name for the soil type based on the relative proportions of silt, sand and clay.

3.5.2 Particle density (ρ_s)

The particle density of the coarse fragments (which consisted of plinthite and relic plinthite) at depth C for all five profile pits were determined with the pycnometer method described by Blake and Hartge (1986b). The particle density of the coarse fragments was only determined at depth C, because this was the one depth of all four depth increments that contained the most coarse fragments. The particle densities of both the plinthite and relic plinthite were determined separately. Each determination was done in triplicate. The particle density of soil was also determined with the pycnometer method described by Blake and Hartge (1986b). The particle density of the soil from all four depths of each profile pit was determined in duplicate, *i.e.* a total of 40 measurements were made.

A dry pycnometer with its stopper was weighed and its weight (W_a) was noted. A small piece of plinthite/relic plinthite was placed in the pycnometer which was closed with its stopper and weighed. For determination of the soil particle density, approximately 3 grams of soil was placed into the pycnometer. This mass of the plinthite/relic plinthite/soil and pycnometer (W_s) was recorded. Water was added to the pycnometer that contained the coarse fragment/soil and filled entirely. The stopper was carefully inserted and seated. The outside of the pycnometer was thoroughly dried with a cloth and the pycnometer with its contents were weighed (W_{sw}). The coarse fragment/soil was removed from the pycnometer and the pycnometer was washed, filled with water, closed with its stopper and weighed again (W_w).

The following equation was used to determine the particle density of both the plinthite and relic plinthite:

$$\rho_s = \frac{W_s - W_a}{(W_s - W_a) - (W_{sw} - W_w)}$$

3.5.3 Bulk density (ρ_b)

The bulk density of the soil was determined in the field using the sand-funnel method as described by Blake and Hartge (1986a). For this method a metal funnel fitted with a valve on the stem and a template also consisting of metal with a diameter of 15.9 cm was used (Figure 3.5). Dry sand with a particle size smaller than 0.8 mm was used. The bulk density of the sand (ρ_{sand}) was calculated by dividing the mass of dry sand by its volume as determined in a measuring cylinder.

Bulk densities in all five profile pits at depths increments A to D (as mentioned earlier) were done in duplicate. For each determination the soil surface was levelled and loose soil removed. The template was placed on the soil surface and a soil sample excavated through the centre hole of the template leaving a hole in the soil with a diameter of approximately 15 cm and a depth also approximately 15 cm. The excavated soil was quantitatively collected in a paper bag, dried at 105 ºC for 48 hours and weighed (M_{DS}).

Figure 3.5: The metal funnel (right) and the template (left) which was used to determine the bulk density in the irrigation trial on Oak Valley Estate.

Subsequently the funnel was filled using a bag of sand (which weighed 3 kg) by allowing the sand to flow freely through the funnel. When the sand stopped flowing, the valve on the stem of the funnel was closed and the sand left in the upper part of the funnel returned to the sand bag. Sand bags for each determination were marked and weighed. Firstly, the mass of sand that flowed through the cone (M_{FT}) was determined in order to calculate the mass of sand in the hole (M_H). The calculations were done as follows:

$$M_{FT} = M_B - M_{LO}$$

$$M_H = M_{LC} - M_{FT}$$

where M_B = total mass of the sand bag (3 kg), M_{LO} = mass sand left over after filling the cone (weighed) and M_{LC} = mass sand to fill the lower part of the cone (0.88 kg)

The volume of the hole (V_H) was calculated as follows:

$$V_H = \frac{M_H}{\rho_{sand}}$$

With the volume of the hole known it was possible to calculate the bulk density of the soil. The bulk density of the soil (ρ_b) was then determined as follows:

$$\rho_b = \frac{M_{DS}}{V_H}$$

3.5.4 Porosity (f)

The porosity of the soil was calculated for a relative indication of the volume fraction of pores in the soil using the following equation (Hillel, 2004):

$$f = 1 - \frac{\rho_b}{\rho_s}$$

The particle density that was used to determine the soil porosity was calculated for each profile pit at their four depth increments using the following equation:

$$\rho_s = \left(\rho_{srp} \times \frac{V\%\ \text{relic plinthite}}{100}\right) + \left(\rho_{sp} \times \frac{V\%\ \text{plinthite}}{100}\right) + \left(\rho_{ss} \times \frac{V\%\ \text{soil}}{100}\right)$$

where V% represents volume percentage, ρ_{srp} represents the particle density of the relic plinthite, ρ_{sp} represents the particle density of the plinthite and ρ_{ss} represent the particle density of the soil.

3.5.5 Coarse fragments

Samples were taken to the laboratory and air-dried for 48 hours. Each air-dried sample was weighed to obtain the total mass of soil and coarse fragments. The air-dried samples were then crushed and sieved through a 2 mm sieve to separate the soil from the coarse fragments. The sieved soil and coarse fraction were separately weighed again in order to determine the amount of gravel and stones in the soil profile. For an accurate indication of the coarse fragment fraction, all fine soil particles were removed from the uneven surfaces of the stones and gravel through washing the stony fractions with water. The coarse fragments were air-dried for 48 hours and weighed again to determine the percentage coarse fragments by mass. This was done for all five profile pits at the four depth increments, as stated earlier.

All of the coarse fragments consisted of plinthite and relic plinthite. The ratio of plinthite to relic plinthite was determined through separating the plinthite (orange/red) and relic plinthite (darker/black) based on colour (Figure 3.6). This ratio was used to determine how much of the coarse fragments in the sample was plinthite and how much was relic plinthite. The volume of the plinthite and relic plinthite were determined separately by dividing their masses by their densities.

The sample volume (total mass of sample divided by the bulk density of the soil as determined in the field) was used to determine the percentage coarse fragments representative of that sample. This was calculated separately for both the plinthite and the relic plinthite.

3.5.6 Soil water retention

The pressure plate apparatus introduced by Richards and Fireman (1943) and Richards (1948) was used to determine soil water retention for each profile pit at depth increments A to D. Determinations were done in triplicate on disturbed fine soil (<2 mm) samples, *i.e.* a total of 60 samples were measured.

Figure 3.6: The coarse fragments in the irrigation trial on Oak Valley Estate consisting of plinthite (top right) and relic plinthite (bottom left); the plinthite had an orange/red colour while the relic plinthite had a darker, black colour.

Aluminium rings with a volume of 53.386 cm^3 were closed at one end by Whatman 40 filter paper glued to the ring and filled with approximately 70 g of soil. At the time when the experiment was carried out, the bulk density of the soil on the experimental orchard was not known and after inspection of the soil in the irrigation trial, it was decided to pack the rings to a bulk density of 1.333 $kg.m^{-3}$ (Rawls, 1983). Consequently each ring was filled with approximately 70 g of soil. The samples were placed on ceramic plates covered in water and the samples were allowed to saturate overnight. The ceramic plates with samples were placed inside pressure chambers sequentially at pressures of 10 kPa, 20 kPa, 30 kPa, 50 kPa, 100 kPa, 300 kPa, 1000 kPa and 1500 kPa. While the soil samples were pressurized, the ceramic plates were at atmospheric pressure. This created a hydraulic gradient that allowed water to flow from the samples through the ceramic plates. Once the samples reached equilibrium with the imposed pressure, the flow of water ceased. The samples were then removed from the chamber, weighed separately and immediately put back on the pressure plate ready for applying the next higher pressure. Care was taken to prevent evaporation losses during weighing. Water was applied to the plates

before a new pressure was applied to allow good contact between the sample and the surface of the ceramic pressure plates.

After the eight desired pressures were applied and equilibrium was reached at the desired pressures, the samples were dried at 105 ºC for 24 hours and weighed again in order to determine the gravimetric water content of each sample. The bulk density of each sample was determined by dividing the dry mass of the sample by the volume of the aluminium ring. This bulk density was then used to calculate the volumetric water content of each sample. The volumetric water content was plotted against the eight pressures applied to obtain a soil water retention curve for each profile pit at their four depth increments.

3.6 Soil water measurements

Soil water measurements were conducted using CS650 multi-parameter smart sensors (Campbell Scientific, Somerset West, South Africa). Each CS650 multi-parameter smart sensor consisted of two 300 mm long stainless steel rods that were connected to a printed circuit board encapsulated in epoxy. A data logger connection was obtained through a shielded cable that was attached to a board. The sensors measured volumetric water content, dielectric permittivity, temperature and bulk electrical conductivity (EC) of the soil (Campbell Scientific Africa, 2017a).

Readings were taken every ten minutes and the LoggerLink for Android™ mobile application (Campbell Scientific Africa, 2017b) was used to download all the data from the logger. The data were used to draw graphs to illustrate the water content of each experimental plot.

3.6.1 Sensor installation

The sensors were installed at four depths (A to D) in nine experimental plots, *i.e.* in three replicates of all three treatments. The nine experimental plots where soil water measurements were taken are T1 repetition two, four and five (T1R2, T2R4, T1R5), T2 repetition one, two and four (T2R1, T2R2, T2R4) and T3 repetition two, three and four (T3R2, T3R3, T3R4).

The sensors were installed in the middle row of the three experimental rows (Figure 3.7), always at the same position relative to each other and at the same distance from the tree on all plots.

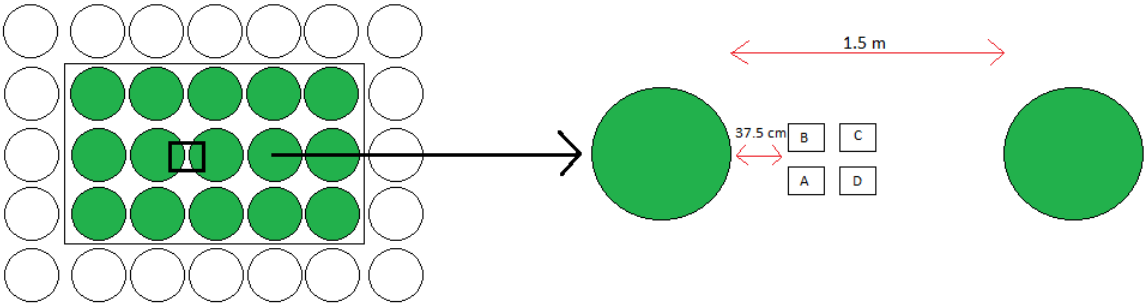

Figure 3.7: Installation of sensors in the experimental blocks; the green circles represent the experimental trees and the clear circles represent the border trees; the blocks marked A to D, are the positions where the four sensors at the four depth increments (A to D) were installed.

A modified Thompson auger was used to drill a hole to a depth 300 mm shallower than the desired depth at which the sensors were installed. A chisel with a length of 300 mm and a width of 40 mm was used to create an opening that was the same size as the sensors in order to install the sensors to the desired depth. The chisel was placed with its shaped end at the bottom of the auger hole and hammered a further 300 mm into the soil. The sensor was then installed into the hole created by the chisel and soil slurry was poured between the two rods of the sensor to ensure good contact between the rods and the soil. The auger hole was filled with the excavated soil.

3.6.2 Sensor calibration

3.6.2.1 Containers

Four CS650 multi-parameter smart sensors, one for each depth increment, were used for the calibration. Unsieved soil samples (*i.e.* samples that still contained all their coarse fragments) at the four depth increments (*i.e.* four unsieved soil samples, one at each depth) were taken from the field and air dried at 25 ºC for one week. For each depth increment, a container with a volume approximately 10.6 litres was filled

with its unsieved soil and compacted to the corresponding bulk density (as determined in field) of that depth.

Each container was filled with soil to a level two cm from its top. The mass of soil that was necessary to fill the containers was calculated through multiplying the bulk density (C_{DS}) (as determined in field) by the volume of the container. The volume of the containers was individually determined by placing the containers on an electrical scale, setting the scale to zero and accurately determining the mass of the water once the containers were completely filled. The volume of the two cm segment at the top of the container was subtracted from the total volume of the container in order to determine the accurate mass of soil necessary to fill the containers to a level measured two cm from the top of the containers. The volume of the two cm top segment was calculated with the formula $\pi r^2 h$, where r refers to the radius of the container and h refers to the height of the container of which the volume needed to be calculated. The radius of the container was determined with measuring tape and the height is known to be two cm.

Water was added to the dry soil sample to obtain a gravimetric water content of 15%. Firstly the bottom part of each container was filled with the wetted soil. Sensors were then placed in the in the middle of the containers and the rest of the wet soil was placed around the sensors to ensure good contact between the stainless steel rods and the soil. The total mass of the container, sensor and wet soil of all four containers were recorded.

All four containers were taken outside in order for the wet soil to dry out in the sun. The four sensors from each container were connected using a shielded cable to a printed circuit board for a data logger connection. The mass of the containers containing the wet soil and sensors were determined with an electrical scale, each day at 09:00 and 16:00, for two weeks. The following masses were used to calculate the gravimetric water content of the soil in each container:

C_{DS} = Mass of dry soil (determined)

C_c = Mass of the empty container

C_s = Mass of the sensor

C_{SSC} = Total mass of wet soil, sensor and container

C_{WS} = Mass of wet soil

The gravimetric water content (C_{GWC}) was calculated as follows:

$$C_{WS} = C_{SSC} - C_S - C_C$$

$$C_{GWC} = \frac{C_{WS} - C_{DS}}{C_{DS}}$$

The volumetric water content of each container was calculated by multiplying the bulk density with the calculated gravimetric water content. The calculated volumetric water content was plotted against the volumetric water content as read by the sensor and obtained from the data logger. This plotted graph was used to obtain a calibration curve for each depth in order to subsequently determine the actual volumetric water content in the field as read by the sensors installed in the orchard.

3.6.2.2 Orchard calibration

Gravimetric soil samples were taken in the orchard with an Edelman auger at the four depth increments A to D. Samples were taken in a radius of two meter from the sensors and each treatment plot where sensors were installed, was sampled. Soil samples were collected in tins having a volume of approximately 212 cm^3. Each clean empty tin was weighed and its mass (T_e) was recorded. After the samples were collected, the tins were weighed again (T_w). The tins were then placed in the oven and the samples were allowed to dry for 48 hours at 105 ºC. The tins were removed from the oven, placed in a desiccator to cool down and weighed (T_d) again. The gravimetric water content (T_g) of each sample was determined as follows:

$$T_g = \frac{(T_w - T_e) - (T_d - T_e)}{(T_d - T_e)}$$

The volumetric water content of each sample were determined by multiplying the bulk density (as determined in field) of the corresponding layer with the calculated gravimetric water content of the sample. A calibration curve was obtained by plotting the calculated volumetric water content against the volumetric water content as read by the sensors obtained from the data logger. This plotted calibration curve was

used to determine the actual volumetric water content in the field as read by the sensors installed in the orchard.

3.7 Soil water balance

Evapotranspiration (ET) of each irrigation treatment during the growing season was calculated using the following root-zone water balance equation described by Hillel (2004):

$$\Delta S + \Delta V = (P + I + U) - (R + D + E + T_r)$$

where E is the evaporation, T_r is the transpiration, P is the precipitation (*i.e.* rainfall), I is irrigation, U is upward capillary flow into the root zone and ΔS is the change in soil-moisture storage in the root-zone.

Assuming that ΔV (amount of water incorporated in vegetative biomass), R (runoff) and D (drainage out of the root zone) did not occur and was therefore negligible, the water balance equation was modified as follows:

$$ET = (P + I + U) \pm \Delta S$$

where ET is the evapotranspiration.

Soil water content was measured during the growing season (December 2016 to May 2017) with CS650 multi-parameter smart sensors as described in point 2.6. Measurements taken at 08:00 were used in the water balance equation. The rainfall data was obtained from a weather station on Beaulieu, which is a farm *ca.* 5 km away from Oak Valley Estate.

The upward capillary flow (U) was determined based on the soil water content increase, *i.e.* when the change in soil water content was more than the sum of the irrigation and precipitation in the same period, there was an excess of water which must have come from somewhere else and it is therefore assumed that his excess of water was due to upward capillary flow. Based on this assumption, the upward capillary flow was determined as follows: if the absolute value of change in soil water content was less than the sum of the irrigation and precipitation during the same period, there was no upward capillary flow (*i.e.* if $|\Delta S| < (I + P)$, then $U = 0$); when the absolute values of change in soil water content was greater than the sum of irrigation

and precipitation during the same period, there was an excess of water due to upward capillary flow (*i.e.* if |ΔS| > (I + P) then U > 0) and U was then calculated by subtracting the sum of irrigation and precipitation by the absolute value of ΔS (*i.e.* U = |ΔS| – (P + I)). Therefore ET was regarded as zero when upward capillary flow occurred.

Evapotranspiration was calculated for the intervals between irrigations for T1 and T2, but in the case of T3 (longest irrigation cycle) an additional ET calculation was performed midway between irrigations. Cumulative ET figures from December 2016 to May 2017 were also calculated for each irrigation treatment.

3.8 Root studies

3.8.1 Rhizotrons

3.8.1.1 Construction

Rhizotrons were constructed of Perspex (with a thickness of 8 mm) in the form of a rectangular box which was open at the top (Figure 3.8). The Perspex was cut into sheets (dimensions shown in Figure 3.8) and glued to each other with Magma bond – C1 glue (the glue contained dichloromethane & methylmethacrylate) (Falcon, 2015). Before the sheets were glued to each other, a grid (100 mm × 100 mm) was engraved on the sheets used as side walls (dimensions 1000 mm × 1100 mm). Each grid block was marked (from the second block onwards) from left to right from A to I and numbered downwards (also from the second block onwards) from one to nine (Figure 3.9).

The open end of each rhizotron was covered with a lid made from marine plywood with a thickness of 9 mm. The cover prevented light penetration into the rhizotrons and it also prevented water from entering. Each rhizotron contained five props to support the rhizotron side walls and prevent them from bending inwards as a result of the soil mass pressing against the sides. The props were made from marine plywood and covered with felt to prevent scratches that may occur when the props were removed or replaced before and after measurements (Figure 3.10).

3.8.1.2 Installation

Rhizotrons were installed at the experimental site in T1R5, T2R4 and T3R3 during January 2017. The rhizotrons were installed in the third experimental row of the treatment between the third and fourth trees (Figure 3.11). Soil was excavated between two trees to a depth of 900 mm and the rhizotron placed in the pit with its large side panels parallel to the tree row. Props were placed inside the rhizotron which was then covered with its lid (Figure 3.12) and the excavated soil filled back around the rhizotron until only its lid was visible above the soil surface.

3.8.1.3 Root scans

A scanner (LiDE-220, Canon, Cape Town, South Africa) was used to scan the roots in the rhizotrons during the first season at three dates namely 21 February, 11 April and 4 June. An extension was made on which the scanner fitted in order to scan roots to a depth of 1000 mm. The scanner scanned an area of 216 × 297 m at a time. The scanner was connected to a laptop via an USB port. All scans were saved onto the laptop.

The side walls of the rhizotrons were scanned by locating the scanner in the left corner of the rhizotron. After the scan was saved onto the laptop, the scanner was lowered 160 mm for the next scan, *i.e.* the scanner was lowered five times to scan to a depth of 1000 mm. After these five scans the scanner was moved 170 mm to the right and scans were further conducted to a depth of 1000 mm. The scanner was moved to the right five times to scan a length of 1100 mm. In total, 25 scans were made on each side wall to scan the roots on one side of the rhizotron.

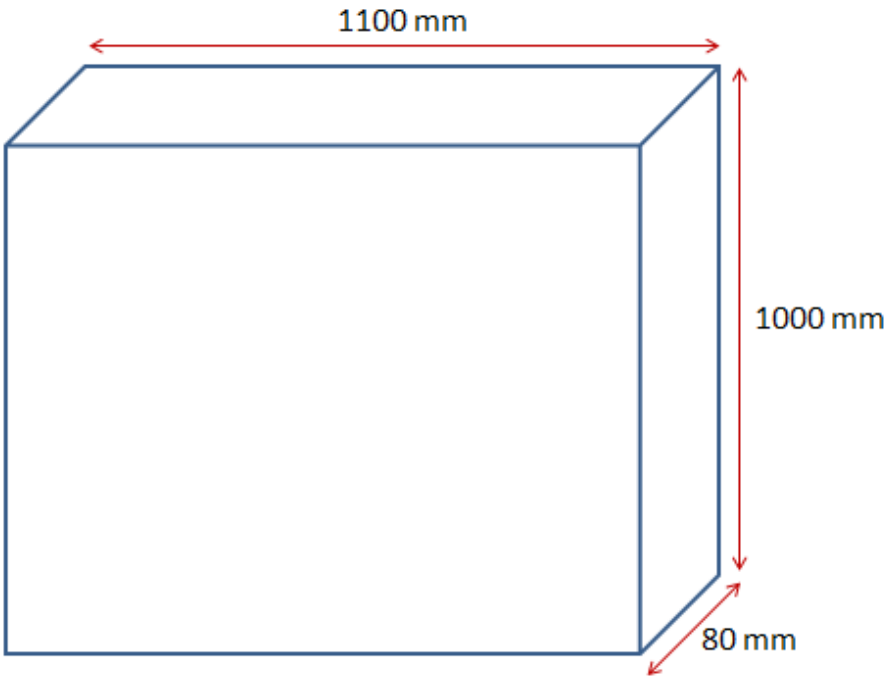

Figure 3.8: Dimensions of rhizotrons

	A1	B1	C1	D1	E1	F1	G1	H1	I1	
	A2	B2	C2	D2	E2	F2	G2	H2	I2	
	A3	B3	C3	D3	E3	F3	G3	H3	I3	
	A4	B4	C4	D4	E4	F4	G4	H4	I4	
	A5	B5	C5	D5	E5	F5	G5	H5	I5	
	A6	B6	C6	D6	E6	F6	G6	H6	I6	
	A7	B7	C7	D7	E7	F7	G7	H7	I7	
	A8	B8	C8	D8	E8	F8	G8	H8	I8	
	A9	B9	C9	D9	E9	F9	G9	H9	I9	

Figure 3.9: Grid (100 mm x 100 mm) that was engraved on the Perspex sheets

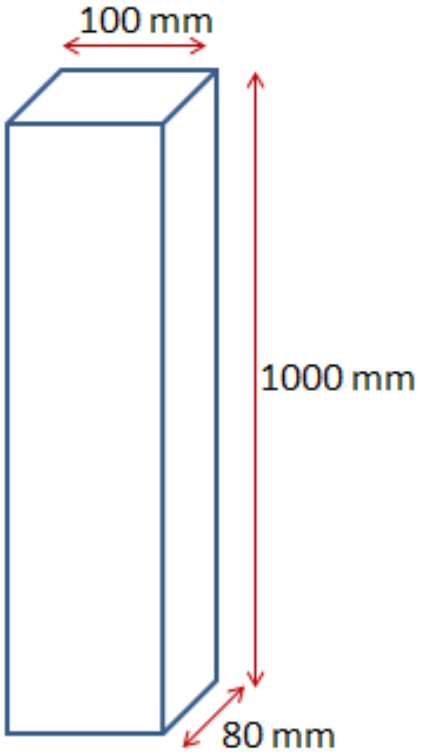

Figure 3.10: Dimensions of the props used to support the rhizotrons from the inside.

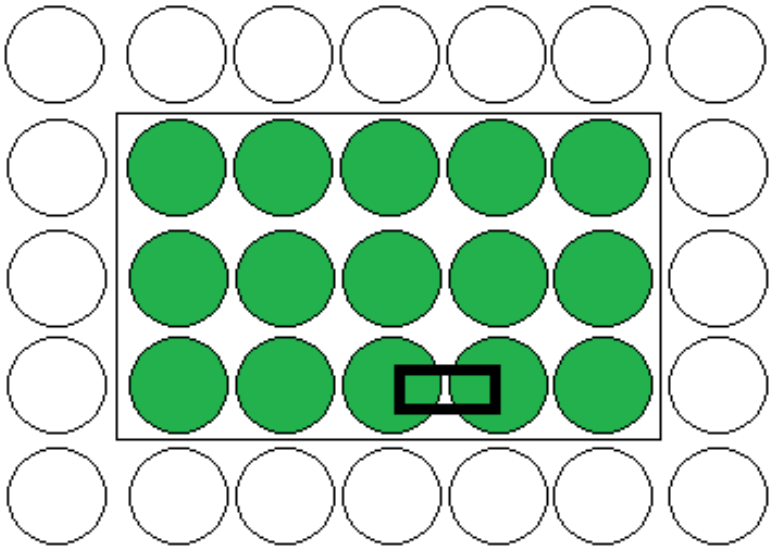

Figure 3.11: An illustration of rhizotrons positions; rhizotrons were installed between two trees with its longest side walls parallel to the tree row as indicated by the black outlined block.

Figure 3.12: Rhizotron with its props and lid installed between two trees parallel to the tree row.

3.8.2 Profile wall

In July 2017, *i.e.* during dormancy, root studies using the profile wall method were done on the same treatment plots where the sensors were installed, *i.e.* T1R2, T2R4, T1R5 T2R1, T2R2, T2R4 T3R2, T3R3 and T3R4. Profile pits with a length of 1200 mm and a depth of 1000 mm were dug between two 'Bigbucks' trees parallel to the row (Figure 3.13 (a)). The soil profile was also excavated into the working row to a distance of 800 mm (Figure 3.13 (b)). The profile pits were excavated between the second and third experimental trees in the first experimental row (Figure 3.14).

After the soil profile was excavated, the trench wall was cleaned in order to improve the visibility of the roots. This was done through teasing the soil away from the roots which emerged from the trench wall. All the roots were then cut so that the length of the roots that emerged from the wall was 2 cm long. A grid (1200 mm × 1000 mm) was placed against the trench wall. Each grid block had a size of 100 mm × 100

mm. The root distribution in the soil profile was drawn onto a plan with a 1:10 scale. The root distribution of the trench wall between the trees was drawn as well as both of the side trenches (*i.e.* the trench at the tree on the left and the trench at the tree on the right). The soil horizons were marked onto the plan and root distribution was indicated onto the plan in different thickness classes. The root thickness classes that were used were: very fine (root diameter < 0.5 mm), fine (root diameters of 0.5-2 mm), medium (root diameters of 2-5 mm), thick (root diameters of 5-10 mm) and very thick (root diameter > 10 mm). Each thickness class had its own symbol to distinguish the difference between the roots drawn on the plan.

