DEVELOPMENT AND TESTING OF A SMARTPHONE APPLICATION FOR PREDICTING CROP WATER REQUIREMENTS IN APPLE ORCHARDS 1 TO 7 DAYS IN ADVANCE

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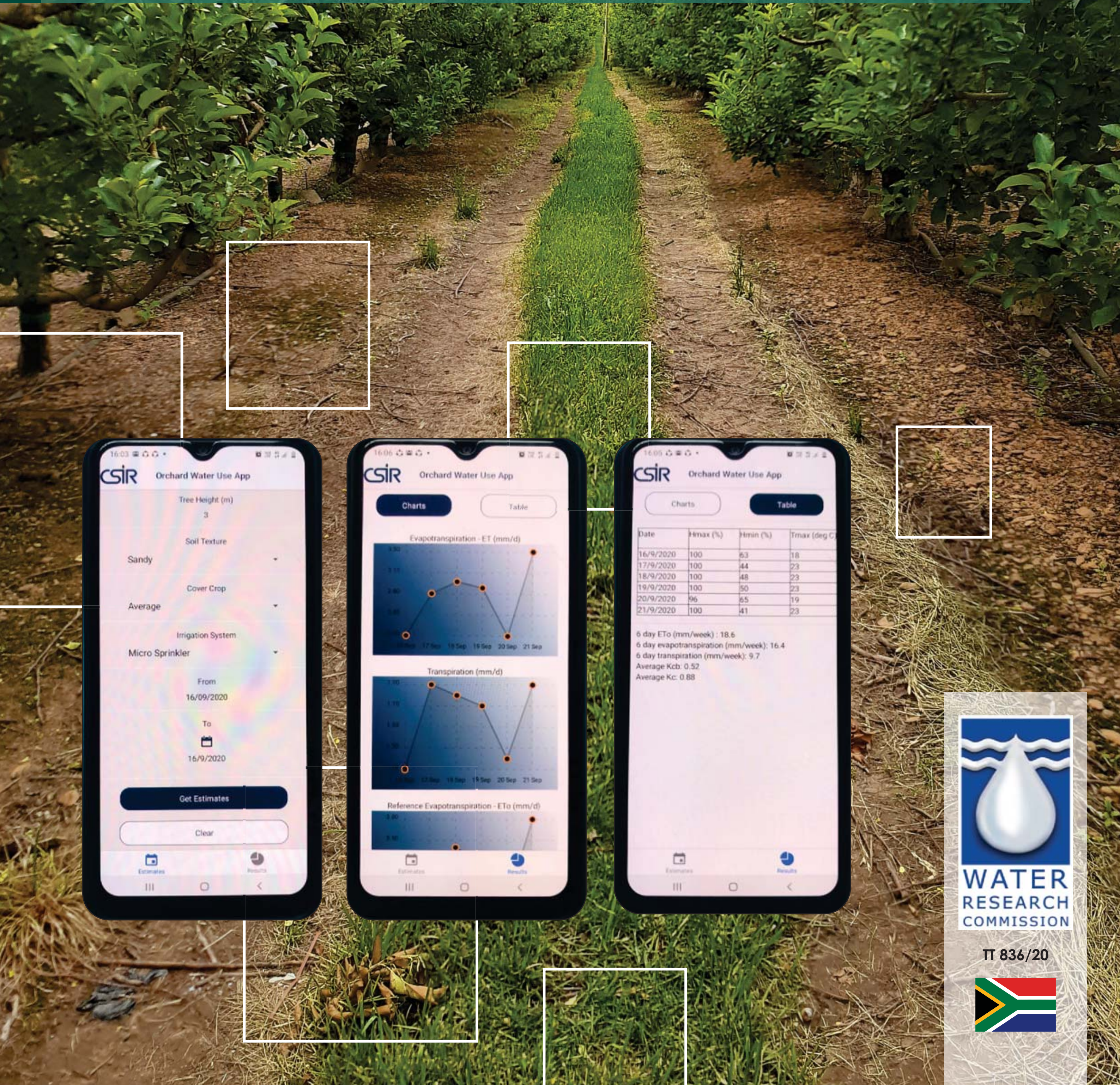

WATER RESEARCH COMMISSION

TT 836/20

DEVELOPMENT AND TESTING OF A SMARTPHONE APPLICATION FOR PREDICTING CROP WATER REQUIREMENTS IN APPLE ORCHARDS 1 TO 7 DAYS IN ADVANCE

Report to the
WATER RESEARCH COMMISSION

by

SEBINASI DZIKITI[1,4], ZANELE NTSHIDI[1], TREVOR LUMSDEN[1], NOMPUMELELO MOBE[1], MUNYARADZI MANDAVA [2], MARK GUSH[3]

[1]Council for Scientific and Industrial Research, Smart Places Cluster
[2]TEQOA Pty Ltd
[3]Royal Horticultural Society, UK
[4]Stellenbosch University, Department of Horticultural Science

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Obtainable from
Water Research Commission
Private Bag X03
Gezina
Pretoria, 0031

orders@wrc.org.za or download from www.wrc.org.za

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EXECUTIVE SUMMARY

Motivation

Over the years, the Water Research Commission (WRC), in collaboration with fruit industry partners, has initiated and funded several research projects aimed at establishing the water requirements of orchards across South Africa. Many of the studies focused on apple orchards in the prime production regions in the Western Cape (Volschenk *et al.*, 2003; Gush and Taylor, 2014; Dzikiti *et al.*, 2018). There are currently ongoing related studies in these areas (Midgley *et al.*, 2019). So, the volume of good quality data of actual orchard water use measurements is growing.

With this in mind, a study aimed at consolidating and adding value to these data was initiated. The priority of the study was to develop a simple but scientifically credible online tool that operates on platforms that are easily accessible to end users, e.g. farmers, irrigation boards, etc. to assist them with irrigation planning in real-time. The project therefore investigated the possibility of developing a Smartphone Application (APP) for forecasting orchard water requirements a few days in advance using readily available data as inputs. Focus was on apple orchards which have some of the largest volume of measured water use data. This innovation comes at the right time when the fruit industry is grappling with water scarcity as a result of frequent droughts and the increasing demand for the limited water resources.

Aims and objectives

General aim: The overall aim was to develop and test a pilot version of a smartphone application that can be used to predict apple orchard water requirements using online weather forecasts and appropriate crop coefficients one to seven days in advance.

Specific objectives:

The specific objectives of this project were to:

- Review and consolidate latest literature which includes reports, scientific publications, relevant data and stakeholder perceptions on orchard water management;
- Generate databases of spatially and temporally representative reference evapotranspiration data and crop water requirements for different orchards;
- Develop an application to incorporate near real-time weather forecasts and associated weekly water requirements for orchards, and;
- Test, refine, and finalise the application through stakeholder consultation and participation.

Methodology

The project which spanned the period April 2018 to October 2020 had several phases. The first phase involved developing the methods and identifying the right data sources. We developed the APP following the internationally acclaimed FAO 56 principles (Allen *et al.*, 1998) which irrigators are familiar with. According to this approach, the orchard water requirements, which numerically are equal to the crop evapotranspiration (ET), is calculated as the product of a crop coefficient (K_c) and the reference evapotranspiration (ET_o). Selecting and identifying an accurate online source of daily weather forecasts to predict ET_o a few days in advance was therefore an important consideration.

The second phase involved developing a method for deriving the orchard K_c values. Crop coefficients vary widely between fields even for the same crop type due to a range of factors. These include the fractional vegetation cover, size of the wetted area, orchard management practices, e.g. cover crops, mulching, etc. This variability in K_c values is evident in the data collected in apple orchards by previous studies. Because each orchard requires unique

K_c values, it was important to develop a method to accurately estimate the crop coefficients taking the conditions of each specific orchard into account. We therefore adopted and improved a K_c calculating algorithm developed by Allen and Pereira (2009) that uses readily available information such as the fractional vegetation cover and tree height.

The improvements, which targeted apple orchards, were validated with actual measured data from twelve different orchards in the Western Cape. Details of the improved method were published in an international peer reviewed journal (Mobe *et al.*, 2020b). The last phase was the field testing of the application. This was done by comparing the APP's water use forecasts with actual measurements collected in three orchards during the 2019/20 growing season. This task was done in collaboration with selected growers. Roll out of a free version of the pilot application on Play Store and Google Play Store is expected before October 2020.

Results and discussion

A pilot version of the smartphone APP has been developed for apple orchards which uses readily available data as inputs. The inputs include, orchard coordinates, an estimate of the fractional vegetation cover, average tree height, soil type, cover crop status and irrigation system. The user then decides how far ahead they wish to get the daily forecasts. We recommend a maximum of seven days ahead because the accuracy of the weather forecasts declines with longer forecasting intervals.

The APP works on both Android and the iPhone Operating System (IOS) platforms. The outputs from the APP include the daily orchard transpiration, evapotranspiration and reference evapotranspiration. A weekly summary of the crop coefficients is also produced. While there are similar online tools being used to forecast orchard water use in the country, none of them predict both the transpiration and evapotranspiration components. The existing tools forecast only the reference evapotranspiration and the user is left to decide their own crop coefficients which leads to significant uncertainties in the water use estimates.

Validation of the APP's water use forecasts with field measurements yielded promising results, but further testing or improvements are needed to arrive at a fully operational tool. While the forecast ET_o closely matched the observed trends, the APP tended to slightly over estimate the reference evapotranspiration on hot dry days by just over 1.0 mm d^{-1}. In high density orchards in which individual tree canopy volumes were small, the APP's forecasts of orchard transpiration were fairly accurate with the root mean square error less than ±1.0 mm d^{-1}. However, in a mature orchard in which row spacing was wide and hence the trees had large canopy sizes, the APP significantly under-estimated the transpiration rates, possibly because of the inaccurate estimates of the fractional vegetation cover.

Conclusions

The orchard water use APP developed in this study has the potential to improve irrigation scheduling and water allocation planning by providing detailed forecasts of the actual orchard evapotranspiration and its components. The performance of the current version against field measurements can be described as fair. Although the seasonal irrigation requirements in some orchards were predicted to within 10% of the actual applied volumes, error margins were fairly high for other variables. Further testing and improvements are needed if this tool is to evolve into a commercially operational product.

Recommendations

It is important to note that this application is only a pilot product. Interested users are therefore encouraged to further test it and to tamper it to their specific conditions. Detailed validation data were collected in only three orchards – further tests are clearly necessary. In addition, the current version of the APP only works in apple orchards. There is need to include other fruit types, but this requires more resources.

Extent to which contract objectives have been met

The contract objectives have to a large extent been met, and in some instances, exceeded. A smartphone application has been developed and tested as planned. The APP works on both Android and IOS's systems and a free version will be available online before October 2020. Testing of the APP was done against actual measured water use data under field conditions in collaboration with selected participating farmers.

One popular article was published in the Water Wheel to publicise the project as planned. In addition, a peer reviewed article was also published in an international journal and this was not a planned output.

