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The water footprint of selected crops within the Olifants/Doorn Catchment, South Africa

A thesis submitted in fulfilment of the requirements for the degree of Magister Scientiae

By

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KEYWORDS

Crop water use

Reference evapotranspiration

Crop water productivity

Apparent Water Productivity

Water footprint

Effective rainfall

Blue water

Green water

ABSTRACT

The water footprint of selected crops within the Olifants/Doorn Catchment, South Africa

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Rapidly increasing global population is adding more pressure to the agricultural sector to produce more food to meet growing demands. However the sector is already faced with a challenge to reduce freshwater utilisation as this sector is currently using approximately 70% of global water freshwater resources. In South Africa, the agriculture sector utilizes approximately 62% of freshwater resources and contributes directly about5% to the Gross Domestic Product. South Africa is a water scarce country receiving less than 500mm/year of precipitation in most parts of the country, and consequently approximately 90% of the crops are grown under irrigation. Studies have evaluated irrigation practices and crop water use in the country. However information is lacking on the full impact of South African horticultural products on freshwater resources. The water footprint concept can be used to indicate the total and source (blue/green) of water used to produce the crops. Information about water footprint (WF) can be used for identifying opportunities to reduce the water consumption associated with production of vegetables and fruits at the field to farm-gate levels, including the more effective use of rainfall (green water) as opposed to water abstracted from rivers and groundwater (Blue water). It can also be used to understand water related risks associated with the production of crops and facilitate water allocation and management at catchment/water management scale. While the potential value of water footprint information is well recognized there is still inadequate knowledge on how best to determine the water footprints of various crops within a local context. The aim of this study was to determine the water footprint and the crop water productivity of navel oranges, pink lady apples and potatoes produced with the Olifant/Doorn water management area in South Africa.

The water footprint of the navel oranges, pink lady apples and potatoes assessed following the water footprint network method was 125 litres/ kg, 108 litres/kg and 65 litres/ kg respectively. The study concluded that water footprint studies should be carried out on the whole catchment instead of one farm in order to assess the sustainability of the process.

Declaration

I declare that **the water footprint of selected crops within the Olifants/Doorn Catchment, South Africa** is my own work, that it has not been submitted for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged by a complete reference.

Full name ………………………………………………..

Date……………………………………………………

Signature ………………………………………………

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Thesis dedication

This thesis is dedicated to my late mother Evodia Pone and late Aunt Florinah Tsietso Pone. Thank you both for always encouraging me to study.

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Abbreviations

WMA	Water Management Area
DWA	Department of Water Affairs
CSIR	Council for Scientificand Industrial Research
WFN	Water Footprint Network
LCA	Life Cycle Assessment
MDG	Millennium Development Goals
UNEP	United Nations Environmental Program
BR	Bowen Ratio
MOST	Monin-Obukhov similarity theory
CWP	Crop water productivity
WUE	Water use efficiency
AWP	Apparent Water Productivity
SEBAL	Surface Energy Balance Algorithm for Land
MAP	Mean Annual Precipitation
FAO	Food and Agriculture Organization
AWS	Automatic Weather Station

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Glossary of words

Blue water footprint is the volume of surface and ground water required for the production of a good or service.

Carbon footprint is the amount of carbon emitted throughout the supply chain for the production of a product.

Crop coefficients the ratio of the actual crop evapotranspiration (ET_c) to reference evapotranspiration (ET_o).

Deciduous plants are plants that shed their leaves at the end of each growing season

Dekad refers to the time unit referring to 10 days.

Ecological footprint is the amount of biologically productive land and sea required to supply the resources consumed by human population and to absorb waste.

Ecological Reserveis an allocation of water specified as a volume and quality underpinned by flow and duration requirements to sustain ecosystems along a specified river.

Evapotranspiration is the quantity of water that is actually removed from a surface due to the processes of evaporation and transpiration.

Green water footprint isthe volume of rainwater used to produce a product which does not run off or recharge groundwater, but is stored in or temporarily on top of the soil.

Grey water footprint is thevolume of freshwater that is required to dilute or assimilate the load of pollutants based on existing ambient water quality standards.

Reference evapotranspiration (ET_o) is defined as the evapotranspiration rate from a reference surface not short of water. The reference surface is a hypothetical grass reference crop with an assumed height of 0.12 m, an albedo of 0.23 and a fixed surface resistance of 70 s m^{-1}.

The **Monin-Obukhov similarity theory** (MOST) describes non-dimensional mean flow and mean temperature in the surface layer under non-neutral conditions as a function of the dimensionless height parameter.

Virtual water the amount of water consumed in the production process of a product which is also known as the water embodied in the product.

Water scarcity is the lack of adequate water resources to meet the demand for water within a region.

Water stress refers to the ability, or lack thereof, to meet human and ecological demand for water.

1 INTRODUCTION

1.1Background

Globally, water resources are threatened due to increase in human population and climate change. It is estimated that by 2020 approximately 75% of the world's population will live in areas experiencing physical or economic water scarcity, with most of these areas being in Africa and Asia wherethe majority of the population dependsprimarily on agriculture (Molden et al., 2003). The agricultural sector is already under pressure to reduce water usage because irrigation is already the world's largest user of freshwater (Comprehensive Assessment of Water Management in Agriculture (CA, 2007).

Approximately 70% of global freshwater is allocated to the agricultural sector, of which 90% is utilized for irrigation(CA, 2007).In South Africa approximately 62% of freshwater is allocated to the agricultural sector (CSIR, 2010). In some areas where water is already scarce high water usage in one sector has a negative impact in other sectors.

The population density, and limited rainfall determine water scarcity projections in both Asiaand Africa (Rijsberman, 2006).The uneven spatial distribution and seasonal variation of rainfall contribute to physical scarcity of water in African and Asian countries. The seasonal variation of the rainfall causes water scarcity in China despite the country receiving high rainfall (Rijsberman, 2006). Both the spatial and seasonal variation of rainfall are high for South Africa which has an annual average rainfall of 500mm/year less than the world average rainfall. The eastern part of the country receives 500mm/year of rainfall, while the western part receives less than 300mm/year (Rouault and Richard, 2003).

1.1 Agriculture and water scarcity

Although the agricultural sectoris allocated the largest portion of the total freshwater resources and its consumptive use is higher than other economic sectors it is still the most sensitive sector to water scarcity (CA, 2007). According to the FAO (2012),rapidly increasing population is the driving factor behind agricultural water use.Without major changes in land and agriculture productivity, agricultural water demand is predicted to increase by 70–90% (De Fraiture and Wichelns, 2010). Increasing water productivity in agriculture is the only feasible solution for coping with the water demand.

Increasing agricultural water productivity is a key element of strategic water resources planning (Zwart and Bastiaanssen ,2004). It is also very important in achieving the Millennium Development Goal (MDG) of halving the proportion of people living in absolute poverty by 2015(Prowse and Braunholtz-Speight,2007).Increasing agriculture production contributes towards poverty alleviation in numerous ways.The sector contributes indirectly to poverty eradication through job creation and also directly by providing food(von Braun et al., undated). A study by the World Bank (2004) showed that poverty decreased from almost 64% to just 16.6% between the year 1981-2001 in China, whenagriculture productivity increased in this country. Agricultural productivity increased with irrigation development (Jin et al., 2012). Irrigationdevelopment hasboth positive and negative impacts on the environment. The positive impact includes increase in agriculture productivity while the negative impacts include modification of stream flow patterns,depletion of aquifers, non-point pollution and soil salinization (Diaz, 2001; Agardy and Alder, 2005).

Water resource managers have identified various strategies for solving the negative impacts associated with irrigation development, water scarcity and water quality (De Fraiture and Wichelns, 2010). Traditionallywater resource managers focused mainly on water scarcity and the technical aspects of irrigation and drainage,rather than convincing the consumers to choose those agricultural products that have low adverse impacts on freshwater resources(Deurer et al., 2011).The water footprint (WF),defined as the total volume of water use (direct and indirect) along a production chain, was introduced asa viable tool for a sustainable use of freshwater(Jefferies et al., 2012). But the lack of a generally accepted methodology for quantifying the water footprint is a problem for utilizing this concept to sustainably use water resources. Thus far, the discussion around the definition and application of water footprints has been led mainly by economists and life-cycle analysts (Hoekstra, 2009; Ridoutt et al., 2009).

Historically, studies in the agricultural sector assessed water use of different crops by considering only water withdrawn from a fresh water basin for crop production (Aldaya et al., 2009). These studies did not incorporate water used for other activities related to production of an agricultural product. The studies assumed that the water used for estimating crop water requirement was sufficient for water management and water allocation in agriculture.This approach ignored other significant uses of water important in water management, such as water lost (indirectly) from storage dams through evaporation, which is very high in semi-arid areas (Hoekstra et al.,2011).

Excluding the indirect water use while estimating crop water use does not provide the full picture of the amount of water required to produce a crop.

The water footprint concept includes the total water use and the source (blue/green) of water used to produce the crops. WF information can also be used for identifying opportunities to reduce water consumption associated with production of vegetables and fruits at the field to farm-gate level, including the more effective use of rainfall (green water) as opposed to irrigation water (blue water) resources(Hoekstra et al.,2011).

The main objective of this study is to estimate the water footprint of three major crops (Navel oranges, Pink Lady Apples and Mondial potatoes) produced under irrigation within a semi-arid region in the Western Cape Province of South Africa

1.2 Specific objectives

- To estimate the amount of water used in the production of selected crops in a semi–arid region.
- To establish the crop water productivityfor the selected crops.

1.3 Thesis outline

- Chapter 1: presents the background of the study including the aims, hypothesis and the research questions.
- Chapter 2: presents the literature review of this study focussing on evapotranspiration, water footprint methodologies, crop water productivity and apparent water productivity
- Chapter 3: Presents the general methodology of the study including general description of the study area, approach to data collection and data analyses

- Chapter 4, 5 & 6: Presents the specific crop case studies (Navel oranges, Pink Lady Apples and Mondial Potatoes) of the thesis.
- Chapter 7: Presents general discussion ,conclusions and recommendations
- Chapter 8: References

Chapters 4-6 of the thesis are written as case studies but avoid repetition of the methodology described in chapter 3 as the approach was standardised for all case studies. Only specific methodological approaches that differ from those described in the general methodology section (Chapter 3) are highlighted in Chapters 4-6.

2 LITERATURE REVIEW

2.1 Introduction

Until recently, there have been few studies examining water consumption and pollution along whole production and supply chains. Hoekstra et al., (2002)developed the water footprint concept as an indicator of freshwater use that considers both direct and indirect water use of a consumer or producer (UNEP, 2012). The water footprint of an individual, community or business is defined as the total volume of freshwater that is used to produce the goods and services consumed by an individual or community or produced by the business (Hoekstra et al .,2011).

Water footprint assessment can be helpful in understanding how activities and products relate to water scarcity and pollution, and what can be done to make sure activities and products do not contribute to unsustainable use of freshwater (Vanham and Bidoglio, 2014). The water footprint concept is very close to the virtual water content concept, the ecological footprint and the carbon footprint.

The water footprint concept was introduced as an analogy to the ecological footprint and carbon footprint family (Hoekstra et al., 2007). The main difference between water footprint and carbon footprint that that water footprint can be assessed at both large scale and small scale (farm-gate level) levels whereasthe carbon footprint can only be determine accurately at a large scale (Hastings and Pegram, 2012). Carbon emissions will have similar implications regardless of where emissions occur. The ecological footprint represents the amount of biologically productive land and sea required to supply the resources consumed by human population and to absorb waste(Rees, 1992).

Closely linked to the concept of water footprint is that of virtual water. Virtual water is definedas the amount of water consumed in the production process of a product which is also known as the water embodied in the product (Allan, 1997). The virtual water concept encourages the trade of water intense products from water rich countries to water scarce countries instead of physical water(Zimmer and Renault , 2003). The water footprint is conceptually similar to virtual water in that both represent the water required to make a product considering all inputs in the supply chain (Aldaya et al., 2009). Trade of real water between water abundant and water scarce regions is generally impossible due to the large distances and associated costs, but trade in water-intensive products (virtual water trade) is realistic(Hoekstra and Hung , 2005).

The water footprint considers the source (irrigation or rainwater) of water used (Hoekstra et al., 2007). Understanding the source of the water used in a product's supply chain is necessary for better management of water resources and has a potential to assist in water allocation within a catchment level (Hastings and Pegram, 2012).Traditionally, the focus was given to the blue water (irrigation water) only while neglecting part of the water that is used by the crop which results from rainfall and soil moisture (Aldaya et al., 2009). Studies (Falkenmark and Rockström 2004; Allan,1997) have emphasized the importance of including green water in agriculture as a potential for reducing irrigation water consumption.

Green water is the water retained in the upper layer of the soil profile following a rainfall event, which is subsequently drawn on by a plant's root system. Irrigation scientists have traditionally called this “effective rainfall”, i.e. that proportion of rainfall that directly contributes to plant transpiration (Perry , 2014). Blue water is referred to as water that in the rivers and aquifersused in the production process, for example water used for irrigation (Hoekstra et al., 2011).

The water footprint concept is relatively new and until recently there was no internationally accepted method for estimating the water footprint. The aim of this literature review is to review approaches used to determine the water footprint and water productivity of crops.

2.2 Method for water footprint assessment

2.2.1 Life Cycle Assessments Approach

A Life Cycle Assessment (LCA) aims to determine the environmental impacts caused by products from starting with impacts of producing raw materials up to disposal of waste associated with the product (cradle to grave)(Jefferies et al., 2012). LCA methodologies therefore include impacts of depriving human users and ecosystems of water resources, as well as specific potential impacts from the emitted contaminants affecting water, through different impact pathways (Canals et al., 2009). The LCA methodology includes four phases;setting the goal and scope, inventory accounting, impact assessment and interpretation(Boulay et al., 2013). Quantitative impact indicators are at the core of the impact assessment phase (Ridoutt and Pfister, 2010). There are different methods proposed to quantify impact oriented water footprints within the standard framework of LCA (Canals et al., 2009; Pfister et al., 2009; Ridoutt et al., 2010). Water consumption is often used to describe water removed from and not returned to a drainage basin, e.g change in evaporation caused by land use change is often referred to as water consumption when using the LCA approach.

The LCA approach proposes that when estimating the WF, green water should not be included as this is used by natural ecosystems regardless of the production system being considered (Canals et al., 2009). The LCA approach enables a comprehensive impact assessment of freshwater consumption (Pfister et al., 2009).

2.2.2 Hydrological Based Water Footprint Approach

Dreuer et al.(2011) introduced a method for determining the water footprint based on considering all components of the water balance and not just water consumption. According to this method a negative water footprint is possible if the recharge of the blue water resource through return flows and precipitation exceeds the volumes abstracted. A negative water footprint is therefore required to sustain ecosystems that are dependent on groundwater. A positive water footprint indicates water abstraction exceeds recharge through return flows and precipitation (Deurer et al., 2011). A zero water footprint occurs if return flows and precipitation are equal to abstraction. Data used to calculate water footprints is obtained at a local scale and over an annual hydrological year (Herath et al., 2013). The methodology is also best applied at a watershed level where there is sufficient data of flows and abstractions.

2.2.3 Water Footprint Network (WFN) Methodology

In 2011 the WFN published the first comprehensive water footprint assessment manual containing recommended methodology to determine the impact on water resources by individuals, communities, businesses as well as during the production of products (Hoekstra et al., 2011).According to the WFN a full water footprint assessment consists of four steps(Hoekstra et al., 2012). The steps are;

1. Setting goals and scope ,
2. Water footprint accounting

3. Water footprint sustainability assessment and
4. Water footprint response formulation

2.2.3.1 Setting goals and scope

The WFN puts an emphasis on setting goals and scope because a water footprint study can be undertaken for many different reasons, therefore setting the goals and scope allows for transparency. For example, private sector organizations are often interested in understanding water dependencies in their supply chain of products to understand the risk associated with water shortage, whereas for the public sector knowledge of the water footprint will inform policy and strategies. Different types of analyses and information are required to achieve these different goals (Hastings and Pegram, 2012).