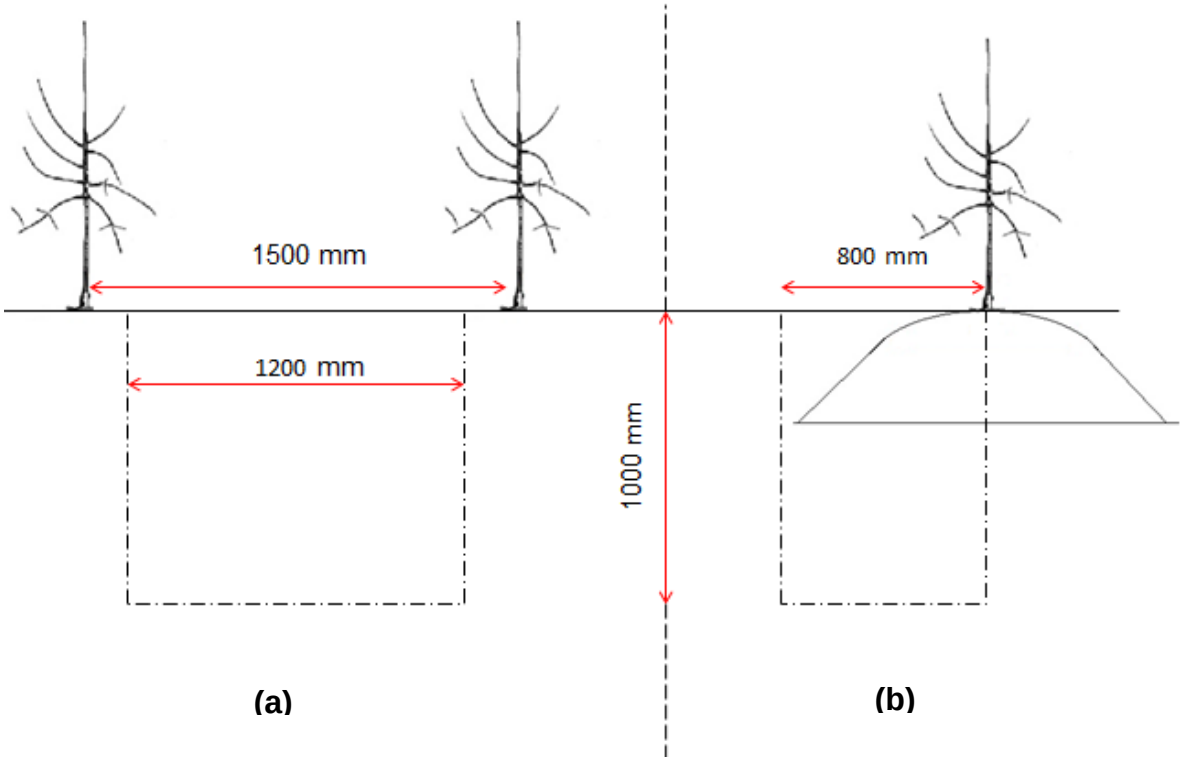

Figure 3.13: Dimensions of (a) the profile pit between two experimental trees and (b) the width of the profile pit perpendicular on the tree row

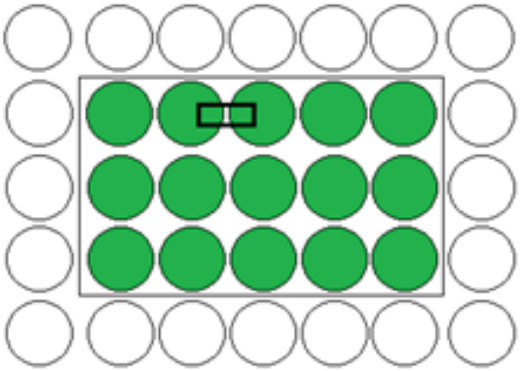

Figure 3.14: An illustration of the position of the soil profile pits used for root mapping; profile pits were excavated between the two trees as indicated by the black outlined block.

3.9 Vegetative growth

At the end of the growing season in June 2017, the vegetative growth of each experimental tree (pollinators excluded) in all the treatment plots was measured, *i.e* a total of 210 trees were measured. The basal stem circumference of each tree was measured *ca.* 1 cm above the interstem and the apical stem circumference was measured at the top of the central leader. Tree height was measured by measuring the length of the central leader and the leader extension growth. The lengths of all the branches that were present on the trees were also measured (Figure 3.15).

3.10 Comparative laboratory study

In a comparative study the soil water retention of six soils was determined using both the pressure plate apparatus and the WP4C dew point potential meter. The soils selected for a comparison between the two methods were not from the orchards on Oak Valley Estate where the irrigation experiment took place, but represented a texture range consisting of sand, sandy loam, sandy clay loam, loam, clay loam and silty clay loam. Soil textures were determined using the method as described in point 3.5.1.

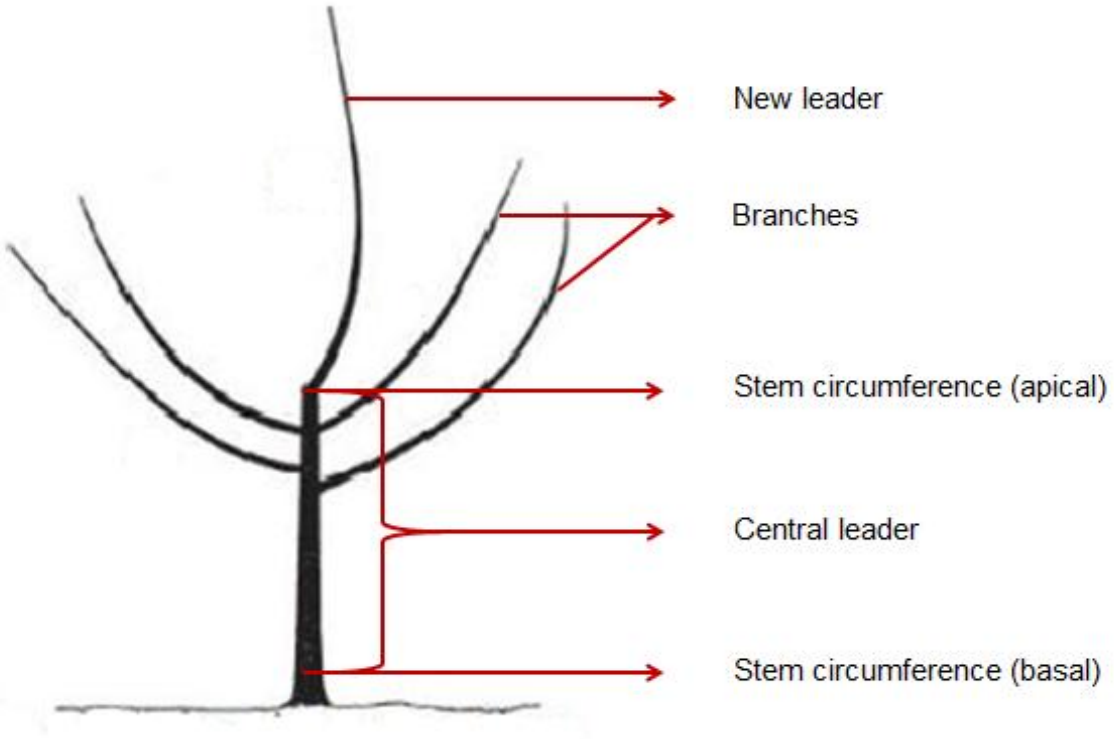

Figure 3.15: Illustration of the different vegetative measurements that were taken and the position of each measurement on the tree

3.10.1 Pressure plate apparatus

The same method as described in point 3.5.6 was used to determine the soil water retention of the soils. Determinations were done in triplicate on disturbed fine soil (<2 mm) samples, *i.e.* a total of 18 samples were measured. Samples were packed into aluminium rings to a bulk density of 1.333 $kg.m^{-3}$.

3.10.2 WP4C Dew point potential meter

The soil water potential of the soil samples was measured with the WP4C as described in the WP4C Dew Point PotentiaMeter Operator's manual (Decagon Devices, 2015a). The WP4C was calibrated with 0.5 $mol.kg^{-1}$ potassium chloride (KCl) at 25 ºC before each use.

Disturbed fine soil (<2 mm) samples were used for determinations. The WP4C measures matric potential and therefore a range of soil samples with different gravimetric water contents had to be prepared in order to determine a soil moisture retention curve of the soil. For each soil, ten jars were used to prepare the soil

samples. An appropriate amount of water was added to 10 g of air dried soil to obtain the desired water content. Samples with gravimetric water content in the range of 0.75% to 15% were used. The samples were allowed to equilibrate in closed jars for 24 hours. Each prepared soil sample was measured in triplicate, *i.e.* a total of 180 measurements were done.

Stainless steel WP4C sample cups with a volume of 15 mL were used for measurements. The empty mass of the stainless steel cups was determined (B_e) and about three grams of the soil placed in the stainless steel cup and the water potential measured. Immediately after the reading (matric potential of soil) was taken, the mass of the wet soil and the sample cup was determined (B_w). This was done quickly to prevent moisture loss to the air between the water potential measurement and weighing. The samples were placed in the oven and dried at 105 ºC for 24 hours. These samples were cooled in a desiccator, weighed (B_d) and the water content (Bwc) of the samples was then calculated as follows:

$$B_{wc}(\%) = \frac{B_w - B_d}{B_d - B_e} \times 100$$

The gravimetric water content (%) was plotted against the water potential to obtain a soil water retention curve for each soil.

3.11 Statistical analyses

Microsoft® Excel was used to capture raw data, sort and calculate means and the standard deviation thereof. Statgraphics® XV (version 2, Statgraphics Technologies, Inc., The Plains, Virginia) was used to subject data to an analysis of variance (ANOVA) and the least significant difference (LSD) values calculated to facilitate comparison between treatment means. Analyses with p values ≤ 0.05 were considered significantly different.

CHAPTER 4: SOIL PROPERTIES

4.1 Soil description and classification

Ridging and soil preparation modified the soil profile substantially, but it was, however still possible to identify the natural soil horizons. In all five profile pits that were excavated in the experimental orchard, the soil was classified as a Kroonstad soil form and specifically part of the Grabouw soil family (Soil Classification Working Group, 1991). The Kroonstad soil form consists of an orthic A horizon and E-horizon overlying a G-horizon (Figure 4.1). The colour of the E-horizon was 2.5 YR 6/4 in its moist condition, but in its dry condition the horizon was bleached with a colour of 2.5 YR 8/2. The E-horizon had a very weakly developed structure and was very hard in its dry condition while it was more loose and friable in its moist condition. The G-horizon occurred at 900 mm depth. The delve plough used in soil preparation caused an undulating boundary between the A and E horizons that affected root distribution in the soil (see chapter 6). No subsoil material was, however, brought to the soil surface.

4.2 Soil chemical properties

The chemical status of the soil, with specific reference to the soil pH, indicated that no problems regarding root growth, development and functioning or nutrient deficiencies were to be expected (Table 4.1). According to Jonkers and Hoestra (1978) the optimal soil pH for apple tree growth is between 6 and 6.5. These pH values are, however, pH values measured in water. On average, pH values measured in KCl will usually be 0.70 pH units lower than those measured in water (Van Lierop, 1981). The soil $pH_{(KCl)}$ for the first three depths was between 5.9 and 6.3 and therefore apple tree growth will not be restricted as it is well within the range for apple tree root growth and only pH values below 5.4 will negatively affect the growth of apple trees (Li & Utkhede, 1991).

According to Ayers and Westcot (1985), apple trees are sensitive to soil salinity and yield loss starts to occur at EC_e levels of 1.3 $dS.m^{-1}$ or higher. No salinity hazards occurred as all four depths showed EC_e values below 1.3 $dS.m^{-1}$. The sodium

absorption ratio (SAR) for depth layers 0-300 mm, 300-600 mm, 600-900 mm and 900-1200 mm was 0.091, 0.086, 0.010 and 0.155 respectively. These SAR values with their corresponding pH values below 8.5 indicate that there were no salinity hazards in the soil (Lamond & David, 1992).

Soil depths A and B (in which most of the root growth occurred, see chapter 6) had a sufficient amount of soil phosphorous (P), potassium (K), sodium (Na), calcium (Ca) and magnesium (Mg) before planting (Kapp, 2017). The organic material content of the upper two dark-coloured soil layers (0 – 600 mm) was more than 2% which is considered high for South African conditions (Du Preez *et al.*, 2011). The high organic material content was probably due to the prior use of the soil for apple orchards.

Figure 4.1: Soil profile classified as a Kroonstad in the irrigation trial on Oak Valley Estate.

Table 4.1: The average chemical status of the soil in which the irrigation trial was carried out on Oak Valley Estate.

Soil depth (mm)	$pH_{(KCl)}$	EC_e ($dS.m^{-1}$)	Bray II ($mg.kg^{-1}$)		Exchangeable cations (cmol(+)/kg)				Organic C (%)
			P	K	Na	K	Ca	Mg	
0-300	6.3	0.9	52	111	0.19	0.28	6.65	2.03	2.56
300-600	5.9	0.8	39	92	0.16	0.24	5.37	1.50	2.13
600-900	5.9	0.6	15	60	0.16	0.15	4.12	1.04	1.16
900-1200	5.3	0.6	6	54	0.23	0.14	3.27	1.12	1.08

4.3 Soil physical properties

The soil is an important medium which plants need to supply them with minerals and water and to anchor the roots (Kramer & Boyer, 1995). Soil is complex as it is a disperse three-phase system comprising of a solid phase (soil matrix), liquid phase (soil solution) and the gaseous phase (soil atmosphere). The complex soil system can be characterized physically through determining the volume and mass relationship of the three phases among each other (Hillel, 2004). In this study the soil particle-size distribution, the amount of coarse fragments, the particle density of the coarse fragments and the soil, the bulk density, porosity and the water retention properties of the soil are terms used to express the quantitative interrelationship of the three soil phases.

4.3.1 Soil particle-size distribution (soil texture)

The soil texture results (Table 4.2) indicate substantial differences in soil texture throughout the experimental site. These results confirmed that soil properties within a small area can vary significantly (Wierenga *et al.*, 1991; Russo & Bouton, 1992). Although there were differences in soil texture within the experimental site, most of the subsoils that were analysed had a clay loam texture. The top soil (depth A) consisted mostly of loamy textured soils and the clay contents in the deeper soil layers were higher than those in the top soil. The effect the soil texture had on the

bulk density of the soil and their growth-limiting bulk densities will be discussed in 4.3.4.

Table 4.2: The soil textural classes and the mean particle size distribution of five profile pits at four depth increments in the soil of the irrigation trial on Oak Valley Estate.

Profile pit	Depth (mm)	Soil texture	Clay (%)	Silt (%)	Sand (%)
1	0-300	Loam	22.5±2.4	32.4±2.3	45.2±0.2
	300-600	Clay loam	35.7±1.1	30.9±0.5	33.4±1.5
	600-900	Clay loam	34.7±2.9	34.2±0.3	31.1±3.1
	900-1200	Clay loam	34.7±0.8	36.4±0.9	28.9±0.3
2	0-300	Sandy loam	19.1±1.1	24.6±0.9	56.3±2.0
	300-600	Clay loam	27.5±0.8	32.7±3.3	39.9±4.0
	600-900	Clay loam	38.1±0.9	38.6±0.9	23.3±1.5
	900-1200	Clay loam	42.6±0.7	35.0±0.9	22.3±1.5
3	0-300	Loam	24.3±1.3	32.8±1.9	42.9±1.8
	300-600	Clay loam	32.5±0.5	30.5±0.8	37.0±0.5
	600-900	Clay loam	39.8±0.6	29.0±0.9	29.6±1.5
	900-1200	Silty clay loam	47.5±0.2	40.3±0.7	12.1±0.9
4	0-300	Sandy clay loam	22.0±2.0	23.2±2.4	54.7±1.3
	300-600	Sandy clay loam	26.7±1.0	24.2±1.0	49.1±0.8
	600-900	Clay loam	30.9±0.1	35.1±0.4	34.0±0.4
	900-1200	Clay loam	34.0±1.6	33.5±0.9	32.5±1.5
5	0-300	Loam	26.1±1.0	35.2±0.2	38.7±1.2
	300-600	Clay loam	31.1±0.8	35.3±1.1	33.6±1.7
	600-900	Clay	43.4±0.6	29.1±0.3	27.5±0.5
	900-1200	Clay loam	37.3±1.4	32.4±1.2	30.4±1.7

4.3.2 Coarse fragments

The amount of coarse fragments present in the soil influences the water holding capacity, the hydraulic conductivity and infiltration in the soil. It is therefore important to make a correction for the coarse fragments when determining the plant available water (Brakensiek & Rawls, 1994). Such a correction was made in the current experiment using the average coarse fragment percentages in Table 4.3. The effect the volume percentage coarse fragments had on the bulk density of the soil is discussed in 4.3.4.

Table 4.3: The mean volume percentage coarse fragments that was present at four depth increments in the soil of the experimental site on Oak Valley Estate.

Depth	Volume coarse fragment (%)
A: 0-300 mm	19.10±2.79
B: 300-600 mm	32.88±7.16
C: 600-900 mm	42.70±4.00
D: 900-1200 mm	42.33±5.34

The mean percentages of coarse fragments were lowest in the topsoil and increased with depth while the two deepest soil layers contained the same volume percentages. Viewed separately, the volume percentage coarse fragments of profile pit three and five followed the same trend, *i.e.* the volume percentage coarse fragments increased with depth continuously (Figure 4.2). Depth A of all five profile pits had the lowest volume percentage coarse fragments compared to all other depths.

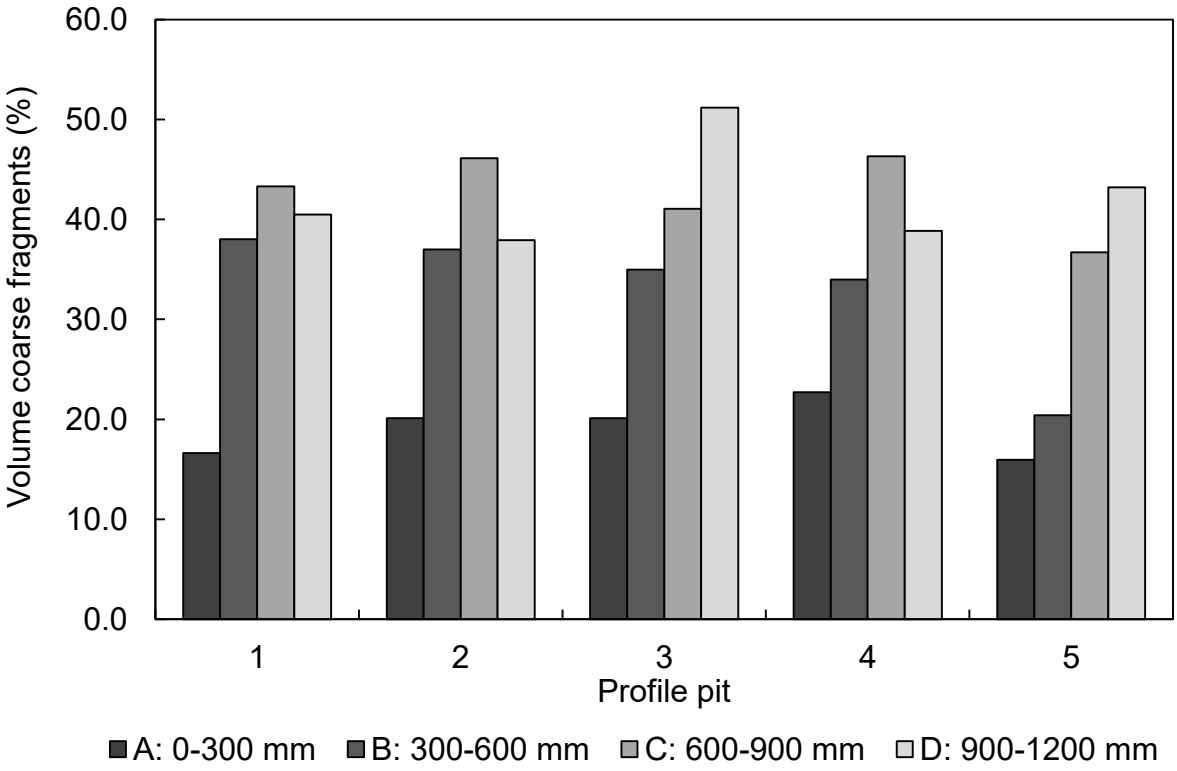

Figure 4.2: The volume percentage coarse fragments that were present at four depth increments in five profile pits in the soil of the experimental site on Oak Valley Estate.

4.3.3 Particle density

The particle density of the plinthite and relic plinthite was well within the common range of specific densities of plinthite (Table 4.4). The results indicate that the particle density of plinthite was lower than that of the relic plinthite for all five profile pits (Table 4.4). Plinthite will have a lower particle density than relic plinthite, because the sesquioxides within the plinthite are still active and the formation of plinthite is still in process. The relic plinthite contains more boehmite and hematite and less sesquioxides than the plinthite, *i.e.* relic plinthite contains more iron. An increase in iron content will increase the particle density of the plinthite and therefore the relic plinthite will have a higher particle density than the plinthite (Driessen *et al.*, 2001).

The particle density of the soil ranged between 2.31 $g.cm^{-3}$ and 2.66 $g.cm^{-3}$ (Table 4.5). Although the particle density of the Oak Valley Estate samples did not fall in the

range common among soils (2.55 g.cm^{-3} and 2.7 g.cm^{-3}), the lower densities were a result of the humus that was present in the top soil layers. Humus has densities that are usually below 1.5 g.cm^{-3} (Blake, 2008). The sandy loam, loam and sandy clay loam soils were representative of the top soil layers of the experimental trial and therefore these samples had a lower particle density. The particle density of the soil increased as the clay content increased. This was expected as the density of clay minerals is higher than that of humus. The clay loam, silty clay loam and clayey soils were present in the deeper soil layers (soil layers deeper than 300 mm), thus these soil contained less humus and had a higher clay percentage and therefore also had a higher particle density.

Table 4.4: The average particle density of plinthite and relic plinthite for the five profile pits in the experimental site on Oak Valley Estate.

	Particle density (g.cm^{-3})	
Profile pit	**Plinthite**	**Relic plinthite**
1	2.880±0.1	3.132±0.1
2	2.954±0.1	3.082±0.1
3	2.939±0.0	3.042±0.1
4	2.760±0.1	3.188±0.1
5	2.970±0.1	3.117±0.2

Table 4.5: The mean particle density for the different soil textures that was present in the soil of the experimental site on Oak Valley Estate.

Soil texture	Particle density (g.cm^{-3})
Sandy loam	2.312±0.06
Loam	2.413±0.06
Sandy clay loam	2.530±0.02
Clay loam	2.563±0.18
Silty clay loam	2.626±0.00
Clay	2.659±0.01

4.3.4 Bulk density

In general, soil bulk density will increase with depth. This is due to the changes in porosity and organic matter through the soil profile. Soils with higher amounts of organic matter will have a lower bulk density, *i.e.* the bulk density will increase with depth as lower amounts of organic matter are present in the deeper soil layers (Chaudhari *et al.*, 2013). This pattern of increasing bulk density with depth was also found in profile 5 of the Oak Valley Estate soil (Figure 4.3), but the high percentage gravel at some soil depths, disrupted the pattern somewhat in the other four profiles.

The bulk densities of profile pit one and two increased from depth A to C with depth D having a lower bulk density than depth C (Figure 4.3). The trend that the bulk densities showed at these two profile pits correlated with the volume percentage stones that were present in those profile pits at those depths (Figure 4.2), *i.e.* the volume percentage stones increased from depth A to C with depth D having less stones than depth C. These results also correlate with those of Rücknagel *et al.* (2013) who showed that the total bulk density of a soil will increase with an increase of gravel content by volume percentage. This can also be observed at depth D for profile pit three which had a higher bulk density than that of depth A, B and C. This depth has the highest bulk density (Figure 4.3) and the highest volume percentage coarse fragments (Figure 4.2) of all the soil layers in the five profiles on the experimental site.

In two soil profiles (three and four) bulk densities of the two upper soil layers (A & B) were almost similar despite an increase in gravel content with depth. The small decrease in bulk density from depth A to B can be a result of the soil texture. In profile three, depth A has a loam texture with 24.33% clay and depth B has a clay loam texture with 32.48% clay while the corresponding clay contents for profile four was 22.03% and 26.66% (Table 4.2). Soils with a lower clay content tend to have higher bulk densities than those which contain more sand (Chaudhari *et al.*, 2013).

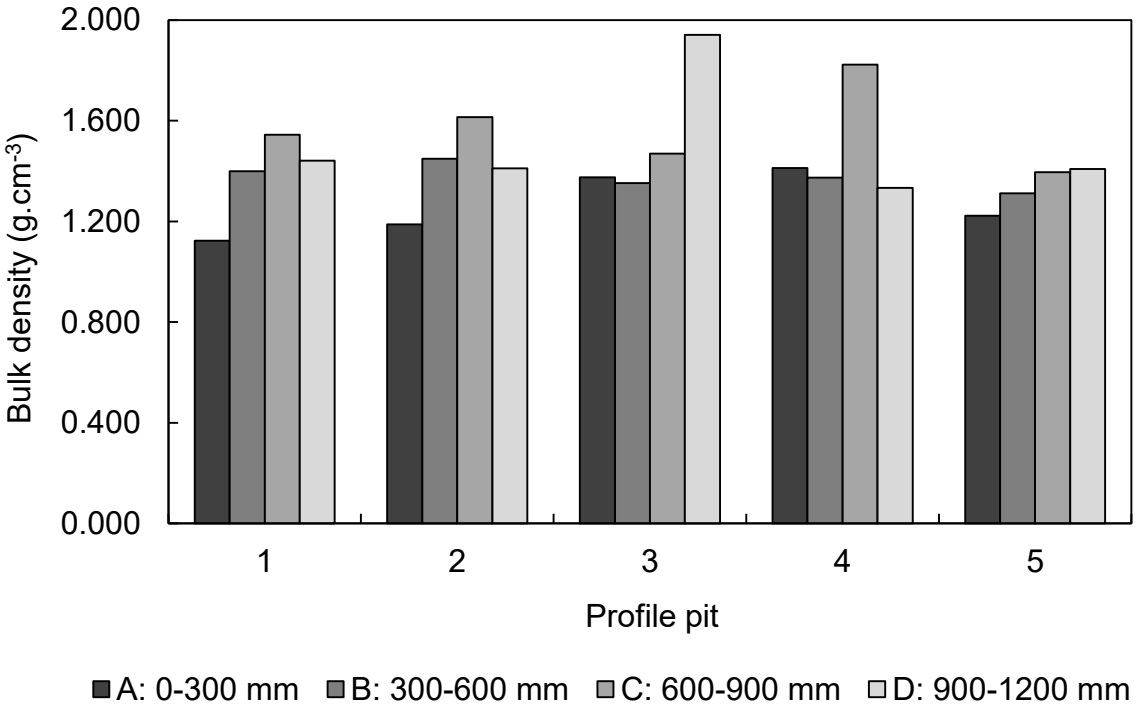

Figure 4.3: The bulk density of the soil determined at four depth increments of five profile pits on the experimental site on Oak Valley Estate.

The mean bulk density for the experimental site can be found in Table 4.6. The soil texture results are based on the average percentage clay, silt and sand of all five profile pits at each depth layer that were analysed while the bulk density results are average values of the five profile pits of each depth layer. Soil texture must be taken into consideration when estimating the growth-limiting bulk density (Daddow & Warrington, 1983). The higher the clay contents in a soil, the greater the pore space. Consequently, the bulk density of such a soil must be lower than those of sandy or loamy soil in order for root growth not to be restricted. For loamy soils, the ideal bulk density for root growth is bulk densities lower than 1.600 $g.cm^{-3}$ while clay loam soils with bulk densities higher than 1.580 $g.cm^{-3}$ will restrict root growth (Arshad *et al.*, 1996). From the results in Table 4.6 it is evident that root growth will not be restricted in any of the soil layers on the experimental site.

Table 4.6: The mean bulk density and soil textural class of four depth increments in the soil of the irrigation trial on Oak Valley Estate.

Depth	Soil texture	Bulk density ($g.cm^{-3}$)
A: 0-300 mm	Loam	1.264±0.14
B: 300-600 mm	Clay loam	1.377±0.18
C: 600-900 mm	Clay loam	1.569±0.24
D: 900-1200 mm	Clay loam	1.507±0.24

4.3.5 Porosity

The mean total porosity of the experimental site for depths A to D can be seen in Table 4.7. The total porosity for all four depths was well above 0.30, which indicated that apple tree root growth was not expected to be restricted (Webster, 1978).