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Dr L Nhamo	Water Research Commission
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Prof. WJ Steyn	Hortgro Science
Prof. JG Annandale	University of Pretoria
Dr NJ Taylor	University of Pretoria
Prof. C Everson	University of KwaZulu-Natal
Dr N Benade	NB Systems

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LIST OF ABBREVIATIONS

A&P	Allen & Pereira
API	Application Programming Interface
APP	Smart phone Application
ARC	Agricultural Research Council
AWS	Automatic Weather Station
BCP	Bearing ‘Cripps’ Pink’
BGD	Bearing ‘Golden Delicious’
BGR	Bearing ‘Golden Delicious Reinders’
CSIR	Council for Scientific and Industrial Research
CWR	Crop Water Requirement
EGVV	Elgin/Grabouw/Villiersdorp/Vyeboom
FAO56	Food and Agriculture Organization, paper no 56
FBCP	Full-bearing ‘Cripps’ Pink’
FBGD	Full-bearing ‘Golden Delicious’
FC	Field Capacity
FTP	File Transfer Protocol
GD	‘Golden Delicious’
GFS	Global Forecast System
GS	‘Granny Smith’
HPV	Heat Pulse Velocity
HRM	Heat Ratio Method
IBCP	Intermediate Bearing ‘Cripps’ Pink’
IBGR	Intermediate Bearing ‘Golden Delicious/Reinders’
IOS	iPhone Operating System
IRGA	Infrared Gas Analyser
KBV	Koue Bokkeveld
LAI	Leaf Area Index
MAE	Mean Absolute Error
NBCR	Non-Bearing ‘Cripps’ Red’

NBGD	Non-Bearing ‘Golden Delicious’
NBGR	Non-Bearing ‘Golden Delicious Reinders’
NBRG	Non-Bearing ‘Rosy Glow’
NCEP	National Centre for Environmental Prediction
NSE	Nash-Sutcliffe Efficiency
NWRS	National Water Resource Strategy
PWP	Permanent Wilting Point
REW	Readily Evaporable Water
RMSE	Root Mean Square Error
SAI	Sapwood Area Index
SAPWAT	South African Procedure for determining crop WATer requirements
SW	Shuttleworth and Wallace
SWB	Soil Water Balance
TEW	Total Evaporable Water
WP	Permanent Wilting Point

ROMAN SYMBOLS

Cl	Percentage fraction of clay in soil (%)
E_s	Soil evaporation (mm d^{-1})
E_{so}	Potential evaporation rate from a wet soil surface (mm d^{-1})
ET	Actual evapotranspiration (mm d^{-1})
ET_o	Reference evapotranspiration (mm d^{-1})
f_c	Fraction of the ground surface covered by vegetation at midday
f_{ceff}	Effective vegetation cover
F_r	Stomatal sensitivity adjustment factor (0-1)
K_{cbfull}	Basal crop coefficient under conditions of full ground cover
K_{cmin}	Minimum basal coefficient for bare soil (-)
K_d	Density coefficient (-)
K_c	Crop coefficient (-)
K_{cfull}	Crop coefficient from a fully covered soil (-)
K_{cmax}	Maximum crop coefficient (-)
K_{cb}	Basal crop coefficient (-)
$K_{cb\ cover}$	Basal crop coefficient due to cover crop (-)
K_{cbfull}	Basal crop coefficient of a mature well-watered orchard (-)
$K_{cbfullc}$	Maximum cover crop basal crop coefficient (-)
K_{dc}	Density coefficient for the cover crop (-)
K_{edry}	Evaporation coefficient for dry soil
K_{soil}	Average crop coefficient from non-vegetated surface (-)
LAI_c	Leaf area index of the cover crop
M_L	Multiplier for canopy size
r_l	Mean leaf resistance (s m^{-1})
RH_{max}	Maximum relative humidity (%)
RH_{min}	Minimum relative humidity (%)
Sa	Percentage fraction of sand in soil (%)
SAI	Sapwood area index (m^2 m^{-2})
SF	Sap flow (cm^3 h^{-1})

T	Orchard level transpiration (mm d^{-1})
T_a	Average air temperature (°C)
T_c	Cover crop transpiration (mm d^{-1})
T_{min}	Minimum air temperature (°C)
T_{max}	Maximum air temperature (°C)
T_w	Average time between independent wetting events
U	Sap flux density (cm^3 cm^{-2} d^{-1})
U_2	Mean wind speed (m s^{-1})
VPD	Vapour pressure deficit of the air (kPa)
Z_e	Effective depth of soil evaporation (m)

GREEK SYMBOLS

Δ	Slope of the saturation vapour pressure vs air temperature curve (kPa K^{-1})
γ	Psychrometric constant (kPa K^{-1})
α	Canopy resistance parameter (s m^{-1})
θ	Volumetric soil water content (m^3 m^{-3})
ψ_x	Xylem water potential (kPa)

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND AND RATIONALE

Irrigated agriculture uses approximately 62% of South Africa's surface water resources, and competition for this scarce resource is growing. Water availability and climate-related issues are the greatest risks to the sustainability and growth of irrigated agriculture, especially the water-intensive fruit industry (Gush and Taylor, 2014; Hortgro, 2016). Improvements in water productivity, defined in this study as yield per unit volume of water consumed, are critical mitigation actions in this regard. As competition for water heightens, the need to improve water productivity also increases. This is important to reduce water wastage and to produce more fruit with less water thereby increasing profits, driving job creation while protecting the environment. Consequently, efforts aimed at increasing the efficiency of irrigation have merit.

In recent years, many studies in the country have quantified the actual water use of crops, mostly with funding from the WRC and its industry partners. There has been a particular interest on commercial fruit orchards which are almost entirely dependent on irrigation. Substantial volumes of data have been collected in apple (*Malus domestica* Borkh) orchards. These data were collected in studies by Volschenk *et al.* (2003); Gush and Taylor (2014); Volschenk (2017) and Dzikiti *et al.* (2018a). The data were collected using innovative state-of-the-art methods that quantified orchard water use, soils, microclimate, growth, yield and fruit quality. So the database of good quality orchard water use observations in South Africa is growing.

Information also exists on the main drivers of water use in apple orchards. These include variations induced by cultivar, e.g. Cripps' Pink, Golden

Delicious and related cultivars, e.g. Rosy Glow, Cripps' Red, Golden Reinders, Royal Gala, etc. (Mobe *et al.*, 2020a), canopy cover for orchards of different age groups (e.g. young, intermediate, and full-bearing), productivity ranges (normal to high-yielding), and microclimates (e.g. Koue Bokkeveld and Grabouw, Vyeboom / Villiersdorp) (Dzikiti *et al.*, 2018a,b; Ntshidi *et al.*, 2018; Gush *et al.*, 2019). Some of the studies partitioned orchard evapotranspiration (ET) into its constituent components, e.g. tree transpiration (T), soil evaporation (E_s), and cover crop evapotranspiration. Nearly all the studies derived crop coefficients (K_c = ET/ET_o) following the FAO 56 guidelines (Allen *et al.*, 1998) using the short grass reference crop evapotranspiration (ET_o).

However, to significantly impact orchard water management, there is need to transfer the water use data to other orchards where data were not collected. One way of achieving this is by using the measured water use data to develop tools and products that growers can use to make accurate irrigation decisions. In this study we decided to use the internationally acclaimed FAO 56 guidelines to develop a smartphone application (hereafter called APP) to forecast the water requirements of apple orchards. Although adequate data were available to develop the APP, a major drawback was the lack of transferability of the K_c values between orchards. Orchard crop coefficients vary widely with canopy cover, row orientations, tree spacing, irrigation systems (i.e. wetted soil fraction), crop loads, cover crops, mulching, etc.

To overcome this problem, we adopted and improved the method for transferring crop factors developed by Allen and Pereira (2009) (hereafter A&P). These authors effectively extended the FAO 56 approach by estimating K_c using a density coefficient (K_d) calculated using the fraction of ground covered by vegetation and plant height. They also included a stomatal sensitivity function which differentiates between the stomatal responses of different crop types to environmental stresses. The use of a density coefficient in calculating the crop factors is an important innovation because it takes into account the canopy volume. Hence young orchards with sparse canopies will have different crop coefficients, and hence water requirements, from mature orchards with dense canopies, for example. In addition, the drought responses of different crop types, even with a similar fractional vegetation cover and height are taken into account using the stomatal sensitivity function. Another advantage of this technique is that it lends itself to automation requiring limited input data thereby making it appropriate for use in the APP.

Similar products to the APP developed in this study are already available in the fruit industry. An example is Hortec's iLeaf (www.ileaf.co.za) product that is used primarily to forecast ET_o. With this system, the user decides on, and to apply, appropriate crop factors which arguably is a source of significant uncertainty given the paucity of accurate crop coefficients. The APP developed in this project attempts to minimize these uncertainties by providing not only the ET_o forecasts, but also the crop factors derived using a technique validated using actual measured crop factors from 12 apple orchards with different characteristics.

1.2 AIMS AND OBJECTIVES

The overall aim of this project was to develop and test a pilot version of a smartphone application (APP) that can predict apple orchard water requirements using online weather forecasts and appropriate crop coefficients one to seven days in advance. The water use is split into whole orchard ET and tree transpiration, so the user has information on orchard floor evaporative losses as well. Such a tool has potential applications in irrigation planning, especially forecasting the orchard water requirements a few days in advance. We restricted the APP to seven days ahead as the accuracy of weather forecasts become unreliable the longer the forecasting period.

The specific objectives of this project were to:

- Review and consolidate latest literature which includes reports, scientific publications, relevant data, and stakeholder perceptions on orchard water management;
- Generate databases of spatially and temporally representative reference evapotranspiration data and crop water requirements for different orchards;
- Develop an application to incorporate near real-time weather forecasts and associated weekly water requirements for orchards, and;
- Test, refine, and finalise the application through stakeholder consultation and participation.

A schematic representation of the APP is shown in Figure 1.1.

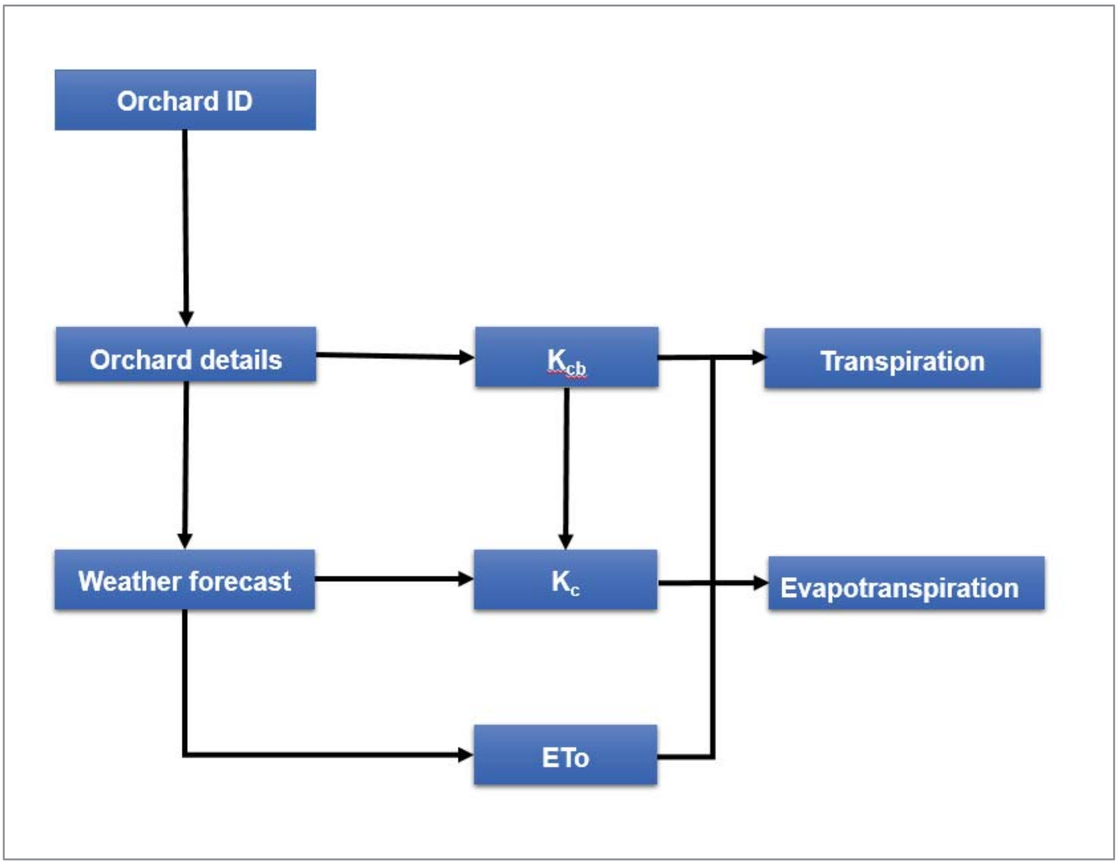

Figure 1.1: Schematic representation of the steps involved in developing the Smart Water Use Application for predicting the water requirements of orchards.