2.2.3.2 Water footprint accounting

The accounting phase includes the quantification and mapping of freshwater use with three distinct types of water sources; the blue, grey and green water footprints (Mekonnen and Hoekstra,2011). The water footprint of crops is most sensitive to the method used for estimating the reference evapotranspiration and the crop coefficient, followed by the crop growing season (Zhuo et al., 2014). Therefore when estimating water footprint of crops the first step is to estimate ET_c (equation 2.1). The green water footprint is assumed to be the minimum of evapotranspiration and effective rainfall (Hoekstra et al., 2011). This is because when effective rainfall is higher than evapotranspiration then it is assumed that the farmer will not irrigate, while if effective rainfall is low the farmer will have to irrigate to supplement the crop water use.

$$ET_C = ET_o \ * K_c \qquad (2.1)$$

where ET_c = crop evapotranspiration

ET_o = reference evapotranspiration

K_c = crop coefficients

Effective rainfall (P_{eff}) refers to the part of the total amount of precipitation that is retained by the soil and is potentially available for meeting the water need of the crop (Hoekstra et al., 2011). There are various methods used to estimate effective rainfall based on total rainfall. Effective rainfall is assumed to be any daily rainfall greater than 5mm/day in different climatic regions (Rahman et al., 2008; Dastane,1978). Rainfall less than 5mm/day is considered not effective because it will evaporate, while only approximately 75% of rainfall above 5mm/day is considered useful to the crop because excessive runoff will become runoff (Rahman et al., 2008).

2.2.3.3 Water footprint sustainability assessment

According to Hoekstra et al.(2011), water use in a catchment is not sustainable when the ecological reserveand or ambient water quality standards are compromised, or when water allocation is inefficient or unfair. Two criteria for judging sustainability are when (1) a process is located in a certain catchment at a certain time of year where the overall water footprint is unsustainable, and (2) either the blue, green or grey water footprint can be reduced or avoided altogether at acceptable societal cost. The overall sustainability of the water footprint of the catchment or basin as a whole needs to be known before a sustainability assessment for a product or process can be assessed.

Hoekstra et al., (2011) suggest that sustainability be assessed from three different perspectives as follows:

1) **Environmental** – River and groundwater flows must be maintained at levels that adequately support the dependent ecosystems and human livelihoods. Pollutant levels must remain below water quality standards (although these standards are not always prescribed).
2) **Social** – A minimum amount of safe and clean water is needed for basic human needs, namely drinking, cooking and washing. The Universal Declaration of Human Rights established food as a human right, so the water required for producing this food can be linked and considered a right even if not formally established. As communities can import their food from other catchments, allocation of water to food security should be secured at a global level.
3) **Economic** – The allocation and use of water needs to be done in an economically efficient way, and the benefits of use should outweigh the costs.

Identifying and quantifying sustainability criteria, followed by the identification of hotspots are the first two steps of a site-specific sustainability assessment. Deciding at which scale to look for hotspots appears to be a challenge as hotspots may disappear at coarse spatial resolutions, and much more data is needed to identify hotspots at fine spatial resolutions. For the case of pollution, pollutants may accumulate downstream, in which case problems might only emerge at larger scales.

2.2.3.4 Water footprint response formulation

The final step in a water footprint assessment as recommended by WFN is to formulate mitigation measures if the process is unstainable (Hoekstra et al., 2011). Mitigation is often done by the water user responsible for unsustainable water use (Hastings and Pegram 2012).

2.2.3.4.1 Application of the WFN

Water footprints within the agricultural sector have been studied extensively, mainly focusing on the water footprint of crop production, at different scales from catchment(Aldaya and Llamas, 2008), national level (Hoekstra and Chapagain, 2007; Kampman et al., 2008) to global scale (Hoekstra and Chapagain, 2007; Mekonnen and Hoekstra, 2011; Hoekstra and Mekonnen, 2012). Although the WFN approach has been used successfully to estimate the water footprint of crops in the above mentioned studies the approach have also received some harsh criticism from different scholars (Wichelns, 2011; Perry 2014; Ridoutt and Pfister, 2010).

2.3 Evapotranspiration

The estimation of evapotranspiration is central during the determination of the water footprint. Methods used for evapotranspiration are therefore reviewed in this section. Evapotranspiration (ET_c) is a combination of evaporation and plant transpiration from the earth's surface to the atmosphere, and is an important component of the hydrologic cycle (Shuttleworth,2008). Evapotranspiration rates are influenced by several factors such as weather parameters, crop characteristics, crop management and environmental aspects (Allen et al., 1998).

In semi-arid areas where water is scarce, reliable estimates of evapotranspiration (ET_c) are important for efficient irrigation scheduling and water resource planning (Hunsaker et al.,2005). Proper estimation of ET_c is also important for improved water management, and water productivity in agriculture in general (Lee,2004). ET_c is different for each crop and is strongly affected by factors such as the location of the crop, climatic conditions and the plant canopy.

There are several methods that have been successfully used to estimate evapotranspiration from crops(Mo and Liu,2001; Nouri et al., 2013; Schrader et al., 2013; Lee,2004; Kairu,1991; Sabziparvar and Tabari, 2010; Shuttleworth, 2008). The most common types of direct evapotranspiration measuring techniques that have been used in various studies in South Africa includethe use of surface layer scintillometers(Savage et al., 2010), lysimeters, eddy covariance and indirect techniques such as remote sensing(Singels and Laan,2011a; Savange et al.,2010; Dzikiti et al., 2014; Singels and van der Laan,2011b; Franke et al., 2011).

2.3.1 Lysimeters method

Lysimeters are tanks filled with soil in which crops are grown under natural conditions to measure the amount of water lost by evaporation and transpiration(Kairu, 1991). There are two types of lysimeters, the weighing and non-weighing type. The non-weighing type estimates crop water use as the residual term in the soil water balance equation after measuring all the other components including water inputs (rain and irrigation), outputs (drainage and runoff), and change in soil water storage(Hutson et al., 1980). While weighing lysimeters measure crop water use directly by measuring the change in weight of an isolated soil volume. Use of lysimeters assumesthat the sample of soil and overlying vegetation on which measurements are made are representative in terms of soil water content, and vegetation growth (Shuttleworth, 2008).Globally lysimeters have been successfully used to measure $ET_c$of crops such as rice, potatoes, maize (Tyagi et al., 2000; Kang et al., 2004).

In South Africa lysimeters have been used to estimate evapotranspiration of crops which belong to the *Poaceae*family (sugarcane, wheat and maize),*Solanaceae* family (potatoes and tomatoes) and *Amarylidaceae* family(Hutson et al., 1980; Olivier and Singels, 2012; Berliner and Oosterhuis, 1987; Inman-Bamber and McGlinchey, 2003; Mottram and Clemence, 1984; Zerizghy et al., 2013). Some authors(Trajkovic,2010)consider that lysimeters ET_c measurements are the most accurate. However it is impractical to use lysimeters for the whole farm as they are too expensive(Malek and Bingham, 1992; Spittlehouse and Black,1978).

2.3.2 Bowen Ratio Energy Balance Method (BR)

The Bowen Ratio Energy Balance Method (BR) uses air temperature and water vapour pressure above the canopy, surface net irradiance and soil heat flux densityto estimate ET_c(Malek and Bingham, 1992; Tomlinson, 1996; Spittlehouse and Black, 1978; Shuttleworth, 2008). The method assumes that the turbulent diffusion coefficient for sensible heat and latent heat are the same in the lower atmosphere in all conditions of atmospheric stability, and that plot-scale measurements of energy budget components(net radiation, soil heat) are representative of upwind conditions(Shuttleworth,2008).The BR method is usually derived from air temperature and water vapour pressure sensors at two levels.A limitation of this method is that the two sensors need to enable accurate estimates of small differences of temperature and vapour pressure at two heights (Euser et al., 2014). Another disadvantageof the BR method is that it is a point measurement and is easily affected by winds. According to studies done by Malek and Bingham (1992), and Spittlehouse and Black (1978)the method gives the closest evapotranspiration results to lysimeters compared to the other methods.

2.3.3 Eddy Covariance method

The eddy covariance method is a commonly used micrometeorological technique providing direct measurements of latent heat flux (or evapotranspiration). A sonic anemometer is used to measure high-frequency vertical wind speed fluctuations and an infrared gas analyser to measure high frequency water vapour concentration fluctuations (Consoli, 2008). These fluctuations are paired to determine the mean covariance of the wind speed and humidity fluctuations to directly estimate latent heat flux (Kairu, 1991;Consoli, 2008). The method also estimates the sensible heat flux using the covariance of the fluctuation in vertical wind speed and variations in temperature (Kairu, 1991). The eddy covariance method also avoids soil surface heterogeneity issues by placing the sensors above the crop canopy and can be used for various types of vegetation(Shuttleworth, 2008).The eddy covariance method has been used widely in agriculture and forestry in South Africa(Gush et al., 2009; Mengistu et al., 2005),because the method involves few theoretical assumptions (Farahani et al., 2007).

2.3.4 Scintillometry

A scintillometer is used to measure path-weighted sensible heat flux. The fluctuations in the intensity of visible or infrared radiation above the plant canopy of interest are measured(Shuttleworth, 2008). Scintillometers optically measures the structure parameter of refractive index of air, reflecting the atmospheric turbulence structure. Depending on the aperture size, scintillometers are classified into small (SLS, beam path length of 50 – 250 m) and large aperture scintillometers (LAS, beam path length of 250m– 5km, and path length of >10 km for boundary layer scintillometers). Sensible heat flux is estimated using what is referred to as Monin-Obukhov similarity theory(Meijninger et al., 2002; Savage, 2009). A scintillometers cover a much larger area compared to all the methods discussed above. Scintillometers have been successfully used in several studies(Odhiambo and Savage,2009; Savange et al., 2004 ; Savange et al.,2010).

2.3.5 Surface Energy Balance Algorithm for Land (SEBAL) model

Over the last decade remote sensing techniques have been widely used to estimate evapotranspiration(Nouri et al., 2013; Sabziparvar and Tabari, 2010).Remote sensing methods provide a powerful means to compute ET_c from the scale of an individual pixel right up to an entire raster image (Matinfar, 2012). There are several different remote sensing methods (MODIS, SEBS, and SEBAL) that can be used to estimate evapotranspiration and most of these techniques have been reviewed intensively for application in South Africa and globally (Gibson et al., 2013). These techniques have been applied in agriculture(Klaasse et al., 2011; Jarmain et al., 2011)for water resource management (Gibson et al., 2009; Hellegers et al., 2011).

One such model, namely SEBAL, is an image-processing model comprising of 25 computational steps that calculate the evapotranspiration and potential evapotranspiration rates as well as other energy exchanges between land and atmosphere (Wang et al., 2009). The key input data for SEBAL consist of satellite radiance data (visible, near-infrared, thermal infrared portions of the spectrum), and local meteorological data (humidity, wind speed, solar radiation, air temperature). Klaasse et al.,(2008) used the SEBAL method to estimate the evapotranspiration, biomass production and water use efficiency of grapes (table and wine) in the Western Cape for three crop seasons. The study generated interest in different sectors and led to the development of an operational project where remote sensing-based data and other information were made available at a weekly time step via a GrapeLook website (Klaasse et al., 2011).

Grapelook subsequently extended to include deciduous fruit producing areas of the Western Cape and the additional product was termed Fruitlook (Jarmain and Klaasse, 2012). The resolution of Fruitlook is 30m×30m and it is fine enough to allow identification of spatial differences within a typical orchard block (Figure 2.1). Grapelook “operational” approach has been replicated in sugarcane and grain crops to assess the water use efficiencies of these crops.

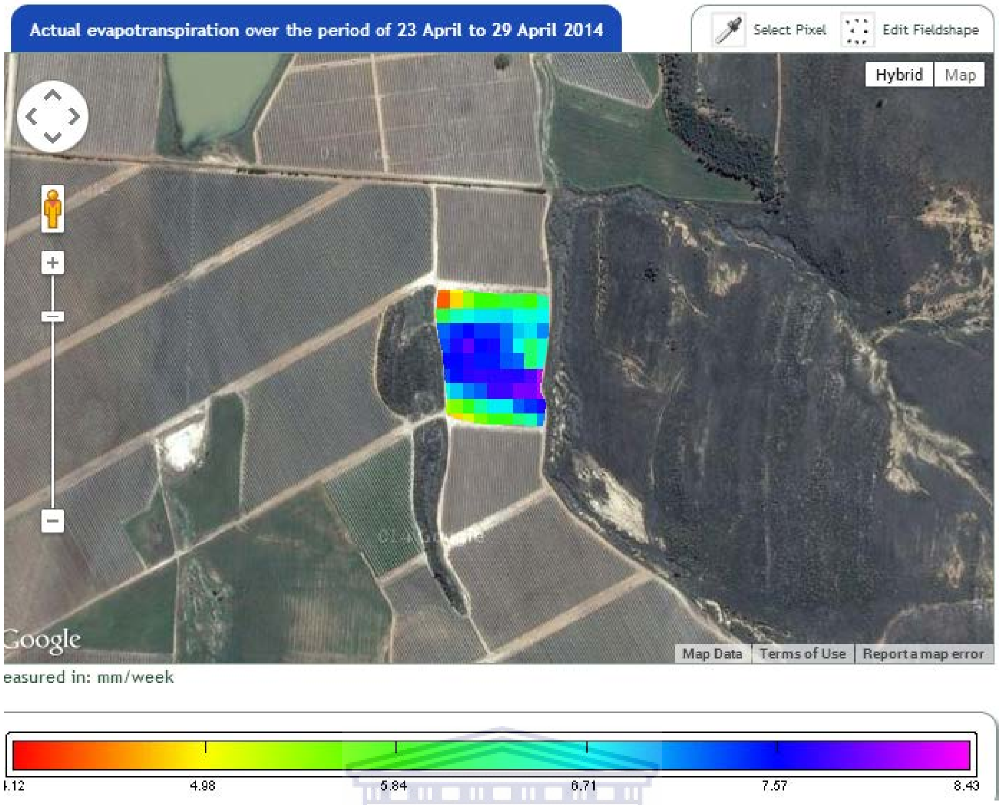

Figure 2. 1 Evapotranspiration of pink lady apples at Nooitgedacht farm downloaded from the Fruitlook website (www.fruitlook.co.za).

2.3.6 Penman-FAO 56 method

In most cases where estimates of crop ET_c rates are required, the available instrumentation or resources are not sufficient to allow use of the ET_cmeasurement techniques described above, empirical models are used instead(Farahani et al., 2007). The most commonly used method for estimating evapotranspiration of plants is the FAO-Penman Monteith Method (Allen et al., 1998).FAO-Penman Monteith Method is a two-step approach used to estimate crop evapotranspiration(Farahani et al., 2007). The first step is to calculate reference evapotranspiration using the Penman-Monteith equation (Equation 2.1) and the second step is to determine the specific crop coefficient (Allen et al., 1998).

$$ET_o = \frac{0.408\,\Delta\,(Rn - G) + \gamma\frac{900}{Ta} + 273U2\,(es - ea)}{\Delta + \gamma(1 + 0.34U2)} \qquad (2.1)$$

where ET_o= reference evapotranspiration (mm day^{-1});

Rn = net radiation (MJ m^{-2} day^{-1});

G = soil heat flux (MJ m−2 day−1);

γ = psychrometric constant (kPa $°C^{-1}$);

es = saturation vapour pressure (kPa) ;

ea = actual vapour pressure (kPa);

Δ=slope of the saturation vapour pressure-temperature curve (kPa °C−1);

T = mean daily air temperature (°C)

U_2 = mean daily wind speed at 2-m height (m s^{-1}) (Allen et al. 1998).

The Penman-Monteith method has been used successfully around the world to estimate the reference crop evapotranspiration and also in South Africa(Gibson et al., 2013; Matinfar 2012; Israel, 1998; Savage, 2009; Odhiambo and Savage ,2009). The Penman-Monteith methodwas adopted as a standard by the Food and Agriculture (FAO).

Jensen (1968) developed the concept of crop coefficient (K_c). There are two types of the K_c values (Allen et al., 1998), the first and the most commonly used type is the single K_c approach while the second one is referred to as the “dual” K_c approach.Single K_c approach is defined as the ratio of the actual crop evapotranspiration (ET_c) to reference evapotranspiration (ET_o) andthis varies predominately with crop characteristics(Farahani et al., 2007).

Single crop coefficients are influenced by climate, irrigation method, mulching practice, growth in greenhouse,indicators of the development of the crops, such as both leaf area index (LAI) and ground cover indexes (Allen et al., 1998). To take into account these factors local estimated K_c values where available should be used to get accurate estimates of ET_c. However in cases where there are no locally derived crop coefficients then published crop coefficients are the best alternative (Farahani et al., 2007). K_c values are estimated from reference evapotranspiration and the actual evapotranspiration. For most agricultural crops $K_c$increases from a minimum value at planting until maximum K_c is reached at approximately full canopy cover. The $K_c$tends to decline at a point after a full cover is reached before the harvest season.