A direct relationship exists between the bulk density of soil and its porosity. A higher soil bulk density will result in lower soil porosities. When the mean bulk densities of the soil at the four depth increments in the irrigation trial (Table 4.6) are compared with the mean soil porosities at the same depths (Table 4.7), it is clear that the lower soil bulk densities had a higher soil porosity and *vice versa*.

Table 4.7: The mean porosity and soil textural class for four depth increments in the irrigation trial on Oak Valley Estate.

Depth (mm)	Soil texture	Porosity (%)
A: 0-300	Loam	0.477±0.04
B: 300-600	Clay loam	0.461±0.02
C: 600-900	Clay loam	0.392±0.07
D: 900-1200	Clay loam	0.416±0.08

4.3.6 Soil water retention properties

The soil water retention curves, correlation coefficients and the non-linear regression equations for depth layers A to D are presented in Figure 4.4 to Figure 4.7. The water holding capacities (or plant available water) of depth layers A to D were determined on the assumption that field capacity (FC) was at -6 kPa and permanent wilting point (PWP) was at -1500 kPa. Taking the amount of coarse fragments into account, the plant available water (PAW) values were corrected and can be seen in Table 4.8. Depth A had the highest water holding capacity followed by depth B. Although depth C to D had higher clay contents than depth A and depth B (Figure 4.3), depth C to D had *ca.* 12-20% more coarse fragments than depth A (Figure 4.4). The water holding capacity of depths C and D were therefore less than depth A, because the water retention of bulk soil decrease when more coarse fragments are present per unit volume of soil (Baetens *et al.*, 2009). The total soil water holding capacity for the root zone depth (0-1100 mm) was 184.4 mm/1100 mm.

Table 4.8: The field capacity (FC), permanent wilting point (PWP) and the plant available water (PAW) of four depth increments in the soil of the irrigation trial on Oak Valley Estate.

Depth	FC	PWP	PAW	
(mm)	($mm.mm^{-1}$)	($mm.mm^{-1}$)	($mm.mm^{-1}$)	(mm/300 mm layer)
A: 0-300	0.324	0.114	0.210	63.0
B: 300-600	0.274	0.115	0.159	47.4
C: 600-900	0.294	0.149	0.145	43.5
D: 900-1200	0.299	0.148	0.151	45.3
Total			0.665	199.2

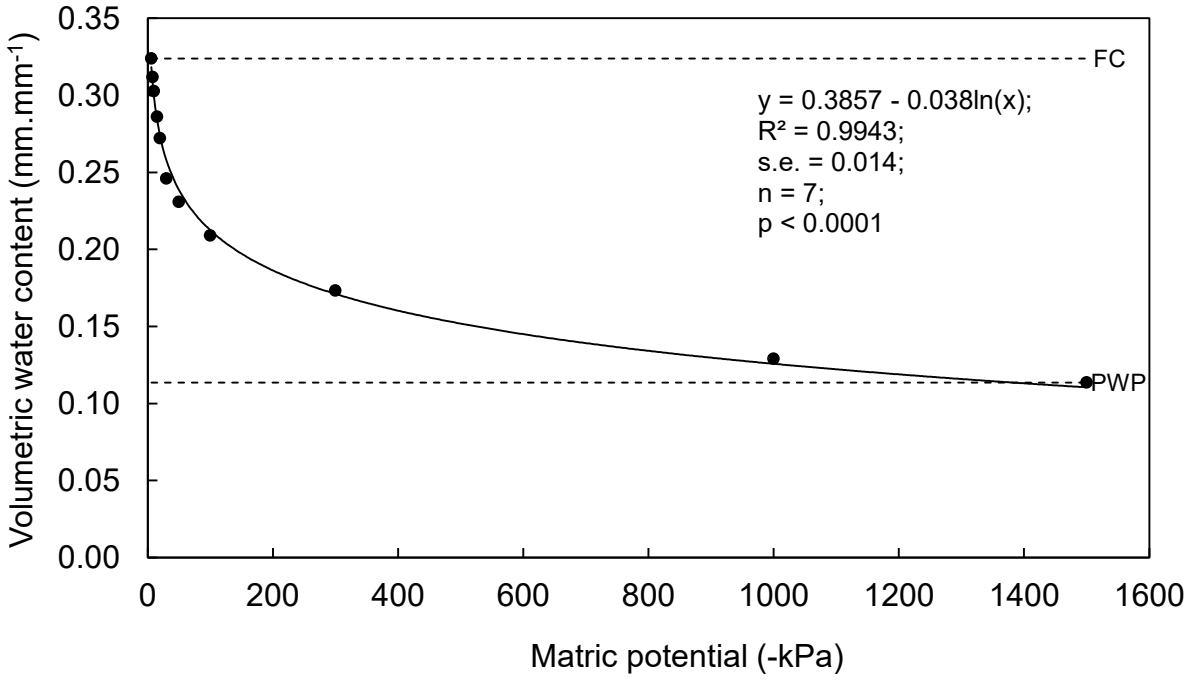

Figure 4.4: Soil water retention curve for depth A (0-300 mm) of the loam soil on Oak Valley Estate; FC represents the field capacity of the soil and PWP the permanent wilting point of the soil.

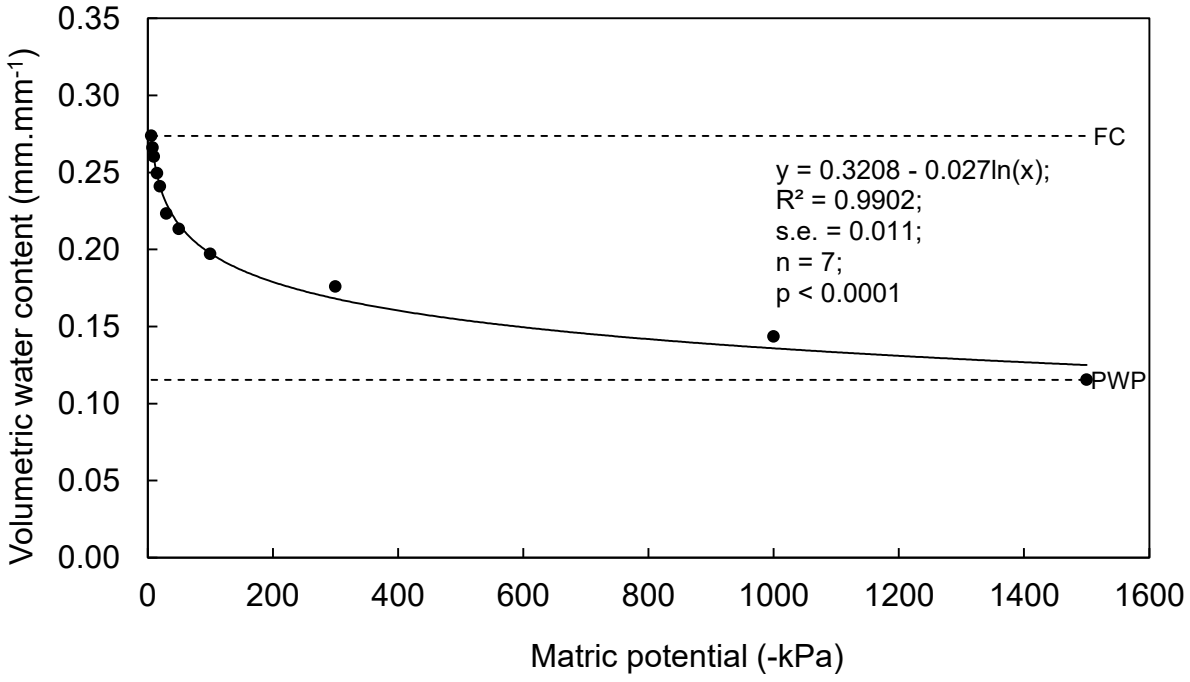

Figure 4.5: Soil water retention curve for depth B (300-600 mm) of the clay loam soil on Oak Valley Estate; FC represents the field capacity of the soil and PWP the permanent wilting point of the soil.

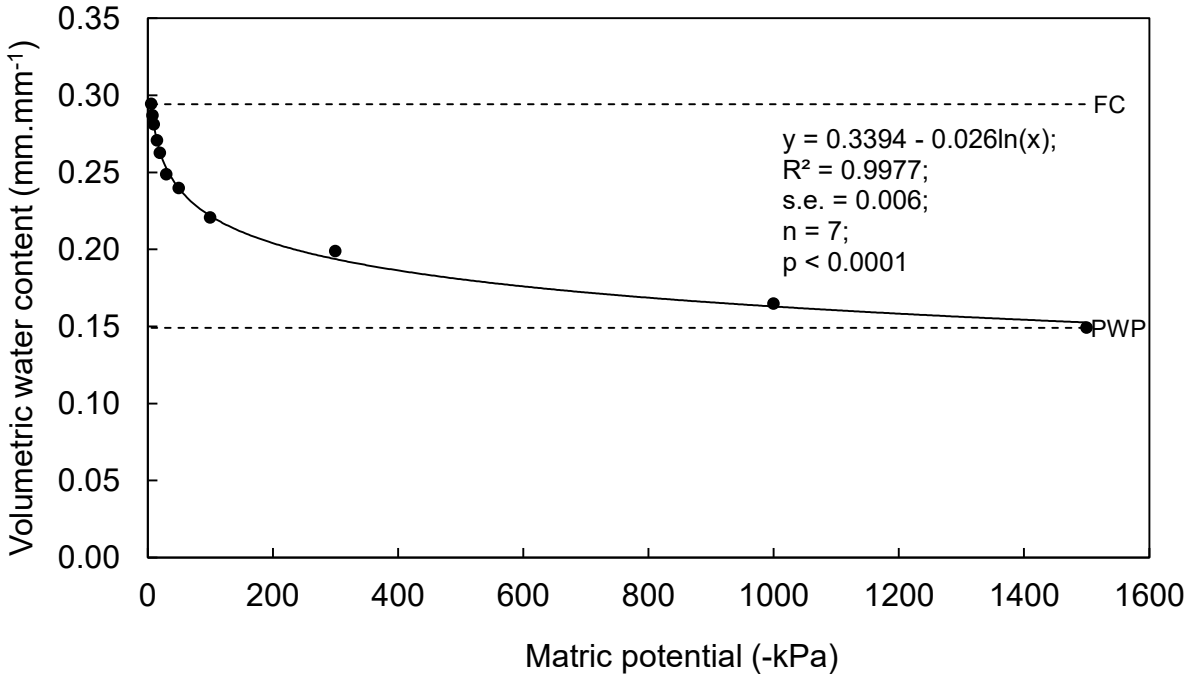

Figure 4.6: Soil water retention curve for depth C (600-900 mm) of the clay loam soil on Oak Valley Estate; FC represents the field capacity of the soil and PWP the permanent wilting point of the soil.

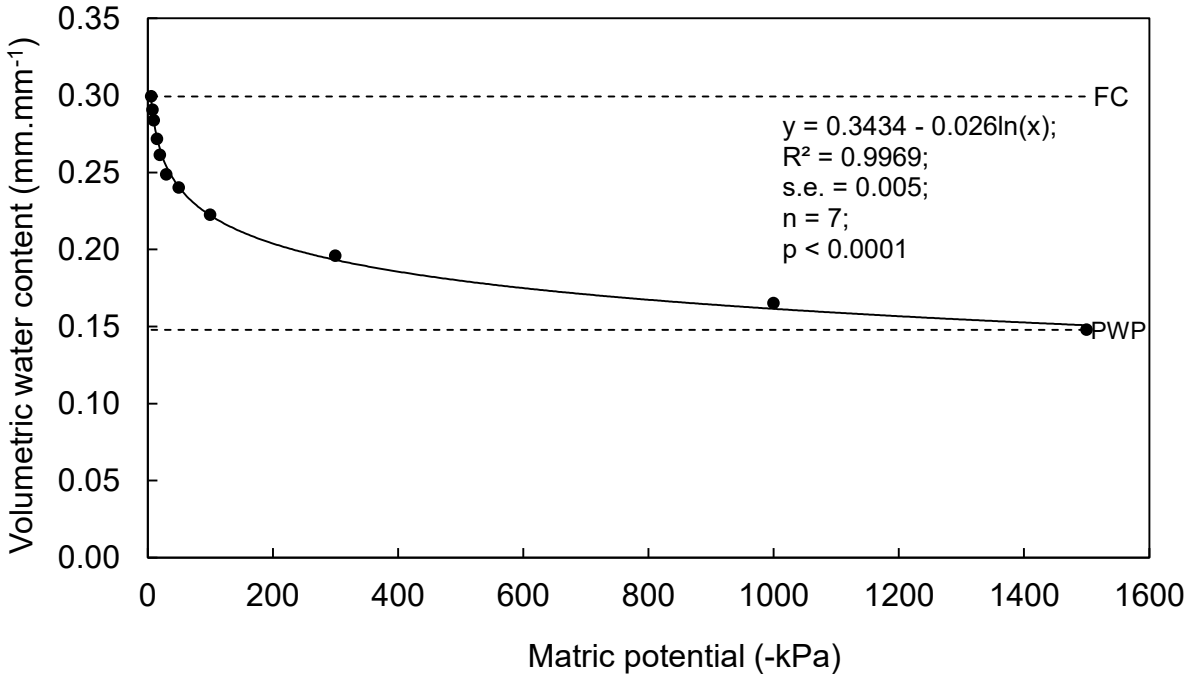

Figure 4.7: Soil water retention curve for depth D (900-1200 mm) of the clay loam soil on Oak Valley Estate; FC represents the field capacity of the soil and PWP the permanent wilting point of the soil.

4.4 Comparison between pressure plate technique and dew point method

Figure 4.8 and Figure 4.9 illustrate the soil water retention curves for six different soil textural classes obtained with the pressure plate apparatus and the WP4C dew point potential meter, respectively. The WP4C gave lower water content values than the pressure plate apparatus at the same water potential for all the soil textures. These results correlate with those of Bittelli and Flury (2009) who also found that the pressure plate apparatus constantly gave higher water content values than the dew point technique.

One would expect that the lower gravimetric water content values obtained with the WP4C would differ by a constant value from those obtained with the pressure plate apparatus, but this was, however, not the case. This is also evident from Figure 4.8 and Figure 4.9 as the soil retention curves of the different soil textural classes did not even follow the same sequence when the two methods were compared. For example from Figure 4.8 where the SWRC was determined using the pressure plate apparatus, it can be seen that the silty clay loam soil had the highest water holding capacity followed by the clay loam soil. Compared to Figure 4.9 the silty clay loam soil, however, had the highest water holding capacity followed by the sandy clay loam soil with the clay loam soil having the second lowest water holding capacity. The data was analysed statistically to determine whether there was any correlation between the gravimetric water content values obtained with the pressure plate and those obtained with the WP4, but no correlation was found (data not shown). Consequently the methods could not be compared to establish which method underestimated or overestimated the plant-available water for a specific soil textural class.

Although it is possible to obtain soil water potential readings accurately at -100 kPa (Decagon Devices, 2015a), we were not able to obtain soil water potential readings at -100 kPa. Once the gravimetric water content exceeded 15%, the WP4C gave constant water potential readings even though the water content of samples differed. We therefore assumed that the WP4C could not give accurate readings when the gravimetric water content of samples exceeded 15% and we were not able to get accurate readings in the wet range. Bittelli and Flury (2009) and Solone *et al.* (2012)

were both, however, able to obtain soil water potential readings at -100 kPa and -1000 kPa using the dew point potential meter which they then used to compare water content values obtained at -100 kPa and -1000 kPa using the pressure plate apparatus and the dew point potential meter. They both concluded that the dew point potential meter gives lower water content measurements compared to the pressure plate apparatus. Our results do not agree with theirs as we were not able to obtain water content values at the same potential (*i.e.* -100 kPa and -1000 kPa) for the two methods. Furthermore, the manufacturer (Decagon Devices, 2015a) states that an unacceptable percentage of error occurs using the dew point potential meter at samples wetter than -0.1 MPa and they even suggest that other methods such as tensiometers must be used to obtain water potentials in the wet range. We therefore did not compare the two methods at -100 kPa and -1000 kPa as both Bittelli and Flury (2009) and Solone *et al.* (2012) did.

Our results were in contrast with those of Solone *et al.* (2012) who showed that limitations for measuring the SWRC with the pressure plate apparatus was mainly in fine textured soils and no significant errors were found in coarse textured soils as we could not even compare the two methods with each other. Both Bittelli and Flury (2009) and Solone *et al.* (2012) used volumetric water content values when they compared the pressure plate apparatus with the dew point technique. This can be the reason why our results did not correlate with theirs since we used gravimetric water content values and not volumetric water content values. When the pressure plate apparatus was used, it was possible to convert the gravimetric water content to volumetric water content, because the bulk density at which the aluminium rings were packed with soil was known. When the WP4C method was used loose soil was placed into the sample cup and according to the manufacturer (Decagon Devices, 2015a) the sample cups, which are very small, may not be covered more than half full as the soil may contaminate the sensor in the chamber. The bulk density of the soil was therefore not known as the volume the soil occupied in the sample cup was not known and consequently it was impossible to calculate volumetric water content for the soil in the measuring chamber. This is in agreement with instructions from the manufacturer (Decagon Devices, 2010) to calculate the gravimetric water content when generating a soil water characteristic curve.

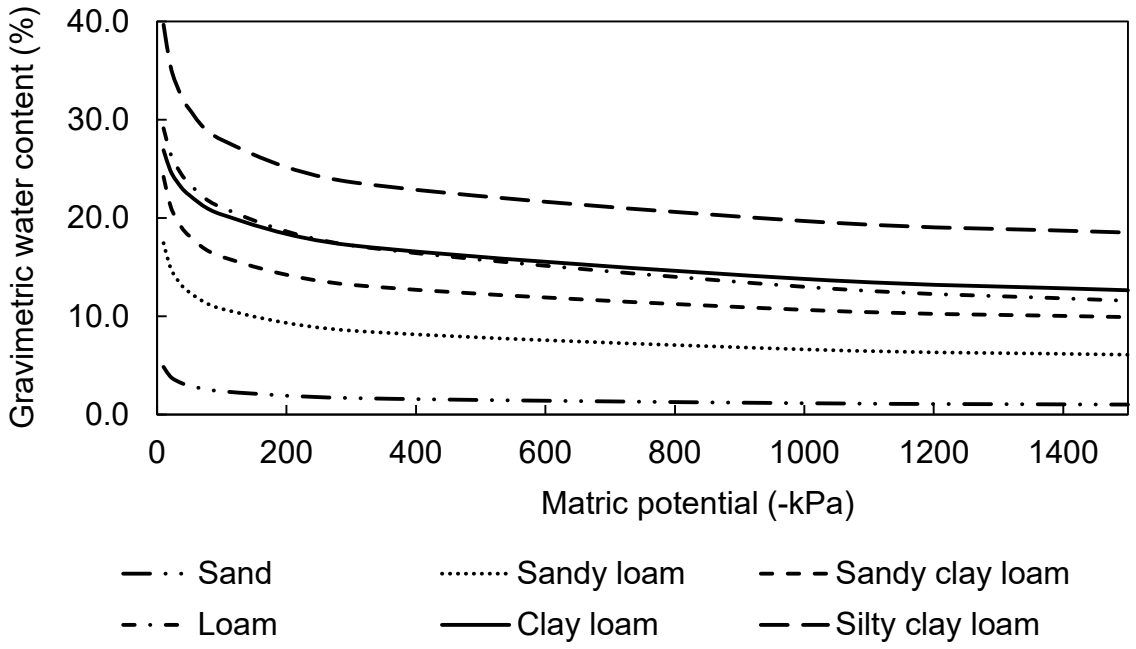

Figure 4.8: Soil water retention curves obtained with the pressure plate apparatus for six different soil textural classes.

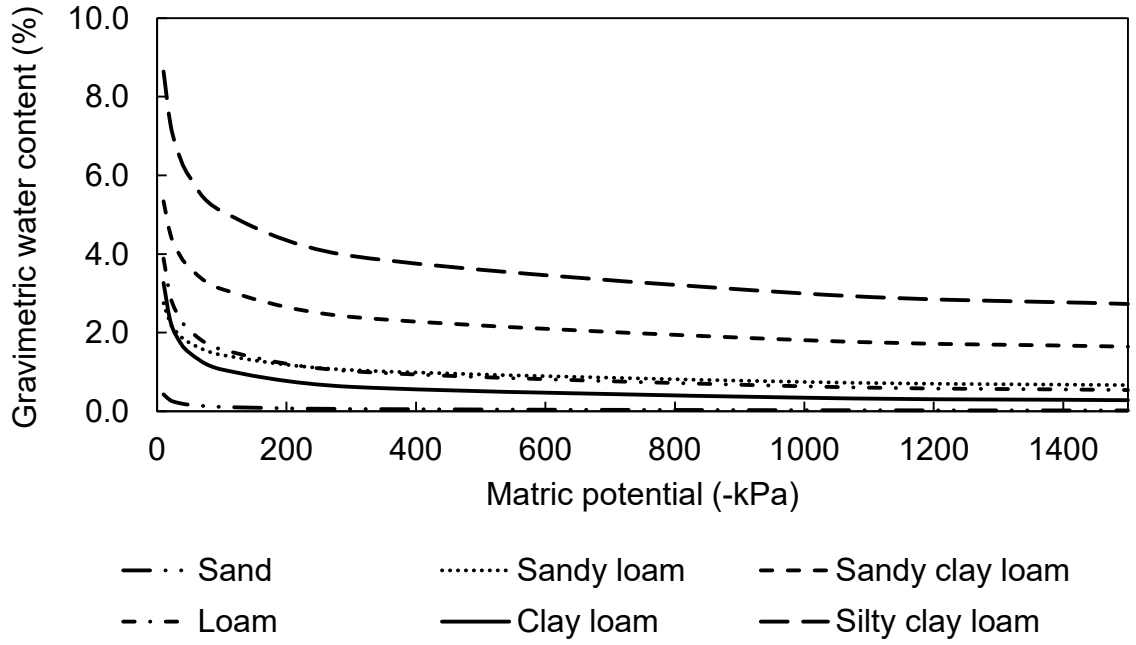

Figure 4.9: Soil water retention curves obtained with the WP4C dew point potential meter for six different soil textural classes.

Soil water availability will differ for different soil types varying in texture. Table 4.9 shows the common range (Scherer *et al.*, 2013) of PAW for the six soil textural classes that was used for the comparative study. Although one is not able to determine the volumetric water content when the WP4C is used, a mean bulk density of 1.333 $kg.m^{-3}$ (Rawls, 1983) was used to determine volumetric water for all the samples. This was also the bulk density to which soil was packed into the aluminium rings when the pressure plate apparatus was used. The plant available water for the six soil textures was determined assuming a field capacity of -10 kPa and a permanent wilting point of -1500 kPa. Except for the silty clay loam soil, the PAW of the other five soil textures was well within the common range of PAW when determined using the pressure plate apparatus. None of the PAW values obtained with the WP4C was within the common range of PAW, but rather well below it (Table 4.9). Our results therefore did not support those of Bittelli and Flury (2009) who concluded that the plant-available water was underestimated when the pressure plate apparatus was used.

Table 4.9: The common range of plant available water (PAW) (mm/mm) for six soil textural classes and the PAW (mm/mm) obtained with the pressure plate apparatus and the WP4C.

Soil texture	Plant available water (mm/mm)		
	Common range	Pressure plate	WP4C
Sand	0.04 – 0.09	0.05	0.01
Sandy loam	0.11 – 0.15	0.15	0.03
Sandy clay loam	0.13 – 0.20	0.19	0.05
Clay loam	0.14 – 0.21	0.19	0.04
Loam	0.17 – 0.23	0.23	0.05
Silty clay loam	0.14 – 0.21	0.28	0.08

From the results it can be concluded that the water content values obtained with the pressure plate apparatus and those obtained with the WP4C differ from one another. However, it is not possible to establish which method gives more accurate readings at the same water potential as we were not able to obtain soil water readings at the same potential for the two methods. We can, however, conclude that the pressure

plate apparatus gave more reliable results than the WP4C as the water holding capacity obtained with the use of the pressure plate apparatus showed the expected curves (Figure 4.8). The silty clay loam soil had the highest water holding capacity followed by the clay loam soil. In contrast, the WP4C indicated that the clay loam soil had the second lowest water holding capacity of the six different soil textures (Figure 4.9). The conclusion in favour of the pressure plate apparatus is further confirmed when PAW values obtained with the WP4C was well below the common range of PAW (Table 4.9).

CHAPTER 5: EFFECT OF DIFFERENT IRRIGATION TREATMENTS ON EVAPOTRANSPIRATION

5.1 Atmospheric conditions

The monthly average air temperature from July 2016 to December 2016 and January 2017 to June 2017 was lower compared to the long term mean (LTM) air temperature values (Table 5.1) while the average relative humidity from July 2016 to December 2016 and January 2017 to June 2017 was higher compared to the LTM relative humidity values (Table 5.2) The rainfall during the growing season (December 2016 to May 2017) was inconsistent compared to the LTM rainfall values (Table 5.3) During July and December 2016 and January 2017 the rainfall was higher compared to the LTM values, but during the growing season (December 2016 to May 2017) the total rainfall was 91.6 mm less than the LTM rainfall. Rainfall to an amount of 313.6 mm contributed to the water supply of the trees after the trees were planted (10 October 2016) until the end of June 2017. The average wind speed during the growing season was lower than 1.6 $m.s^{-1}$ (Table 5.3)

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Table 5.1: The long term mean (LTM) values and the monthly mean daily maximum (T_x), minimum (T_n) and average (T_{ave}) temperatures from July 2016 to June 2017 at the Beaulieu weather station near Oak Valley Estate.

Month	T_x (°C)		T_n (°C)		T_{ave} (°C)	
	LTM	2016/17	LTM	2016/17	LTM	2016/17
January	27.2	24.8	14.9	12.9	21.0	18.7
February	26.7	26.2	14.5	13.7	20.6	19.6
March	25.7	25.6	13.1	11.1	19.4	17.8
April	22.6	23.9	9.8	9.6	16.2	15.9
May	19.8	20.9	8.3	5.9	14.0	12.5
June	16.8	16.5	6.2	3.6	11.5	10.2
July	16.5	16.0	5.4	5.4	10.9	10.4
August	17.4	18.8	6.3	6.4	11.8	11.8
September	18.3	17.4	7.4	6.9	12.9	12.2
October	21.0	21.0	9.7	7.8	15.4	14.5
November	22.5	22.9	11.0	10.5	16.7	16.6
December	25.1	25.6	13.5	12.3	19.3	19.0

Table 5.2: The long term mean (LTM) values and the monthly mean daily maximum (RH_x), minimum (RH_n) and average (RH_{ave}) relative humidity values from June 2016 to June 2017 at the Beaulieu weather station near Oak Valley Estate.

Month	RH_x (℃)		RH_n (℃)		RH_{ave} (℃)	
	LTM	2016/17	LTM	2016/17	LTM	2016/17
January	88.0	91.3	46.3	51.6	67.1	73.8
February	88.5	90.8	47.0	48.9	67.7	73.5
March	89.4	93.3	48.0	46.7	68.7	74.6
April	91.3	93.5	47.6	51.4	69.4	79.1
May	93.3	94.3	52.4	52.1	72.8	81.0
June	93.2	94	53.2	53.7	73.2	79.0
July	93.1	93.5	52.0	57.5	72.6	79.4
August	92.7	93.6	48.9	54	70.8	77.6
September	91.8	93.7	49.1	56.1	70.4	78.8
October	91.6	93.1	49.0	49.8	70.3	75.0
November	91.2	92.1	47.6	49.4	69.4	73.3
December	90.3	91.3	46.2	46.9	68.2	71.5

Table 5.3: The long term mean (LTM) values and the monthly mean daily solar radiation and wind, as well as the monthly rain from June 2016 to June 2017 at the Beaulieu weather station near Oak Valley Estate.