1.3 SCOPE OF WORK

The scope of work had the following components: 1) conceptualization of an appropriate smartphone application (APP) framework for forecasting apple orchard water requirements; 2) development of the APP; 3) testing of a pilot version of the APP; 4) engagement with end users, and; 5) deployment of the pilot APP. Important considerations during conceptualization of the APP included, accuracy of the crop water use forecasts, simplicity of the APP, and the ability to function on various smartphone platforms. For these reasons we decided to use the internationally accepted FAO 56 approach to calculate the crop water requirements for a short grass reference using appropriate crop coefficients. This approach is widely used in water resources management and would ensure that the water use estimates would be comparable at different locations. To implement this approach required a reliable online weather data source to accurately forecast the reference evapotranspiration. Another requirement of this approach are accurate crop factors. Therefore considerable effort was expended in firstly identifying appropriate online weather data sources and secondly developing a protocol for calculating accurate crop factors using readily available data. For simplicity, the APP was developed for apple orchards under unstressed conditions only. To ensure access by a wide range of end users the APP was developed for both Android and IOS operating systems. Validation of the APP was done using actual field measurements to establish the reliability of the APP. Limited engagements were conducted with the farmers to demonstrate the APP. Two farmers participated directly in the testing of the APP during the 2019/20 growing season. Further engagements with more farmers were not possible due to the lockdown restrictions to curb the spread of the covid-19 pandemic. A pilot version of the APP will be deployed on Google Store and Play Store before the end of the project.

1.4 PROPOSED FUTURE RESEARCH

Proposed further research to improve the APP includes:

1) Further testing of the APP with actual measured water use data in apple orchards in the summer rainfall growing regions, e.g. parts of the Eastern Cape and the Free State Provinces;

2) This APP is developed for apple orchards only. But a generic tool is required for all irrigated fruit types in the country given that the fruit industry is one of the highest water users. Before the APP can be updated to include other fruit types, detailed studies are required to extend the protocol for estimating the crop factors using readily available data to other crop types. This requires detailed measurements of actual transpiration and evapotranspiration, orchard microclimate, stomatal conductance dynamics, fractional vegetation cover, etc. These data have already been collected in previous WRC and industry funded projects on species such as citrus, macadamia nuts, pecan nuts, nectarines, plums and avocados. However, there is need to update the water use database for fruit trees to include species such as mango, litchis, banana, etc.
3) There is also a need to establish whether the APP can be coupled with remote sensing data to provide spatial water use forecasts.

CHAPTER 2

KNOWLEDGE REVIEW

2.1 WATER USE IN SOUTH AFRICAN APPLE ORCHARDS

Nearly all apples exported from South Africa are grown under irrigation. Yet between 30 and 45% of water allocated for irrigation is wasted mainly due to poor irrigation practices, transmission losses, and leakages (NWRS, 2013). Inefficient irrigation practices, growing populations, increasing economic activities, and changing climatic conditions all contribute to increasing water scarcity in the major fruit producing regions in the country (Volschenk *et al.*, 2003; Dzikiti *et al.,* 2018a,b; Gush *et al.*, 2019; Mobe *et al.*, 2020a,b). According to the Second National Water Resources Strategy, adopting suitable technologies can significantly reduce water wastage (NWRS, 2013). This is critical for the long-term sustainability and growth of water-intensive industries such as the fruit industry.

The FAO-56 approach, described by Allen *et al.* (1998) is the most widely used climate-based crop water requirement estimation method due to its simplicity and robustness. In this approach crop evapotranspiration (ET) is estimated as the product of the reference evapotranspiration (ET_o) and a crop coefficient (K_c). Allen *et al.* (1998) tabulated typical K_c values for a range of irrigated crops. However, several studies compared the results obtained using the FAO-56 method with actual evapotranspiration measured using various techniques (Casa *et al*., 2000; Allen, 2000; Lascano, 2000; Dragoni *et al*., 2005; Paco *et al*., 2006; Volschenk, 2017). The results demonstrate the need to adjust the FAO tabulated crop coefficients to specific growing conditions.

A lot of studies have been done internationally to quantify the water use of apple orchards. For brevity, and since the primary focus of this study was to develop a potential tool for the South African apple industry, we restricted our knowledge review to research done in South African orchards only. The intention was to highlight the variability in the crop coefficients justifying the need for a method for calculating the crop coefficients that not only uses readily available data, but is also amenable to automation.

Internationally, there are reports in literature that present information on transpiration and evapotranspiration by field grown apple trees (Green and Clothier, 1988; Li *et al.*, 2002; Green *et al.*, 2003; Dragoni *et al.*, 2005, Gong *et al.*, 2007). However, very few provide the corresponding crop coefficients (Allen *et al.*, 1998). Specific South African-based information is slowly increasing, but is still quite limited. South African studies focussing on apple orchard water requirements comprise the A-pan evaporation based “Green Book” (Green, 1985a; Green, 1985b), soil water balance-based estimates (Volschenk *et al.*, 2003; Volschenk, 2017), transpiration and evapotranspiration estimates for an “average” apple orchard of a particular cultivar (Gush *et al.*, 2014), and for pre-bearing, mid-bearing and mature high yielding apple orchards of various cultivars and at contrasting sites (Dzikiti *et al.*, 2018a,b).

2.2 GREEN (1985)

In the past, growers commonly used the American Class A evaporation pans and relevant pan coefficients to calculate irrigation requirements. Application of the Class A pan evaporation figures in scheduling is based on a direct relationship between actual ET and the corresponding A-pan evaporation value. Crop evapotranspiration was thus calculated by multiplying the A-pan evaporation by a unique pan coefficient. This was the approach used in the development of the original “Green Books” for estimated irrigation requirements of crops in South Africa (Green, 1985a, b). The crop coefficient varies depending on the species, growth stage of the crop and time of year. Crop coefficients for deciduous fruit, as recommended by Green (1985b), and which would be appropriate for apple orchards, distinguish between "Early", "Midseason" and "Late" varieties (Table 2.1). These correspond to active growing season start dates of 1st August, 1st September and 1st October.

The main disadvantage of determining orchard water requirements using this method is that fewer and fewer growers have access to reliable A-pan evaporation data.

Table 2.1: Crop coefficients for early, midseason and late deciduous fruits (Green, 1985b).

	Crop Coefficients		
Month	**Early**	**Midseason**	**Late**
July	0.20	0.20	0.20
August	0.23	0.20	0.20
September	0.27	0.23	0.20
October	0.29	0.27	0.24
November	0.39	0.31	0.27
December	0.45	0.41	0.36
January	0.54	0.50	0.45
February	0.58	0.59	0.57
March	0.37	0.42	0.48
April	0.20	0.20	0.20
May	0.20	0.20	0.20
June	0.20	0.20	0.20

There is a concerted move towards increased use of data collected by Automatic Weather Stations (AWS) to calculate reference evapotranspiration (ET_o) according to the FAO-56 approach (Allen *et al.*, 1998). Furthermore, there are high levels of uncertainty in the appropriate crop coefficients to use with A-pan data, and subsequent research has improved upon and refined these for use with FAO-56 based estimates of reference evapotranspiration (ET_o). While they did account for seasonal differences between varieties / cultivars, the

“Green Book” crop coefficients were only compiled for mature trees and thus require adjustment for immature trees which have a smaller canopy size.

They also do not take into account the soil water holding capacity, effectiveness of irrigation or rain events, depth of water infiltration, depth of plant water extraction and effects of plant health on water usage, although this is a challenge common to most applications of the crop coefficient approach. Finally, the “Green Book” deciduous fruit crop coefficients were acknowledged by Green (1985b) to be influenced to a greater extent by seasonal growth patterns than by other factors such as physical growth habit or nature of the canopy of different species. However, this is contrary to the findings of subsequent field studies (see Dzikiti *et al.*, 2018a,b in section 2.1.5).

2.3 FAO 56 (ALLEN *et al.*, 1998) / SAPWAT (VAN HEERDEN and WALKER, 2016)

Due to its physical and biological basis, the FAO-56 modified Penman-Monteith-based model (Allen *et al.*, 1998) is the most widely used method to estimate orchard water use. It provides a means of calculating reference and crop evapotranspiration from meteorological data and crop coefficients. The effect of climate on crop water requirements is given by the reference evapotranspiration (ET_o), and the effect of the crop by the crop coefficient K_c. Actual crop evapotranspiration (ET) is derived as $ET = K_c * ET_o$.

The calculation of ET_o based on the Penman-Monteith combination method, represents the ET of a hypothetical reference crop (short grass) that is healthy, actively growing, not short of water, and uniformly covering the ground. ET_o is calculated using readily available weather variables. The technique uses standard climatic data that can be easily measured or derived from commonly collected weather station data. Differences in the canopy and aerodynamic resistances of the crop being simulated, relative to the reference crop, are accounted for within the crop coefficient (K_c). K_c serves as an aggregation of the physical and physiological differences between crops. Two calculation methods to derive ET from ET_o are possible. The first approach integrates the relationships between evapotranspiration of the crop and the reference surface into a single coefficient (K_c). The second approach splits K_c into two factors that separately describe the evaporation (K_e) and transpiration (K_{cb}) components.

Multiplication of the reference evaporation by the crop coefficient represents the upper envelope of crop transpiration where no limitations are placed on plant growth or evapotranspiration. The option to split the crop coefficient (K_c) into two factors that separately describe the evaporation (K_e) and transpiration (K_{cb}) components is particularly suited to studies where transpiration (excluding soil evaporation) is measured, as crop coefficients calculated from these results equate directly to estimates of K_{cb}. The predicted transpiration may also be adjusted to non-standard conditions using stress modifiers.

Allen *et al.* (1998) lists crop development stages and crop coefficients for numerous crops under “standard conditions.” The first requirement is the selection of an appropriate set of crop development stages, and the most appropriate category for apple orchards is listed under group “n.”-Fruit Trees (Deciduous Orchards). Regional values are provided for High Latitudes, Low Latitudes and California (USA), but nothing specifically for southern Africa. Of these, the “Calif., USA” category has a growing season length of 240 days and is considered the most appropriate for the Western Cape Mediterranean climate region. Based on this category, the crop development stages (in days) are: Initial = 30, Development = 50, Mid = 130 and Late = 30, giving a total of 240 days. In the Western Cape bud break in apple orchards typically commences around the beginning of October, so the crop development stages coincide roughly with the following dates: Initial = 1 to 31 October, Development = 1

November to 20 December, Mid = 21 December to 30 April, and Late = 1 May to 31 May. The period 1 July to 30 September is deemed to be the dormant / senescent stage of the tree as the species is typically leafless during this period (i.e. no transpiration).