The FAO-Penman Monteith method led to the development of CROPWAT tool. CROPWAT was developed by Allen et al.,(1998). Its main objectives are to calculate reference evapotranspiration, crop water requirements, irrigation requirements, scheme water supply, develop irrigation schedules under various management conditions and evaluate the efficiency of irrigation practises. CROPWAT has been successfully used in several studies globally (Dinpashoh ,2006; Bekele and Tilahun 2007; Cavero et al., 2000; Feng et al., 2007). In South Africa a version of CROPWAT called SAPWAT was developed to suite South African conditions and SAPWAT is supported by an extensive South African climate and crop database (Woyessa et al ., 2004).

2.4 Water productivity

Due to rapidly increasing population (CA, 2007) the agricultural sector is faced with a challenge to produce more food while using less water.Food insecurity and water stress cannot be addressed in isolation because water is a key resource in food production(Peck,2007). Improving access to water and productivity in its use can contribute to greater food security, nutrition, healthstatus, income ,and resilience in income and consumption patterns(Brauman et al., 2013).

Water productivity is the ratio of the net benefits from crop, forestry, fishery, livestock and mixed agricultural systems to the amount of water used to produce those benefits. In its broadest sense, water productivity reflects the objectives of producing more food, income, livelihood and ecological benefits at less social and environmental cost per unit of water consumed(Renault and Wallender ,2000).

2.4.1 Crop Water Productivity (CWP)

Agronomists often interchange the waterproductivity concept and the water use efficiency (WUE) concept. They define both concepts as the ratio of yield to water consumed (kg/m^3) by the crop through evapotranspiration at the field scale(Fan et al., 2013; Mdemu and Francis,2006; Ferrara et al., 2008). Several authors refer to this definition as misleading because the two concepts exist in agriculture and are defined differently (Molden,1997; Passioura, 2005; Ali and Talukder 2008; Perry et al., 2009). The simple definition of any efficiency should be expressed as a percentage or ratio, the input and output units should be similar (Sadras et al., 2011), while crop water productivity (CWP) is also a ratio of output to input but with different units (Equation 2.2).

$$\mathrm{CWP} = \frac{\mathrm{Y\ (kg)}}{ET_c}\ (\mathrm{Kg/m^3}) \qquad (2.2)$$

Where Y is the actual marketable crop yield (Kg ha^{-1}) and ET is the seasonal crop water consumption by evapotranspiration (m^{-3} ha^{-1}).

2.4.2 Apparent Water Productivity

The concept of AWP is used to describe the economic efficiency of crops. Salmoral et al.,(2011)defined the AWP as the market price per water footprint of a crop. Salmoral et al., (2011) applied the concept of apparent water productivity of oliveoil intwo provinces in Spain and established that the AWP of olive oil differs per region and also per time of the year. This is because market prices of products are influenced by interaction of supply and demand.

Factors Affecting Crop Water Productivity

There is an incorrectassumption that improving crop water productivity is often only related to irrigation water management.However Zwart and Bastiaanssen (2004) proposed that crop water productivity is influenced by controllable factors such as irrigation practises, crop rotation, quantity of chemical fertilizers, pests and weed control.

Irrigation systems include the use of sprinkler system, drip system, centre pivot irrigation (Al-ghobari et al., 2014; Zhang ,2003). Irrigation management is crucial in determining plant ability to take up the nitrogen available in the soil since a well-watered crop is more capable to take benefit of the applied fertilizer (Costa et al., 1997). Several studies have assessed the impact of deficit irrigation on the crop water productivity (Mdemu and Francis 2006; Ali et al., 2007; Ali and Talukder 2008; Geerts and Raes ,2009) using different irrigation system.

2.5 Summary

The LCA methods and the water balance analyses are more suitable for water footprint assessments at a larger scale (a river system) than farm gate level. The LCA approach is by far the closest approach to the ISO water footprint standard (ISO

14046) approach. The ISO standard (ISO 14046) approach was developed to avoid confusion around the definition of water footprints, and provides a consistent approach to the quantification of water footprints. The ISO standard approach is very similar to the LCA approach and the approaches are more concerned on the impacts related to the water footprint rather than the volumetric water footprint recommended by the WFN approach.

The WFN approach requires the estimation of the actual evapotranspiration and is suitable for estimation of water footprint at the farm gate level compared to all the other methods. According to the WFN approach over 90 % of crop water footprint is evapotranspiration. Proper estimates of ET_c are important in water resource management as underestimation or overestimation of water use can have negative impacts on crop production. There are several methods that can be used to directly or indirectly measure/ model ET_c.

Direct measurement of $ET_c$is the most accurate and preferred over indirect methods;however they are also very expensive and not always practical. Indirect ET_c estimating methods have also been widely used in different regions around the world and they have shown a small margin of error and they have been trusted as an alternative in the absence of direct measurements.One of the methods that are trusted in the absence of direct measurements is the FAO-Penman Monteith Method.

Increasing/improving blue water productivity in irrigated agriculture is critical in meeting food demands of the growing population density. There are several factors which affects the water productivity some controllable and some uncontrollable. There are several definitions of water productivity however in this study crop water productivity was defined as crop yield per crop water use while apparent water productivity was defined as water footprint per market price.

3 METHODOLOGY

3.1 Description of study area

The Olifants/Doorn Water Management Area (WMA) was chosen for the study area as this experiences extreme water scarcity (CSIR, 2012) and is consequently a relevant area to apply emerging water-conservation principles and approaches. The WMA lies along the west coast of South Afric and is shared by the Western Cape and Northern Cape provinces. The mean annual precipitation (MAP) of much of this WMA is generally less than 200mm/year, while potential evaporation rates exceed 1800mm/yr (Figure 3.1), which renders it largely unsuitable for dryland agriculture. Consequently there is approximately 500km² under irrigated agriculture, which accounts for 87% of the total water use of this WMA (DWA, 2012). Irrigation water is sourced primarily from Olifants River, Doorn River and farm dams in the Citrusdal and the KoueBokkeveld region. Within the Sandveld region, groundwater is the main source of water irrigation for potatoes(de Lange and Mahumani, 2012).

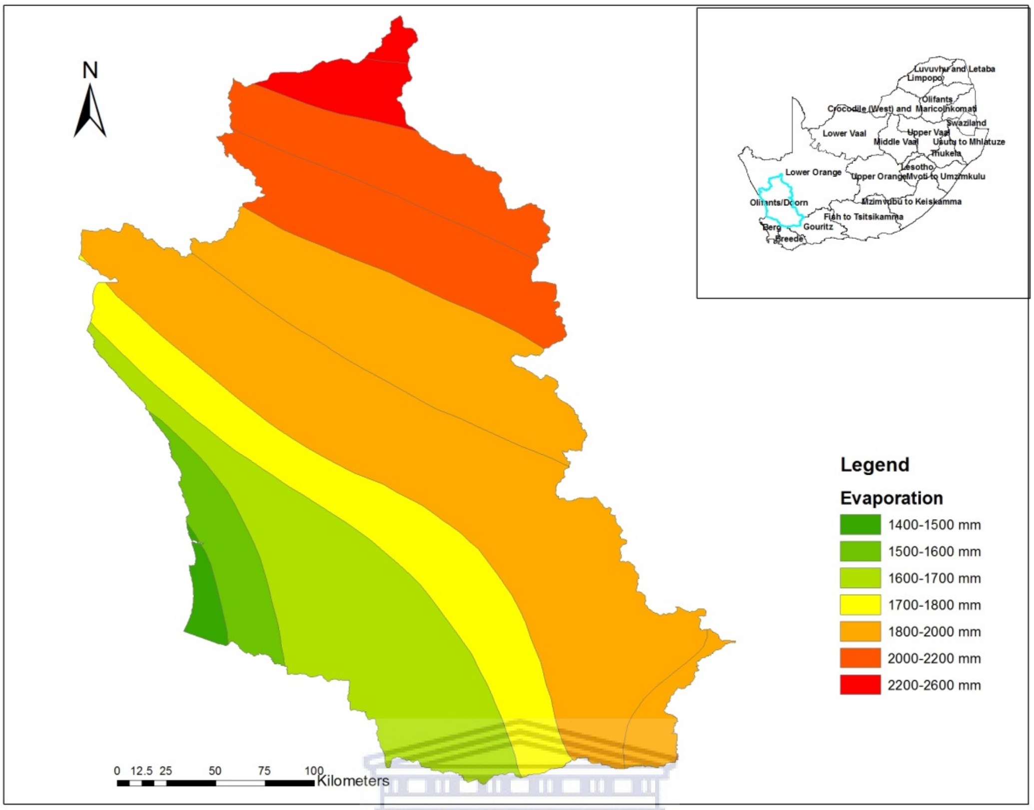

Figure 3.1: Annual potential evaporation rates (mm) at Olifants/Doorn WMA (data source: WR2005).

The geology of the Olifants/Doorn WMA (Figure 3.2) is dominated by metamorphic rocks on the western part of the WMA, while the eastern part is dominated by the shale rocks. On the northern and north-eastern parts, the rocks of the pre-Cape Van Rhynsdorp Group, the sedimentary rocks of the lower Karoo Supergroup as well as intrusive Karoo dolerites are dominant. Various metamorphic rocks (i.e. quartzites, granulite and schists), augen gneisses as well as mafic gneisses of the Garies and Bitterfontein Subgroups (Okiep Group) are overlain by sediments of the Nama Group in the north-western portion of the WMA (DWA, 2012).

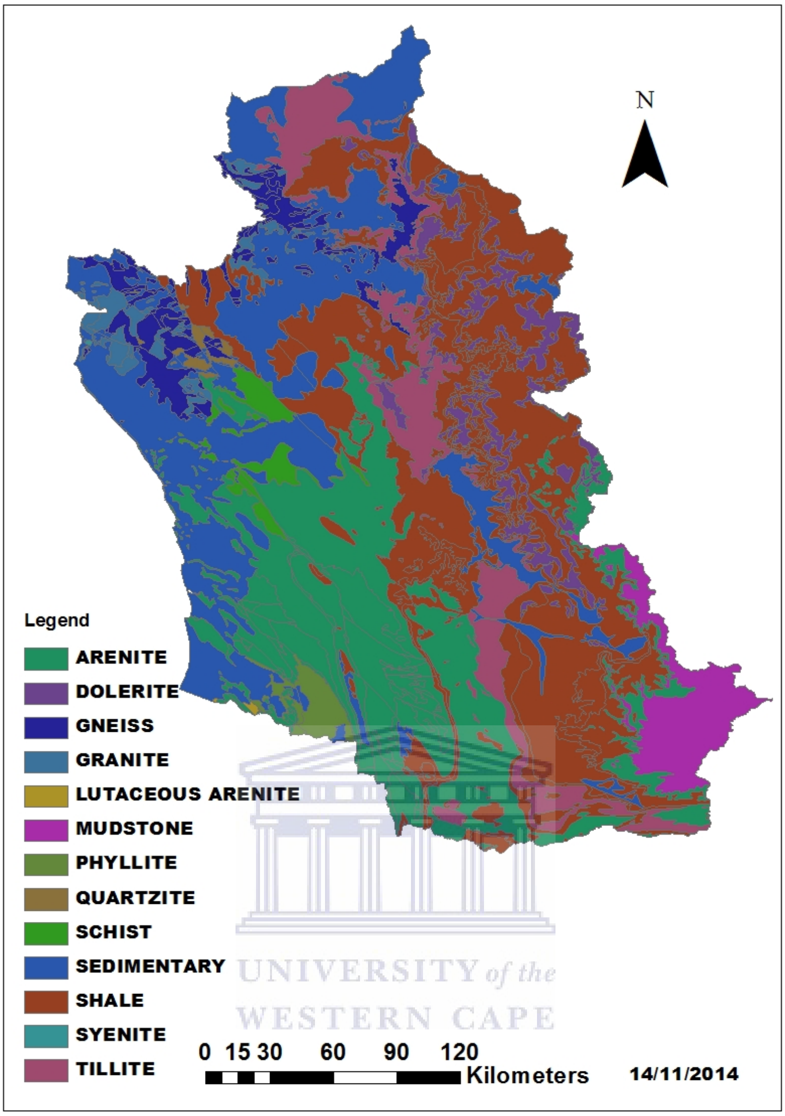

Figure 3.2:Geology of the Olifants/Doorn WMA (Data source WR2005)

The Olifants/Doorn WMA has four regions in terms of crop production (DWA 2012), namely the:

1. KoueBokkeveld (deciduous fruits),
2. Citrusdal (citrus),
3. Lower Olifants (wine grapes), and
4. Sandveld area (potatoes)

For the purpose of this study, three farms were selected comprising one farm for citrus (Navel oranges), one for deciduous fruit (Pink lady apples), and one farm for potatoes (Mondial). The selection criterion of the farms was dependent on the willingness of the farmer to participate in the study and also on the availability of historical weather and crop water use data close to the farm.

3.2 Data collection

To estimate water footprint and crop water productivity of crops, meteorological data, crop yield and indirect water use data for one growing season was obtained for the three farms within the Olifants/Doorn WMA.

3.2.1 Meteorological data

Hourly and daily weather data was obtained from the automatic weather stations installed at each farm by the CSIR (Council for Scientific and Industrial Research) and the University of Pretoria. Each AWS (Figure 3.3) had been installed according to standard conditions specified in FAO-56 (Allen et al., 1998). The weather data collected was used to determine ET_o using the Penman-Monteith method (equation 2.1) as described by Allen et al., (1998).

Figure 3. 3:An automatic weather station at Modderfontein Farm within the Sandveld catchment.

This study aims to assess thevolumetric blue and green water footprints of the three commercial crops. The scope of this study is presented Table 3.1 and it was created following the scope guideline questions provided in the Water Footprint Network (WFN) manual (Hoekstra et al., 2011).

Table 3. 1: The water footprint scope applied in the study

Scope Criteria	**Scope Applied in study**
Consider blue, green and/or grey water footprint?	Blue and green water footprint
Where to truncate the analysis when going back along the supply chain	From production to packhouse
Which period of data?	One growing season
Consider direct and/or indirect water footprint?	Both Direct and indirect

Growing season for Navel oranges was (May 2013-April 2014), for Pink lady apples growing season (October – April) and for Mondial potatoes growing season was 120 days (February- June 2013).

3.3 Water footprint accounting

Green and blue water footprints for production were estimated for all the three crops following the water footprint network approach for one growing season. Green water footprint was estimated as the minimum between evapotranspiration and effective rainfall (P_{eff}) divided by crop yield (Mekonnen and Hoekstra,2011). Effective rainfall isdefined as part of rainfall that is stored in the root zone and can be used by the plants after percolation and runoff. Effective rainfall was determine following Equation (3.1) below

$$P_{eff} = Max\ (P - 5{,}0) * 0.75 \text{ (mm/day)} \qquad (3.1)$$

Where P_{eff} = effective rainfall (mm/day), P = daily rainfall in mm/day

5.0 = minimum effective per day (mm/day) and 0.75 = the percentage which is considered effective until runoff occur.

The blue water footprint was estimated as the sum of blue crop water use (CWU_{blue}) and the additional water used in other stages of crop production divided by crop yieldfor the same growing season (Mekonnen and Hoekstra ,2011). The blue water use was estimated as the difference between ET_c and effective rainfall, but was zero if effective rainfall exceeded ET_c (Equation 3.2).

$$CWU_{blue} = ET_c - P_{eff};\ CWU_{blue} \qquad (3.2)$$

CWU_{blue}= 0 if $P_{eff} > ET_c$

Where CWU_{blue} = blue crop water use (mm/day)

P_{eff} = effective rainfall (mm/day)

ET_c= cropevapotranspiration (mm/day)

Both blue and green water use were estimated from the first day (d=1) of the crop growing season to the last day of harvest(Mekonnen and Hoekstra, 2011). Additional water use included packhouse water use, damevaporation,water used for pesticides and fungicides for crop washing from farm dams (Appendix 1). Two flow meters were installed at Modderfontein Farm to measure packhouse water use and water used to wash potatoes respectively, while at Patrysberg Farm a flow meter was installed to measure packhouse water use. Dam evaporation was estimated using the Penman equation.

3.4 Crop water productivity

Crop water productivity for each crop was estimated as the ratio of marketable crop yield to crop water use Equation (3.5):

$$\mathrm{CWP} = \frac{\mathrm{Y}}{ET_c} \ \mathrm{kg/m^3} \qquad (3.5)$$

where Y is the actual marketable crop yield (Kg ha^{-1}) and ET$_c$ is the seasonal crop water consumption by evapotranspiration (m^{-3} ha^{-1}).