Month	Solar radiation (mJ/h)	Wind (m/s)	Rain (mm)	
	2016/17	2016/17	LTM	2016/17
January	15.4	1.4	24.0	45.0
February	15.1	1.4	21.9	11.6
March	13.7	1.4	32.6	21.8
April	9.2	1.2	53.8	35.6
May	7.1	1.1	98.7	17.6
June	5.0	1.7	166.6	134.6
July	5.9	1.6	137.7	158.9
August	11.6	1.9	139.5	97.5
September	10.3	1.6	74.1	73.6
October	13.2	1.5	53.1	19.2
November	15.5	1.5	62.8	8.0
December	17.6	1.5	18.2	26.0

5.2 Soil water

The calibration of the sensors and flow meters is discussed and the variation in soil moisture will follow after these discussions. Values presented in the variation of soil water and the amount of water irrigated for each treatments are average values.

5.2.1 Sensor calibration

Figure 5.1 is an example of a linear calibration line obtained in an attempt to calibrate the CS650 sensors in containers in order to determine the actual volumetric water content. The volumetric water content (VWC) on the X-axis is the values the sensors logged on the data logger while the VWC on the Y-axis is the values which were calculated from the gravimetric water content as explained in chapter 3. The calibration line for all four depths followed the same trend as the example in Figure 5.1. The linear regression equation and correlation coefficients (R^2) of the four depths which were calibrated in the containers can be found in Table 5.4.

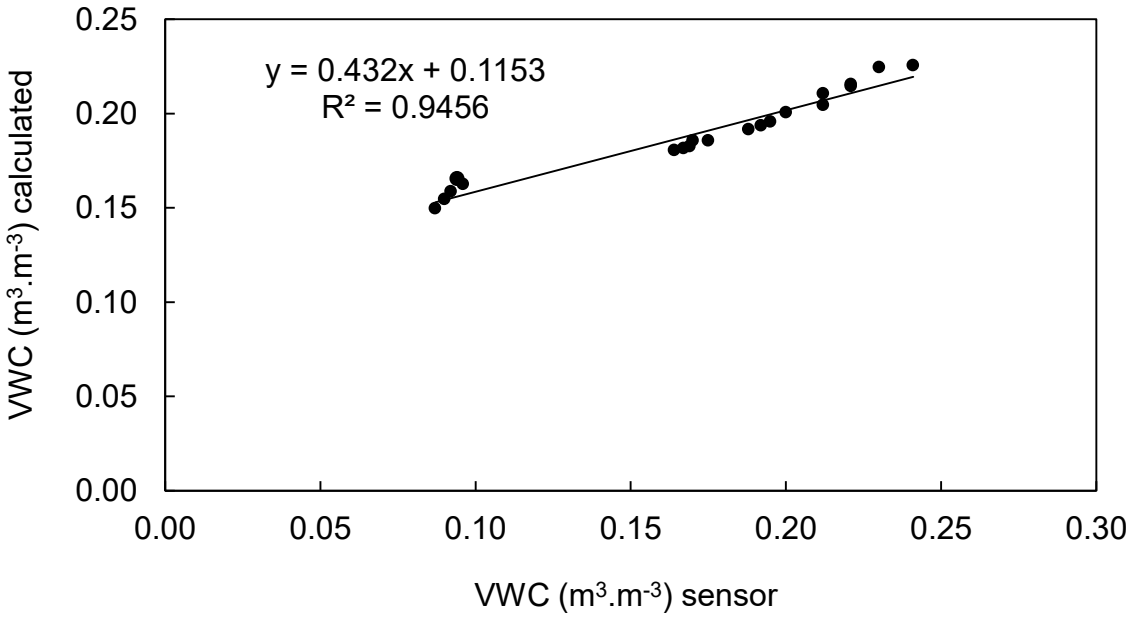

Figure 5.1: Linear calibration line between sensor readings and calculated volumetric soil water content for depth A (0-300 mm) as determined in containers.

All four depths had R^2 values greater than 0.8, *i.e.* there was a good correlation between the VWC readings of the sensors and the calculated VWC. The calibration curves could, however, not be used as unrealistic VWC values were obtained when the linear regression equations were used. For example, the sensor that was used to calibrate depth A logged VWC values as low as 0.087. This was probably due to a loss of contact between the sensors and the soil during the calibration process.

Table 5.4: The linear regression equation as well as the correlation coefficient for four depth increments obtained by the calibration of the sensors in containers

Depth layer	Linear regression equation	Correlation coefficient (R^2)
A: 0-300 mm	y = 0.432x + 0.1153	0.9456
B: 300-600 mm	y = 1.0897x - 0.1349	0.8902
C: 600-900 mm	y = 0.4496x + 0.0637	0.8373
D: 900-1200 mm	y = 0.3346x + 0.1446	0.8509

To obtain reliable VWC values, an orchard calibration was done (as described in chapter 3) as another attempt to calibrate the sensors. The calibration curves obtained in field followed the same trend as in Figure 5.1, except for depth A of T2R1 and T2R2. The slopes of the calibration curves on the last mentioned two plots were negative (Figure 5.2) which indicated that an increase in VWC as measured by the sensor was an actual loss of water when compared with the VWC as determined through the gravimetric soil samples. This is contradictory to the principle on which the functioning of the CS650 sensors is based. The R^2 values of some treatments were as low as 0.2 (data not shown), which indicate a weak correlation between VWC readings as logged by the sensors and the calculated VWC.

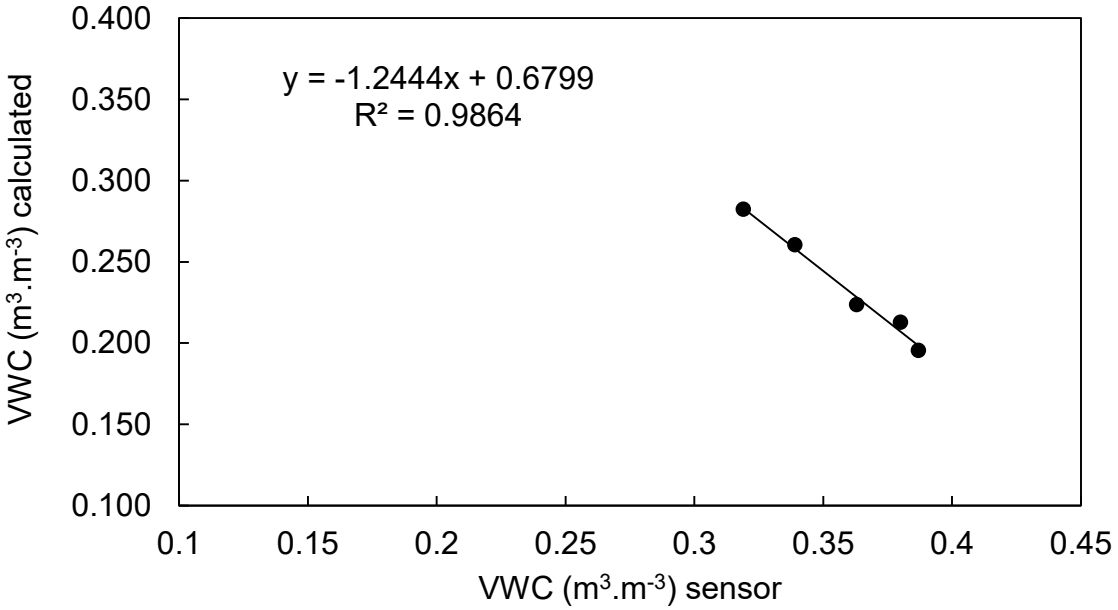

Figure 5.2: Example of a linear calibration line between sensor readings and calculated volumetric water content for depth A (0-300 mm) as determined in the orchard.

Another concern about the orchard calibration was that when some of the linear regression equations were used to calculate the actual VWC, negative values were obtained. An example of such a calibration curve can be seen in Figure 5.3. This can be due to the fact that the soil medium in which the sensor was installed were not the same as the soil medium where the gravimetric sample was taken. It may be due to a soil textural difference or because soil preparation before planting caused an undulating boundary between the A and E horizons. It was therefore decided not to make use of these calibration curves either.

As both calibration methods were unsuccessful, the factory calibration was used to obtain VWC readings. It is, however, suggested that further calibrations should be done to improve the VWC values logged by the sensors.

5.2.2 Water meter calibration

The amount of water indicated on the three main water meters did not differ from the amount registered by the data logger (data not shown). Therefore no regression equation was necessary to calculate the total amount of water each irrigation treatment received during the season.

The linear calibration line, linear regression equation and the correlation coefficient for the calibration of the in-line flow meters can be seen in Figure 5.4. The R^2 value of 0.9959 indicates that there was a strong correlation between the amount of water registered by the logger and the amount of water that actually flowed through the water metres. The linear regression equation was used to determine the actual amount of water applied after each treatment was irrigated. The total mean amount of water that each irrigation treatment received during the growing season can be found in Table 5.5. The more frequently irrigations were applied the higher the total seasonal irrigation volumes received *i.e.* T1>T2>T3 (Table 5.5).

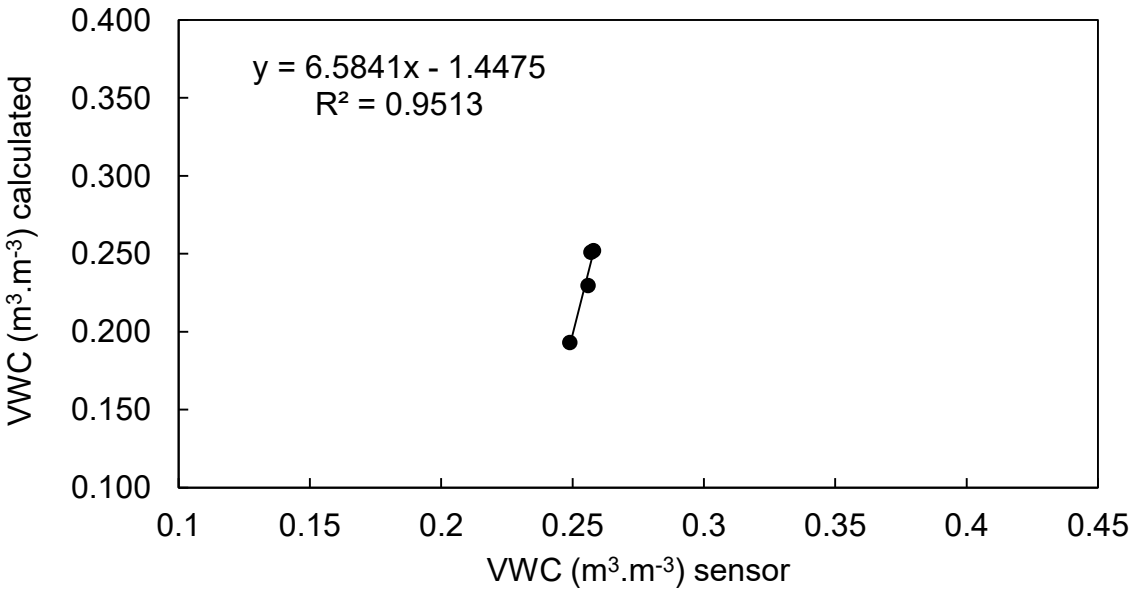

Figure 5.3: Example of a linear calibration line between sensor readings and calculated volumetric water content for depth D (900-1200 mm) as determined in the orchard.

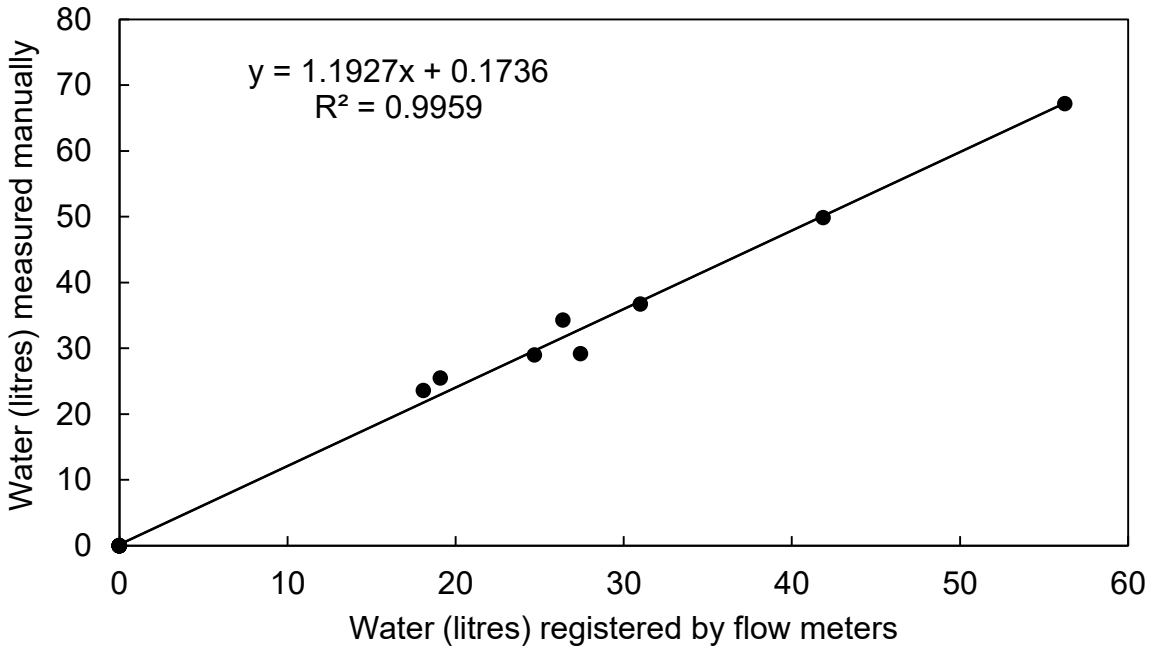

Figure 5.4: Linear calibration line for in-line flow meters

Table 5.5: Total mean amount of water each treatment received at the end of the growing season.

Treatment	Total amount of water (mm)	
	Wetted area	Full surface
1	426.20	193.68
2	370.20	162.45
3	327.10	145.99

5.2.3 Variation in soil water content

The variation in soil water content for the three treatments during the growing season (December 2016 to May 2017) for depth layers 0-600 mm and 600-1200mm is illustrated in Figure 5.5 to 5.10. Variation in soil water content for all for depth layers (A to D) for the three treatments can be found in the Appendix. These depth layers best represent the major root zone in the topsoil (0-600 mm) and root penetration in the subsoil (600-1100 mm). From planting of the trees (10/10/2017) until irrigation treatments commenced on 10/12/2017, the orchard, including the experimental plots of all three treatments, received a blanket irrigation consisting of 15 mm/week. Treatment one (T1) was irrigated with *ca.* 9.2 mm of water every 3 to 4 days, T2 with *ca.* 15.4 mm water every 7 days and T3 received *ca.* 22.7 mm water every 12 days. This implies that irrigations were applied at water potentials of -13 kPa, -21 kPa and -36 kPa for T1, T2 and T3, respectively. Rainfall to an amount of 153 mm also added to the water supply of the trees. Irrigations were, however, withheld when more than 10 mm of rain was measured between water applications.

Figures 5.5 to 5.7 represent the variation in soil water content for T1, T2 and T3 at a depth of 0-600 mm. From the figures it is evident that T1 constantly had the highest soil water content, followed by T2 and T3. A high increase in soil water content (above field capacity, *i.e.* the soil was saturated) was observed for all three treatments at the 0-600 mm depth layer between 24 and 28 January 2016. This was due to 44 mm of rainfall during that period. After 28 January 2016 all three treatments showed a gradual decrease in soil water content until 31 March 2017. This was observed for both the 0-600 mm and 600-1200 mm depth layers (Figure 5.5 to Figure 5.10). This could be due to the combined effect of high maximum air temperatures during February and March 2017, the warmest months of the entire growing season (Table 5.1) and a gradual increase in leaf area of the trees. Due to these high temperatures and evapotranspiration during this period, the amount of water irrigated for each treatment was not enough to fully replenish water losses from the soil. Water from the soil reserve was consequently used to meet water demands of the trees. The soil water potential of the wettest treatment remained, however, high at -17 kPa in the 0-600 mm depth layer (irrigations took place at -13 kPa on average during the season) *i.e.* at 20% depletion of plant available water

(PAW). The soil water potentials of T2 and T3 decreased to –27 kPa (-21 kPa on average for the season equal to 28 % depletion of PAW) and – 42 kPa (36% depletion of PAW) at their lowest point, respectively. This slight decrease of soil water potential below the average level is not considered significant since it normally is not possible to maintain the soil water status exactly within the specified limits.

From 2 April 2017 to 14 May 2017 for T1 and from 26 April 2017 to 10 May 2017 for T2 the soil water content in the 0-600 mm soil depth layer was above FC, *i.e.* the soil contained free water. This is believed not to be true as gravimetric soil samples taken four times during that period gave volumetric water content values below FC. Considering, however, the difficulty of matching gravimetric soil water content with that of the soil water sensors in this gravelly and highly heterogeneous soil profiles, some uncertainty exists as to which method gave the most reliable results. The possible overestimation of soil water content during this period emphasizes the importance of future soil-specific calibration of the sensors used in the irrigation trail. If necessary, data logged by the CS650 sensors can be reworked using an improved calibration in future.

At the beginning of the growing season (December 2016) all three treatments had high soil water contents in the 600-1200 mm soil layer (Figure 5.8, Figure 5.9 and Figure 5.10). During the growing season the soil water content at this depth layer decreased for all three treatments until the end of March 2017 (as described previously). The soil water content of T1 was below FC at the beginning of April 2017 (Figure 5.8) until the end of the growing season (May 2017), while T2 already showed soil water contents below FC at the end of February 2017 (Figure 5.9). T3 only had soil water contents below FC in middle of May 2017 with a slight decrease in soil water content, but was refilled back to FC after irrigated once (Figure 5.10). Comparing figures 5.8 to 5.10, T3 had the highest soil water content in the subsoil (600-1200 mm) during the growing season.

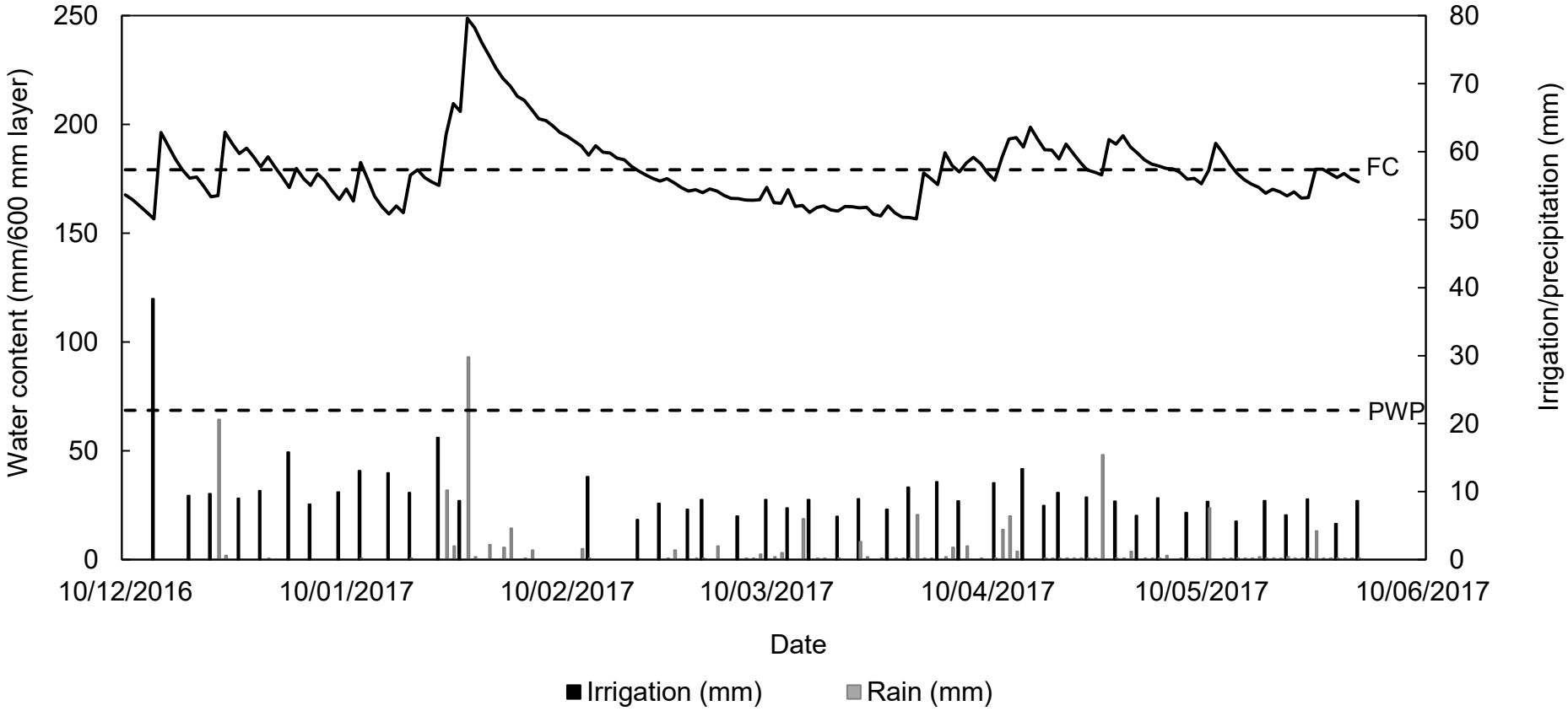

Figure 5.5: Variation in soil water content of T1 during the growing season (December 2016 to May 2017) at a depth layer of 0-600 mm. FC and PWP represent field capacity and permanent wilting point, respectively.

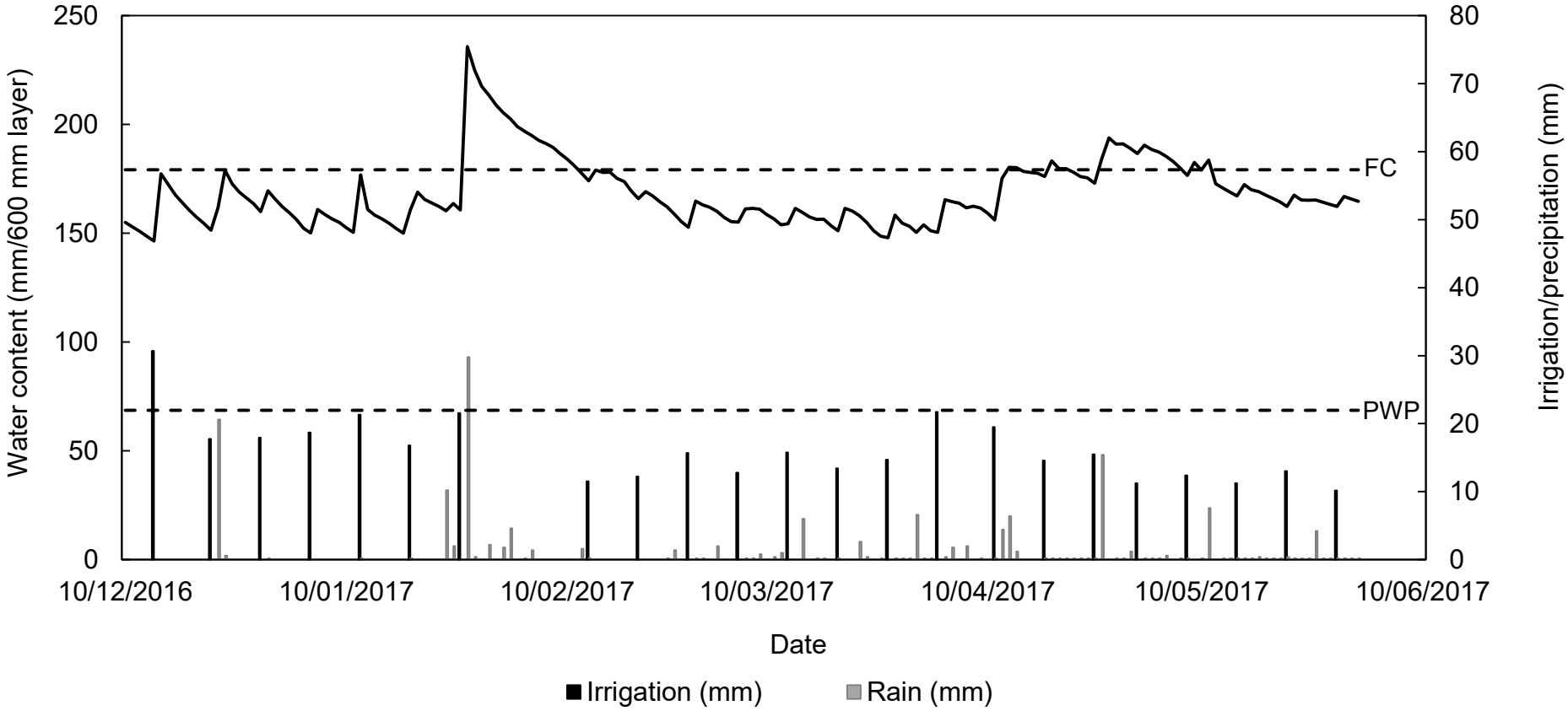

Figure 5.6: Variation in soil water content of T2 during the growing season (December 2016 to May 2017) at a depth layer of 0-600 mm. FC and PWP represent field capacity and permanent wilting point, respectively.