The category selected for the full crop coefficients (K_c) is again under group "n."-Fruit Trees (Apples, Cherries, Pears) with various sub-options, the most appropriate of which is considered to be "active ground cover, no frosts." This yields crop coefficients of $K_{c\ ini}$ = 0.8, $K_{c\ mid}$ = 1.2 and $K_{c\ end}$ = 0.85. The $K_{c\ end}$ values represent K_c prior to leaf drop. After leaf drop, $K_{c\ end}$ ≈ 0.2 for bare, dry soil or dead ground cover and $K_{c\ end}$ ≈ 0.5 to 0.8 for actively growing ground cover. Basal crop coefficient (K_{cb}) values suggested by Allen *et al.* (1998) for the same category are given as $K_{cb\ ini}$ = 0.75, $K_{cb\ mid}$ = 1.15 and $K_{cb\ end}$ = 0.80. Again, the $K_{cb\ end}$ values represent K_{cb} prior to leaf drop. After leaf drop, $K_{cb\ end}$ ≈ 0.15 for bare, dry soil or dead ground cover and $K_{cb\ end}$ ≈ 0.45 to 0.75 for actively growing ground cover (Table 2.2).

Recommended FAO-56 crop coefficient values, as published in Allen *et al.* (1998), can be modified to better represent a particular crop and its development stages when observed data for the species of interest is available. This option is available in the SAPWAT model for example. The **S**outh **A**frican **P**rocedure for determining crop **WAT**er requirements model (SAPWAT v4) (Van Heerden and Walker, 2016) determines crop water use (or evapotranspiration, ET) using the FAO-56 guidelines which apply the four stage crop factor approach (Figure 2.1). This approach ensures transparent and internationally comparable estimates of crop water use.

Table 2.2: Crop coefficients for deciduous fruit orchards growing in a Mediterranean climate with active ground cover and no frost (Allen et al., 1998).

Month	K_{cb}	K_c
July	0.45	0.50
August	0.45	0.50
September	0.45	0.50
October	0.75	0.80
November	0.88	0.93
December	1.01	1.06
January	1.15	1.20
February	1.15	1.20
March	1.15	1.20
April	1.15	1.20
May	0.80	0.85
June	0.45	0.50

In SAPWAT, ET_o is calculated at the hourly, daily or monthly time steps, and has an inbuilt database of daily weather data for all quaternary catchments (QCs) in South Africa and about 14 QCs in Swaziland over a 50 year period (1950-1999).

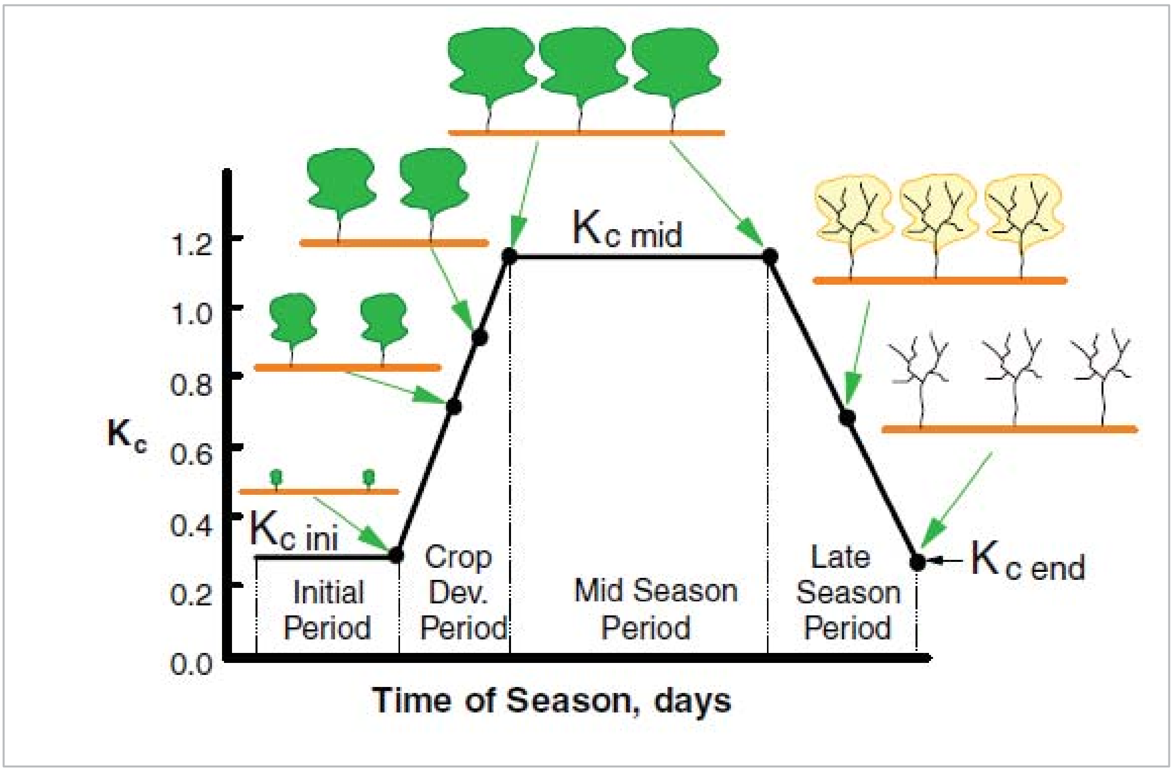

Figure 2.1: ***Example of the seasonal variations in crop coefficients (K_c) of crops and their typical ranges.***

2.4 VOLSCHENK *et al.* (2003) AND VOLSCHENK (2017)

Volschenk *et al.* (2003) recorded transpiration rates of approximately 1 739 m³ ha⁻¹ (174 mm) per season in four-year-old 'Golden Delicious' trees, planted at 1 428 trees ha⁻¹ under micro-sprinkler irrigation at Molteno Glen farm in Elgin, South Africa. They also measured seasonal total transpiration of between 3 556 m³ ha⁻¹ (356 mm) and 4 224 m³ ha⁻¹ (422 mm) per season for 8-10 yr. old full-bearing 'Golden Delicious' orchards at Grabouw Farms and Oak Valley in Elgin. With corresponding measurements of weather variables to calculate reference evapotranspiration, basal and full crop coefficients were established for the study orchards (Table 2.3).

Table 2.3: Monthly average daily basal crop coefficients (K_{cb}) and full crop coefficients (K_c) for Golden Delicious (GD) and Granny Smith (GS) apple trees at selected sites (after Volschenk et al., 2003).

	Molteno Glen 4-yr GD		Grabouw Farms 8-yr GD		Grabouw Farms 8-yr GS	Oak Valley 8-yr GD	
Month	**K_{cb}**	**K_c**	**K_{cb}**	**K_c**	**K_c**	**K_{cb}**	**K_c**
Oct	0.13	0.22	0.20	0.20	0.24	0.19	0.31
Nov	0.19	0.28	0.33	0.37	0.53	0.33	0.47
Dec	0.21	0.39	0.42	0.40	0.65	0.38	0.52
Jan	0.22	0.41	0.46	0.51	0.69	0.42	0.60
Feb	0.22	0.41	0.48	0.60	0.73	0.44	0.71
Mar	0.19	0.35	0.48	0.55	0.84	0.49	0.62
Apr	0.11	0.40	0.42	0.72	1.05	0.53	0.78
May	0.02	0.31	0.22	0.41	1.11	0.40	0.45

The soil water balance method is another commonly applied approach for quantifying orchard evapotranspiration, and has been used in apple orchards in South Africa (Volschenk, 2017). In this latter study, the ET of Golden Delicious apple trees, growing on M793 rootstocks, was determined. They reported the following crop coefficients for 13-year old planted at 1 481 trees ha^{-1} under micro-sprinkler irrigation in the Koue Bokkeveld (Figure 2.2).

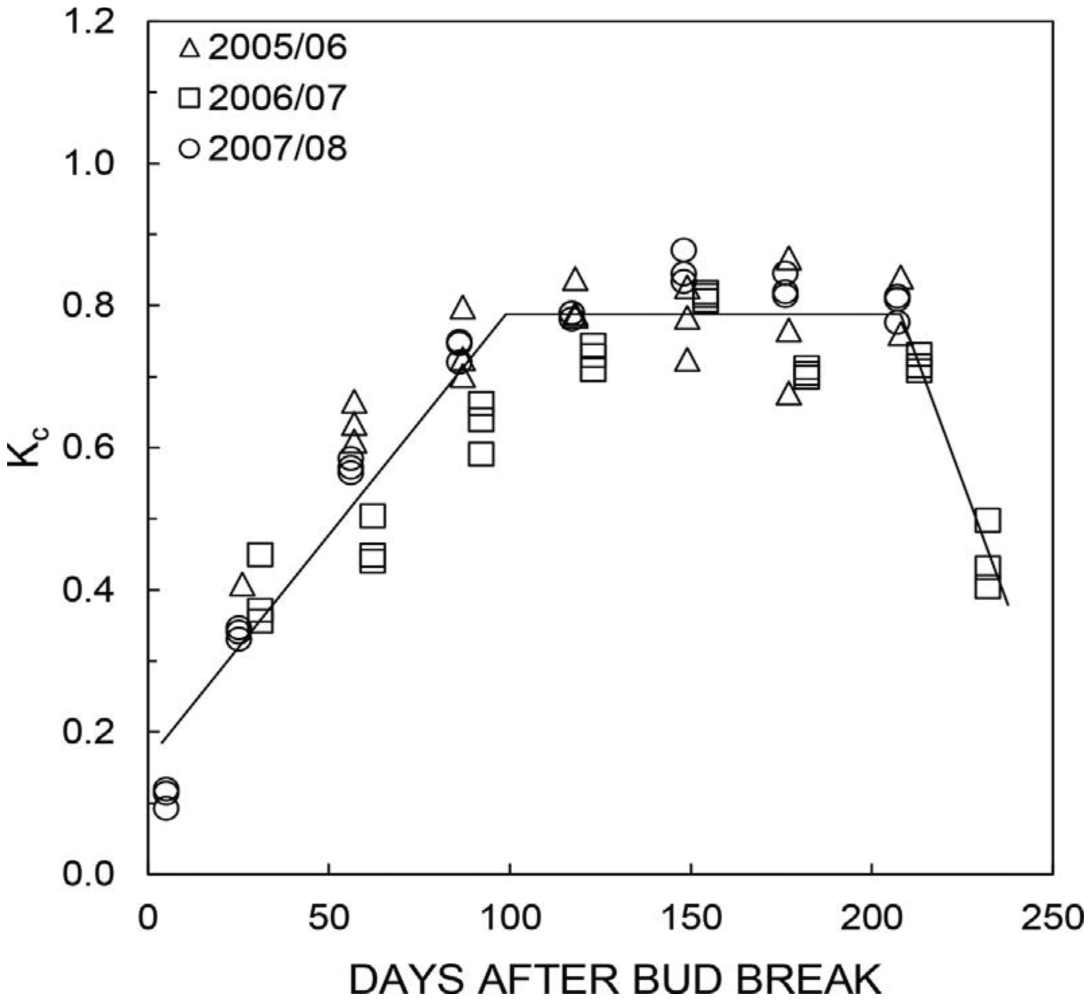

Figure 2.2: ***Crop coefficients (K_c) of full bearing Golden Delicious apple trees from budbreak until the end of the growing season from 2005/06 to 2007/08 in the KoueBokkeveld (Volschenk, 2017). Sloped lines indicate K_c for the development and late stages, respectively, whereas the horizontal line represents K_c= 0.79.***

2.5 GUSH AND TAYLOR (2014)

Gush and Taylor (2014) report on results of water use measurements (transpiration and evapotranspiration) in a range of fruit tree orchards across South Africa. Amongst others, these included observations from an apple orchard in the winter-rainfall Western Cape region (Gush *et al.*, 2014). Water-use measurements were conducted in the same orchard over two years between May 2008 and July 2010 in a 12-year old ‘Cripps Pink’ (‘Pink Lady’) apple (*Malus domestica*) orchard in the Koue Bokkeveld region of the Western Cape, near Ceres. Tree density was 2 000 trees per hectare, and sap flow (transpiration) was measured on an hourly basis for the entire period, using the Heat Ratio Method (HRM) of monitoring sap flow. Measurements were conducted on six trees, comprising four mature ‘Cripps’ Pink’ apple trees and 2 ‘Hillary’ Crab-apple pollinators. In addition, short-term seasonal measurements of ET were measured periodically above the orchard, using an open path eddy covariance system. These observations were combined with site-specific information on weather, irrigation volumes, soils and tree characteristics, in order to calibrate and validate a dual-source model of orchard water-use.