Apparent water productivity

The apparent water productivity (AWP)of each crop was estimated as the ratio of market price (Pr) and the water footprint (Litres/kg).

$$\mathrm{AWP} = \frac{Pr}{WF} \qquad \text{Rand/litres} \qquad (3.6)$$

where AWP= apparent water productivity, Pr = the market price in South African Rands/litre and WF = the water footprint of each crop in Litres/kg.

The 2014 market price for each crop was collected from the relevant organizations; Potato SA (Potatoes), South African Apple and Pear Producers' Association (Apples) and Citrus growers Association of South Africa (Oranges)

4 NAVEL ORANGES

4.1 Introduction

*Citrus sinensis*commonly known as orangesare citrus fruitsthat belong to the Rutaceae family. Citrus species are produced all over the world due to their ability to adapt to different climatic conditions. Major citrus producing areas are within the southern hemisphere, of which Brazil is the leading producer. Brazil produces over a quarter of all oranges produced globally. Within the SADC region, South Africa is the leading producer of oranges. In terms of gross value in South Africa, the citrus industry is the third largest horticultural industry after vegetables and the deciduous fruit industry (DAFF, 2011).

In South Africa the Western Cape Province (Citrusdal region) is the second largest producer of navel oranges after the Eastern Cape Province.Citrusdal is known for citrus production hence its name “Citrusdal”, and exports more citrus fruits than any citrus producing area in South Africa. Irrigated agriculture is dominant in this area and farmers abstracts freshwater from the Olifants River and Clanwilliam Dam for irrigation during dry summer months (DWA, 2012). Some farmers rely on runoff from the mountains to fill their dams during the rainy season.

Citrus trees are subtropical in origin and cannot tolerate severe frosts. Citrus production in South Africa is therefore confined to areas with mild and almost frost-free winters where temperatures (not more than once in several years) never below –3 °C. The average minimum temperature for the coldest month should not be below 2 to 3 °C if no protection is provided(DoA, 2003).

Citrus trees require water all year round and normally the peak demand for water is during summer. The trees are sensitive to soil moisture availability. Soil moisture strongly influences flowering and fruit set and can affect fruit drop, fruit size, yield, internal quality characteristics and canopy development (Hutton et al.,2007).Water stress during late spring and summer (November-February) at the time of late cell division and expansion will have an impact on fruit size. Water stress closer to harvest influences internal fruit quality characteristics such as acidity, juicecontent and fruit maturity (Hutton, 2000).

The knowledge of crop water requirement is crucial for effective management of water during citrus production in order to get optimal yields.Researchneeds to be done on both the direct and indirect water use of oranges along the entire production chain (Water footprint) in semi-arid areas. The knowledge of water footprints assists in improving management of water resources andto improve their crop yield.This chapter presents the results of the assessment of water footprint and the water productivity of Navel oranges in Patrysberg Farm, Citrusdal in the Olifants/Doorn Water Management Area.

4.2 Site description

The study was conducted between April 2013- May 2014 at Patrysberg Citrus farm (32°27'09.15"S and 18°58'16.60"E) in the Citrusdal Area.The farm is located within a Mediterranean climate region and receives winterrainfall. Temperatures in the area range from 5°C in winter to 35°C in summer.The farm size is approximately 750 ha, howeverthis study was conducted for an orchard which was 3.9 ha.The oranges are grown under drip irrigation (2 drip lines per tree). Average tree height was approximately 3m high at the time of the study.The citrus trees were planted in 2001.

Row orientation is North –South and the trees are spaced at 2.4 m by 5 m, giving a planting density of approximately 800 trees per ha, with bare sand between rows.

4.3 Data required and specific method

The following data was required:

- Weather data (temperature , solar radiation, net radiation ,relative humidity, wind speed and rainfall)
- Crop yield
- Indirect water use

Weather data was collected from the automatic weather station at Patrysberg for the whole growing period (May 2013 to April 2014) and wasused for estimation of reference evapotranspiration usingthe Penman-Monteith method. Reference evapotranspiration and locally derived crop coefficients (K_c) values (Figure 4.1) were used to estimate evapotranspiration (ET_c). The K_c values were derived from previous study Taylor et al. (2014). Taylor et al., (2014) derived K_c values from ET_c (measured using Eddy Covariance technique) and ET_o following equation 4.1 below.

$$K_c = \frac{\mathrm{ET_c}}{ET_o} \tag{4.1}$$

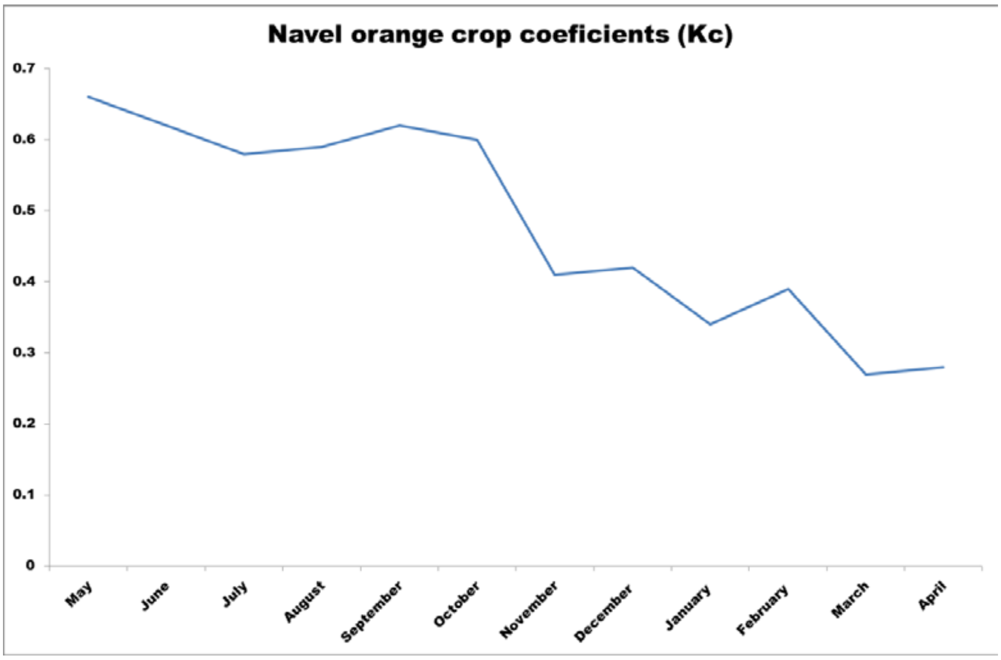

Figure 4.1: Locally derived crop coefficients at Patrysberg Citrus Farm (Taylor et al., 2014).

Indirect water use data required for estimating the blue water footprint was collected through interviews with farmers,monitoring of packhouse water use which was measured using a flow meter (Figure 4.2). Indirect water use in orange production included evaporation of water from storage dams, water use for spraying of pesticides and fungicides, packhouse water use (see appendix 1). Evaporation from farm dams was estimated following Penman equation.

Figure 4.2: Flow meter installed at Patrysberg Farm to measure water that was used in the packhouse for 2013/2014 Navel orange.

The yield of 69 ton/ha of Navel oranges per hectare for the same growing season required to estimate both water footprint and crop water productivity was collected through interviews with the farmer.

4.4 Results

4.4.1 Rainfall and effective rainfall

Figure 4.4 presents rainfall measured at the Patrysberg Farm for the whole growing season (1st May 2013- 30 April 2014). A total rainfall of 344 mm/year was received during the 2013/2014 growing season and 45% of the rainfall was estimated to be effectiverainfall. Fifty percent of the rainfall occurred during the beginning of the growing season (between May-August 2013), which is typical of the Mediterranean climate. Mediterranean climate are known for wet winter and dry summer however rainfall of approximately 28mm of rainfall was measured at the in January.

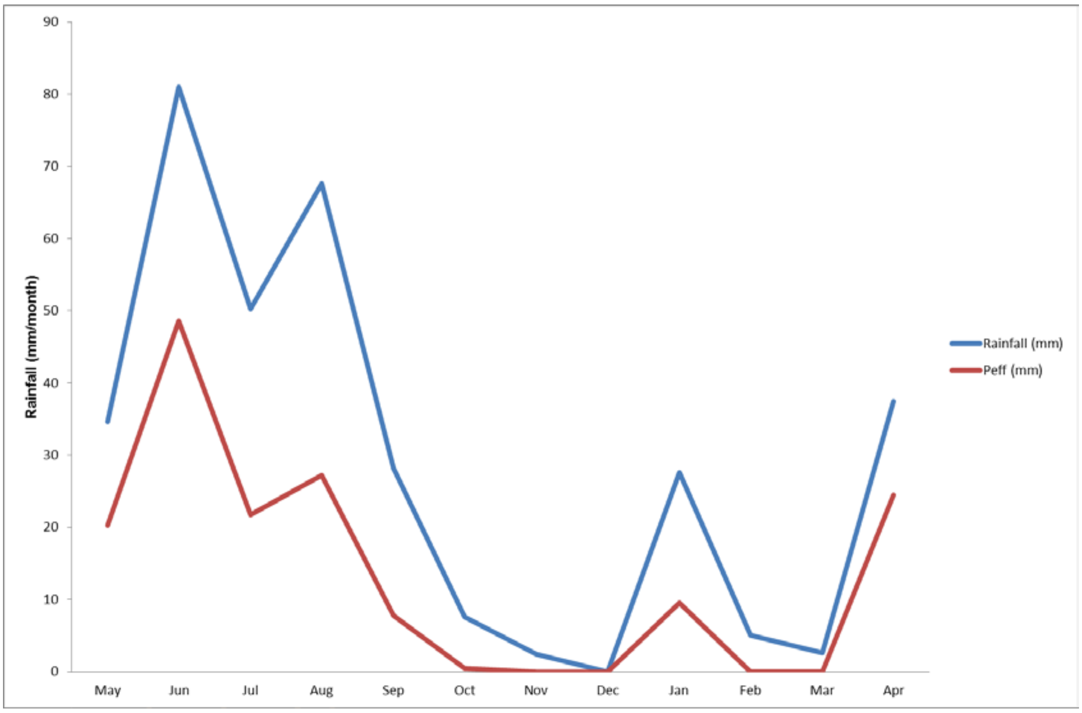

Figure 4.3: Effective rainfall (mm/month) and rainfall (mm/month) at Patrysberg Citrus Farm for the period of 1st May 2013- 30 April 2014.

The rainfall distribution during the growing season was poor. More than half the rainfall received for the whole growing season was received in winter (Figure 4.3). Some dekads (one dekad equals 10 days) during the growing season received very little or no rainfall while others received substantial amounts during winter months. The wet dekad was the first dekad of June with rainfall of approximately 57.4 mm. Approximately34 % of the dekads received no rainfall during the 2013/2014 growing season (Figure 4.4). The poor distribution of rainfall means that the main source of water use by the crop was blue water.

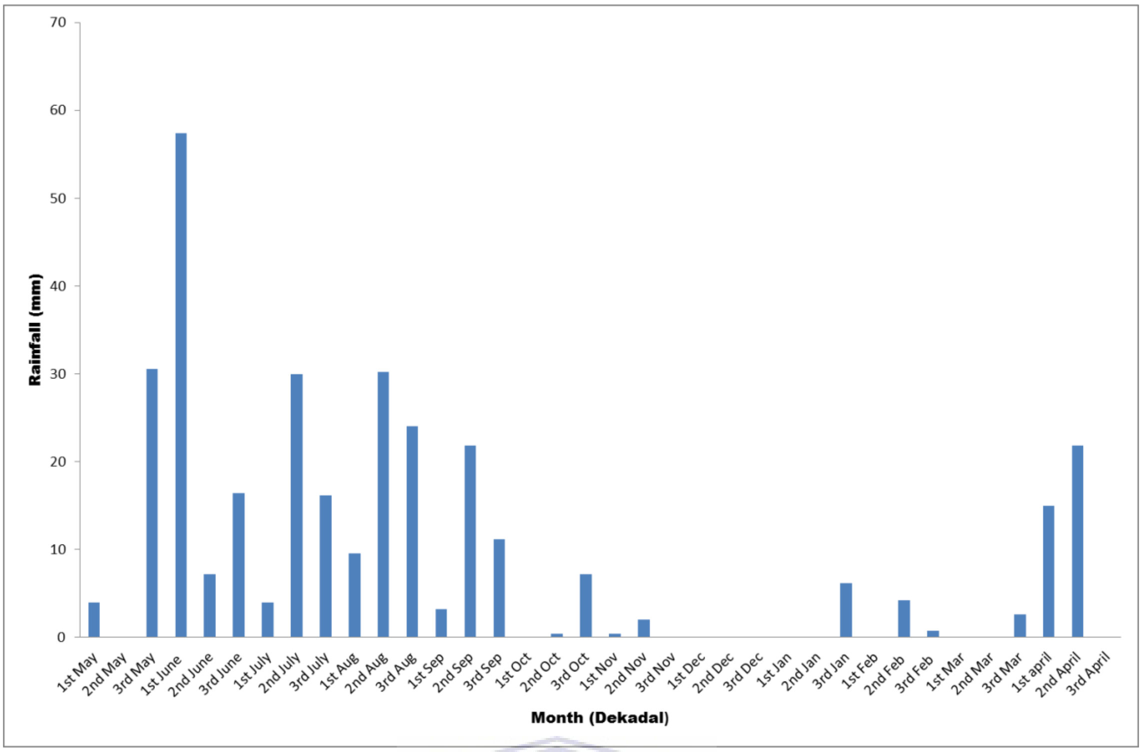

Figure 4. 4: Dekadal rainfall observed at Patrysberg experimental Farm during 2013/2014 growing season.

4.4.2 ET$_o$observed during the growing season

Reference evapotranspiration is the ability of the atmosphere to remove the water from the surface through the process of evaporation and transpiration assuming there is no limited supply of water supply.Reference evapotranspiration was calculated using the Penman Monteith equation (equation 2.1).Meteorological parameters of temperature, relative humidity, wind speed and solar radiation required to calculate ET$_o$ were recorded daily on site using an automatic weather station.Daily ET$_o$ valueswere low in winter when rainfall was high as compared to summer when rainfall was low (Figure 4.5).

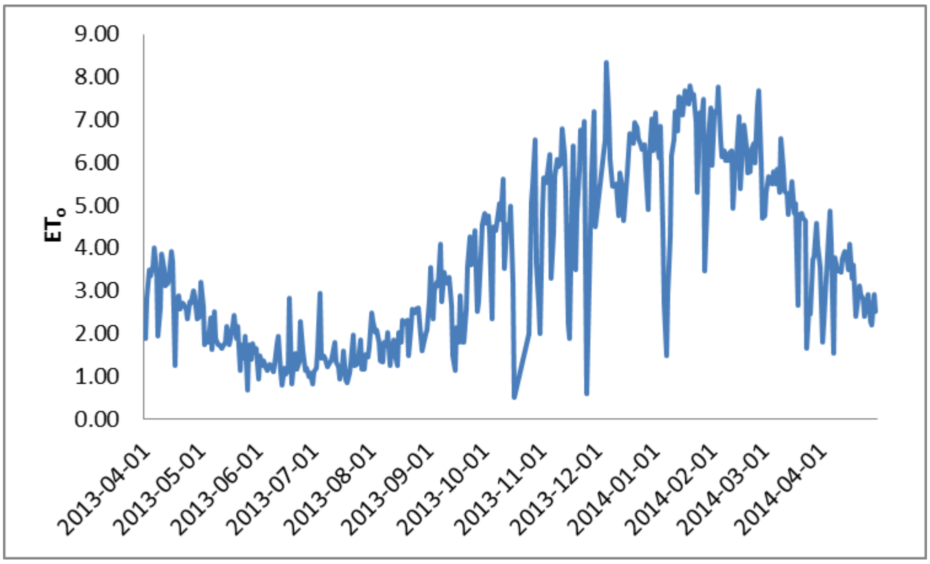

Figure 4. 5: Daily ET$_o$ observed at the site during the growing season from to May 2013-April 2014.

The highest mean daily evaporation rate was observed in February when temperature was 24°C and the lowest was observed in June when mean daily average temperature was 15°C (Figure 4.7) .