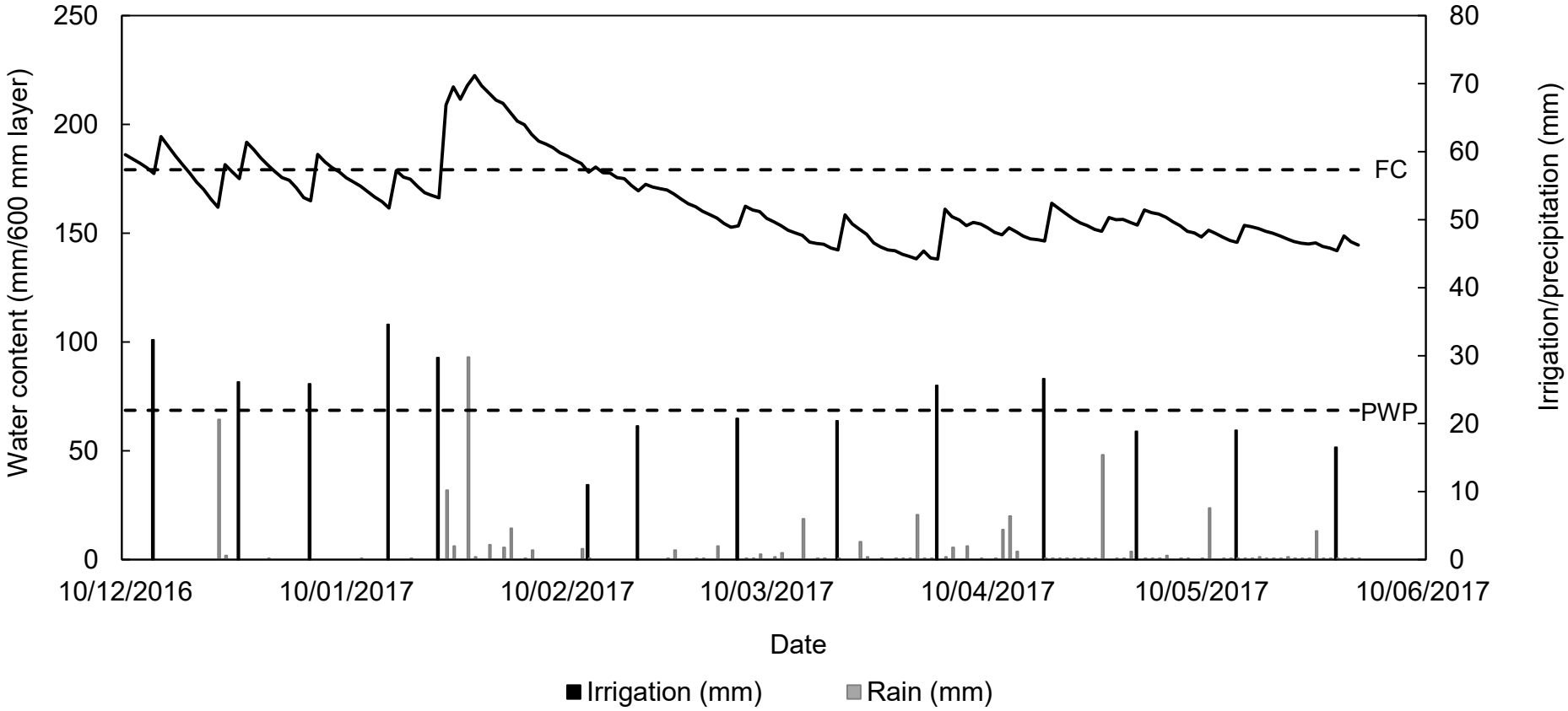

Figure 5.7: Variation in soil water content of T3 during the growing season (December 2016 to May 2017) at a depth layer of 0-600 mm. FC and PWP represent field capacity and permanent wilting point, respectively.

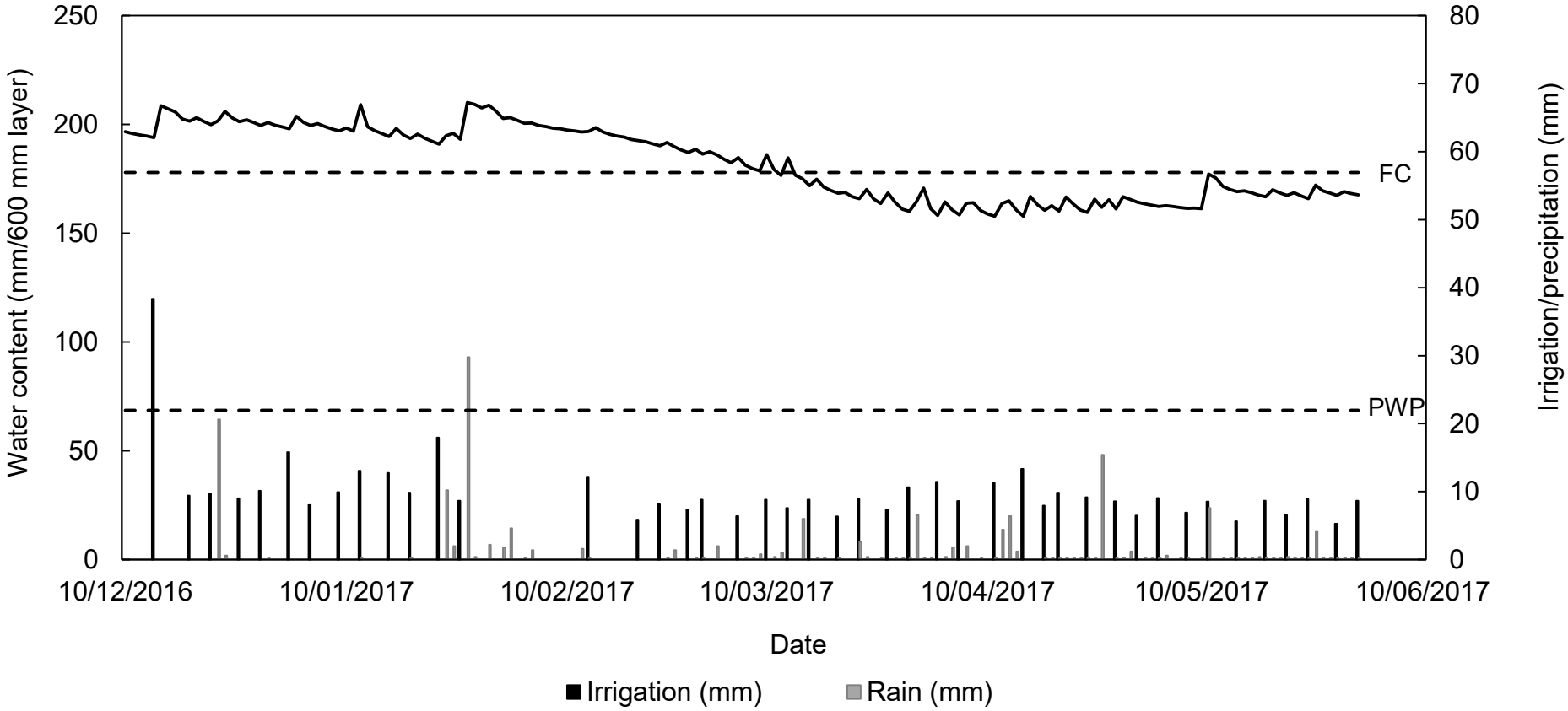

Figure 5.8: Variation in soil water content of T1 during the growing season (December 2016 to May 2017) at a depth layer of 600-1200 mm. FC and PWP represent field capacity and permanent wilting point, respectively.

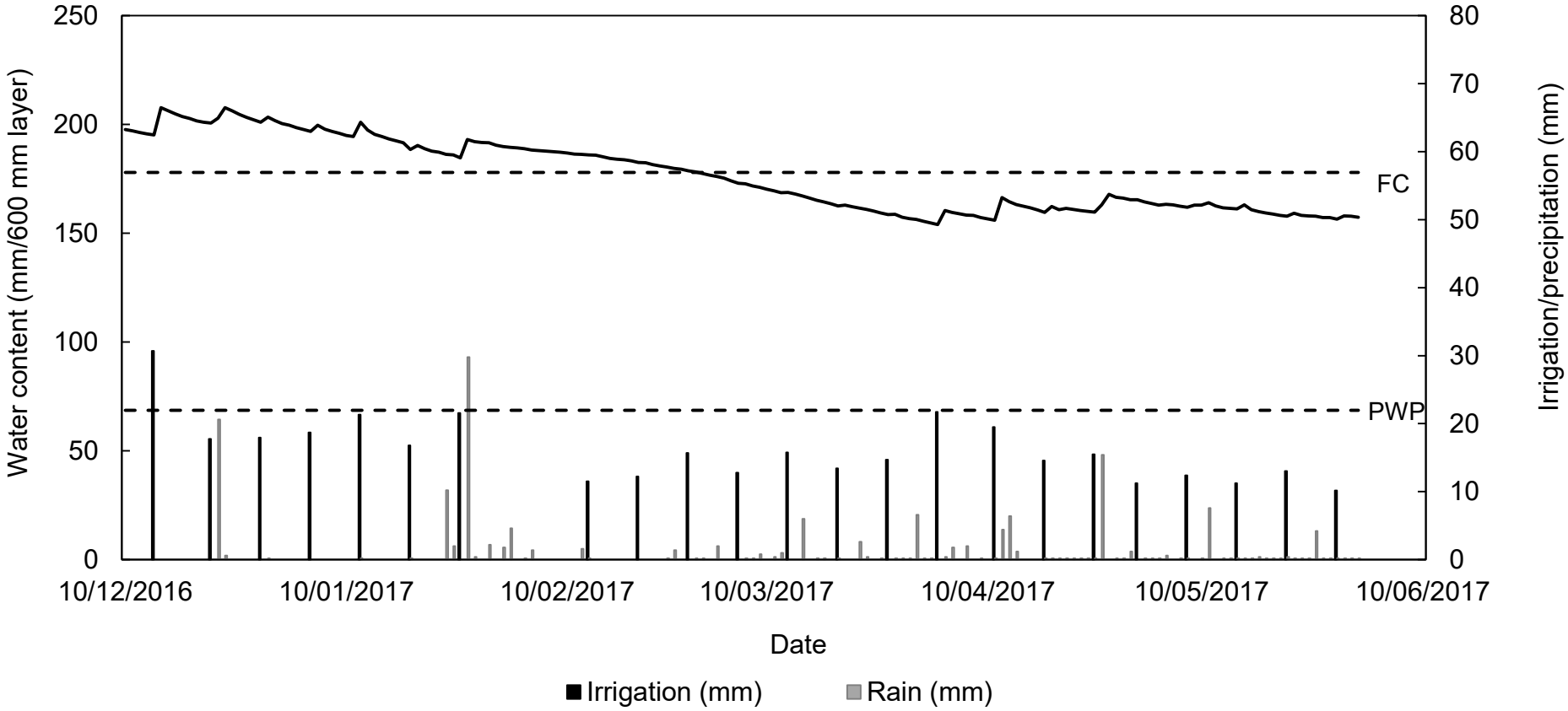

Figure 5.9: Variation in soil water content of T2 during the growing season (December 2016 to May 2017) at a depth layer of 600-1200 mm. FC and PWP represent field capacity and permanent wilting point, respectively.

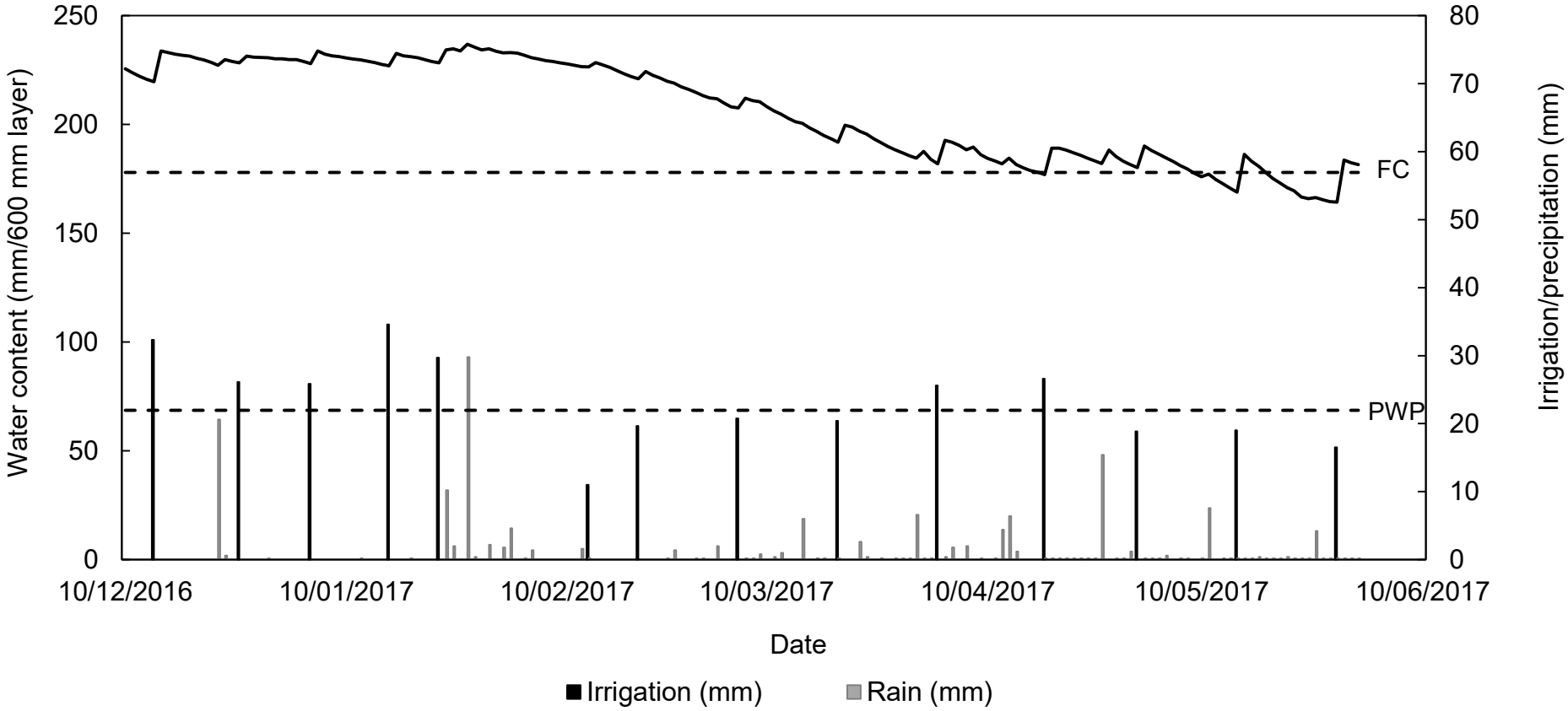

Figure 5.10: Variation in soil water content of T3 during the growing season (December 2016 to May 2017) at a depth layer of 600-1200 mm. FC and PWP represent field capacity and permanent wilting point, respectively.

5.3 Soil water balance

The soil water balance for T1, T2 and T3 can be found in Table 5.6, Table 5.7 and Table 5.8, respectively. All values presented in the tables are in mm, except for ET_c which is in $mm.day^{-1}$. Total SWC refers to the total soil water content in the soil profile (0-1200 mm); ΔS is the difference in soil water content (negative values indicate that there was an increase in soil water content); P represents the precipitation (*i.e.* rainfall); I refers to the amount of water irrigated; U refers to the upwards capillary flow; ET is the evapotranspiration, while ET_c represents the average evapotranspiration per day; ΣP, ΣI, ΣU and ΣET represents the cumulative precipitation, cumulative irrigation, cumulative upward capillary flow and cumulative ET, respectively.

On 10 December 2016 when the first soil water measurements were logged, T3 had the highest soil water content in the soil profile (0-1200 mm) (Table 5.8), followed by T1 (Table 5.6) and T2 (Table 5.7). During the first month of the growing season (December 2016), T1 had the highest ET, followed by T3 and T2 (Table 5.9). During the growing season the peak ET for the three treatments varied with T1 having the highest ET in March 2017, T2 had the highest ET in January 2017 and T3 had the highest ET in February 2017. Weeds and cover crops did not contribute to the ET of the trees, as weeds were managed (as described in point 3.2.4) and there were no cover crop.

The upward capillary flow decreased from T1 to T3, *i.e.* T1 had the largest ΣU, followed by T2 and T3 (Table 5.9). When comparing the total change in soil water content during the growing season (Table 5.9) it is observed that T3 had the highest ΔS, an indication that soil of T3 made the largest contribution to the soil water balance in comparison to T1 and T2.

In order for evaporation to occur, water vapour must be removed and there must be a continual supply of water and energy (Hillel, 2004). The shorter the irrigation cycle, the longer the soil surface will remain wet which will increase evaporation drastically compared to periods when the soil surface dries out (Myburgh, 2010). This seems to be the main reason why ET for the total growing season decreases in the sequence T1>T2>T3. (Table 5.9). A lower ET can also be the result of less water that was lost

through stomata due to transpiration. This is caused due to less active stomata or closed stomata (Gindaba, 2014) Stomata of leaves control the biomass production of trees, *i.e.* it controls the balance between carbon gains and water losses. When stomata are fully open, the production of carbohydrates and the rate of photosynthesis are at a maximum. During the day stomata aperture will be regulated by a number of factors including the inability of the vascular system to keep up with evapotranspiration demand as well as high soil water potential. Hence, stomata aperture may decrease even if enough water is available. Considering the irrigation treatments applied in this experiment, it is unlikely that there would have been times of insufficient water availability. Predawn leaf water potential measurements which may provide evidence of water stress (*i.e*. repressed stomatal conduction, transpiration and photosynthesis) were, however, not carried out in the current experiment.

Vegetative growth will dramatically be effected when water stress develop, especially during spring and early summer (Gindaba, 2014). There was no significant difference in the vegetative growth between T1, T2 and T3 (see chapter 6) and therefore the lower ET values of T2 and T3 at the end of the growing season did not restrict apple tree growth. It can therefore be concluded that longer irrigation cycles (irrigation applications every seven and 12 days) resulted in a water saving compared to more regular irrigations (four day cycle) which kept the soil surface wet for extensive periods of time and resulted in more evaporation losses. This water saving was achieved without negative effects on tree growth.

Table 5.6: Soil water balance for T1 during the 2016/17 growing season (all values in mm, except ET_c which is in mm/day).

	Days	0	4	5	3	4	3	4	3	4	3	4	3	4	3	5
	Year	2016						2017								
	Day/month	10/12	14/12	19/12	22/12	26/12	29/12	02/01	05/01	09/01	12/01	16/01	19/01	23/01	26/01	13/02
Depth (mm)	0-300	84.2	76.8	88.4	82.5	97.5	92.9	85.7	87.5	82.2	98.1	78.9	82.4	83.3	114.5	93.2
	300-600	83.6	79.8	87.0	84.3	89.1	87.8	85.4	84.6	83.4	84.5	80.0	94.4	88.8	91.5	92.7
	600-900	103.1	101.7	104.7	103.8	104.6	104.7	104.4	104.3	103.7	106.5	102.9	102.6	101.3	101.7	102.3
	900-1200	107.9	106.2	110.6	109.8	109.8	108.2	107.1	108.2	106.5	116.1	105.3	104.4	103.2	105.0	106.5
	Total SWC	378.6	364.5	390.6	380.4	401.0	393.5	382.5	384.5	375.8	405.2	367.1	383.7	376.5	412.7	394.7
	ΔS	0.0	14.1	-26.1	10.2	-20.6	7.5	10.9	-1.9	8.7	-29.4	38.1	-16.6	7.2	-36.2	18.0
	P	0.0	0.0	0.0	0.0	21.2	0.0	0.2	0.0	0.0	0.0	0.2	0.0	0.2	12.2	42.0
	I	0.0	0.0	38.3	9.4	9.7	9.0	10.1	15.8	8.1	9.9	13.1	12.8	9.8	17.9	8.6
	U	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	19.5	0.0	3.9	0.0	5.8	0.0
	ET	0.0	14.1	12.2	19.6	10.3	16.5	21.3	13.8	16.8	0.0	51.4	0.0	17.2	0.0	68.6
	ET_C (mm/day)	0.0	3.5	2.4	6.5	2.6	5.5	5.3	4.6	4.2	0.0	12.8	0.0	4.3	0.0	13.7
	ΣP	0.0	0.0	0.0	0.0	21.2	21.2	21.4	21.4	21.4	21.4	21.6	21.6	21.8	34.0	76.0
	ΣI	0.0	0.0	38.3	47.7	57.4	66.4	76.5	92.3	100.5	110.4	123.5	136.2	146.1	164.0	172.6
	ΣU	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	19.5	19.5	23.4	23.4	29.2	29.2
	ΣET	0.0	14.1	26.3	45.9	56.2	72.7	94.0	107.8	124.6	124.6	176.0	176.0	193.2	193.2	261.8

Table 5.6 (continued): Soil water balance for T1 during the 2016/17 growing season.

	Days	7	3	4	2	5	4	3	3	4	3	4	3	4	3	5
	Year								2017							
	Day/month	20/02	23/02	27/02	01/03	06/03	10/03	13/03	16/03	20/03	23/03	27/03	30/03	03/04	06/04	11/04
Depth (mm)	0-300	92.4	91.1	89.6	90.3	89.9	90.5	89.3	87.5	89.0	90.3	88.4	88.1	96.0	100.1	96.5
	300-600	86.3	83.0	79.8	78.3	76.1	80.7	80.7	72.2	71.3	71.4	74.3	69.2	76.4	78.2	77.9
	600-900	100.2	98.4	95.9	94.7	93.6	92.0	92.1	87.0	85.4	84.2	84.8	81.0	80.9	82.4	84.3
	900-1200	104.3	103.5	102.5	102.8	102.3	104.3	103.8	94.8	92.9	91.4	93.2	88.2	86.9	86.1	84.3
	Total SWC	383.1	375.9	367.7	366.0	361.8	367.4	365.9	341.4	338.4	337.2	340.5	326.4	340.1	346.7	342.9
	ΔS	11.6	7.2	8.2	1.7	4.2	-5.6	1.5	24.5	3.0	1.2	-3.3	14.1	-13.7	-6.6	3.8
	P	0.2	0.0	1.6	0.2	2.2	1.2	1.4	6.0	0.4	0.2	3.2	0.4	7.2	2.2	2.2
	I	12.2	5.9	8.3	7.4	8.8	6.4	8.8	7.6	8.8	6.4	8.9	7.4	10.7	11.4	8.6
	U	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	ET	23.9	13.1	18.1	9.2	15.2	2.0	11.7	38.0	12.2	7.8	8.8	21.9	4.2	7.0	14.6
	ET_C (mm/day)	3.4	4.4	4.5	4.6	3.0	0.5	3.9	12.7	3.1	2.6	2.2	7.3	1.1	2.3	2.9
	ΣP	76.2	76.2	77.8	78.0	80.2	81.4	82.8	88.8	89.2	89.4	92.6	93.0	100.2	102.4	104.6
	ΣI	184.8	190.7	199.0	206.3	215.2	221.5	230.4	237.9	246.8	253.1	262.0	269.4	280.1	291.5	300.1
	ΣU	29.2	29.2	29.2	29.2	29.2	29.2	29.2	29.2	29.2	29.2	29.2	29.2	29.2	29.2	29.2
	ΣET	285.7	298.8	316.9	326.1	341.3	343.3	355.0	393.0	405.2	413.3	422.8	444.7	448.9	455.9	470.5

Table 5.6 (continued): Soil water balance for T1 during the growing season.

	Days	4	3	2	4	4	3	3	4	3	4	4	3	3	4	3
	Year															
	Day/month	**15/04**	**18/04**	**20/04**	**24/04**	**28/04**	**01/05**	**04/05**	**08/05**	**11/05**	**15/05**	**19/05**	**22/05**	**25/05**	**29/05**	**01/06**
Depth (mm)	**0-300**	106.7	104.7	102.2	97.8	105.9	102.0	98.6	94.2	97.8	94.8	90.3	90.2	90.6	95.3	93.6
	300-600	83.0	83.7	82.1	81.3	85.1	84.9	82.4	80.7	81.2	82.8	78.2	77.0	75.8	80.4	80.0
	600-900	86.1	90.2	89.4	89.3	89.9	92.0	90.9	90.6	91.7	95.3	93.2	93.2	92.4	96.0	96.5
	900-1200	83.3	83.3	83.4	82.8	83.7	85.4	84.0	83.4	98.6	87.9	87.0	87.6	86.9	86.0	85.8
	Total SWC	359.0	361.8	357.0	351.2	364.5	364.2	355.8	348.9	369.2	360.8	348.6	347.9	345.6	357.6	355.8
	ΔS	-16.1	-2.8	4.8	5.8	-13.3	0.3	8.4	6.9	-20.3	8.4	12.2	0.8	2.3	-12.0	1.8
	P	12.2	0.0	0.4	0.8	15.8	1.6	0.4	1.0	0.4	8.0	1.0	0.6	0.8	4.8	0.6
	I	11.3	13.3	8.0	9.8	9.2	8.6	6.5	9.0	6.9	8.5	5.6	8.6	6.6	8.9	5.3
	U	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.9	0.0	0.0	0.0	0.0	0.0	0.0
	ET	7.4	10.5	13.2	16.5	11.6	10.5	15.3	16.9	0.0	24.9	18.8	10.0	9.6	1.7	7.7
	ET_C (mm/day)	1.9	3.5	6.6	4.1	2.9	3.5	5.1	4.2	0.0	6.2	4.7	3.3	3.2	0.4	2.6
	ΣP	116.8	116.8	117.2	118.0	133.8	135.4	135.8	136.8	137.2	145.2	146.2	146.8	147.6	152.4	153.0
	ΣI	311.4	324.7	332.7	342.5	351.7	360.3	366.7	375.8	382.7	391.2	396.9	405.5	412.1	420.9	426.2
	ΣU	29.2	29.2	29.2	29.2	29.2	29.2	29.2	29.2	42.1	42.1	42.1	42.1	42.1	42.1	42.1
	ΣET	477.9	488.8	501.6	518.1	529.7	540.2	555.5	572.4	572.4	597.3	616.1	626.1	635.7	637.4	645.1

Table 5.7: Soil water balance for T2 during the 2016/17 growing season (all values in mm, except ET_c which is in mm/day).

	Days	0	4	8	7	7	7	7	7	18	7	7	7	7	7	7
	Year	2016				2017										
	Day/month	10/12	14/12	22/12	29/12	05/01	12/01	19/01	26/01	13/02	20/02	27/02	06/03	13/03	20/03	27/03
Depth (mm)	0-300	78.5	71.9	73.7	80.6	72.9	92.1	74.6	81.5	88.8	86.4	80.4	86.0	87.6	86.4	84.8
	300-600	76.5	74.6	77.7	79.4	77.3	84.8	86.1	79.2	85.4	79.5	72.3	69.2	66.8	64.8	63.2
	600-900	90.2	89.3	90.8	91.2	89.6	92.1	84.9	83.4	84.6	82.7	80.9	78.2	77.3	74.4	73.2
	900-1200	103.1	100.5	104.9	106.1	104.0	108.2	99.5	93.0	96.2	92.6	84.6	76.1	64.4	59.3	54.6
	Total SWC	348.2	336.2	347.0	357.2	343.7	377.1	345.0	337.1	354.9	341.1	318.2	309.3	296.0	284.9	275.7
	ΔS	0.0	12.0	-10.8	-10.2	13.5	-33.5	32.1	8.0	-17.9	13.8	23.0	8.9	13.4	11.1	9.1
	P	0.0	0.0	0.0	21.2	0.2	0.0	0.2	12.4	42.0	0.2	1.6	2.4	2.6	6.4	3.4
	I	0.0	0.0	30.7	17.8	17.9	18.7	21.3	16.8	21.6	11.5	12.2	15.7	12.8	15.8	13.4
	U	0.0	0.0	0.0	0.0	0.0	14.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	ET	0.0	12.0	19.9	28.8	31.6	0.0	53.6	37.1	45.7	25.5	36.8	27.0	28.7	33.3	26.0
	ET_C (mm/day)	0.0	3.0	2.5	4.1	4.5	0.0	7.7	5.3	2.5	3.6	5.3	3.9	4.1	4.8	3.7
	ΣP	0.0	0.0	0.0	21.2	21.4	21.4	21.6	34.0	76.0	76.2	77.8	80.2	82.8	89.2	92.6
	ΣI	0.0	0.0	30.7	48.5	66.4	85.1	106.4	123.2	144.8	156.3	168.5	184.2	197.0	212.7	226.2
	ΣU	0.0	0.0	0.0	0.0	0.0	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7
	ΣET	0.0	12.0	31.9	60.7	92.3	92.3	145.9	183.1	228.8	254.3	291.1	318.0	346.7	380.0	406.0

Table 5.7 (continued): Soil water balance for T2 during the 2016/17 growing season.