Distinct seasonal trends in water-use were observed. On average, each ‘Cripps’ Pink’ apple tree transpired around 4 000 L $year^{-1}$, with mid-summer peak daily transpiration volumes of up to 58 L $tree^{-1}$ day^{-1}. The pollinators used a mere 1 100 L $tree^{-1}$ $year^{-1}$, with maximum daily transpiration volumes of just 15 L $tree^{-1}$ day^{-1} due to their small canopy sizes. Seasonal total orchard transpiration equated to 680 mm per year, while ET amounted to 950 mm. Basal (K_{cb}) and full (K_c) crop coefficients were derived for the orchard (Figure 2.3 and 3.4) by combining the transpiration and ET results with daily reference evaporation (ETo) data. Representative monthly K_{cb} and K_c crop coefficient values were determined by averaging values for the 2008/2009 and 2009/2010 seasons (Table 2.4).

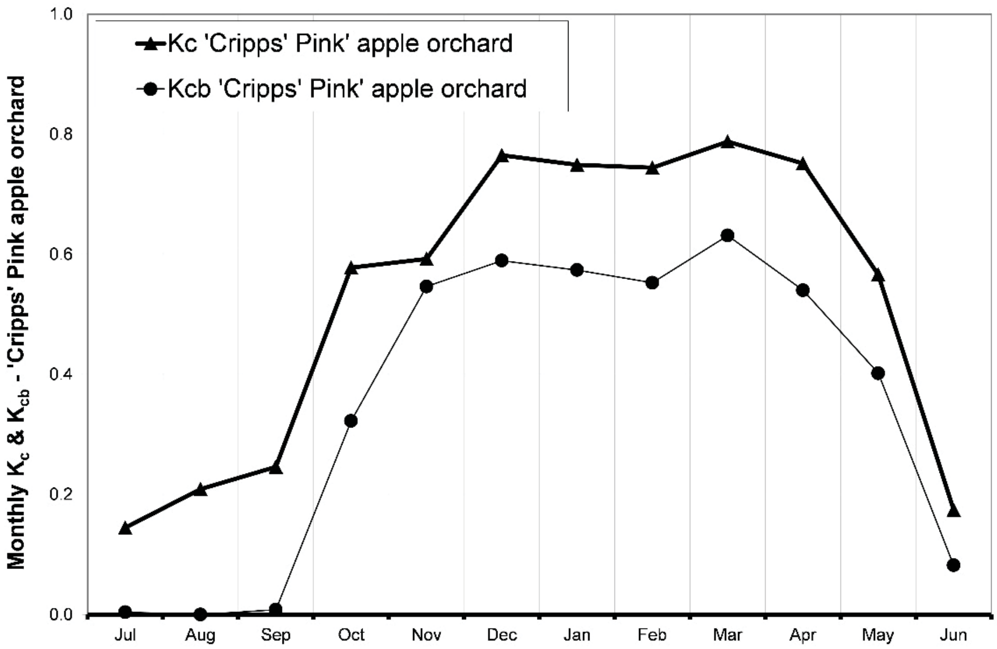

Figure 2.3: ***Monthly basal (K_{cb}) and full (K_c) crop coefficient values determined for the apple orchard over the 2008/2009 season.***

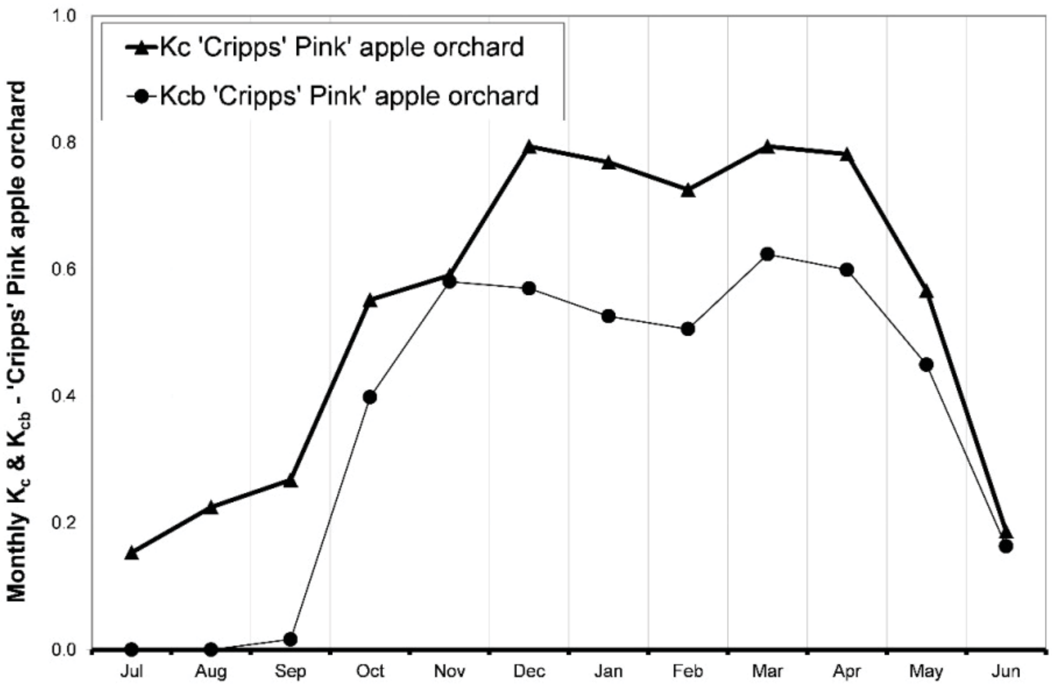

Figure 2.4: ***Monthly basal (K_{cb}) and full (K_c) crop coefficient values determined for the apple orchard over the 2009/2010 season.***

Table 2.4: Monthly basal (K_{cb}) and full (K_c) crop coefficient values determined over two years for an 11/12-year old 'Cripps' Pink' apple orchard in the Koue Bokkeveld (Gush et al., 2014).

Month	K_{cb} 08/09	K_{cb} 09/10	K_{cb} Average	K_c 08/09	K_c 09/10	K_c Average
Jul	0.01	0.00	0.00	0.14	0.15	0.14
Aug	0.00	0.00	0.00	0.19	0.22	0.21
Sep	0.00	0.02	0.01	0.22	0.27	0.25
Oct	0.25	0.40	0.32	0.60	0.55	0.58
Nov	0.51	0.58	0.55	0.59	0.59	0.59
Dec	0.61	0.57	0.59	0.74	0.79	0.77
Jan	0.62	0.53	0.57	0.73	0.77	0.75
Feb	0.60	0.51	0.55	0.76	0.73	0.74
Mar	0.64	0.62	0.63	0.78	0.79	0.79
Apr	0.48	0.60	0.54	0.72	0.78	0.75
May	0.35	0.45	0.40	0.57	0.57	0.57
Jun	0.00	0.16	0.08	0.16	0.19	0.17

2.6 DZIKITI *et al.* (2018)

Exceptionally high yielding (> 100 t ha^{-1}) apple orchards are becoming common in South Africa and elsewhere in the world. However, no quantitative information currently exists on the water requirements of these orchards. Information is also sparse on the water use of young apple orchards. Dzikiti *et al.* (2018a,b) estimated the water requirements of high yielding and young apple orchards in the winter rainfall areas of South Africa. Dynamics of water use were investigated in twelve apple orchards planted to 'Golden Delicious' and the red cultivars, i.e. 'Cripps' Pink', 'Cripps' Red' and 'Rosy Glow' in order to understand how canopy cover and crop load influence orchard water use. Four of the orchards were young (3-4 years after planting) and non-bearing, while the other four were mature high yielding orchards (Table 2.52.5). Transpiration was monitored using HRM sap flow sensors while orchard evapotranspiration (ET) was measured during selected periods using eddy covariance systems. Scaling up of ET to seasonal water use was done using a modified Shuttleworth and Wallace model that incorporated variable canopy and soil surface resistances. This model provided reasonable estimates in both mature and young orchards.

Table 2.5: Summary of the study sites used in the KBV and EGVV production regions from 2014-2017. High, medium and low canopy cover denotes > 45%, 30-44% and < 30% vegetation cover, respectively (Dzikiti et al., 2018).

Year	**Region**	**Cultivar**	**Rootstock**	**Age (yr.)**	**Canopy cover**	**Area (ha)**	**Plant density (trees.ha^{-1})**	**Farm name**
2014/15	KBV	Golden Delicious	M793	22	High	11.1	1 667	Kromfontein
	KBV	Cripps' Pink	M793	9	High	6.0	1 667	Kromfontein
	KBV	Golden Delicious Reinders	M793	3	Low	3.2	1 667	Lindeshof
	KBV	Rosy Glow	MM109	4	Low	6.0	2 285	Paardekloof
2015/16	EGVV	Golden Delicious	M793	29	High	5.5	1 250	Southfield
	EGVV	Cripps' Pink	M793	12	High	5.2	1 667	Radyn
	EGVV	Golden Delicious	MM109	3	Low	6.0	1 250	Vyeboom
	EGVV	Cripps' Red	MM109	3	Low	5.0	1 250	Vyeboom
2016/17	KBV	Golden Delicious Reinders	M793	5	Medium	2.5	1 667	Lindeshof
	KBV	Cripps' Pink	M793	7	Medium	4.2	1 111	Esperanto
	EGVV	Golden Delicious Reinders	M7	5	Medium	5.5	1 250	Vyeboom
	EGVV	Cripps' Pink	MM109	6	Medium	2.8	1 250	Dennebos

The average yield in the two mature ‘Cripps’ Pink’ orchards was ~110 t ha^{-1} compared to ~88 t ha^{-1} in the ‘Golden Delicious’ orchards. However, average transpiration (Oct-Jun) was ~638 mm for the ‘Cripps’ Pink’ and ~778 mm in the ‘Golden Delicious’ orchards. The peak leaf area index was ~2.6 and ~ 3.3 for the mature ‘Cripps’ Pink’ and ‘Golden Delicious’ orchards. Dzikiti *et al.* (2018) consequently concluded that canopy cover rather than crop load was the main driver of orchard water use. Transpiration by the young orchards ranged from 130 to 270 mm. The predicted seasonal total ET varied from ~900 to 1 100 mm in the mature orchards and was ~500 mm in the young orchards. Orchard floor evaporation accounted for ~18 to 36% of ET in mature orchards depending on canopy cover and this increased to more than 60% in young orchards.