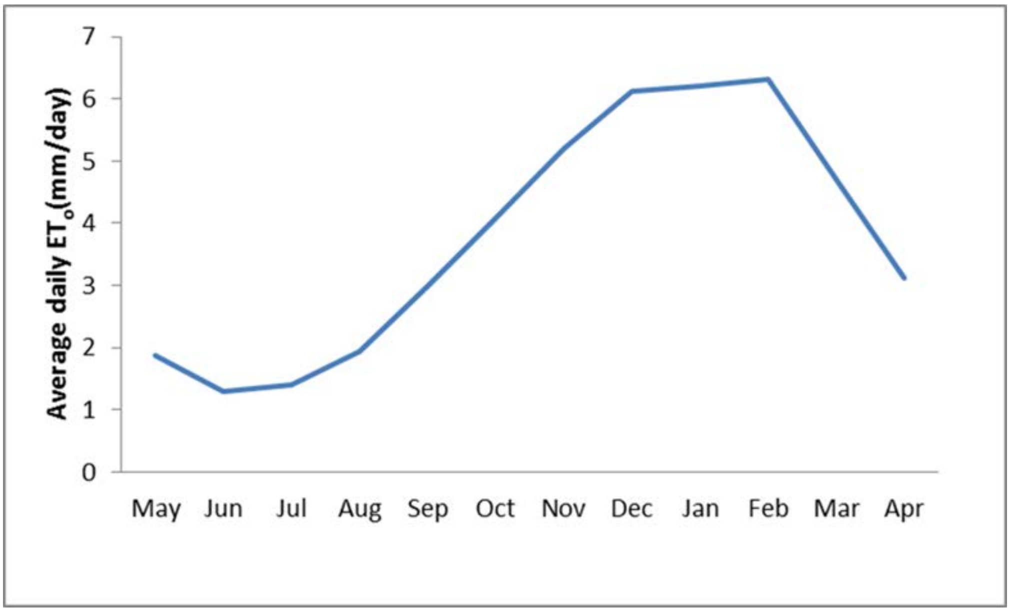

Figure 4.6: Average daily ET$_o$ observed at the site during the growing season from to May 2013-April 2014

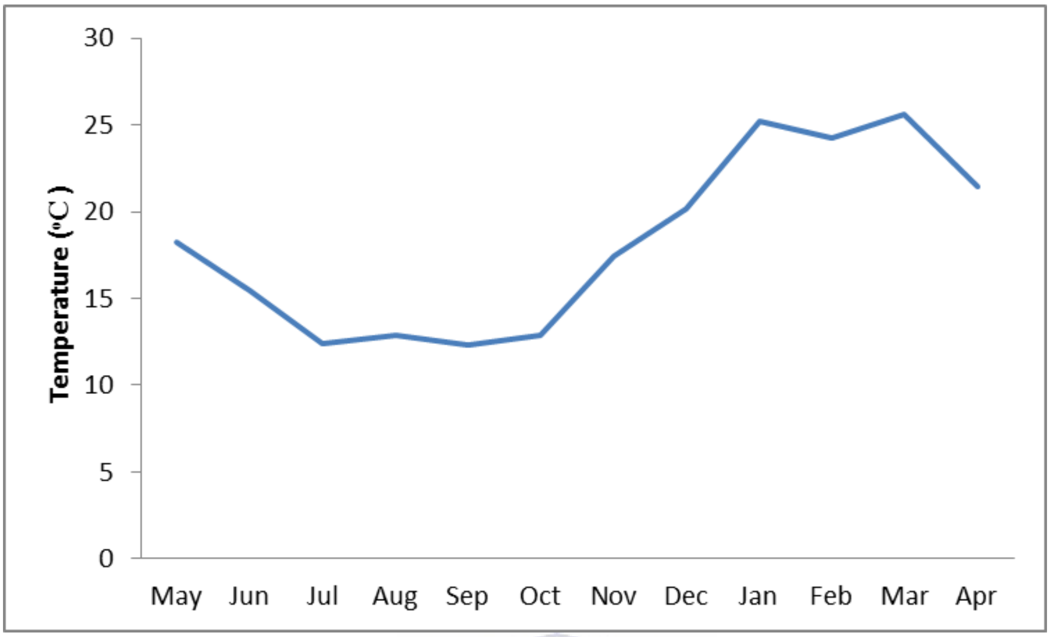

Figure 4.7: Mean air temperatures during the whole growing season at Patrysberg Farm.

Average daily evaporativedemand at the site during the whole growing season showed a decrease with an increase in relative humidity which means that in winter when relative humidity was high, evaporative demand at the site was low (Figure 4.8).

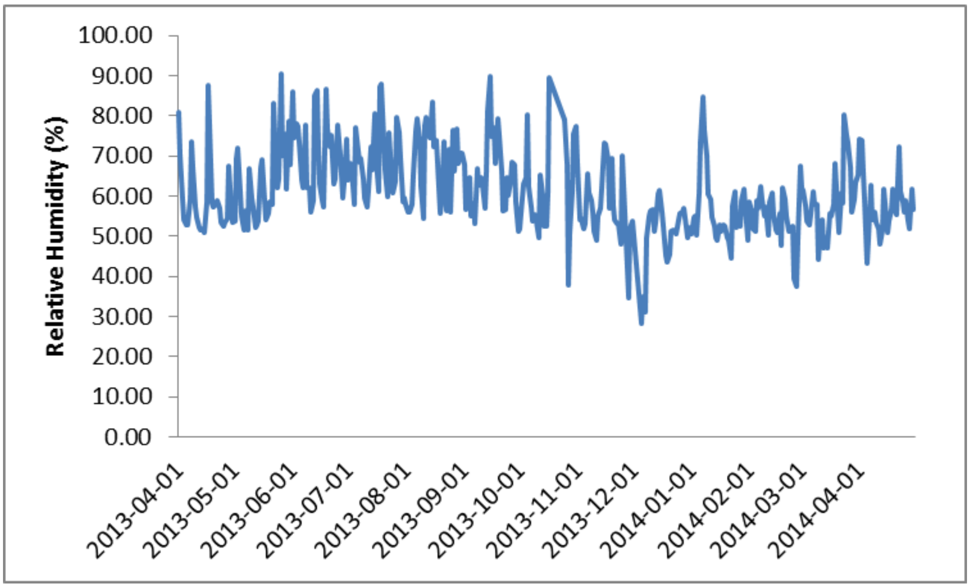

Figure 4.8: Daily relative humidity (%) observed at the site during 2013-2014 Navel orange growing season at Patrysberg Farm.

4.4.3 Evapotranspiration

The total evapotranspiration estimated using the FAO-Penman Monteith method (Equation 2.1)of navel oranges for the whole growing season (12months)was 716 mm (7160 m^3/ ha^{-1}) .Blue water evapotranspirationobserved at the study site was higher than green water use for the whole growing period (Figure 4.9).The highest green water use was observed in June when rainfall measured at the site was the highest (Figure 4.4).

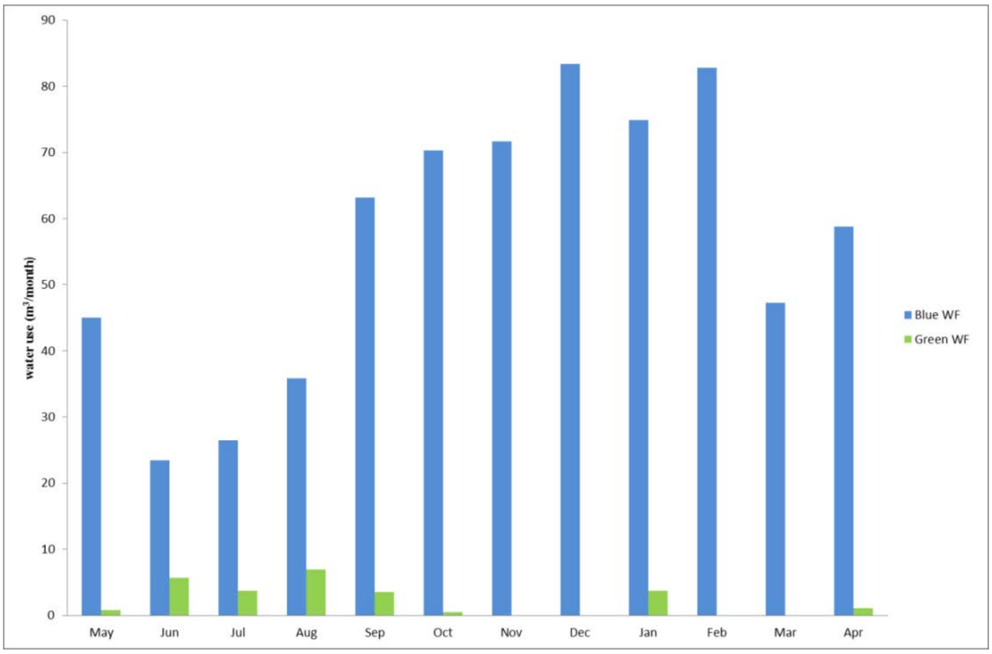

Figure 4.9: Blue and green evapotranspiration (m^3/ha) of Navel oranges estimated at Patrysberg Farm during 2013/2014 growing season.

4.4.4 Water footprint

The total water footprint of Navel oranges estimated as the total water consumed during the entire production stage was 108 litres/kg. Indirect water used for the whole growing period was 204 m^3/ ha for the whole growing period, of which dam evaporation estimated following Penman equation (Equation 3.3) and packhouse water use was approximately 79%. Packhouse water use was measured using a flow meter (Figure 4.2). Water used to mix chemicals used to kill pests was significantly lower for the whole growing season (Table 4.1). The water footprint comprised mostly of the blue water footprint which was 96 % of the total water footprint and the green water footprint was only 4 % (Figure 4.10).

Table 4. 1: Water use (mm) for Navel Orange Production at Patrysberg Farm

Water-use Component	**Water use (mm/yr)**
Evapotranspiration	716
Evaporation from storage dam	10.1
Spraying Micronutrients	1.2
Spraying Fungicides	2.0
Spraying Pesticides	0.4
Spraying Herbicides	0.3
Chemical Fruit Thinning	0.4
Packhouse Water-use	7
Total	736

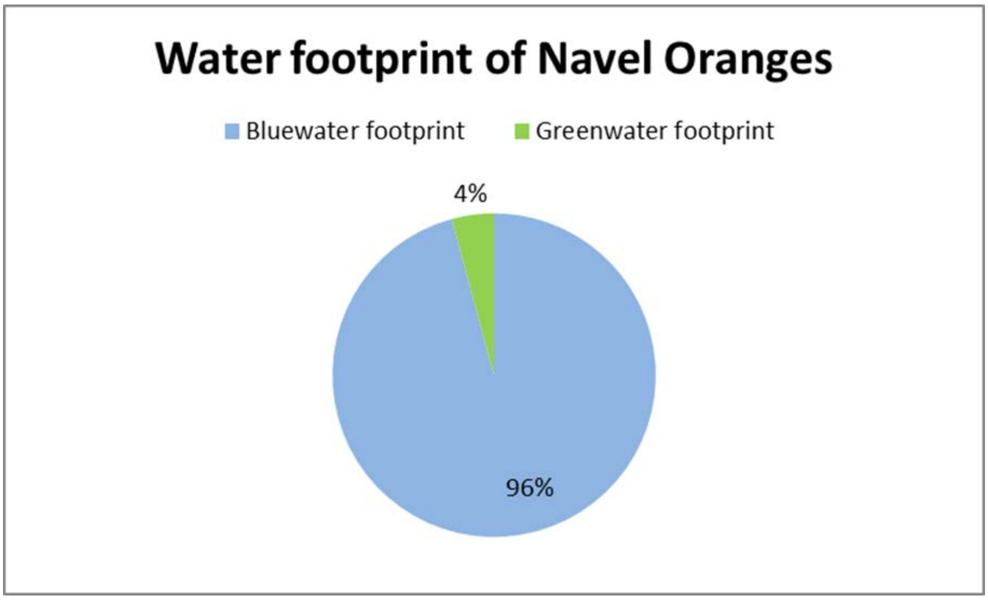

Figure 4.10: Percentages of Blue and green water footprint component in Navel orange production.

4.4.5 Water productivity

Crop water productivity of Navel oranges defined as the ratio of yield to water consumed was 9kg/m^3 and the apparent water productivity defined as the market price per water footprint of a cropwas 0.09 Rand/ Litre.

4.5 Discussion

The total water footprint of Navel oranges estimated for a crop yield of 68 tons/ha at the site was 108litres/kg which was lower than the water footprint of Oranges estimated byMekonnen and Hoekstra (2011). The water footprint of oranges according Mekonnen and Hoekstra 2011 is 560litre/kg without including the grey water footprint component.

The crop water productivity of navel oranges was 9kg/m^3 while the apparent water productivity (AWP) was 0.09 R/Litres. The apparent water productivity estimated using the South African estimated market price was low. However most oranges produced in Citrusdal are forexport market and international market price are higher than local market price(DAFF, 2012)

The crop water productivity waswithin range with CWP of oranges in other studies when compared to the global average water productivity established in other studies (Renault and Wallender,2000., Quinones et al., 2010; Perez-Perez et al., 2012; Aguado et al., 2012).

5 PINK LADY APPLES

5.1 Introduction

*Malus domestica*commonly known asapple is one of the most important deciduous fruits grown in the world(Tetens and Alinia , 2009). Besides the old public saying “An apple a day keeps the doctor away” research have shown that one apple a day can provide the body with important vitamins, minerals and antioxidants. Although other fruits also have these benefits, apples are the only fruits which have all of benefits combined in one(Boyer and Liu,2004).

Globally, China is the world’s leading apple producer, accounting for 50% of the production during the 2012/2013 apple growing season.According to FAOSTAT report (2014), South Africa is the leading apple producing country in Africa. The South African apple industry is export oriented with half of the apples produced being exported (DAFF, 2011).Over fifty percent of apple orchards are within the Western Cape Province. In 2010 21553 hectares were planted with apples in the Western Cape Province of which 1 925 ha were planted with pink lady apples (DAFF, 2011).

Apple production in the Western Cape Province and producing regions in South Africa are faced with severe threats such as climate change, and water scarcity(DAFF, 2011). In irrigated agriculture management of water through efficient irrigation is the only sustainable solution. Irrigation management is also vital in apple orchards because over irrigation and under irrigation have severe impacts on fruit yield(Fallahi et al., 2010). Over irrigation slows root growth, increases waterlogging effects such as iron-induced chlorosis, stunted growth and root rots (Black et al., 2008; Al-Yahyai, 2012), while under irrigation can affect physiological processes such as leaf expansion (Sepulcrecanto et al., 2007). While a number of studies have emphasized the importance of proper irrigation system, most studies acknowledge that irrigation systems and water use of crops are influenced by the environmental conditions where the crop is being produced. Growers therefore need to know the water use of each crop in order to avoid over/under irrigation, improve yield and to save on water cost.

This study assessed the water use, water footprint, water productivity of pink lady apples.

5.2 Site description

Nooitgedacht farm is located within the KoueBokkeveld area in the Western Cape Province, South Africa. The name “KoueBokkeveld” is an Afrikaans word which translates to “Cold Buck Shrub land”. KoueBokkeveld is located on the south eastern part of the Olifants/Doorn WMA. Due to its high altitude the KoueBokkeveld receives relatively high annual average rainfall(1100mm/year) compared to other areas in the Olifants/Doorn WMA such as Sandveld and Citrusdal. Groundwater recharge is high in the KoueBokkeveld Area and the quality of groundwater is excellent (DWA, 2012). The source of water used for irrigation is mostly groundwater however some farmers depend on surface water abstracted from either Leeu River or Doorn River.

Nooitgedacht Farm (33°12'03.57"S, 19°20'15.06"E) orchard is 2.3 ha in size. The average tree height was 5 m. The study orchard was planted with ‘Cripps Pink’ (‘Pink Lady’) apples on M793 rootstock, with every 8th tree in each row being a ‘Hillary’ Crab-apple pollinator. Row orientation was north - south and the trees were spaced at 1.25 m by 4 m. Irrigation and fertilisation was supplied using short-range micro-sprinklers and irrigation scheduling was based on daily soil moisture and weather data.The annual yield of Pink Lady apples was 69 tons /ha.

5.3 Data collection

Temperature, relative humidity, wind speed and solar radiation data required to calculate ET_ousing the Penman-Monteith equation were recorded daily on site using an automatic weather station. The parameters were recorded for one growing season starting fromOctober 2012 to April 2013. Potential evapotranspiration and locally derived K_c values (Figure5.1) were used to estimate ET_c. K_c values were derived following Equation (4.1) where ET_c was measured using the Eddy covariance technique (Gush and Taylor, 2014).