	Days	7	8	7	7	6	7	7	7	7	3
	Year						**2017**				
	Day/month	**03/04**	**11/04**	**18/04**	**25/04**	**01/05**	**08/05**	**15/05**	**22/05**	**29/05**	**01/06**
Depth (mm)	**0-300**	88.4	87.8	97.8	94.1	104.3	98.1	90.3	87.3	87.9	90.2
	300-600	62.1	68.4	78.3	78.9	82.4	78.5	76.8	75.0	74.4	74.6
	600-900	71.3	73.1	74.6	74.3	75.3	74.3	73.5	72.5	71.9	72.2
	900-1200	53.4	54.2	58.7	58.4	76.1	73.7	71.1	69.3	69.2	69.2
	Total SWC	275.1	283.4	309.3	305.6	338.0	324.5	311.7	304.1	303.3	306.0
	ΔS	0.6	-8.3	-26.0	3.7	-32.4	13.5	12.8	7.6	0.8	-2.7
	P	7.6	4.4	12.2	1.4	17.2	1.4	8.4	1.6	5.6	0.6
	I	14.7	21.7	19.5	14.6	15.5	11.3	12.4	11.3	13.0	10.2
	U	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	ET	22.9	17.9	5.7	19.7	0.3	26.2	33.5	20.5	19.4	8.1
	ET_C (mm/day)	3.3	2.2	0.8	2.8	0.0	3.7	4.8	2.9	2.8	2.7
	ΣP	100.2	104.6	116.8	118.2	135.4	136.8	145.2	146.8	152.4	153.0
	ΣI	240.9	262.6	282.1	296.6	312.1	323.4	335.7	347.0	360.0	370.2
	ΣU	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7
	ΣET	428.8	446.7	452.5	472.2	472.4	498.6	532.1	552.6	572.0	580.1

Table 5.8: Soil water balance for T3 during the 2016/17 growing season (all values in mm, except ET_c which is in mm/day).

	Days	0	4	12	10	11	7	21	7	7	7	7
	Year		**2016**					**2017**				
	Day/month	**10/12**	**14/12**	**26/12**	**05/01**	**16/01**	**23/01**	**13/02**	**20/02**	**27/02**	**06/03**	**13/03**
Depth (mm)	**0-300**	71.5	66.8	80.6	71.2	71.0	74.3	87.3	86.1	84.2	80.3	78.5
	300-600	114.6	110.7	94.5	93.8	90.6	92.0	90.8	83.4	79.4	73.1	72.9
	600-900	102.0	98.7	103.5	105.0	104.9	105.8	105.5	101.3	97.7	93.3	90.8
	900-1200	123.6	120.9	124.8	123.0	122.1	122.6	121.1	119.7	118.5	114.3	112.2
	Total SWC	411.7	397.1	403.4	393.0	388.6	394.6	404.6	390.5	379.7	361.0	354.4
	ΔS	0.0	14.6	-6.3	10.5	4.4	-6.0	-10.0	14.1	10.7	18.8	6.6
	P	0.0	0.0	21.2	0.2	0.2	0.2	54.2	0.2	1.6	2.4	2.6
	I	0.0	0.0	32.3	26.1	25.8	34.6	29.7	11.0	19.7	0.0	20.8
	U	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	ET	0.0	14.6	47.2	36.8	30.4	28.8	73.9	25.3	32.0	21.2	30.0
	ET_C (mm/day)	0.0	3.7	3.9	3.7	2.8	4.1	3.5	3.6	4.6	3.0	4.3
	ΣP	0.0	0.0	21.2	21.4	21.6	21.8	76.0	76.2	77.8	80.2	82.8
	ΣI	0.0	0.0	32.3	58.5	84.3	118.9	148.6	159.6	179.2	179.2	200.0
	ΣU	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	ΣET	0.0	14.6	61.8	98.6	129.1	157.9	231.7	257.0	289.0	310.2	340.2

Table 5.8 (continued): Soil water balance for T3 during the 2016/17 growing season.

	Days	7	7	7	8	7	7	6	7	7	7	7	3
	Year							2017					
	Month	20/03	27/03	03/04	11/04	18/04	25/04	01/05	08/05	15/05	22/05	29/05	01/06
Depth (mm)	0-300	74.4	73.8	73.6	82.6	80.6	84.0	85.9	83.4	80.1	81.3	77.0	78.9
	300-600	68.0	68.6	64.5	67.8	65.9	67.8	67.8	67.5	65.7	66.2	65.0	65.7
	600-900	85.8	84.9	81.8	83.0	81.2	83.1	82.7	82.5	80.1	80.9	78.0	80.7
	900-1200	106.1	105.0	100.2	100.4	95.9	100.2	97.5	97.1	88.8	90.2	86.3	100.8
	Total SWC	334.2	332.3	320.1	333.7	323.5	335.1	333.9	330.5	314.7	318.5	306.2	326.1
	ΔS	20.1	2.0	12.2	-13.7	10.3	-11.7	1.3	3.4	15.7	-3.7	12.3	-19.9
	P	6.4	3.4	7.6	4.4	12.2	1.4	17.2	1.4	8.4	1.6	5.6	0.6
	I	0.0	20.4	0.0	25.6	0.0	26.6	0.0	18.9	0.0	19.0	0.0	16.5
	U	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.8
	ET	26.5	25.8	19.8	16.4	22.5	16.4	18.5	23.7	24.1	16.9	17.9	0.0
	ET_C (mm/day)	3.8	3.7	2.8	2.0	3.2	2.3	3.1	3.4	3.4	2.4	2.6	0.0
	ΣP	89.2	92.6	100.2	104.6	116.8	118.2	135.4	136.8	145.2	146.8	152.4	153.0
	ΣI	200.0	220.4	220.4	246.0	246.0	272.7	272.7	291.5	291.5	310.6	310.6	327.1
	ΣU	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.8
	ΣET	366.7	392.5	412.3	428.6	451.1	467.5	485.9	509.6	533.7	550.6	568.5	568.5

Table 5.9: The amount of rainfall, evapotranspiration (ΣET), irrigation (ΣI), upward capillary flow (ΣU) and the change in soil water content (ΔS) during the growing season (December 2016 to May 2017) for all three treatments; all values are in mm.

Month	Rainfall	Treatment 1				Treatment 2				Treatment 3			
		ΣET	ΣI	ΣU	ΔS	ΣET	ΣI	ΣU	ΔS	ΣET	ΣI	ΣU	ΔS
Dec 2016	21.4	72.7	66.4	0.0	-15.0	60.7	48.5	0.0	-9.2	61.8	32.3	0.0	8.1
Jan 2017	45.0	120.5	97.6	29.2	-51.3	122.4	74.7	14.7	-12.0	96.1	86.6	0.0	-35.5
Feb 2017	11.6	123.7	35.0	0.0	77.2	108.0	45.3	0.0	51.1	131.1	60.3	0.0	59.2
Mar 2017	21.8	127.8	70.4	0.0	34.7	114.9	57.7	0.0	35.4	103.5	41.2	0.0	40.5
Apr 2017	35.6	85.0	82.3	0.0	-33.0	66.2	70.4	0.0	-39.8	75.0	52.3	0.0	-12.9
May 2017	17.6	115.4	74.5	12.9	10.4	107.9	73.6	0.0	16.7	101.0	54.4	2.8	26.2
Total	153.0	645.1	426.2	42.1	23.0	580.1	370.2	14.7	42.2	568.5	327.1	2.8	85.6

CHAPTER 6: APPLE TREE RESPONSE TO DIFFERENT IRRIGATION TREATMENTS

6.1 Root studies

The MM109 rootstock, which was used on the experimental site, is a vigorous rootstock which usually results in high productions (SAPO Trust, 2017). It can therefore be expected that the root system will not be shallow, but rather distributed wider and to deeper soil layers.

6.1.1 Rhizotrons

The determination of apple roots using a scanner in the Perspex rhizotron was successful and gave useful results. Roots, especially young white ones, were clearly visible against the Perspex walls and the same roots could be observed at each subsequent scanning (Figure 6.1). Light penetration from the soil surface during scanning and condensation of water against the Perspex walls inside the rhizotrons caused poor scanned images in some instances, but these problems could be overcome easily. This can be done by cleaning the Perspex walls before scans and covering the top part of the rhizotrons with black bags when scans are conducted.

During the six months when root scans were conducted, no roots were observed through the Perspex wall on the east side of treatment one (T1) and treatment two (T2). In the treatment three (T3) plot, however, roots were present on both the east and west side of the Perspex walls (Table 6.1). The absence of roots on the east side of T1- and T2-rhizotrons is probably caused by the relative short time span between installation of the rhizotrons and the root scans. In their root studies using mini-rhizotrons in vineyards, Smart *et al.* (2006) recommended a six month waiting period after installation of rhizotron tubes before reliable information can be expected. It is unclear why this only happened for T1 and T2 and not for T3.

Roots were observed through the Perspex wall at a soil depth of 600-800 mm for all three treatments when the last scans were conducted (July 2017) with only T3 already showing roots in July 2017 at a depth of 800-1000 mm (Table 6.1). Both T2

and T3 showed root grow to a depth of 600-800 mm when the first scans were conducted in February 2017 (Table 6.1) with only T3 already showing roots to a depth of 800-1000 mm when the first root scans were conducted (Figure 6.2). Although the data in Table 6.1 could not be analysed statistically (only one plot of each treatment were scanned) it is clear that the two driest treatments (T2 and T3) had higher root length densities at deeper soil depths than the wet treatment (T1).

The total root length density (TRLD) for all three treatments increased from February to July 2017. For T2, a slight increase in the TRLD was observed from February to April (Figure 6.3). This small increase (compared to T1 and T3 during the same time) can be a result of the colour of the roots which were initially white and turned partially brown due to lignification (Li *et al.*, 2013). When the roots turned brown, they were not easy to observe through the Perspex wall as they had the same colour as the soil and this complicated root recordings. At the end of the season in July 2017 the TRLD of the two driest treatments (T2 and T3) were much higher than in the wetter treatment (T1).

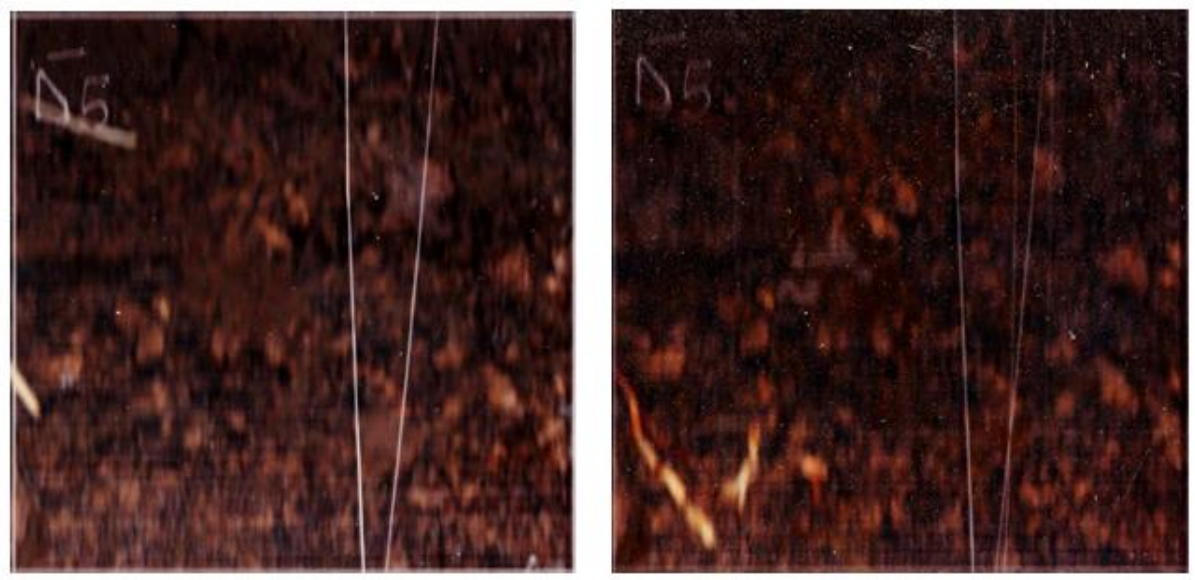

Figure 6.1: Scanned images of the same grid section during February (left) and April (right) 2017, respectively, showing increase in length of the same apple roots in the irrigation trial.

Table 6.1: Root length densities with depth at various stages during the 2017 season and at different sides of the rhizotron.

Treatment	Depth (mm)	Root length density (mm/mm^2)					
		West			East		
		Feb	Apr	Jul	Feb	Apr	Jul
1	0-200	0.000	0.000	0.000	0.000	0.000	0.000
	200-400	0.002	0.010	0.006	0.000	0.000	0.000
	400-600	0.000	0.005	0.009	0.000	0.000	0.000
	600-800	0.000	0.000	0.005	0.000	0.000	0.000
	800-1000	0.000	0.000	0.000	0.000	0.000	0.000
2	0-200	0.006	0.006	0.025	0.000	0.000	0.000
	200-400	0.014	0.013	0.027	0.000	0.000	0.000
	400-600	0.018	0.021	0.025	0.000	0.000	0.000
	600-800	0.000	0.000	0.039	0.000	0.000	0.000
	800-1000	0.000	0.000	0.000	0.000	0.000	0.000
3	0-200	0.000	0.000	0.009	0.000	0.003	0.007
	200-400	0.000	0.004	0.023	0.002	0.007	0.022
	400-600	0.000	0.000	0.000	0.007	0.005	0.031
	600-800	0.000	0.006	0.006	0.015	0.015	0.018
	800-1000	0.000	0.000	0.005	0.000	0.000	0.000

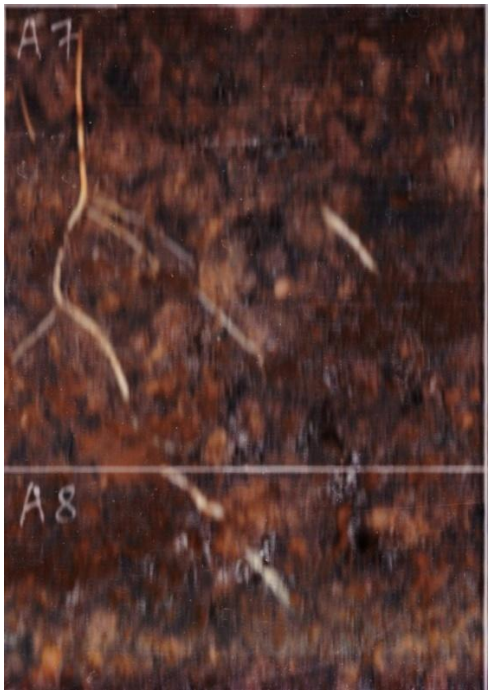

Figure 6.2: Roots of T3 that were observed at a soil depth of 600-1000 mm on the west side of the Perspex wall during February 2017 when the first root scans were conducted.

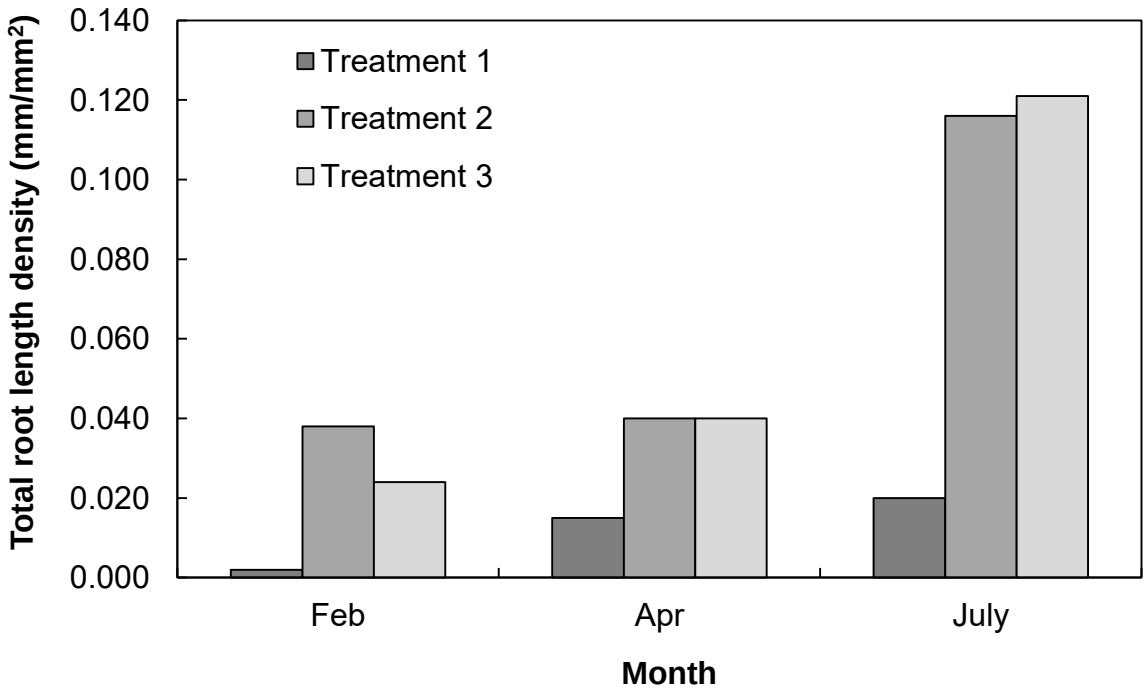

Figure 6.3: The total root length density (mm/mm^2) of the three treatments as observed through the Perspex wall three times during six months in 2017 in the experimental trial on Oak Valley Estate.

6.1.2 Profile wall method

During the in-field root studies with the use of the profile wall method it was visually observed that roots preferred to grow in the loamy textured soil (*ca*. 24.0% ± 1.5% clay content) rather than the clayey textured soil (*ca*. 37.1% ± 0.9% clay content), as is illustrated in Figure 6.4. As the depth of these layers of different textures differed and may have affected statistical analyses of root distribution, it was recorded what soil texture was present while plotting roots per 100 mm × 100 mm wall area.

6.1.2.1 Root distribution

Figure 6.4 and Figure 6.5 illustrate the difference in root distribution between the wettest (T1) and the driest treatment (T3), respectively. From this visual illustration of the root distribution as observed in field, it is clear that T3 penetrated deeper into the soil than T1. These observations were further confirmed with the graphical presentation of the average root distribution of all three treatments (Figure 6.6). It is clear that the roots of T2 and T3 penetrated deeper than *ca.* 500 mm while most of the roots from T1 were only distributed between the soil surface and a depth of *ca.* 500 mm (Figure 6.6). The roots of T2 extended further into the working row than those of T1 and T3 (Figure 6.6: 1(b); 2(b); 3(b)).

The root system of all three treatments primarily consisted of very fine roots (Figure 6.6). The roots in the middle trench (parallel to the tree row) of T1 and T2 consisted of very fine roots, fine roots and medium roots while T3 also contained these thickness classes, but it also contained thick roots (Figure 6.6: 1(a); 2(a); 3(a)). The right trench (perpendicular to the tree row) of T1 and T2 consisted of very fine roots and fine roots while T3 contained very fine roots, fine roots, medium roots and thick roots (Figure 6.6: 1(b); 2(b); 3(b)). Overall, when looking at the visual presentation of root growth (Figure 6.6), T2 and T3 had a better root distribution throughout the soil profile than T1.

Observations of root distribution were statistically analysed by doing ANOVA of the mean root numbers per 200 mm × 200 mm wall area, while the two different soil textures recorded during the root studies were used as covariates. No significant differences in the mean amount of roots were found between the three treatments at

depth increment 0-400 mm and 800-1000 mm with a corresponding width increment of 0-600 mm (distance from the tree) (Table 6.2).

At a depth increment of 400-600 mm and a corresponding width increment of 200-400 mm, T1 had a very low mean number of roots that was significantly less than the number of roots on T2 and T3 plots. Root numbers of T2 and T3 did however differ significantly (Table 6.2). These results indicated that the roots of T2 and T3 penetrated the deeper soil layers at a greater distance from the tree better than those of T1.

At depth increments 400-800 mm and a corresponding width increment of 400-600 mm the mean amount of roots of T1 were significantly less than the mean number of roots of T2 (Table 6.2). Treatment three had an intermediate number of roots, which did not differ significantly from the mean amount of roots of T1 and T2 (Table 6.2). These results indicate that T2 produced more roots at depth increments of 400-800 mm and at a distance of 400-600 mm away from the tree. This can be a result of the amount of water that was applied for T2 penetrating more effectively to these depths throughout the soil profile than those of T1. Although T1 received more water throughout the season, the amounts per application were less than those of T2 and T3.

Table 6.2: Mean amount of roots with depth and distance from the tree of the three treatments on the irrigation trial at Oak Valley Estate.

Depth (mm)	Distance from tree (mm)								
	0 – 200			200 – 400			400 – 600		
	T1	T2	T3	T1	T2	T3	T1	T2	T3
0 – 200	10.7 a[(1)]	16.1 a	11.7 a	3.7 a	7.8 a	4.8 a	1.1 a	4.7 a	5.9 a
200 – 400	11.2 a	12.4 a	14.1 a	7.0 a	9.8 a	10.7 a	2.8 a	8.7 a	12.2 a
400 – 600	4.5 a	7.5 a	8.8 a	0.7 b	6.3 a	5.8 a	3.0 b	10.3 a	6.3 ab
600 – 800	0.5 a	3.1 a	6.1 a	0.0 a	2.4 a	2.5 a	0.0 b	3.2 a	1.9 ab
800 – 1 000	0.0 a	0.1 a	0.0 a	0.0 a	0.0 a	0.0 a	0.0 a	0.0 a	0.0 a

[(1)] Values designated by the same letter within each row do not differ significantly ($p < 0.05$).

Figure 6.4: Root growth and distribution of T1 as observed during root studies using the profile wall method; roots prefer to grow in the darker loamy textured soil rather than the lighter clayey textured soil.

Figure 6.5: Root growth and distribution of T3 as observed during root studies using the profile wall method.

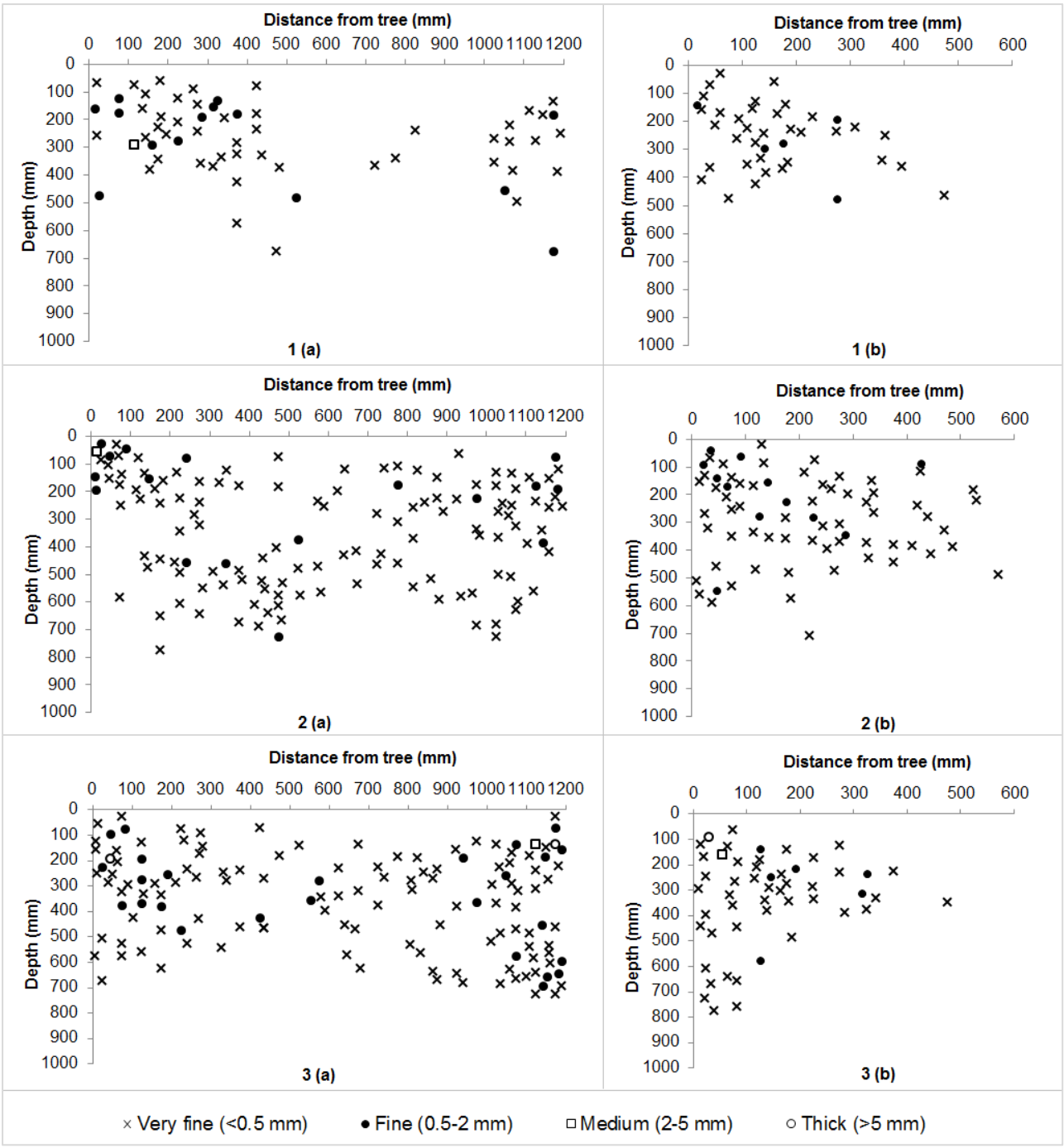

Figure 6.6: A graphical presentation of the average root distribution for the three treatments; (a) refers to the root distribution of the middle trench which was parallel to the tree row while (b) refers to the root distribution of the trench perpendicular to the tree row (within the ridge); the numbers 1, 2 and 3 refers to treatment one, treatment two and treatment three respectively.

6.1.2.2 Rooting index

The rooting index is considered to be a good indicator of soil conditions. A high rooting index reflects more medium and thin roots relative to thick roots as a result of more favourable soil conditions (Van Zyl, 1984). The rooting index was developed for mature plants and it is consequently uncertain how applicable it will be for newly planted trees that do not have a large variety of root sizes due to their age.

Although the results could not be analysed statistically, T2 and T3 had much higher rooting indexes than T1 in the middle trench (parallel to the tree row, thus T2 and T3 had more very fine and fine roots relative to the thicker roots) (Table 6.3). For the trenches perpendicular to the tree row (within the ridge), T2 had the highest rooting index (Table 6.3). It is therefore proposed that the soil conditions were more favourable for T2 in the trenches perpendicular to the tree row (within the ridge) and for T2 and T3 in the trench parallel to the tree row (Van Zyl, 1984).

Table 6.3: The mean rooting index for the three treatments in the irrigation trial on Oak Valley Estate.

Treatment	Rooting index	
	Perpendicular to the tree row (within the ridge)	Parallel inside tree row (within the ridge)
1	20	19
2	38	31
3	17	35

6.1.2.3 Root density (number of roots/m^2)

The mean root density of T1, T2 and T3 throughout the soil profile amounted to 69±41 roots/m^2, 145±62 roots/m^2 and 148±76 root/m^2, respectively. There was no significant difference between the mean root densities of T2 and T3 throughout the soil profile, but both these treatments had significantly higher root densities than T1 (Table 6.4). These results are supported by the visual picture of root distribution that showed fewer roots for T1 plots compared to T2 and T3 (Figure 6.6).