Following the study, transpiration and evaporation data were analysed in conjunction with the simultaneously collected reference evapotranspiration data (Tables 2.6-2.11). This revealed that the mid-season peak basal crop coefficients (K_{cb}) for ‘Golden Delicious’ orchards, based on actual measured transpiration, were in the range 0.70-0.80 for mature orchards (Figure 2.5a) and approximately 0.20 in non-bearing orchards Figure 2.5d). The soil evaporation coefficient (K_e) rapidly dropped from a peak close to 1.0 early in the season stabilizing around 0.2 by mid to late October for mature orchards (Figure 2.5b). However, the variability was smaller (0.6-0.4) in the young orchards (Figure 2.5e) due to the larger proportion of the exposed surface. The mid-season peak crop coefficient (K_c) was between 0.95 and 1.10 for the full-bearing orchards (Figure 2.5c) and around 0.6 for the young orchards (Figure 2.5f).

Table 2.6 Monthly averaged orchard component and total orchard evapotranspiration (ET) to Penman-Monteith reference evapotranspiration (ETo) ratios for the non-bearing 'Cripps Red' at Vyeboom in 2015/16 determined using a soil water balance approach (Dzikiti et al., 2018).

Month	$ET:ET_o$ ratio			
	Irrigated area	Non-irrigated	Cover crop	Orchard
Oct	0.25	0.06	0.12	0.43
Nov	0.28	0.05	0.09	0.42
Dec	0.43	0.03	0.03	0.48
Jan	0.45	0.05	0.04	0.55
Feb	0.46	0.04	0.03	0.53
Mar	0.38	0.06	0.06	0.51
Apr	0.24	0.06	0.10	0.39
May	0.17	0.04	0.08	0.29
Jun	0.09	0.04	0.05	0.18

Table 2.7: Summary of seasonal transpiration of intermediate bearing orchards in the Koue Bokkeveld (Dzikiti et al., 2018).

Month	ET_o (mm)	'Cripps' Pink' Transpiration (mm)	'Golden Delicious Reinders' Transpiration (mm)	'Cripps' Pink' K_{cb} (-)	'Golden Delicious Reinders' K_{cb} (-)
Oct-16	150.8	59.1	32.9	0.39	0.22
Nov-16	199.2	71.7	55.2	0.36	0.28
Dec-16	231.8	83.8	56.8	0.36	0.25
Jan-17	234.3	73.3	59.3	0.31	0.25
Feb-17	202.3	62.6	64.6	0.31	0.32
Mar-17	187.1	64.5	64.8	0.34	0.35
Apr-17	131.2	58.8	41.5	0.45	0.32
May-17	94.3	46.3	30.6	0.49	0.32
Jun-17	52.0	27.3	14.1	0.53	0.27
Total	**1482.9**	**547.4**	**419.8**		

Table 2.8: Summary of seasonal transpiration of intermediate bearing orchards in the EGVV production region (Dzikiti et al., 2018).

Month	ET_o (mm)	'Cripps' Pink' Transpiration (mm)	'Golden Delicious Reinders' Transpiration (mm)	'Cripps' Pink' K_{cb} (-)	'Golden Delicious Reinders' K_{cb} (-)
Oct-16	128.0	41.5	26.8	0.32	0.21
Nov-16	147.5	60.3	36.6	0.41	0.25
Dec-16	177.6	74.4	41.2	0.42	0.23
Jan-17	172.4	70.7	38.3	0.41	0.22
Feb-17	152.2	62.3	32.8	0.41	0.22
Mar-17	136.5	64.3	32.3	0.47	0.24
Apr-17	96.8	43.1	19.4	0.44	0.20
May-17	76.3	34.5	17.2	0.45	0.23
Jun-17	57.9	19.6	4.8	0.34	0.10
Total	**1148.2**	**470.7**	**249.3**		

Table 2.9: Monthly averaged orchard component and total orchard evapotranspiration (ET) to Penman-Monteith reference evapotranspiration (ETo) ratios for the 'Golden Delicious Reinders' at Lindeshof in the Koue Bokkeveld in 2016/17 determined using a soil water balance approach (Dzikiti et al., 2018).

Month	**ET : ET_o ratio**		
	Tree row	**Work row**	**Orchard**
Sep	0.15	0.17	0.31
Oct	0.27	0.14	0.41
Nov	0.31	0.05	0.34
Dec	0.45	0.03	0.48
Jan	0.50	0.02	0.54
Feb	0.52	0.01	0.54
Mar	0.31	0.01	0.32
Apr	0.32	0.03	0.35
May	0.42	0.04	0.44
Jun	0.57	0.35	0.89

Table 2.10: Monthly averaged orchard component and total orchard evapotranspiration (ET) to Penman-Monteith reference evapotranspiration (ETo) ratios for the intermediate bearing 'Cripps' Pink' at Esperanto in the Koue Bokkeveld in 2016/17 determined using a soil water balance approach (Dzikiti et al., 2018).

Month	**ET : ET_o ratio**		
	Tree row	**Work row**	**Orchard**
Nov	0.28	0.34	0.62
Dec	0.33	0.48	0.81
Jan	0.47	0.55	1.03
Feb	0.51	0.20	0.71
Mar	0.44	0.14	0.58
Apr	0.36	0.10	0.46
May	0.20	0.10	0.30
Jun	0.43	0.18	0.61

Table 2.11: Monthly averaged orchard component and total orchard evapotranspiration (ET) to Penman-Monteith reference evapotranspiration (ETo) ratios for the full-bearing 'Golden Delicious' at Southfield in EGVV in 2015/16 determined using a soil water balance approach (Dzikiti et al., 2018).

Month	**ET : ET_o ratio**		
	Tree row	**Work row**	**Orchard**
Sep	0.50	0.15	0.66
Oct	0.54	0.13	0.67
Nov	0.62	0.11	0.72
Dec	0.75	0.11	0.86
Jan	0.66	0.17	0.83
Feb	0.90	0.05	0.96
Mar	0.72	0.09	0.81
Apr	0.62	0.07	0.69
May	0.67	0.13	0.80
Jun	0.51	0.13	0.64

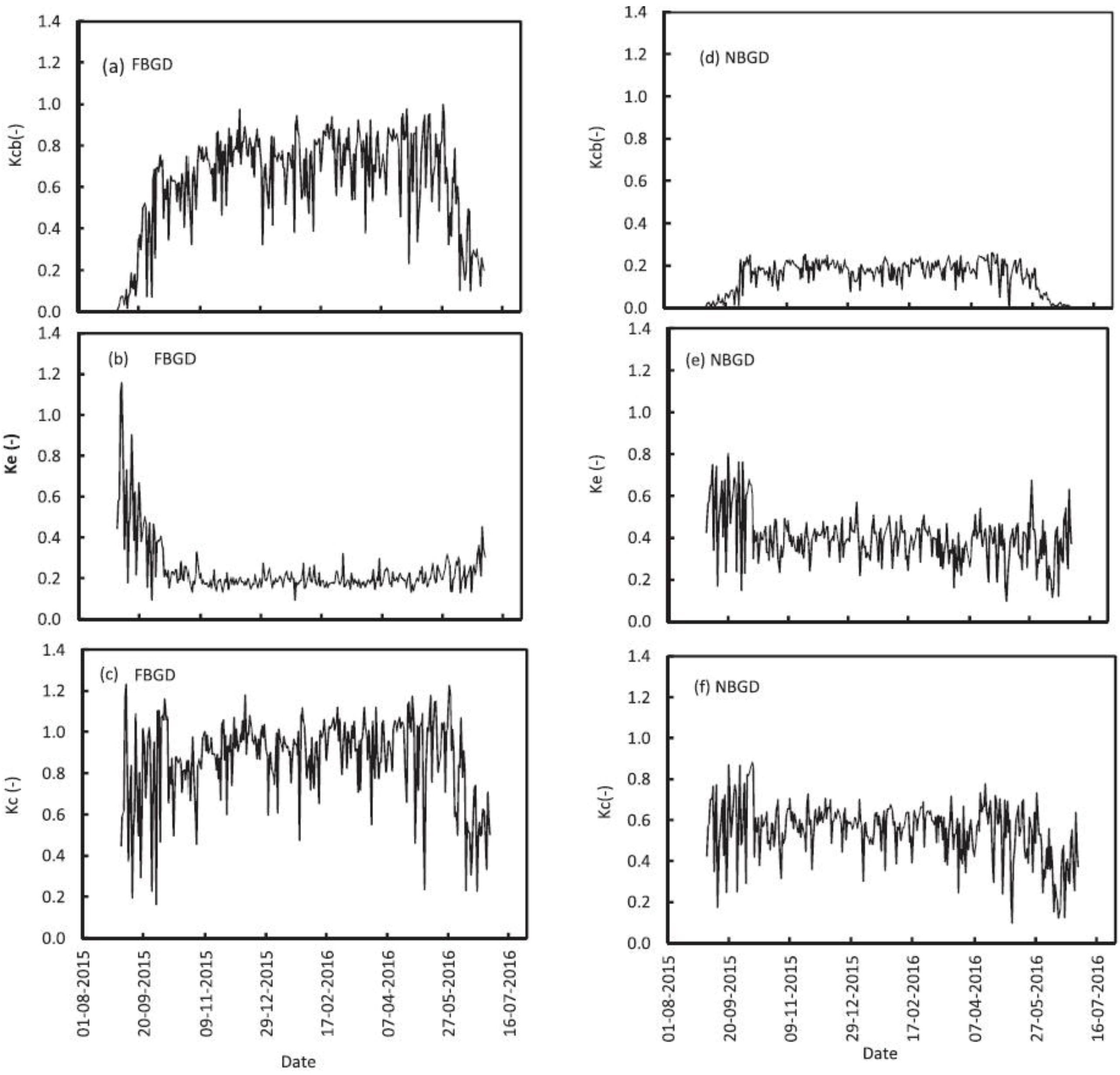

Figure 2.5: ***Seasonal variations in the: (a) basal (K_{cb}), (b) soil evaporation (K_e), and (c) crop coefficients (K_c) for full-bearing apple orchards planted to 'Golden Delicious' trees. Corresponding seasonal variations in the: (d) basal, (e) soil evaporation, and (f) crop coefficients of non-bearing apple orchards.***

2.7 SUMMARY

This review highlights the wide variability in the measured crop coefficients for orchards in the major apple producing regions in South Africa. While these data are indeed useful, it is clear from this review that they cannot be used in the APP as they are given the huge variations in orchard characteristics. For this reason, there is need to develop or adopt an appropriate method for deriving representative crop coefficients that are appropriate to each specific orchard. The method should preferably be simple and user friendly to ensure that the APP is not complex.

2.8 TECHNOLOGIES FOR FORECASTING CROP WATER REQUIREMENTS

Forecasting crop water requirements is essential for a variety of purposes. Short-term forecasts (1-7 days) are used for real-time irrigation scheduling and for water allocation planning, among other uses. Other studies have developed decision support systems for forecasting the water requirements over entire growing seasons. So different tools and products have been developed over the years to improve water resources management at scales from individual fields to entire catchments (Pruitt *et al.*, 2014).

Locally, the most popular forecasting tool currently being used by many farmers is Hortec's iLeaf system (www.ileaf.co.za). This tool uses machine learning algorithms based on long-term climate records for specific weather stations to forecast the reference evapotranspiration (ET_o) a few days in ahead. However, the farmer has to decide the appropriate crop factors in order to calculate the estimated future ET. This, in our view, is a major source of uncertainty as crop coefficients vary greatly between fields. In addition, because this tool is based on long-term trends in weather variables from specific stations, artefacts of the weather station can be carried over into the ET_o forecasts. For example, ET_o forecasts from a poorly cited weather station, e.g. located between buildings or next to tall trees that shade radiation sensors will consistently under-estimate the ET_o forecasts. Another local South African online irrigation forecasting tool is the PULSE system developed by Irricheck (www.irricheck.co.za). This system provides seven day irrigation forecasts using microclimatic and soils data. There is a team of experts in various fields who provide specialist support as needed.