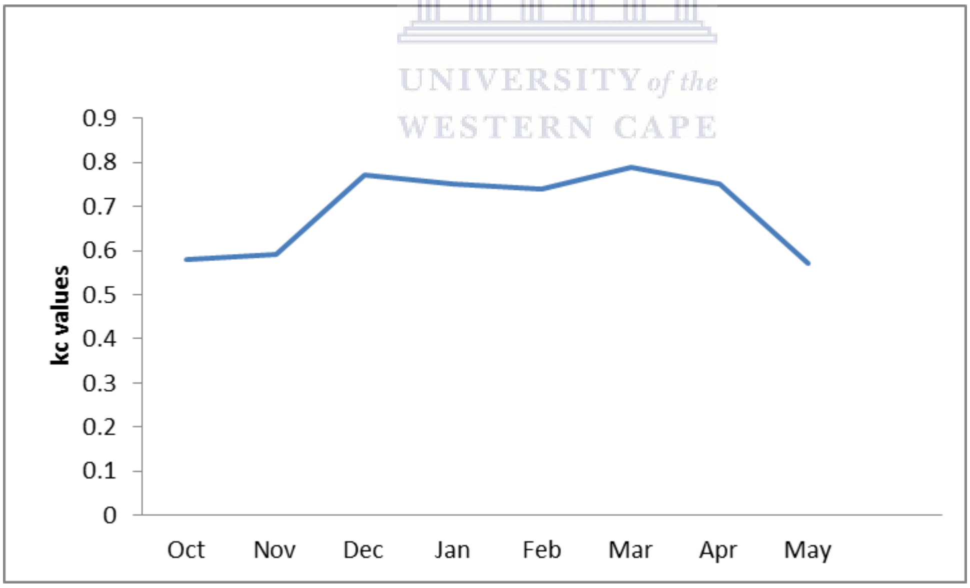

Figure 5.1: Locally derived Kc values at Nooitgedacht Apple Orchard farm (Gush and Taylor, 2014).

Data on indirect water use was collected through interviews with farmers except the evaporation of water from storage farms dam, which was estimated following Penman method (Equation 3.3). The indirect water use also included water use for spraying of pesticides, micronutrients, herbicides, fungicides, chemical fruit thinning, packhouse water use and farm worker water use.

5.4 Results

5.4.1 Effective rainfall and rainfall

The total rainfall that was received during the crop growing period at the site was 110mm.There was a large increase in rainfall (30mm/month) between October and November followed by a steep decrease between November and December, from 54mm/month in November to approximately 1mm/month in December (Figure 5.2).In January there was no rainfall measured at the study site however the rainfall started showing an increase after January (Figure 5.2)

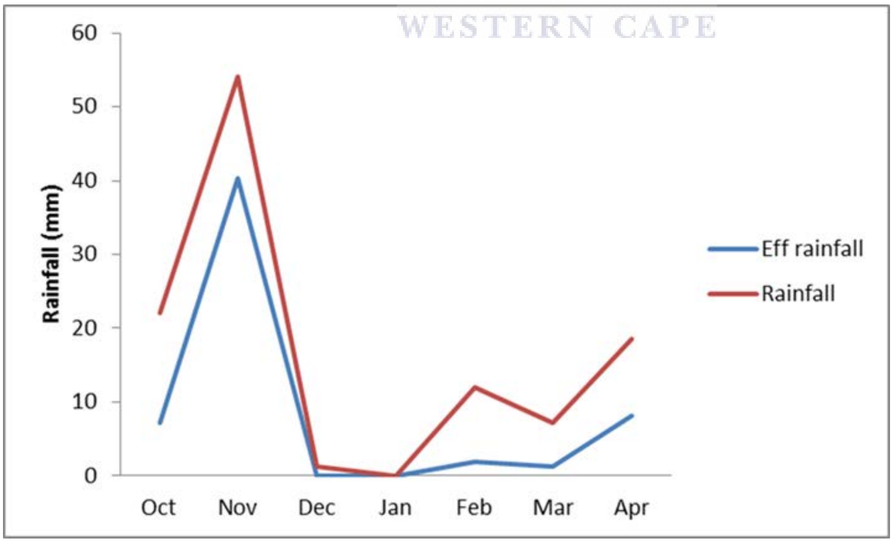

Figure 5.2: Effective rainfall and rainfall at Nooitgedacht Orchard Farm during the 2012-2013 growing season

5.4.2 ET_o observed during the growing season

The ET_o values estimated at the site using Penman Monteith method show the evaporative demand of the atmosphere during the 2012/2013 growing season. The highest mean daily evaporative demand (7mm/day) was observed during the month of January (2013) while the lowest (4mm/day) was towards the end of the growing season in April (Figure 5.3). The evaporative demand on the site was high when relave humidity was low (Figure 5.4) , however it was high with high temperatures (Figure 5.5). Between January- March when mean average temperatures were approximately20° C mean relative humidity (%) recorded at the site was the lowest.

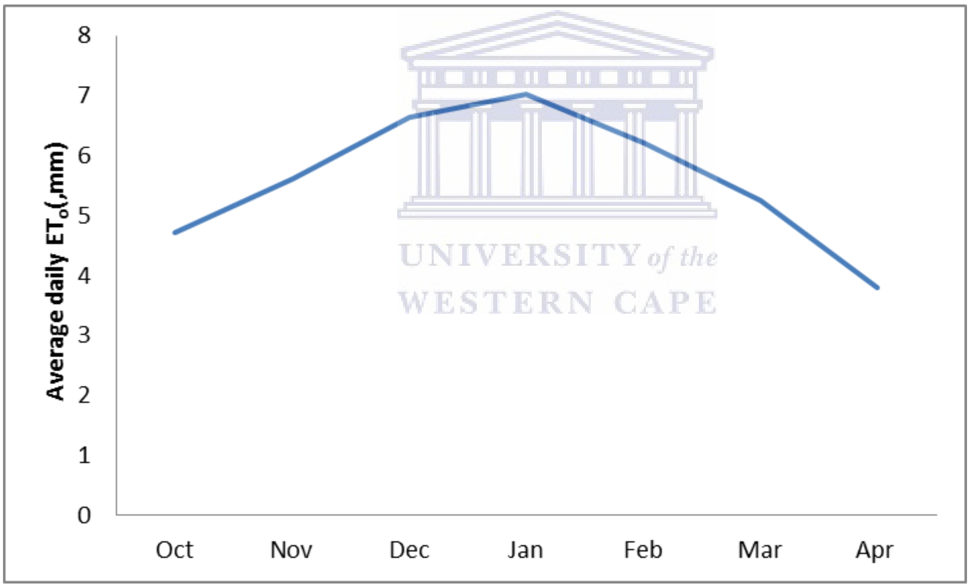

Figure 5.3: Average daily ET_o observed at the site during the growing season from to Oct 2012-April 2013.

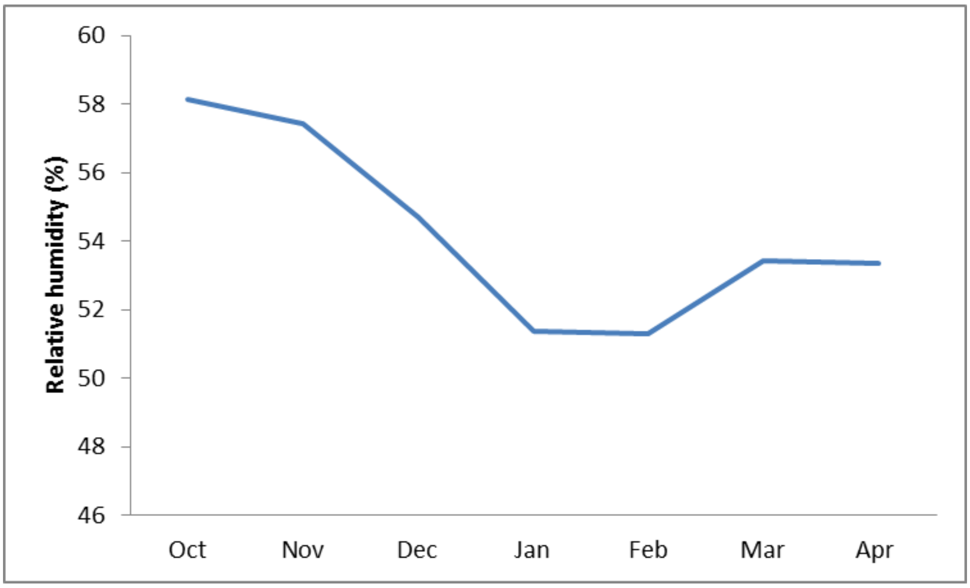

Figure 5. 4: Relative humidity (%) observed at the site during 2012-2013 growing season at the study site

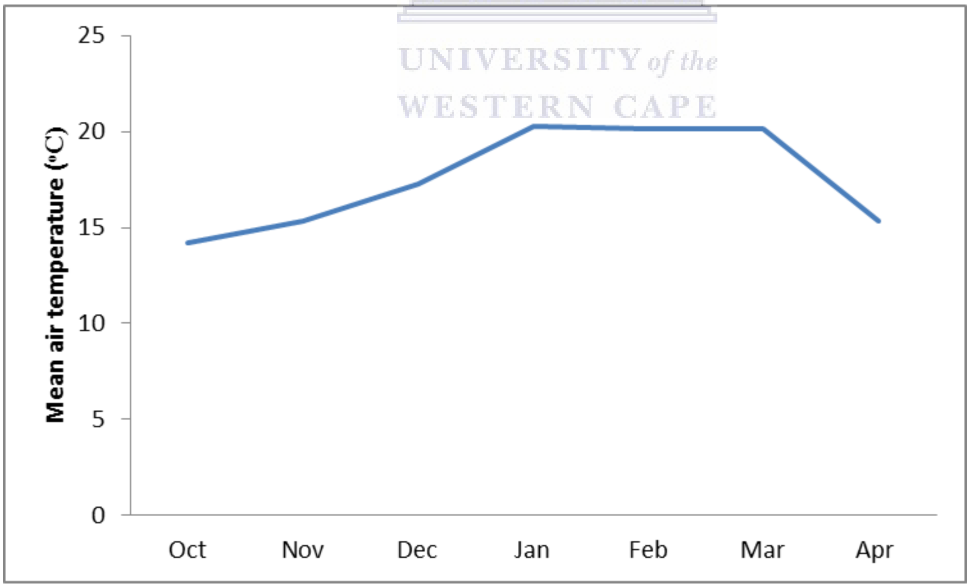

Figure 5.5: The mean air temperatures during the whole growing season at Nooitgedacht Orchard Farm.

5.4.3 Evapotranspiration

The total ET_c of pink lady apples at Nooitgedacht farm estimated following the FAO-Penman Monteith Method (Allen et al., 1998) was 848mm/growing season of which approximately 98% of it was blue water use and evaporation from green water was only 2% (Figure 5.6). In December and January, green water use was zero while in other months it was below $20m^3$/ha.Green water was low in December and January because of low rainfall events during summer in Mediterranean regions. Nooitgedacht Orchard Farm is located within a and it experiences hot dry summer and wet winter and the growing period for Pink Lady apples is in summer.

Figure 5.6: Monthly water use of pink lady apples at Nooitgedacht Orchard Farm during the 2012-2013 growing period

5.4.4 Water footprint

The total water footprint of pink lady apples was 125litres/kg estimated following the water footprint network (WFN) method (Hoekstra et al., 2011). Ninety nine percent of the total water footprint was blue water footprint (Figure 5.7). Indirect water use during the whole growing period was significantly low compared to direct water use (ET_c) at the study site. Evaporation from storage farm dam estimated following the Penman equation (Equation 3.3) was the largest component of indirect water used during pink lady apple production at farm- gate level (Table 5.1).

Table 5.1: Water use of Pink lady apples at Nooitgedacht Orchard Farm during the 2012-2013 growing season

Water-use Component	Water use (mm/growing season)
Evapotranspiration	848
Evaporation from storage dam	12.6
Fungicides Spraying	0.6
Pesticides Spraying	0.4
Herbicides Spraying	0.3
Chemical Fruit Thinning	0.4
Fruit Washing	0.1
Packhouse Water-use	0.5
Total	**864**

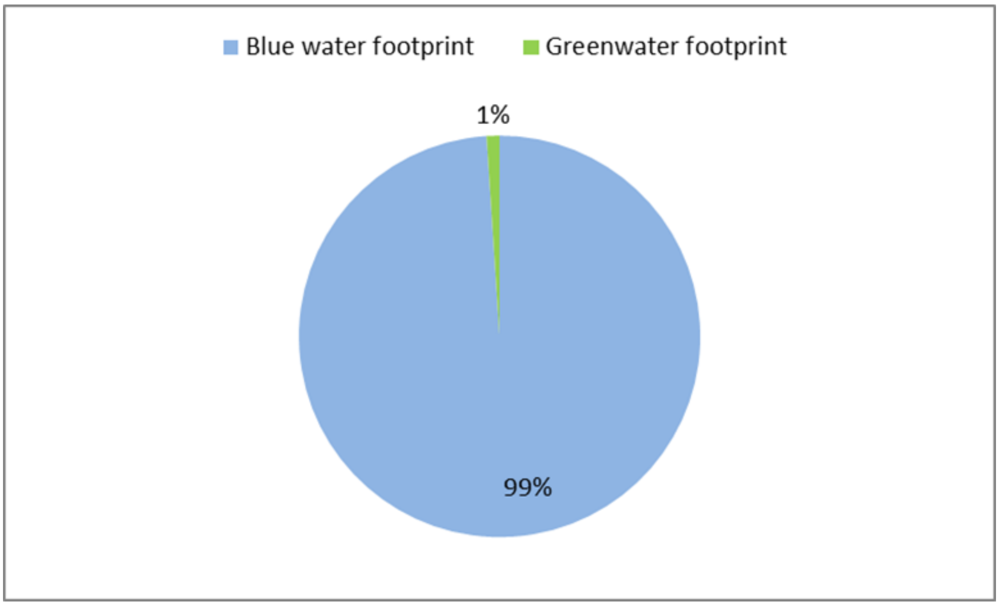

Figure 5.7: Percentage of the blue and the green water footprint of Pink Lady Apples at Nooitgedacht Orchard Farm.

5.4.5 Water productivity

Crop water productivity defined as the ratio of yield to water consumed (kg/m^3) by the crop through evapotranspiration at the field scale was 8kg/m^3. The apparent water productivity defined as the market price per water footprint of a crop was 0.14 Rand/litre 2014 price market.

5.5 Discussion

Mediterranean regions experiences wet winter and dry summer and the Olifants/Doorn WMA is no exception and consequently rainfall recorded during the growing period for pink lady apples was low. The total rainfall received during the entire growing season (Oct 2012- April 2013) was 110mm of which approximately 50% was received in November. Even though highest percentage of rainfall was received in November it was still lower than crop evapotranspiration in that month it was supplemented with blue water.

The total water use (ET_c) of apples was 848 mm for the whole growing season at the study farm which was low compared to the ET_c of apples in other studies of 950-1500mm/year(Renault and Wallender,2000; Fallahi et al., 2010). The water footprint of pink lady apples was also lower than the estimated water footprint values in the literature. The global average water footprint of apples was published by Mekonnen and Hoekstra (2011) as they estimated it to be 822 litre/kg, which was 697litres/kg more than the WF of Pink Lady apples at Nooitgedacht orchard farm.

Apparent water productivity and the crop water productivity of Pink lady apple were 0.14 Rand/litre and 8kg/m^3 respectively. The CWP was high compared to 2.5kg/ m^3 estimated by Renault and Wallender (2000) however low compared to 11.9 kg/ m^3 the water footprint of apples estimated in the study done by Liu et al., (2011).

6 MONDIAL POTATOES

6.1 Introduction

Potatoes *(Solanum tuberosum)*are one of the top ten most produced crops in the world. Potatoes are considered to be the fourth most important food crop after wheat, maize and rice. They are cultivated in temperate and subtropical regions across the world. A recent study conducted by the Food and Agriculture Organization (2012) showed that the demand and production of potatoes has grown over the past decade especially in Africa and Asia. China produces over a third of all potatoes produced globally and is the biggest producer of potatoes. Although production in Africa has increased,Africa still has a long way to go before it can catch up with Asian countries such as China and India.

Potatoes are grown under a wide range of conditions in Africa, from irrigation on commercial farms in Egypt and South Africa to intensively cultivated tropical highland zones of eastern and central Africa, by smallholder farmers.In South Africa approximately 50000 hectares of land is planted with potatoes every year and over 85% of this planted landis under irrigation (Potato SA, 2013). The Limpopo Province, Free State Province and the Western Cape Province produce over 50% of all potatoes in SA (Figure 6.1).