The mean number of roots that grew in the loamy textured soil versus those that grew in the clayey textured soil differed for each treatment. Overall, more roots grew in the loamy textured soil than the clayey textured soil for all three treatments (Table 6.4). T1 had the fewest roots and T3 the highest number – significantly more than T1 – in the clayey textured soil. This is also evident in the visual observation of root distribution in field (Figure 6.4 and Figure 6.5). Although not significant, T2 also tended to have more roots than T1 in the clayey subsoil. In the loamy textured soil, T2 had significantly more roots than T1, but none of the other differences in root number were statistically significant (Table 6.4). T3 tended to have more roots in this soil layer than T1.

Table 6.4: The total mean number of roots within two different soil textures for the three different treatments applied in the irrigation trial on Oak Valley Estate.

	Treatment 1	Treatment 2	Treatment 3
Loamy texture	64.3 b[(1)]	106.9 a	96.7 ab
Clayey texture	7.4 b	28.6 ab	43.5 a
Total	71.7 b	135.6 a	140.1 a

[(1)] Values designated by the same letter within each row do not differ significantly ($p < 0.05$).

The mean root density (number of roots/m^2) in the trench parallel to the tree row in the loamy textured soil did not vary significantly between the three treatments (Table 6.5). This was also the case in the mean root density (roots/m^2) in the trench perpendicular to the tree row (Table 6.6). Thus significant differences in root density between treatments were only found in the clayey textured soil and in the soil profile as a whole. The two driest treatments (T2 and T3) had significantly higher rooting densities than the wettest treatment (T1) in the clayey layer of trenches parallel to the tree row (Table 6.5). The same pattern of root response was found in trenches perpendicular to the tree row except that the difference between T1 and T2 was not significant (Table 6.6). In the trench perpendicular to the tree row no significant differences were found between the treatments for the entire soil profile (Table 6.6),

but for the trench parallel to the tree row there was a significant difference in the mean root density of the entire soil profile between T1 and T2 (Table 6.5).

Table 6.5: The mean root density (number of roots/m^2) in the trench parallel to the tree row (within the ridge) in two different soil textures of the three different treatments applied in the irrigation trial on Oak Valley Estate.

	Treatment 1	Treatment 2	Treatment 3
Loamy texture	69.7 a[(1)]	112.8 a	113.3 a
Clayey texture	11.1 b	38.1 a	31.9 a
Total	80.8 b	150.8 a	145.3 ab

[(1)] Values designated by the same letter within each row do not differ significantly ($p < 0.05$).

For the entire soil profile, only 1% of the roots of T1 grew in the clayey textured soil, while 6% and 11% of the roots grew in the clayey textured soil of T2 and T3, respectively. These results confirm that roots tend to grow to soil layers which are the most favourable (Ruiz-Sánchez *et al.*, 2005) as the roots of the two driest treatments (T2 and T3) not only penetrated deeper soil layers, but were forced to grow into the clayey textured soil layer where the soil water content was higher (chapter 5). Although T1 also had adequate soil water in the deeper soil layers (600-1200 mm), soil water for T1 was easily available in the 0-600 mm soil layers (chapter 5) and roots were not forced to grow to deeper soil layers.

6.2 Vegetative growth

The mean number of shoots per tree for T1 and T2 amounted to 21 and T3 to 20. All of the different vegetative growth parameters that were measured did not differ significantly between the three treatments (Table 6.7). Overall T3 had the largest mean stem circumference of all the treatments, but the mean shoot length, mean length of the central leader and the mean length of the new leader of T3 was the shortest. The mean length of the central leader and the mean length of the new leader of T2 were the largest of all three treatments while T1 had the largest mean shoot length (Table 6.7).

Table 6.6: The mean root density (number of roots/m^2) in the trench perpendicular to the tree row (within the ridge) in two different soil textures of the three different treatments applied in the irrigation trial on Oak Valley Estate.

	Treatment 1	Treatment 2	Treatment 3
Loamy texture	58.8 a[(1)]	101.1 a	80.0 a
Clayey texture	3.6 b	19.2 ab	55.0 a
Total	62.5 a	102.3 a	135.0 a

[(1)] Values designated by the same letter within each row do not differ significantly ($p < 0.05$).

The fact that there were no significant differences in vegetative growth measurements between the treatments indicated that none of the irrigated treatments had a negative effect on the above ground growth of the apple trees. In a study done by Allmendinger *et al.* (1943) they stated that the terminal elongation of the branches of apple trees only start to decrease when 20% of the plant available water is still available. As mentioned previously (chapter 5), all three treatments received adequate water during the growing season and trees were not subjected to water stress. Therefore the vegetative growth for all three treatments was not reduced or affected negatively.

Table 6.7: Vegetative growth of the three treatments in the irrigation trial on Oak Valley Estate; all values are mean values and in mm.

Treatment	Stem circumference	Shoot length	Central leader	New leader	Tree height
1	91 a[(1)]	319 a	1865 a	595 a	2460 a
2	93 a	301 a	1902 a	638 a	2540 a
3	90 a	283 a	1835 a	561 a	2396 a

[(1)] Values designated by the same letter within each column do not differ significantly ($p < 0.05$).

CHAPTER 7: GENERAL CONCLUSION AND RECOMMENDATIONS

7.1 General conclusion

Irrigation experiments require much time and attention to apply the irrigation treatments according to the planned schedule and to measure soil water status as well as other soil variables. This is particularly a problem when such experiments are not close to the researcher. Last mentioned was successfully addressed in this study. Soil water data were captured continuously on a data logger and downloaded with the use of a mobile application namely LoggerLink for Android™. Weather data was easily obtained from the Beaulieu weather station *ca.* 5 km away from Oak Valley Estate to monitor the rainfall and temperature during the growing season. It was also important to apply irrigation treatments remotely with the use of cell phone technology. This was successfully done as one was able to control the irrigation applications from anywhere in the country by simply sending a short message service (SMS). The SMS system made it possible to apply *ca.* 9.2 mm of water every 3 to 4 days for treatment one (T1), *ca.* 15.4 mm of water every 7.3 days for treatment two (T2) and *ca.* 22.7 mm of water every 12.1 days for treatments three (T3). The remote control of irrigation valves and data capturing on the current trial can serve as a model for other irrigation experiments.

The evapotranspiration (ET) of the three treatments were calculated based on the wetted area that was irrigated (rather than the total area) in order to compare how much water was used between the three treatments. The ET of the three treatments decreased as irrigations were applied less frequently, *i.e.* T1 had the highest ET at the end of the growing season, followed by T2 and T3 which received the least water during the growing season. Increasing the irrigation cycles also forced the trees to use more water stored in the soil. The results clearly demonstrated that water can be saved when longer irrigation cycles are used. This water saving is probably due to less evaporation from the soil surface following irrigations. Water savings will

become increasingly more important the more the already limited water resources become further restricted.

The comparative study between the pressure plate apparatus and dew point method was necessary in order to establish if the dew point method will be an easier and/or quicker method to determine a soil water retention curve (SWRC) compared to the pressure plate which can take up to six months (or more) to determine a SWRC. The study was also necessary to establish whether the dew point method will give more accurate results, particularly at -1500 kPa (and lower) compared to the pressure plate apparatus. Unreliable results were obtained when generating a SWRC with the use of the dew point method. Disappointingly the dew point method gave no readings in wet soils. Even when a SWRC determined by the dew point method was extrapolated to the wetter soil water contents, it generated values well below the expected range of plant available water (PAW). It was concluded that the specific apparatus using the dew point method is not usable in the water potential range important for plant growth *i.e*. higher than -1500 kPa. Although cumbersome, results of this study suggest that the pressure plate apparatus is still the best way of determining soil water retention curves.

A cheap and easy *in situ* method to study root growth periodicity was developed and showed promising results. This method based on the scanning of roots that grow against the Perspex sides of a rhizotron, showed root development during the passing of the season. This was the first time that scanning of roots was done in the field using an ordinary mobile document scanner inside a tailor-made rhizotron. This method offers a cheap and effective alternative to expensive existing mini-rhizotron systems. Some improvements to the scanner will further improve image definition and speed of the operation.

The time-tested profile wall method was used to determine the root density, root distribution and rooting index. Mapping of the roots clearly showed a rooting preference for the darker loamy topsoil to the yellow, more clayey subsoil; these soil layers were displaced by soil preparation and no longer occur in their natural positions. The driest treatment had significantly more roots in the clayey subsoil than the wettest treatment. Root distribution with depth on the two dry treatments compared to the wettest one proved that the aim was achieved of encouraging roots

to grow into the subsoil by irrigating less frequently. Furthermore, the root densities of T2 and T3 throughout the soil profile were significantly higher than those of T1 and the roots of the two first-mentioned treatments also penetrated to deeper soil layers at a greater distance from the tree than those of T1. The two driest treatments (T2 and T3) were thus forced to grow into the clayey textured soil layers where the soil water content was higher and therefore penetrated deeper layers than T1. It is also insightful that roots on the two driest treatments have already penetrated to 800 mm in the first season. This deep root system buffers the trees against water stress and will allow the grower to use longer irrigation cycles and save water in future. Deep root development did not take place to the detriment of above-ground tree development. Tree response in terms of stem circumference and shoot lengths was not significantly different between the three irrigation treatments.

7.2 Recommendations

7.2.1 Recommendations for managing irrigation of apple trees in newly established orchards in Grabouw

Although the two driest treatments (T2 and T3) did not differ significantly in the mean amount of roots that grew to deeper soil layers, it is suggested to apply a nett amount of 15 mm water every week (medium irrigation cycle) on young apple trees in newly established apple orchards on gravelly soils in Grabouw. If a medium irrigation cycle is used, the required root distribution is obtained without reducing above-ground vegetative growth. Long cycle irrigations (one irrigation of 23 mm every 12 days) required the least water during the growing season and also promoted root growth to deeper soil layers without restricting above-ground tree development. The small water saving (43 mm for the season) by using a long cycle irrigation schedule compared to a medium cycle, however, does not justify the increase in risk of reducing tree development in case of heat waves, irrigation system breakdowns or other disasters.

7.2.2 Recommendations for further research

It is suggested not to use the WP4C dew point potential meter to obtain soil water potential readings at -1500 kPa or lower, but rather to investigate other methods

such as the vapour sorption analyzer (VSA) or heat dissipation methods which measure water potentials accurately at -1500 kPa or lower. The HYPROP can be used to determine water potentials in the wet range (Decagon Devices, 2015b) and the results of these combined methods can be used to determine the accuracy of the pressure plate apparatus.

The method to determine TRLD *in situ* showed promising results. It is however suggested that at least two more rhizotrons per treatment must be installed in order to analyse TRLD between the three treatments statistically.

The experiment should continue to allow investigation of the longer-term effect of tree response to irrigation cycles and to determine how evapotranspiration and root distribution of young trees will further increase with the concomitant effect on water requirement. It is, however, suggested to calibrate the CS650-sensors to ensure calculated ET values for the three treatments are accurate. Furthermore it is important to determine the field capacity (FC) of the soil in field to ensure irrigations are applied correctly.

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APPENDIX

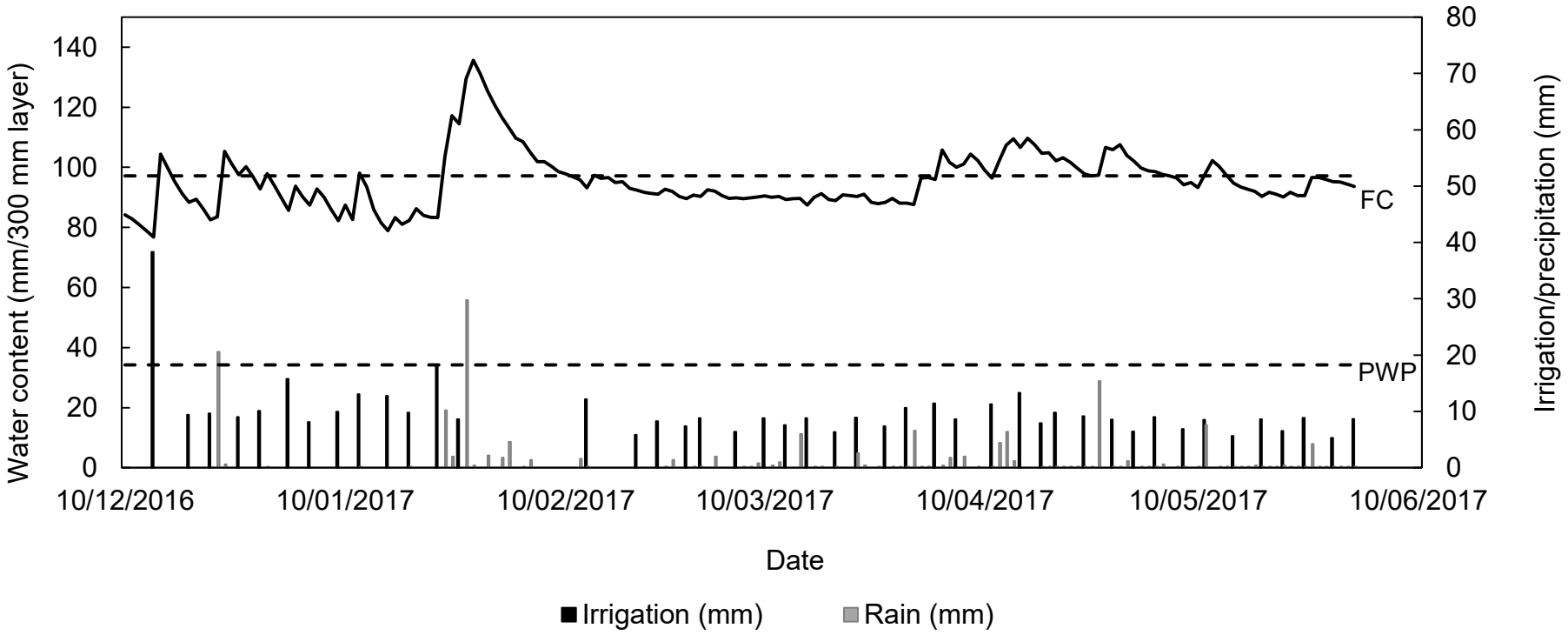

Figure A-1: Variation in soil water content of T1 during the growing season (December 2016 to May 2017) at a depth layer of 0-300 mm. FC and PWP represent field capacity and permanent wilting point, respectively.

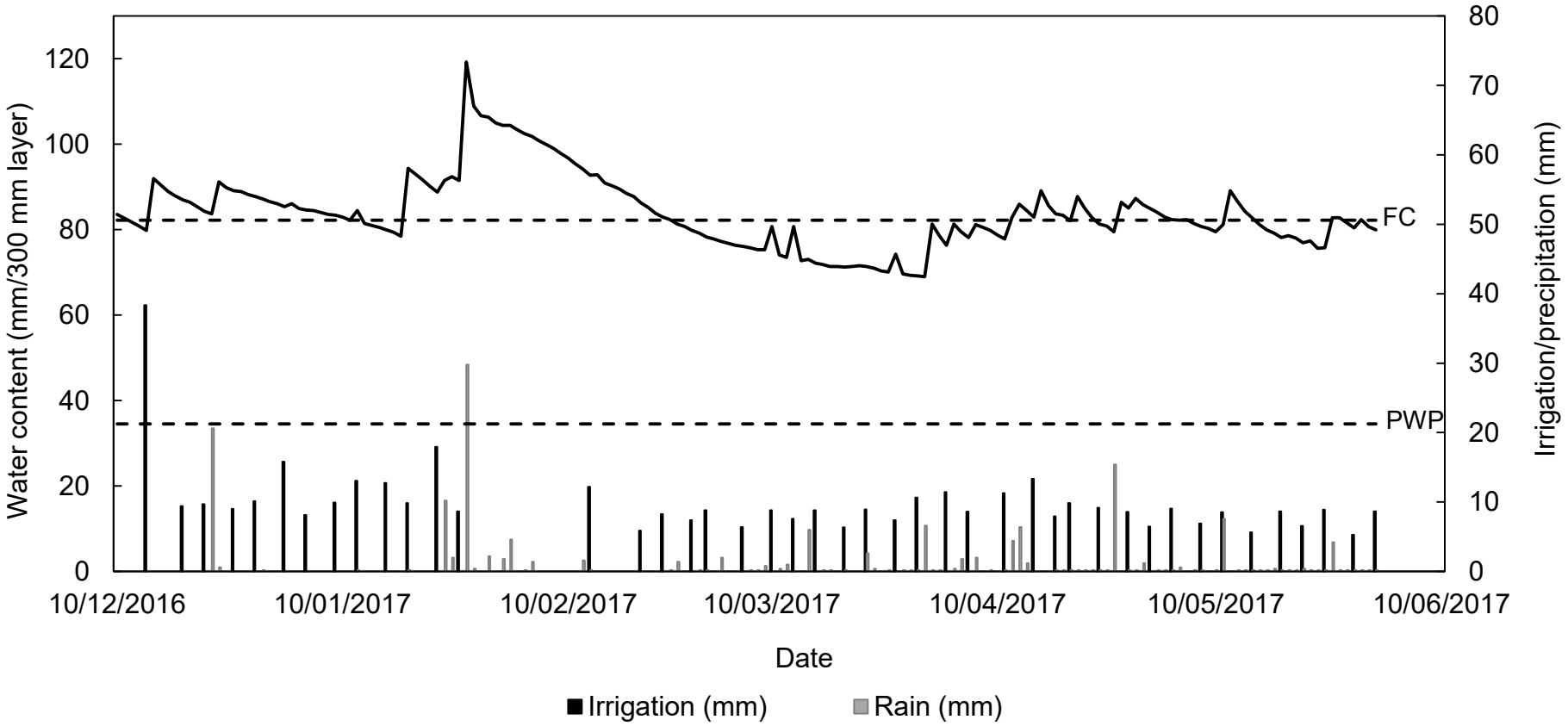

Figure A-2: Variation in soil water content of T1 during the growing season (December 2016 to May 2017) at a depth layer of 300-600 mm. FC and PWP represent field capacity and permanent wilting point, respectively.

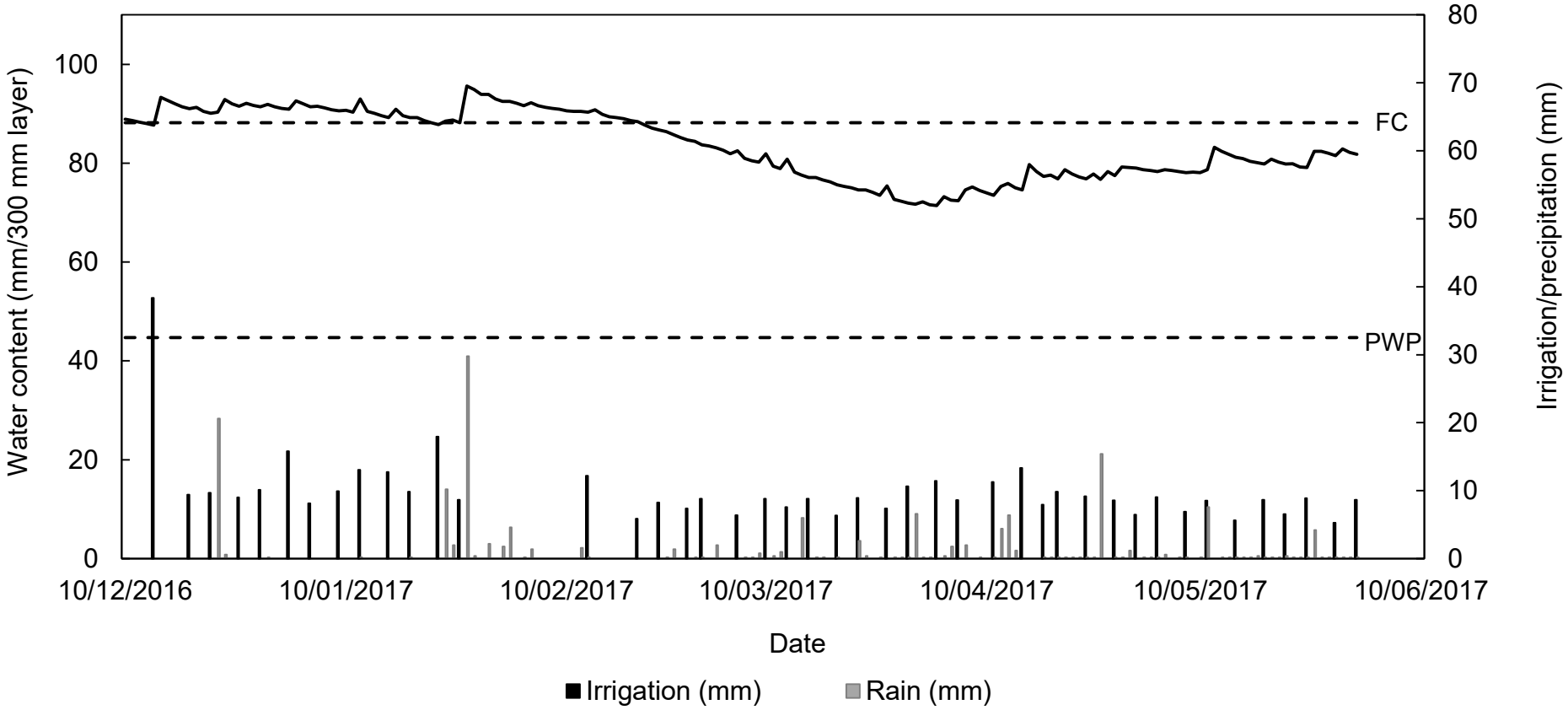

Figure A-3: Variation in soil water content of T1 during the growing season (December 2016 to May 2017) at a depth layer of 600-900 mm. FC and PWP represent field capacity and permanent wilting point, respectively.

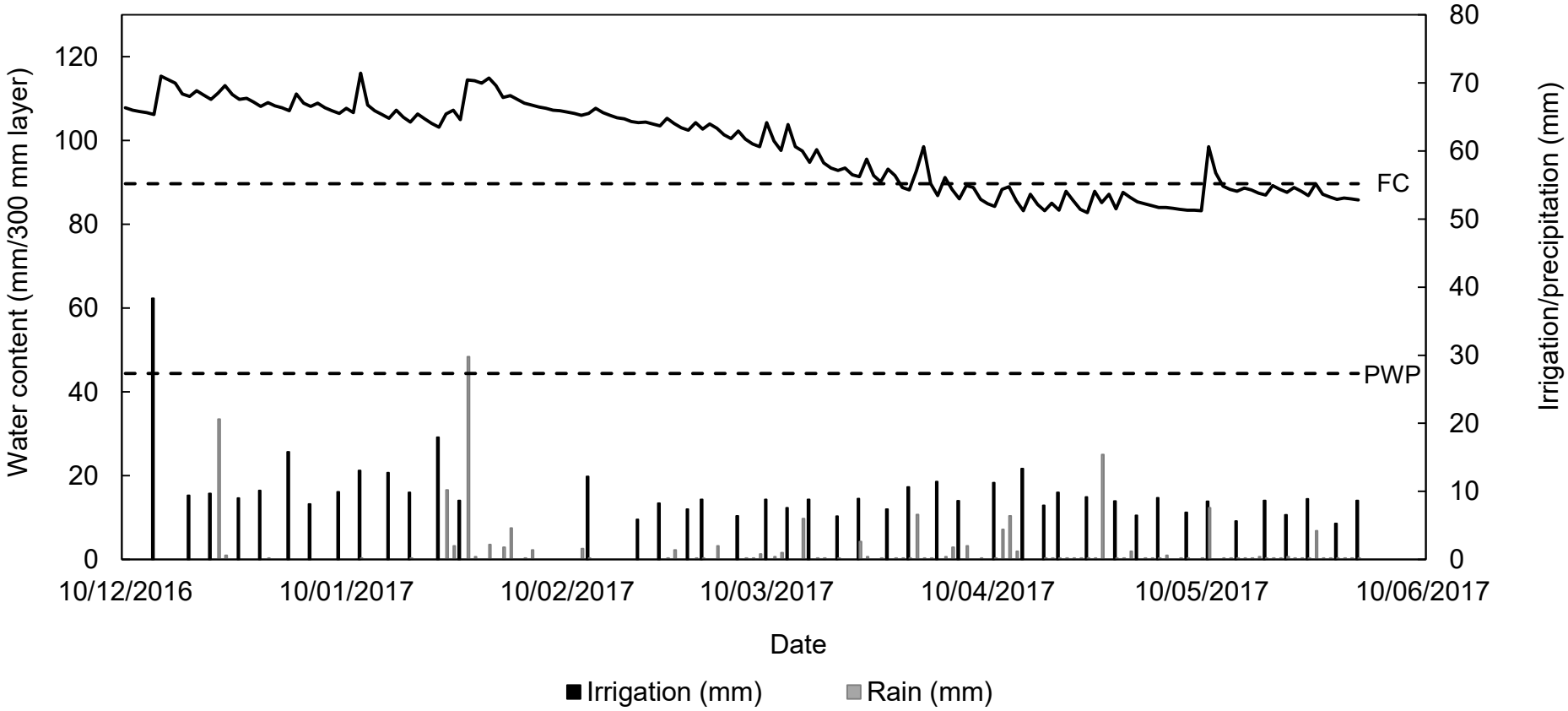

Figure A-4: Variation in soil water content of T1 during the growing season (December 2016 to May 2017) at a depth layer of 900-1200 mm. FC and PWP represent field capacity and permanent wilting point, respectively.

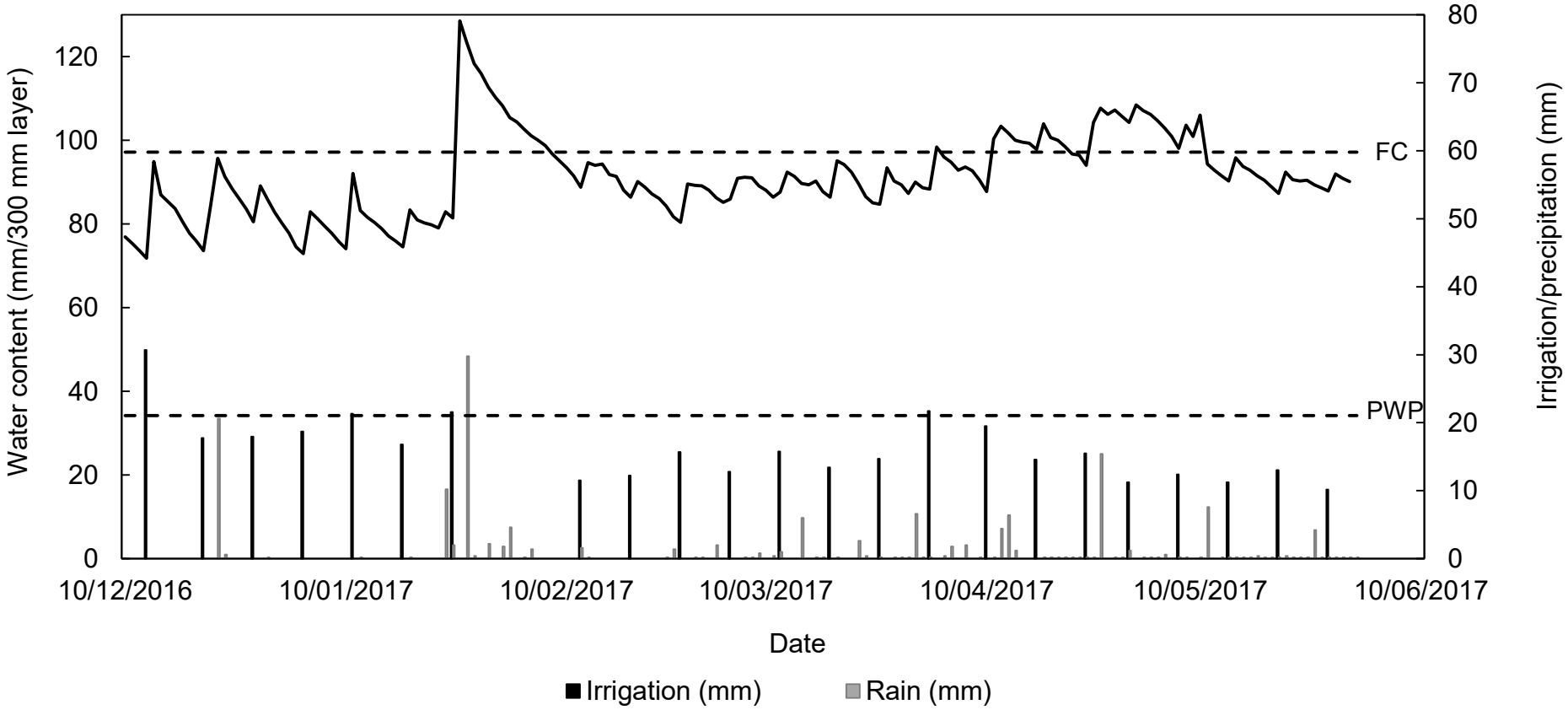

Figure A-5: Variation in soil water content of T2 during the growing season (December 2016 to May 2017) at a depth layer of 0-300 mm. FC and PWP represent field capacity and permanent wilting point, respectively.