The orchard water use APP developed in this project is one more tool in the grower's toolbox which adds value to existing products. Firstly, the origins and subsequent development of this APP is anchored on actual measured orchard water use data under local conditions. Secondly, the tool differentiates between actual tree water use (transpiration) and orchard evapotranspiration. Existing online products do not provide information on ET partitioning. ET partitioning information assists the user to differentiate between beneficial and non-beneficial water uses. Thirdly, the APP generates weekly basal (K_{cb}) and orchard crop coefficients (K_c) based on readily available information which is specific to each orchard. The input data to calculate the crop coefficients include the fractional vegetation cover, average tree height, soil type (texture), irrigation system, and information on the status of the cover crops (e.g. tall dense, average, or none).

Outside South Africa, the tool which is closest to the APP developed here is the ET Demands Model (Pruitt *et al.*, 2014) developed to forecast the water requirements of a range of crops in Colorado in the USA. However, this tool only provided the evapotranspiration component. In addition, the ET Demands Model was designed for both short and long range forecasts spanning a few days to entire growing seasons. Future versions of the APP developed in this study should have a similar focus. Initially the ET Demands Model was developed to operate in Excel. But recent versions have been coded in Python. So it is available as a computer model that operate on a range of platforms (Windows, Linux, etc.) and as a smartphone application for both Android and IOS devices.

Several other APPs exist and Migliacio *et al.* (2016) provides a summary of several types that are principally used for irrigation scheduling in the USA. Most of the APPs are based on either the FAO 56 principles or soil water balance approaches, but no details were provided on how crop coefficients were derived. Two important steps in the development of our APP included; 1) a review of the available most reliable sources of weather data for forecasting ET_o, and; 2) a procedure for calculating the orchard crop coefficients using readily available information. This procedure was validated using measured crop coefficients from 12 different apple orchards.

CHAPTER 3

SCIENTIFIC BASIS OF THE APPLICATION

3.1 SELECTING ONLINE WEATHER FORECAST SOURCES

A review of available online weather forecasts was conducted to guide the selection of the best source to use in the APP. To assist with the selection process, a table of key information on available forecasts was compiled (Table 3.1). As a large number of weather forecasts are available online, it was not possible to review all of them. Therefore, the focus was placed on forecast websites that are more well-known and likely to be credible. These included both research/scientific and more commercially orientated websites. A key requirement was that the websites should make their forecast data available for download in order to be accessible for use in the APP. Forecast websites that were reviewed but found not to meet this requirement are listed below Table 3.1.

The key information reflected in Table 3.1 included whether the site had the required weather parameters (maximum and minimum temperature, maximum and minimum relative humidity, wind speed and solar radiation), the time range of the forecasts (at least 7 days), the file or data format (indicates processing required), the availability of an application programming interface (API – facilitates easier data exchange), the delivery method (affects how data will be connected to the APP), the cost of the forecasts, the forecast models or sources, the spatial resolution of the forecasts, the availability of a forecast archive (for evaluation purposes) and the availability of model simulation data to facilitate performing bias corrections (i.e. analysis runs).

Few websites were found to provide forecasts of all the required weather parameters, with solar radiation and relative humidity (RH) being amongst the parameters that were often not available. Some forecasts were only available via email or FTP and were thus not considered suitable for use in the APP (FTP delivery would have required the project team to have their own FTP server). Some forecasts were prohibitively expensive (e.g. $500 / month). It was noted that the forecasts of the GFS model of the National Center for Environmental Prediction (NCEP) are used by some of the other forecast producers. Only the websites of NCEP and the European Centre for Medium-Range Weather Forecasting maintain an online archive of past weather forecasts and model simulation data that can be used for bias correction of the forecasts. This model simulation data is produced using known (or better known) initial conditions, and allows for systematic error in the weather model to be corrected. Without this data it is not possible to reliably bias correct the weather forecasts, as the systematic error in the weather model (correctable) cannot be distinguished from the random errors associated with characterizing the initial atmospheric conditions (not correctable).

Only the Dark Sky, NCEP and Open Weather Map websites make all the required weather parameters (after relaxing the requirement for solar radiation) available on a routine basis at the required time range. The ECMWF website may offer relative humidity as part of their commercial offerings. Examination of the Open Weather Map forecasts gave rise to concern as the temperature forecasts were found to have significant errors on two random days that they were informally evaluated. Although this is a very small sample to evaluate, it was decided not to pursue these forecasts further.

It was decided that the Dark Sky forecasts (www.darksky.net) would be used in the APP and detailed assessments about its accuracy are presented in Chapter 5. The format of the Dark Sky forecasts is relatively easy to work with and they are available through an API. The forecasts are partly based on data from NCEP's GFS model. It is noted that although the NCEP forecasts have the advantage of an archive of past forecasts and analysis runs, significant processing is required to format the data for application in forecast evaluation and bias correction.

Table 3.1: Key information regarding online weather forecasts considered for the application

Website[1]	All Required Parameter?	Time Range	Update Frequency	File / Data Format	API?	Delivery Method	Cost	Forecast Models / Sources	Forecast Resolution	Forecast Archive?	Model Data for own Bias Correction?
AccuWeather Global (accuweatherglobal.com)	Except RH and solar radiation	7 days 10 days 15 days	4 hourly	XML or text	No	Email or FTP (latter requires **own FTP server**)	$0.79 (7d) $0.87 (10d) $0.95 (15d) (per mo per site)	proprietary models / methods	Available for towns and cities	No	No
AccuWeather (accuweather.com)	Except RH and solar radiation	5 days 10 days 15 days	?	?	Yes	http	$25 (5d) $250 (10d) $500 (15d) (per mo, no site limit, extra costs if > 225 000 requests)	proprietary models / methods	Countries, admin. regions, towns, postal codes points of interest	No	No
Dark Sky (darksky.net)	Except solar radiation	7 days	Hourly	JSON	Yes	http	First 1000 requests per day are free. Thereafter $0.0001 per request	GFS, CMC, ICON	Available for towns and cities or given coordinates	No	No
Yr (Yr.no)	Except RH and solar radiation	10 days	?	XML	Coming soon	http	free	Unified model, HIRLAM, ECMWF	Available for towns and cities	No	No
National Center for Environmental Prediction (NCEP) of the National Oceanic and Atmospheric Administration (NOAA) (https://nomads.ncep.noaa.gov/)	Yes	5 days 10 days	5d: hourly 10d: 3 hourly for 240 hours; thereafter 6 hourly	Text GRIB NetCDF	No	http	free	GFS	0.25 ° grid	For past 10 days 4 year (2015-2019) archive available at UCAR website[2]	Available in UCAR archive Note: Bias corrected forecast data is provided by NCEP at 0.5 degree grid resolution

Table 3.1: continued

Website	All Required Variables?	Lead Time	Update Frequency	File / Data Format	API?	Delivery Method	Cost	Forecast Models / Sources	Forecast Resolution	Forecast Archive?	Model Data for own Bias Correction?
European Centre for Medium-Range Weather Forecasting (ECMWF) (https://www.ecmwf.int/) Requires a research license	Except RH	10 days	Hourly for 90 hours; 3 hourly 93-144 hours; 6 hourly 150-240 hours	GRIB and BUFR	Yes (historical forecasts)	http (historical forecasts) FTP to your server (real-time forecasts)	Data is free for research but a handling / delivery fee may apply	High Resolution Model	0.1 ° grid	Yes (1985-2019)	Yes
The Weather Network (theweathernetwork.com)	Except RH and solar radiation	7 days	?	XML JSON	Yes (1 key for free plan)	http	Free (limited to 10 requests / minute and 10000 requests / month)	Numerous sources (see website)	Available for towns and cities	No	No
Rain4africa.org (collaboration between ARC, SAWS and Dutch partners)	Unsure of exact variables (weather and crop related)	Up to 10 days	?	?	yes	http, FTP	on application	SAWS (probably Unified Model)	according to customer needs	?	?
Open Weather Map (https://openweathermap.org)	Except solar radiation	4 days 5 days 16 days	4 d: hourly 5 d: 3 hourly 16d: daily	JSON or XML	yes	http	4d: $180/mo 5d: free 16d: $40/mo (4d price also includes 16d forecasts)	GFS, CMC			

[1]Other websites visited but not reviewed in-depth as they don't provide for downloading of forecast data: freemeteo.co.za, weather-forecast.com, weather.com, wunderground.com, windguru.cz[2] https://rda.ucar.edu/datasets/ds084.1/#!description

3.2 ESTIMATING APPLE ORCHARD CROP COEFFICIENTS

In this study crop factors for apple orchards under different growing conditions were derived using the A&P method. Despite the clear advantages of the method, published literature shows that its performance is not consistent across different crop types. Therefore, crop specific adjustments are necessary in some instances. For example, Taylor *et al.* (2015) showed that the method overestimated the sap flow derived K_{cb} by up to 127% in citrus orchards under semi-arid sub-tropical and Mediterranean conditions in South Africa. To get acceptable simulations, they applied a variable, rather than fixed, stomatal sensitivity function based on ET_o values. In another study on olive orchards in Portugal, Paço *et al.* (2019) applied the A&P method with K_{cb} derived from sap flow measurements. They also observed poor performance with the original method and used trial and error to adjust the stomatal sensitivity function method to match the calculated K_{cb} with sap flow derived values.

For the purposes of our APP, we evaluated the A&P method using detailed field measured data collected in 12 apple orchards with varying canopy cover ranging from young non-bearing to mature high yielding orchards in the Western Cape. The first step was to validate the A&P method as published using actual measured field data over a range of fractional canopy cover, cultivars, and microclimates. There were significant errors in both the K_{cb} and K_c estimates consistent with the other studies as will be detailed later. The second step was to identify the major sources of uncertainty with the method applied to apple orchards and to propose improvements. Lastly we then extensively validated the improved A&P method. The detailed results are published in Mobe *et al.* (2020b), and here we summarize key aspects of the methodology.

3.2.1 Materials and methods

3.2.2.1 Study area

Field data were collected in 12 apple orchards over three growing seasons (i.e. 2014/15, 2015/16 and 2016/17) in two prime apple producing regions in the Western Cape Province of South Africa (Figure 3.1). These regions are the Koue Bokkeveld (KBV) located about 150 km to the northeast of the city of Cape Town and the Elgin/Grabouw/Vyeboom/Villiersdorp (EGVV) which is about 70 km southeast of Cape Town. Both regions have Mediterranean climate. More than 50% of the rain falls during the winter months from May to August. A typical growing season for apples in these regions extends from September/October to May depending on the cultivar. The two production regions have somewhat different microclimates. The EGVV region has milder summers and winters due to proximity to the Indian Ocean to the south. The inland KBV region, on the other hand, has very cold winters with occasional snowfall in high lying areas. The summers are very hot with maximum temperatures often exceeding 40°C.

During the 2014/15 season, data were collected in four orchards in KBV comprising two mature high yielding (> 100 t/ha) orchards with a high effective fraction of ground covered or shaded by vegetation of about 0.64. One orchard was planted to 'Golden Delicious' trees which is the most widely planted cultivar in South Africa. The second mature orchard was planted to Cripps' Pink trees which is a high value cultivar, but with a long growing season. The other two orchards had young (less than 3 yr. old) non-bearing trees of the Golden Delicious/Reinders® and Rosy Glow cultivars.