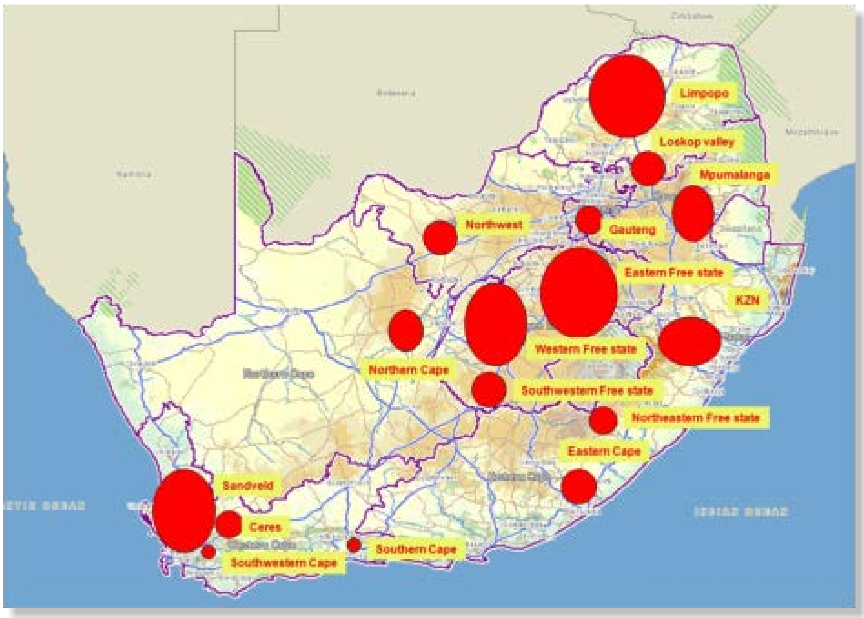

Figure 6.1: Map showing potato production in South Africa. Oval size represents the size of each potato producing region (Map from Potato SA, 2013).

Potatoes are irrigated and fertilized to meet quality standards demanded by the fresh vegetable market. Irrigation however needs to be monitored to ensure that potatoes are not over or under irrigated because potato yield is very sensitive to irrigation management in all the developmental stages for good production.There have been many reports on the effects of water stress and irrigation regimes on potato crop in many parts of the world(Van Loon, 1981; King et al., 2003).In comparison with other species, potatoes are the most sensitive species to water stress because of their shallow root system (Cantore et al., 2014). Water stress is usually reflected in slow growth, a small leaf canopy, early senescence and eventually in reduced yields (Singels,2012).

Potatoes typically take approximately 95-120 days to mature and during the whole growing period soil moisture needs to be monitored closely in order to obtain good yield(Erdem et al., 2006; Kang et al., 2004). The normal growing period of potatoes can be divided into five stages of which irrigation requirements during those stages differs and water availability have different impacts(Dwelle and Love, 1993). For example, if there is water stress during tuber initiation stage which is within 2 to 3 weeks after emergence (second stage) this will limit the number of tubers initiated, while excess water supply induces tuber disorder(Heuer and Nadler,1995).

Several authors studied the water consumption and water productivity of potato crop in different regions (King et al., 2003; Van Loon 1981; Badr et al., 2012; Cantore et al., 2014; Kashyap and Panda , 2001; Steyn et al., 2007; Kang et al., 2004; Kang et al., 2004; Brauman et al., 2013; Singels and van der Laan, 2011). However there is still insufficient knowledge on the water use of potatoes along the whole production chain globally and in South Africa. This case study aimed to assess the water footprint of commercial potatoes produced within a semi-arid area.

6.2 Site description

The Sandveld region is the largest potato producing area in the Western Cape (Figure 6.1). The area is characterized by semi-arid Mediterranean climate and receives between 150mm-250mm/year of rainfall, increasing from the coast towards the eastern part of the WMA. Rainfall is high between April and July when the temperatures are generally low and relative humidity is high. According to Potato SA 1986 hectares were planted with potatoes during the summer of 2013 under irrigation. Groundwater is the primary source of water for irrigation in the Sandveld region. The study was conducted for summer grown potatoes on one commercial farm (Modderfontein Farm) within the Sandveld region.

Modderfontein farm (32°33'34.05"S and 18°20'41.50"E) is located near a small town called Aurora in the Sandveld region. The total farm area is 1300 ha and the crops planted in the farms are wheat and potatoes of which wheat only occupies 100 ha of the total farm size. Potato yieldin the farm during the study period was 45 tons/ha.

6.3 Data Collection

Weather data was collected from an automatic weather station installed by the University of Pretoria at Modderfontein Farm for the February-June (2013) growing season. Reference evapotranspiration and locally derived K_c values (CSIR, 2012) were used to estimate water use (ET_c) of potatoes following the FAO Penman method. To complement the blue water use volumes, the additional indirect water used throughout the various stages of production was determined through a questionnaire (Appendix 1) and interviews with the farmer. The combined data were then used to estimate the blue water footprint.

Additional/indirect water use included the water used for spraying of pesticides, fungicides, and water used in the packhouse to wash potatoes after harvesting . Two flow meters were installed to measure water used in the packhouse and washing potatoes after harvesting (Figure 6.3). Modderfontein farm uses groundwater for irrigation and there was no storage dams used during the study period.

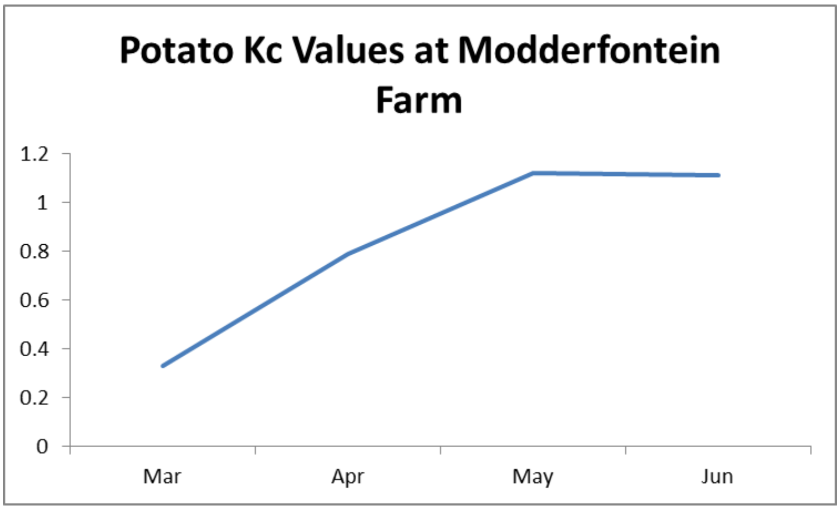

Figure 6.2: Crop coefficients estimated for potatoes at Modderfontein Farm (CSIR, 2012)

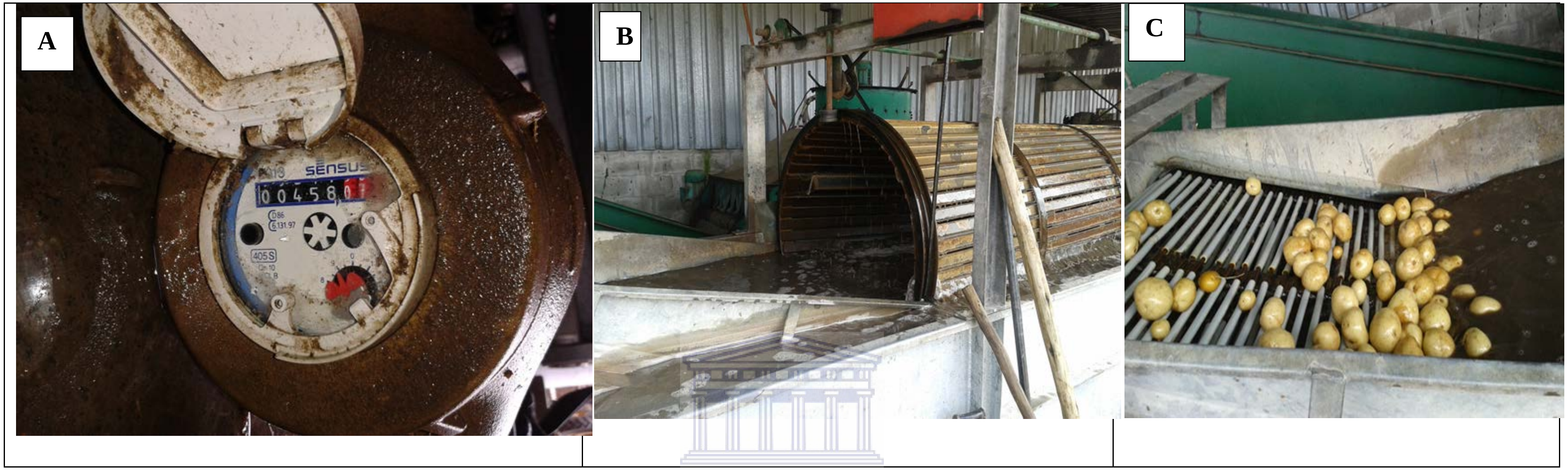

Figure 6.3: (A) Flow meter at installed at Modderfontein Farm used to measure water used to wash potatoes (B) Potato washing machine (C) Potatoes washing after harvest

6.4 Results

6.4.1 Rainfall and effective rainfall

Total rainfall measured at the study farm was approximately 111 mm for the whole growing period (February–June 2013) and only 28% of the rainfall was effective. The highest rainfall of the entire growing season was recorded in June (50mm/month) just before the harvesting (Figure 6.4 and Figure 6.5)even though only 15 days in June were considered. Rainfall observed at the study site was unevenly distributed with some months being drier than the others.For example there was a sharp decrease (49%) in measured rainfall between April and May (from 33mm/month in April to 16mm/month in May) followed by an increase in June (Figure 6.4). Approximately 82% of the total rainfall measured on farm in June was received in the first dekad (Figure 6.5).

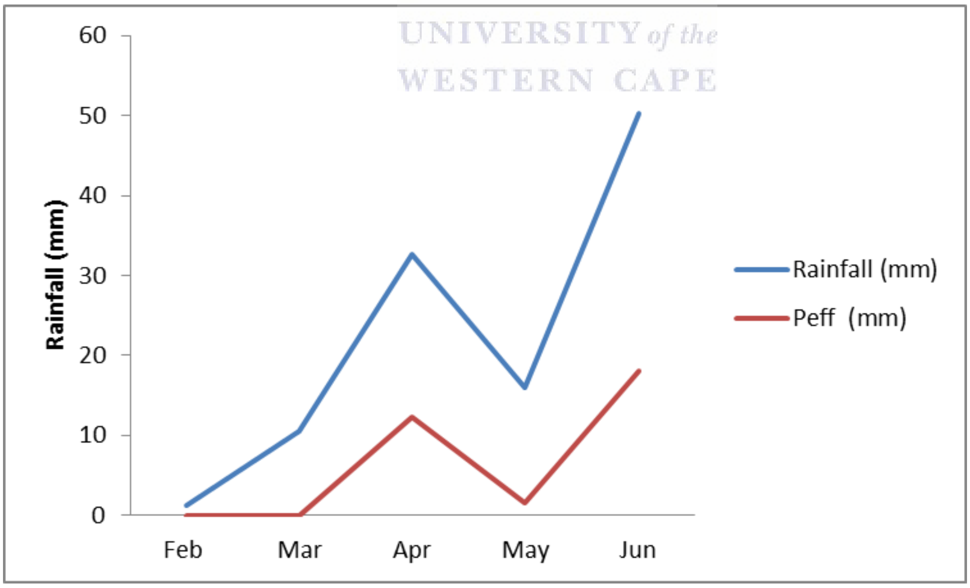

Figure 6. 4: Monthly effective rainfall and rain at Modderfontein Farm

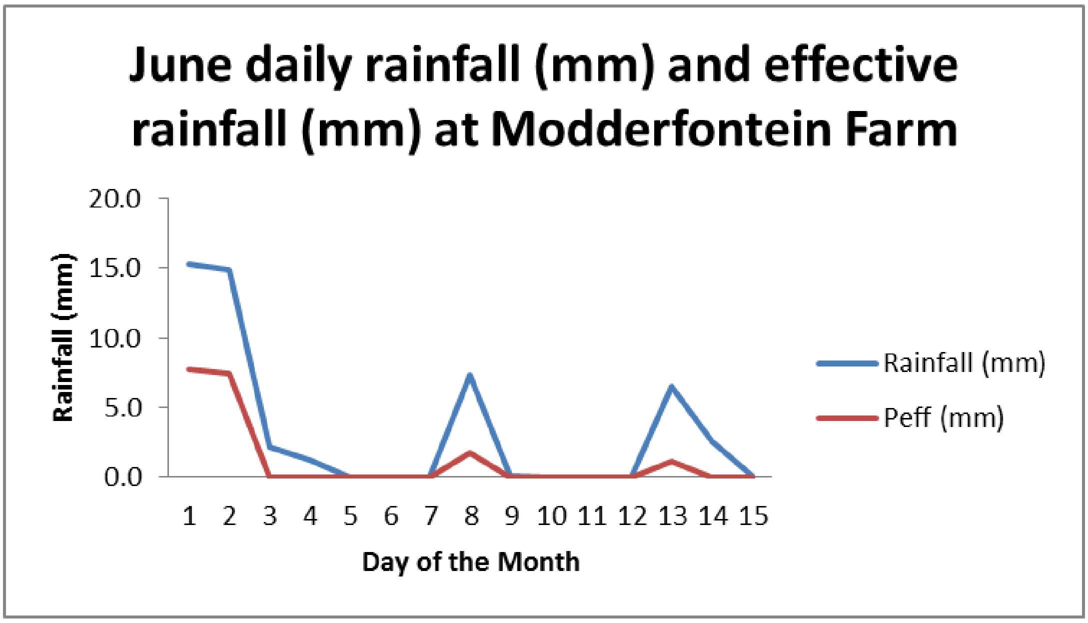

Figure 6.5: June daily effective rainfall (mm) and rainfall (mm) at Modderfontein farm.

6.4.2 ET$_o$observed during the growing season

Daily potential evapotranspiration (mm)estimated following the Penman-Monteith-method at Modderfontein study site during the summer potato growing season (February to June 2013) was high at the beginning of the growing season between (Figure 6.6),when average daily air temperature was approximately 22°Cand low in April (Figure 6.7). ET$_o$ at Modderfontein study site was low in April when daily average air temperature was 17°C (Figure 6.7) and relative humidity was 61% (Figure 6.8).

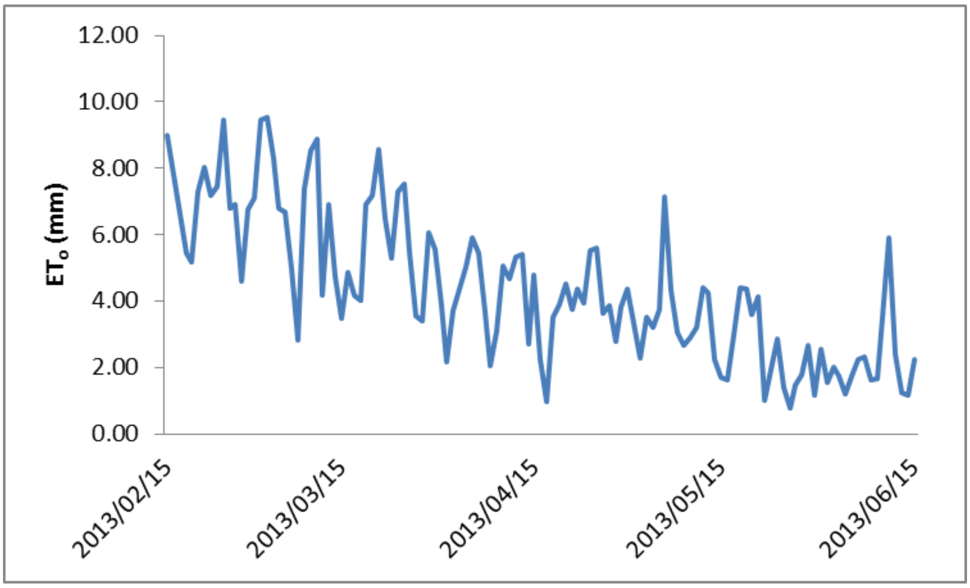

Figure 6.6: Daily ET_o observed at the site during potato growing season (February- June 2013).