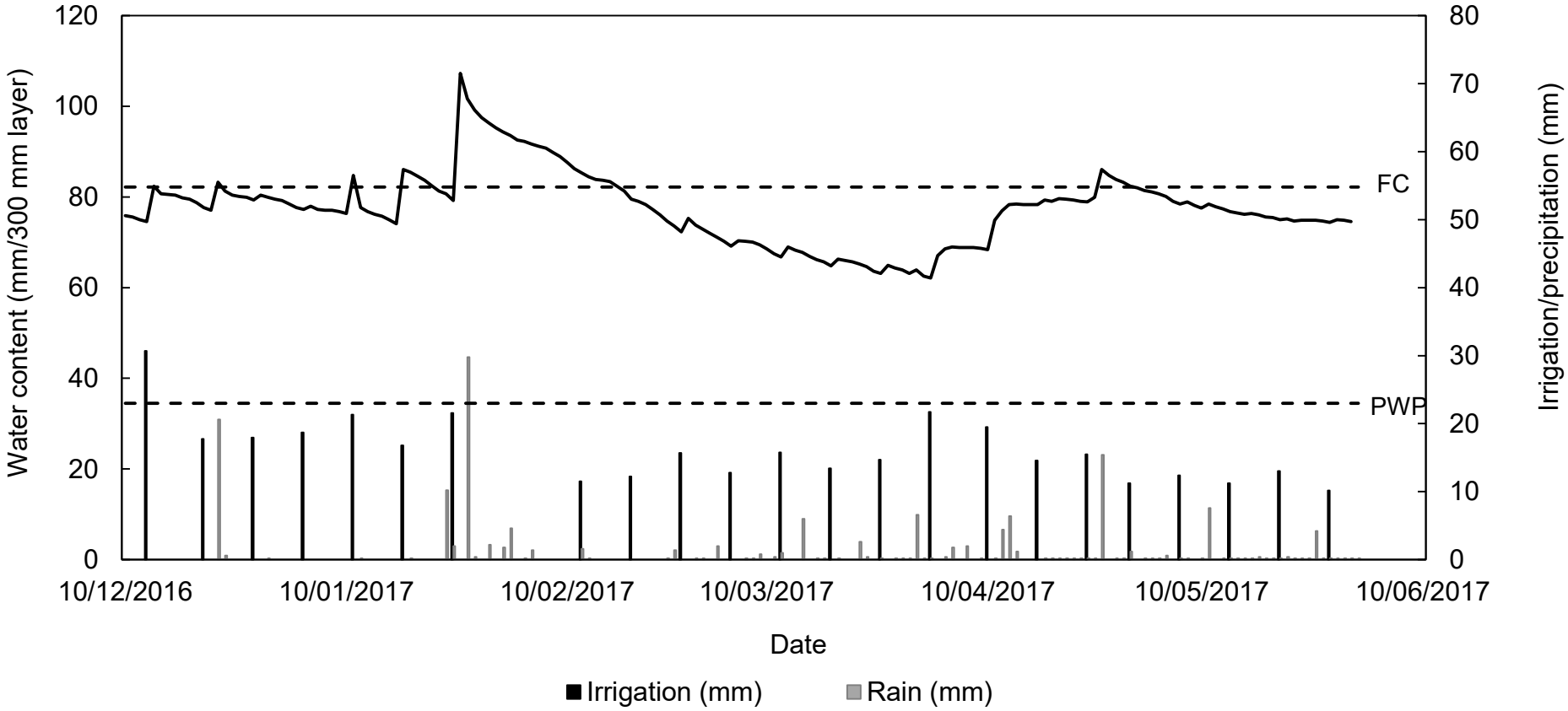

Figure A-6: Variation in soil water content of T2 during the growing season (December 2016 to May 2017) at a depth layer of 300-600 mm. FC and PWP represent field capacity and permanent wilting point, respectively.

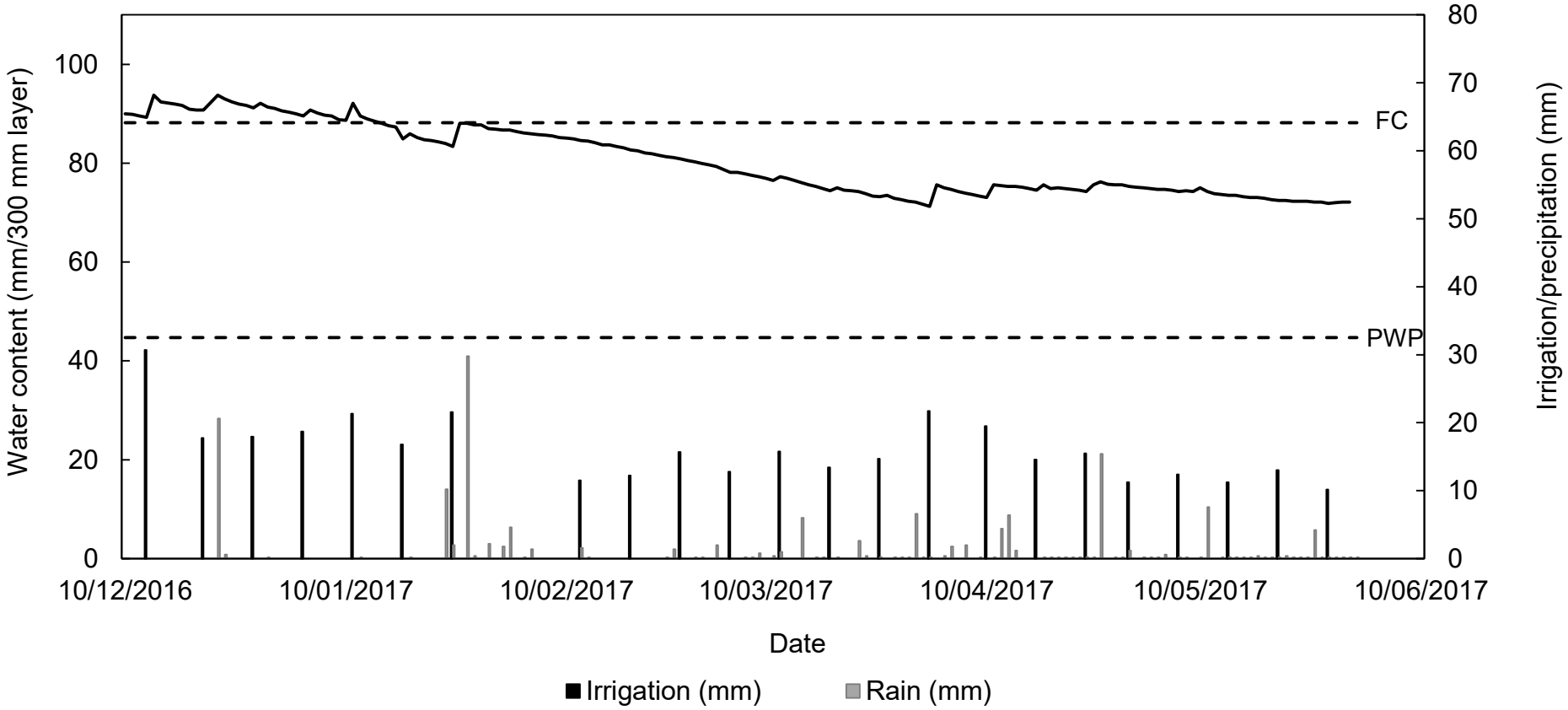

Figure A-7: Variation in soil water content of T2 during the growing season (December 2016 to May 2017) at a depth layer of 600-900 mm. FC and PWP represent field capacity and permanent wilting point, respectively.

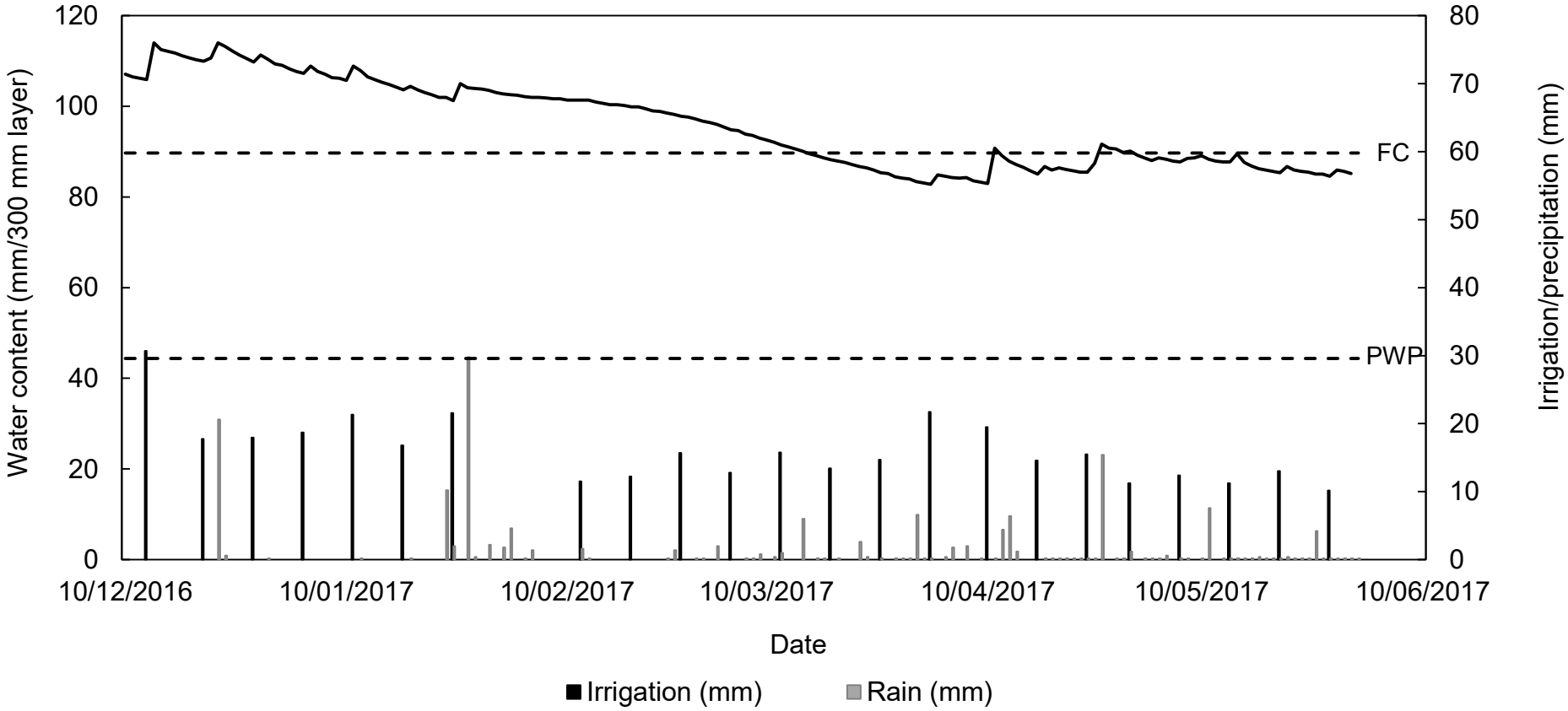

Figure A-8: Variation in soil water content of T2 during the growing season (December 2016 to May 2017) at a depth layer of 900-1200 mm. FC and PWP represent field capacity and permanent wilting point, respectively.

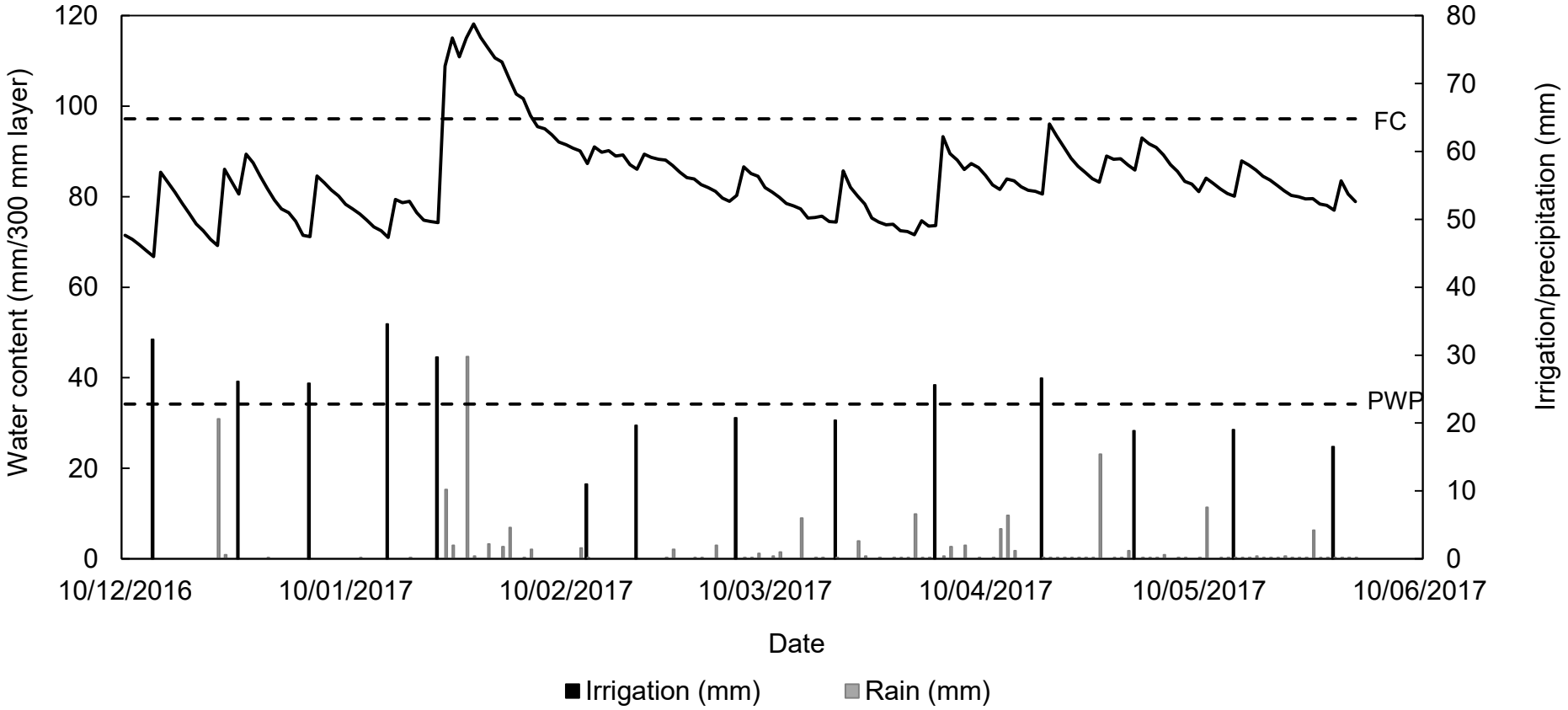

Figure A-9: Variation in soil water content of T3 during the growing season (December 2016 to May 2017) at a depth layer of 0-300 mm. FC and PWP represent field capacity and permanent wilting point, respectively.

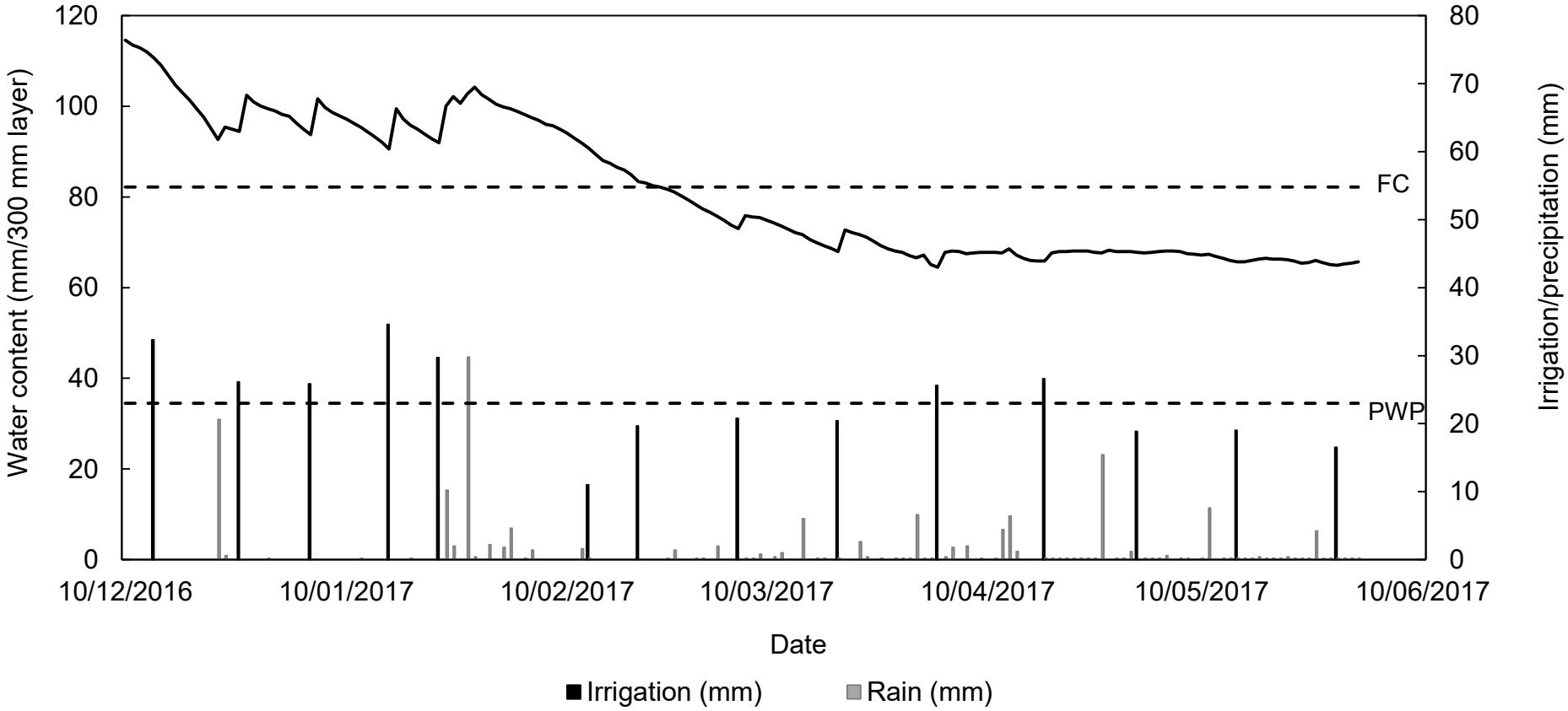

Figure A-10: Variation in soil water content of T3 during the growing season (December 2016 to May 2017) at a depth layer of 300-600 mm. FC and PWP represent field capacity and permanent wilting point, respectively.

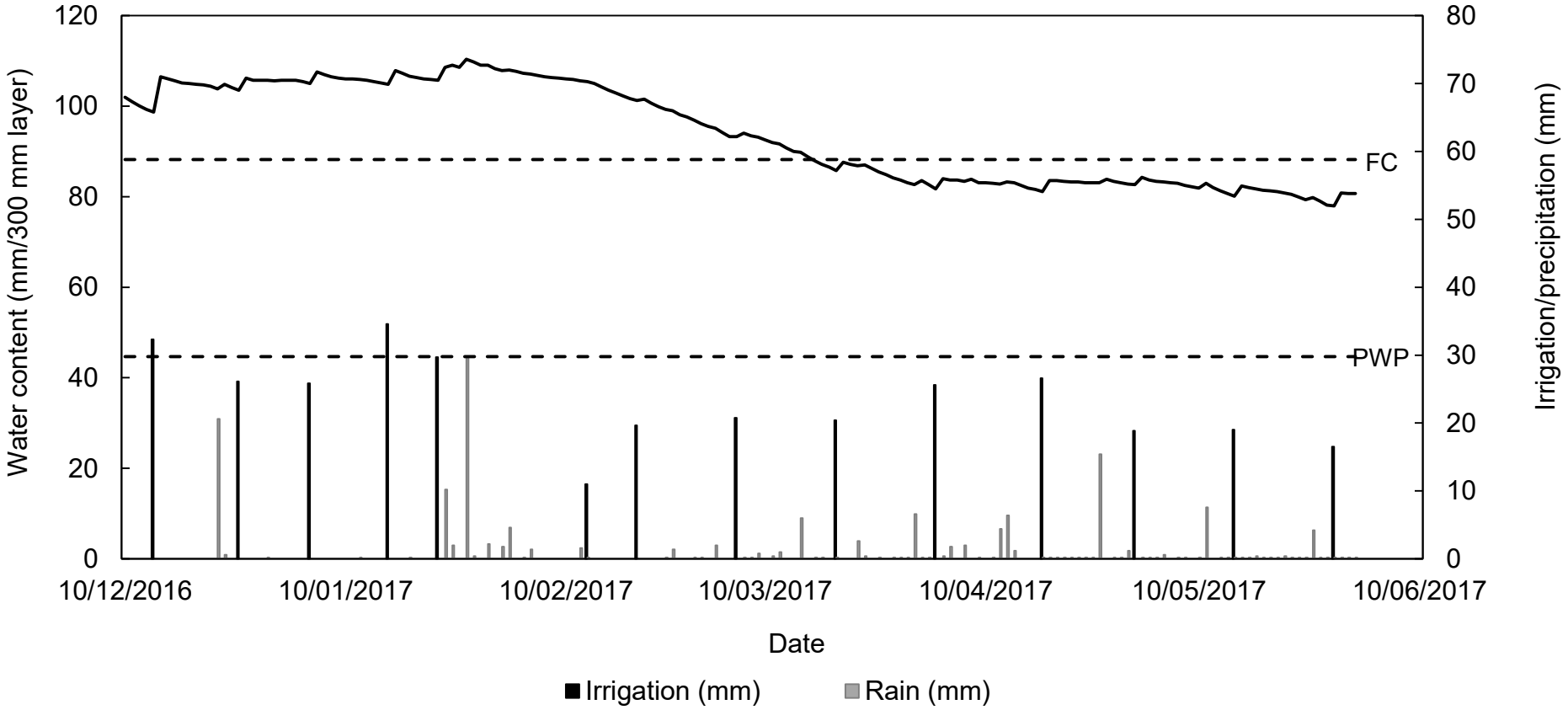

Figure A-11: Variation in soil water content of T3 during the growing season (December 2016 to May 2017) at a depth layer of 600-900 mm. FC and PWP represent field capacity and permanent wilting point, respectively.

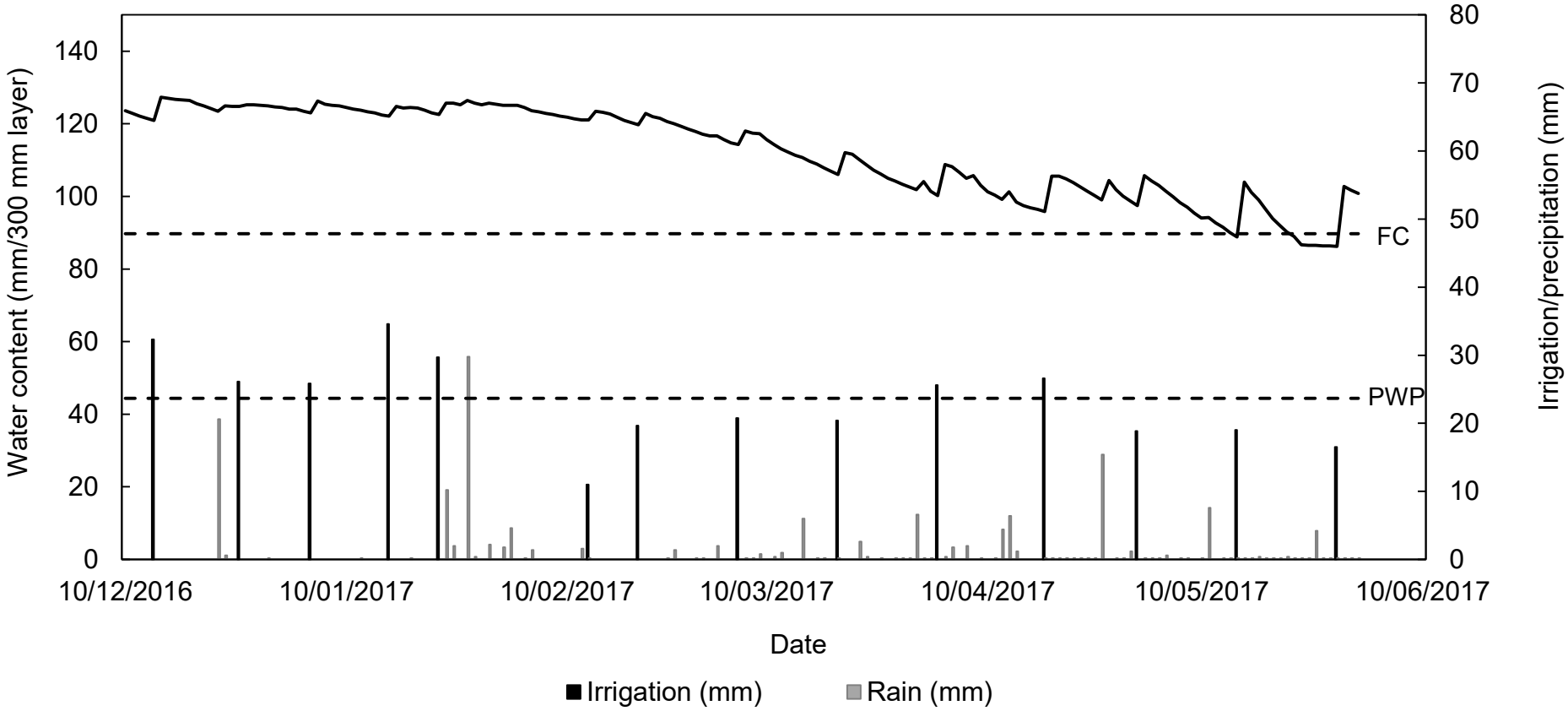

Figure A-12: Variation in soil water content of T3 during the growing season (December 2016 to May 2017) at a depth layer of 900-1200 mm. FC and PWP represent field capacity and permanent wilting point, respectively.