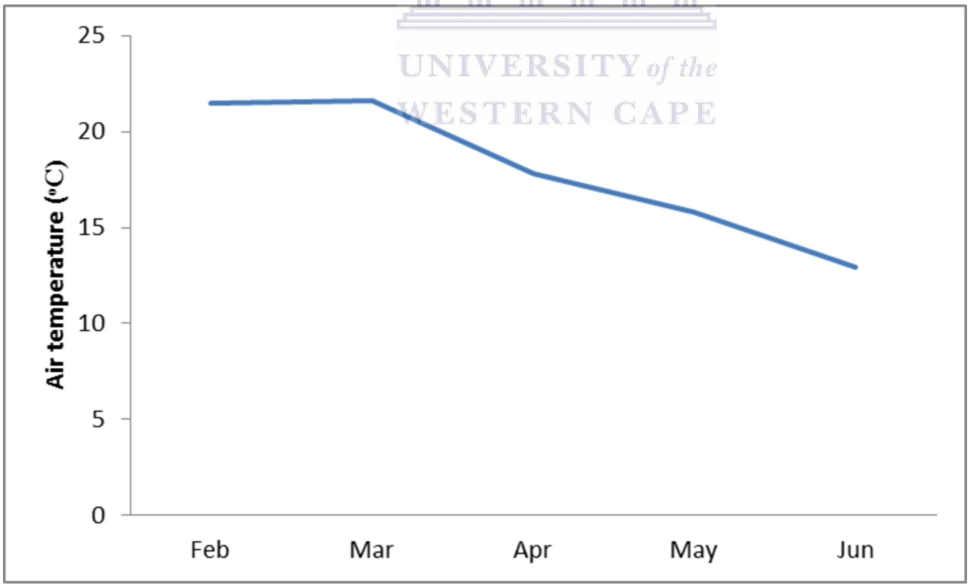

Figure 6.7: Average daily temperature (°C) at Modderfontein study site

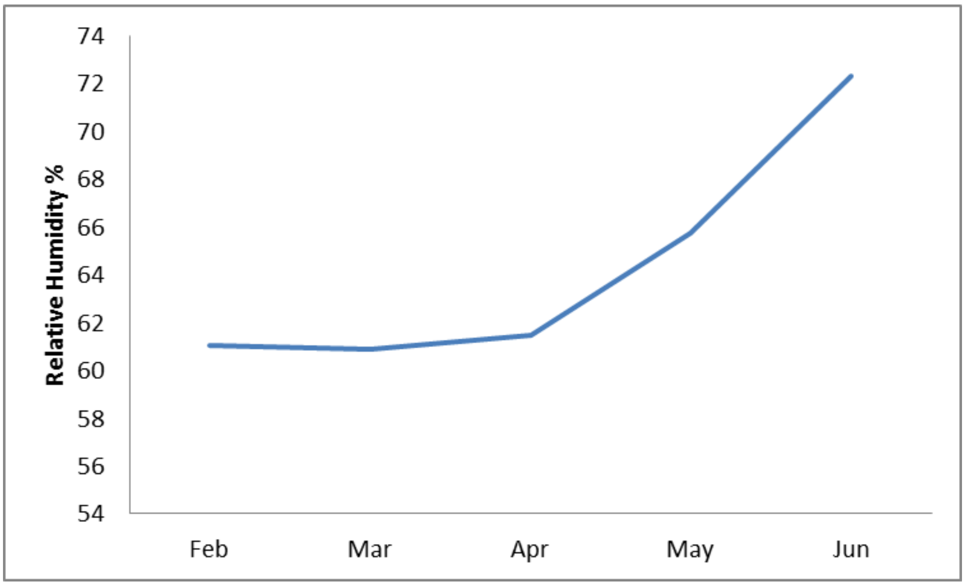

Figure 6.8: Relative humidity (%) observed at Modderfontein Farm during summer Mondial potato production.

6.4.3 Evapotranspiration (ET_C)

The total evapotranspiration of Mondial Potatoes at Modderfontein farm for the whole growing season was 295mm (2950 m3/ha^{-1}) of which blue water use was 286mm and the green water use was 9mm. Green water use in April and May was as low as 0.7 mm (April) and 0.8mm (May) consequently the estimated blue water use was high in those two months (Figure 6.9). Figure 6.9 shows that the green water use for April was due to rainfall of approximately 21mm that was received on the second dekad of the month. The onset of the rainy season in June was reflected in an increasing proportion of the water footprint being attributed to green water in that month.

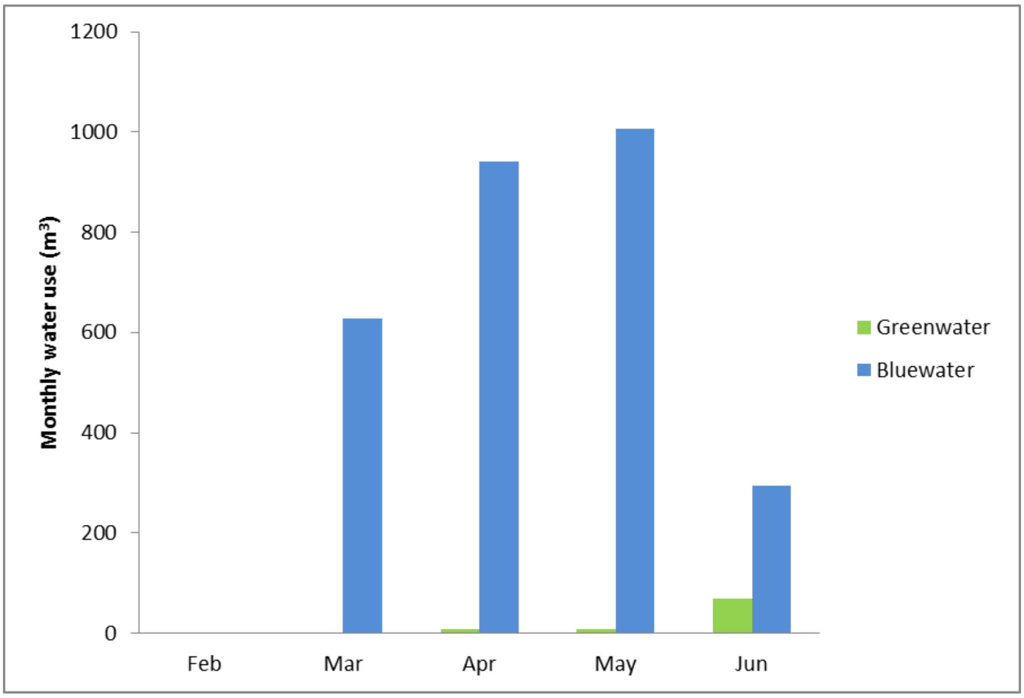

Figure 6.9: Monthly blue and green evapotranspiration of Mondial potatoes (m^3) at Modderfontein Farm.

6.4.4 Water footprint

The total water footprint of Mondial potatoes was 68 litres/kg and the water productivity 15kg/m^3. Ninety seven percent of the total water footprint was blue water footprint and only 3% was green water footprint (Figure 6.10). Potato evapotranspiration contributed approximately 96% to the total blue water footprint component of the crop (Table 6.1). Water used in the pack house and water used to wash potatoes combined contributed 3 % to the total blue water footprint.

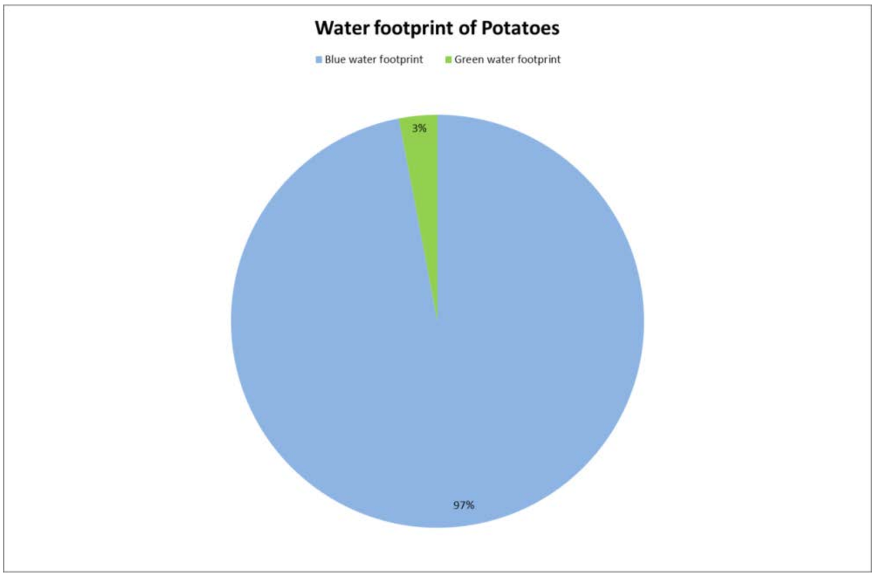

Figure 6.10: Blue and green water footprint percentage of Mondial Potatoes at Modderfontein Farm.

Table 6.1: Total water use (mm/growing season) of Mondial potatoes at Modderfontein study site

Indirect water use	**Depth (mm)**
Evapotranspiration	295
Spraying Fungicides	0.7
Spraying Pesticides	0.8
Potato Washing	4.6
Packhouse Water-use	3.8
Total water use	**305**

Packhouse water use and water used to wash potatoes was measured using a flow meter installed at the farm.

6.4.5 Water productivity

Apparent water productivity and the crop water productivity of potatoes at the study site were 0.15 Rand /litre and 15kg/m^3 respectively. The apparent water productivity was estimated using market price from Potato South Africa organization, which is 10 Rand per one kilogram of potatoes.

6.5 Discussion

The crop water use of potatoes at Modderfontein Farm was 295 mm/growing season which was relatively low compared to water use estimates in other studies. Costa et al.,(1997) and Erdem et al.,(2006)reported that potato ET_c meaured using lysimeters ranged between 334 mm and 385 mmper growing season.Wright and Stark (1990) reported that seasonal water use in irrigated areas of Oregon and Washington ranged from 640 to 700 mm.

Approximately 96% of the total ET_c in the Sandveld region was blue water and only four percent was green water. The high percentage of blue water (irrigation) is typical in semi-arid regions where mean monthly evapotranspiration rate is higher than effective rainfall. The uneven distriburion of rainfall also contributes to the high percentage of blue water use and consequently the blue water footprint.

The total water footprint of potatoes was 64 litres/ kg was low compared to water footprint of potatoes in other studies. Mekonnen and Hoekstra (2011) estimatedthe global averages of potatoes to be 287 litre/ kg while Herath et al., 2013 reported that the water footprint of potatoes in New Zealand was 74 litre/kg. The water footprint of potatoes in the Sandveld region indicated that potato production in the region does not contribute to groundwater depletion in the region.

The crop water productivity was high (15kg/m^3) compared to crop water productivity estimated in other studies which ranges between 9-11kg m^3. (Cantore et al., 2014; Mechlia et al., 2007; Renault and Wallender,2000).

7 GENERAL DISCUSSION AND RECOMMENDATION

South Africa is a water scarce country receiving less than 500mm/year of precipitation in most parts of the country.Consequently approximately 90% of crops are grown under irrigation. Irrigated agriculture plays an important role in terms of supporting rural livelihoods and contributing to the Gross Domestic Product (GDP). The importance of agriculture in South Africa and the SADC region as a whole cannot be overlooked. However agriculture has been allocated 62% of the available freshwater resources. The high proportion of the available water taken up by agriculture adversely affects the provision of water to other sectors, such as water supply for domestic, industrial and mining purposes. In addition, use of water by agriculture adversely affects the provision of water for satisfying ecosystem requirements. These ecosystems provide services and goods for human use. The reduction of water used by agriculture particularly for irrigation is being advocated for in order for South Africa to achieve goals set in the National Water Resources Strategy.

The simplest way to reduce irrigation water use is by encouraging rainfed agriculture instead of irrigated agriculture. However this research has shown that relying on rainfall is not practical especially in semi-arid and arid areas due to high evapotranspiration rates and low rainfall. The study has also shown that indirect water use during crop productions such as for processing and packaging is also high and should be included in the estimation of crop water use.

Even though the Olifants/Doorn WMA is the most water stressed water management area in the country, the crops examined had high water productivity and low water footprint compared to estimate made in other studies. The low water footprint for the crops examined was due to high yields compared to global average yields in other studies and also due to low evapotranspiration estimates.

Pink lady apples had the highest volumetric water footprint of 125 litres/ kg, while Mondial potatoes had the lowest water footprint of 65 litres/ kg. There was no significant difference in the apparent water productivity of these two crops. This is because the market price of pink lady apples per kilogram is higher (18.00 Rand/kg) than that of Mondial potatoes which is 10 Rand/ kg. Oranges in South Africa are amongst some of the cheapest fruits on the market and this was evident in this study with Navel oranges having the lowest apparent water productivity even though it has high crop water productivity compared to Pink Lady Apples. Several studies (Renault and Wallender, 2000; Mechlia et al., 2007; Cantore et al.,2014) established that potatoes utilizes more water for irrigation compared to other crops however this study established that potatoes utilizes less water compared to Navel oranges and also potatoes has high productivity compared to other study crops.

7.1 Recommendations

- Further research on the water footprint should be on developing standard methodology for estimating the water footprint of crops in South Africa.

- For further investigations of water footprint in the WMA, a representative number of farms for each crop per region should be considered in order to assess the impact of the volumetric water footprint on the freshwater resources in the WMA.

- Water footprint should be done for wet and dry years ideally green and blue water footprint will vary with difference in rainfall

- Field measured ET_c and indirect water use should ideally be used as farmers don't always keep records of water use.

- Water footprint of potatoes should be assessed for different growing seasons (summer and winter) as it will differ from summer to winter potatoes.

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9 APPENDEX 1

WATER FOOTPRINTING DATA GATHERING EXERCISE SHEET

A. GENERAL INFORMATION

Your full name	
Name of farm	
Location of farm	
Total size of farm (ha)	
Major crop types	
Areas (ha) under different crop types	
Is there a weather station on the farm, and if so, what is measured and who manages the data? Contact details?	

Can you identify a potato centre-pivot field which has shown good productivity and for which you have good water-use and yield data? Please provide details in the table below.

Centre Pivot number and / or name		
Pivot size (ha)		
Potato Species		
Cultivar name		
Planting date (Month / Year)		
Harvesting date (Month / Year)		
Number of workers working on the pivot for	Permanent	Temporary

Planting?: Harvesting?:		
Number of days required for Planting the pivot?:		
Number of days required for Harvesting the pivot?:		
Number of days required for Sorting potatoes from the pivot?:		
Length of fallow / unplanted period between potato crops (years)?		

B. WATER USE INFORMATION

What are the volumes of water use associated with the potato crop pivot described above? Please give an indication next to each water use category, and specify the units.

Water use category	**Amount**	**Units (e.g. Litres/ha or Litres/pivot)**
Irrigation		
Fertilizer application		
Fertigation		
Spraying of micronutrients Leaf feeding		
Spraying of pesticides and fungicides		
Spraying of herbicides		
Washing harvested potatoes		
Water use in the pack house		
Other(specify)e.g.:Washing equipment		

Flushing spray tanks Domestic use Water used by workers Other?		

What is the source of your irrigation water? Mark the approximate % supplied by each.

Directly from River/ Stream	
Directly from Dam (Runoff from the mountains)	
Groundwater / Borehole	
Other sources e.g. canal (specify)	

If dam water is used, what is the size (surface area) of the dam (m^2 or ha)? This information will help to calculate surface water evaporation.

……………………………………………….

Do any activities on your farm enable the re-use/ recycle of water? Name them.

Activity 1	
Activity 2	
Other (specify)	

Can you specify how much water is saved by the re – use (or recycling) activities specified above (Litres/ yr) ?

Activity 1	
Activity 2	
Other (specify)	

C. CROP YIELD INFORMATION

What was the potato yield for the pivot described above (tons/ha or tons/pivot)?

Season / Year	Yield	Units (e.g. tons/ha or tons/pivot)

Please indicate what the potato yield is during:

A good season (tons/ha)... ton......................A bad season (tons/ha)...under

What aspects affect the yield or results in good or bad yield?

Please indicate the average potato yield for the past 5 years.

Year	2010	2012	2013	2014
Yield (tons/ha)				

D. WATER USE INFORMATION

Weather data

Can you access weather data from a weather station close to the farm? **YES/NO**

If yes please provide the link where I can access this data.

Any further comments or notes?