Detailed information about the orchards is summarized in Table 2.5. The average effective fraction of vegetation cover in the young orchards was less than 0.20 during the mid-summer period when canopy cover was maximum. During 2015/16, data were collected in four orchards in EGVV with similar attributes to those in KBV. These included mature 'Golden Delicious', and 'Cripps' Pink' blocks while the non-bearing orchards were planted to the Golden Delicious/Reinders® and Cripps' Red cultivars (Table 2.5). In 2016/17, measurements were taken in two orchards in each production region with medium fractional canopy cover ranging from 0.26 to 0.37 (Table 2.5). The orchards were planted to 'Cripps' Pink' and 'Golden Delicious/Reinders®' trees, respectively.

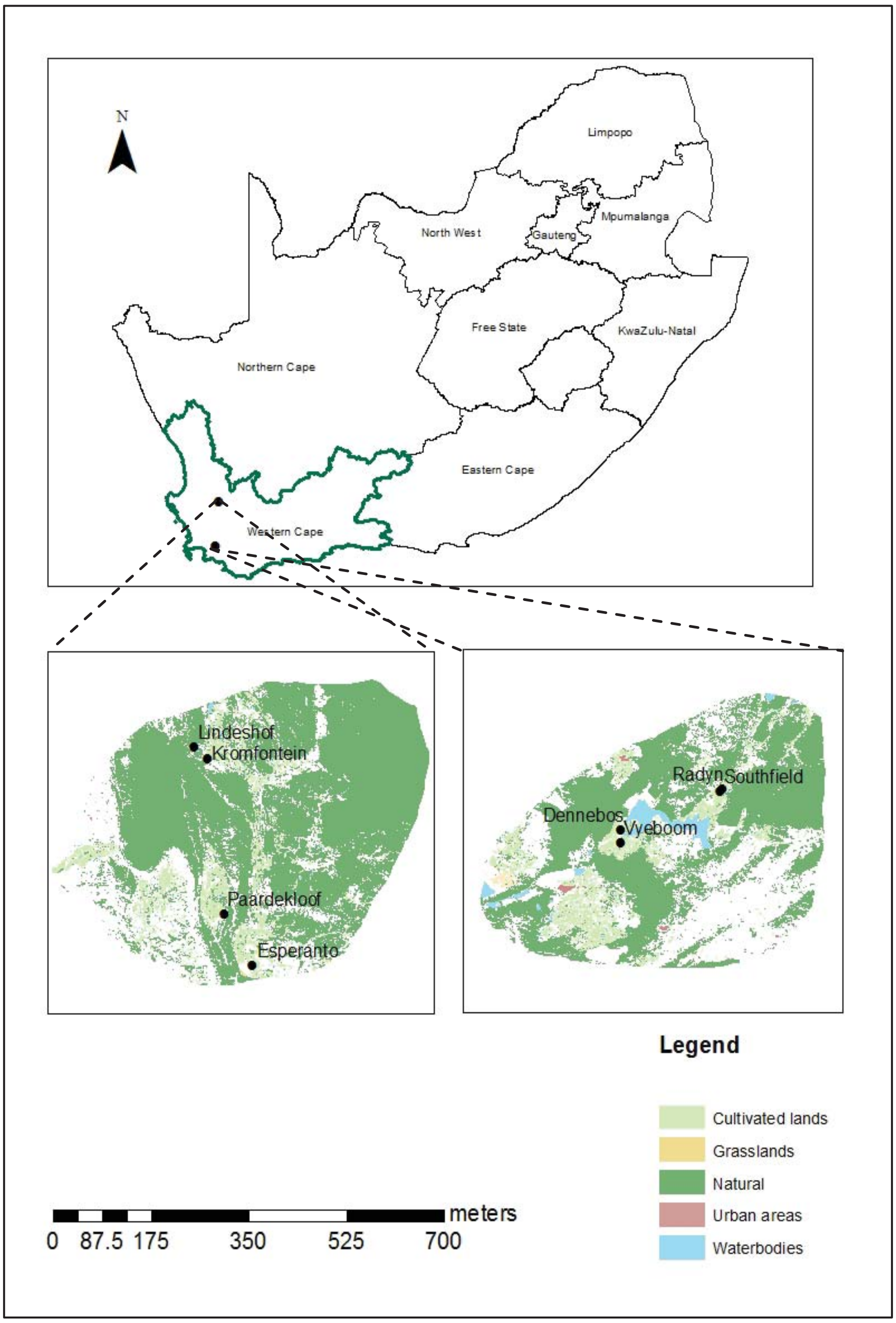

Figure 3.1: ***Location of the study sites in the two prime apple producing regions in the Western Cape Province of South Africa namely: a) the Koue Bokkeveld (KBV), and b) the Elgin/Grabouw/Vyeboom/Villiersdorp (EGVV) region.***

Soil texture was predominantly sandy to sandy loam in both regions except for the medium cover 'Cripps' Pink' in EGVV which had dark red clayey loam soils of the Kroonstad soil form (Ochric Planosol) according to the Soil Classification Working Group (1991). Soil physical and chemical analyses for the 12 orchards were done at a commercial laboratory (Bemlab Pty Ltd., South Africa). Table 3.2 summarizes the physical properties of the soils for all the orchards.

Table 3.2: Typical soil classification analysis for the orchards of different age groups monitored at KBV and EGVV in 2014/15, 2015/16 and 2016/17 growing seasons. θ_{FC}= volumetric soil water content at field capacity; θ_{WP}=volumetric soil water content at the permanent wilting point; REW= readily evaporable water; TEW= total evaporable water, FBGD= Full-bearing 'Golden Delicious', FBCP= Full-bearing 'Cripps Pink', NBGR= Non-bearing 'Golden Delicious Reinders®', NBRG= Non-bearing 'Rosy Glow', NBCR= Non-bearing 'Cripps' Red', BGD= Bearing 'Golden Delicious', BGR= Bearing 'Golden Delicious Reinders®' BCP= Bearing 'Cripps Pink'.

Location	Season	Orchards	Soil texture	Soil water		Soil texture distribution			REW (mm)	TEW (mm)
				θ_{FC} (cm³ cm⁻³)	θ_{WP} (cm³ cm⁻³)	Sand	Silt %	Clay		
KBV	2014/15	FBGD	Sandy loam	0.171	0.027	83.5	2.9	13.6	7.4	23.6
		FBCP	Sandy loam	0.174	0.049	82.7	4.0	13.3	7.6	22.4
		NBGR	Sandy loam	0.187	0.023	81.0	3.3	15.7	11.9	30.4
		NBRG	Sandy	0.193	0.042	92.0	2.0	6.0	11.9	18.1
EGVV	2015/16	FBGD	Sandy loam	0.189	0.055	80.8	8.7	10.3	7.8	24.2
		FBCP	Clay loam	0.230	0.050	33.8	28.4	37.6	11.0	30.8
		NBGD	Sandy clay	0.230	0.055	15.7	35.4	48.9	7.9	26.3
		NBCR	Sandy loam	0.143	0.045	81.4	6.9	11.7	6.7	25.8
KBV	2016/17	BGD	Sandy loam	0.187	0.023	85.4	8.1	6.5	7.1	26.3
		BCP	Loamy sand	0.190	0.032	83.6	13.7	2.8	7.4	26.
EGVV		BGR	Sandy clay loam	0.230	0.055	58.3	15.3	26.5	10.2	30.4
		BCP	Clay loam	0.195	0.030	35.0	25.3	39.7	11.2	27.0

3.2.2.2 Data collection

Transpiration and irrigation measurements

Tree transpiration on medium and high canopy cover orchards, was measured during the growing season (October to May) on between three and six trees of different stem sizes using the heat ratio method of monitoring sap flow (Burgess *et al.*, 2001). Four probes were inserted to four different depths in trunks of the selected trees to capture the radial variation in sap velocity (Wulschleger and King, 2000). Each probe set consisted of two T-type thermocouples placed equidistantly (~0.5 cm) upstream and downstream of a stainless steel heater probe. Heat pulse velocities were measured and logged hourly using data loggers (Model CR1000, Campbell Sci. Inc., Logan, UT, USA) connected to multiplexers (Model: AM16/32B, Campbell Sci. Inc., Logan, UT, USA). The heat pulse velocity signals were converted to sap flow volumes per tree taking into account wound sizes, wood moisture fraction, and wood density according to the procedure described by Swanson and Whitfield (1981). The size of the conducting sapwood area was determined by injecting methylene blue dye into the stems to establish the extent of the active xylem vessels.

Transpiration by the smaller trees in young orchards was measured using Granier probes (TDP 10: Dynamax Inc., Houston USA) (Granier, 1987). Three healthy and actively growing trees were instrumented per orchard. The sensors were installed at a height between 50 and 75 cm from the ground to eliminate errors due to the cold sap especially in the morning. A reflective aluminium foil was wrapped around the probes to minimize the effects of exogenous heating on the sap temperature signals. Data were collected at a scan rate of 10 s and hourly averages of sap velocity were recorded.

All orchards were irrigated using micro-sprinkler systems with one sprinkler per tree delivering between 30 and 32 litres of water per hour. Irrigation frequency ranged from two to three times per week with each event lasting for one to two hours early in the season. The frequency increased to daily or several times a day during hot summer months. Water flow meters (Model: ARAD Multi-Jet Water Meter, Germiston, South Africa) with a resolution of 10 L/pulse were installed on the irrigation line to monitor the irrigation volumes.

Evapotranspiration and physiological measurements

Actual evapotranspiration from the orchards was measured using two open path eddy covariance systems at selected intervals during the growing season as summarised in Mobe *et al.* (2020b). Continuous measurement of ET throughout the study period was not possible because of equipment limitations. The eddy covariance systems comprised of sonic anemometers (Model: CSAT3, Campbell Sci. Inc., Utah, USA) and infrared gas analysers IRGA (Model: LI-7500A, LI-COR Inc, Lincoln, Nebraska, USA) installed at heights ranging from 1.2 to 1.8 m above the mean canopy height depending on the size of the orchard which varied from ~ 3.8 to 7.0 ha. The flux towers were located downstream of the prevailing wind direction to maximize the fetch. Other sensors to quantify the orchard energy balance included the single component net radiometers (Model: CNR1, Kipp & Zonen, Delft, The Netherlands), soil heat flux plates (Model: Hukse Flux, Campbell Sci. Inc., Utah, USA) installed at about 8 cm depth, CS616 soil moisture probes and soil averaging thermocouples installed at 2 and 6 cm depths from the surface to correct the measured fluxes for the energy stored by the soil above the plates. The signals were sampled at a frequency of 10 Hz and the outputs were averaged at 30 min intervals using CR3000 and CR5000 data loggers (Campbell Sci. Inc., Utah, USA). The high frequency data were processed using the EddyPro v 6.2.0 software (LI-COR Inc., Lincoln, Nebraska, USA) to correct the data for the lack of sensor levelness, sensor time lags, fluctuations in the air density, among others. The ET data were further corrected for the lack of energy balance closure using the Bowen ratio approach as described by Twine *et al.* (2000).

Orchard leaf area index (LAI – m^2 of leaf area per m^2 of ground area) was measured at monthly intervals in the 12 orchards using a leaf area meter (Model: LAI-2000, LI-COR Inc., Lincoln, Nebraska, USA). These data were collected on overcast days or just before sunset when the leaves approximated black bodies and transmission of the direct radiation through the leaves was minimal. The fraction of the ground surface covered by vegetation at midday (f_c) was estimated from the canopy dimensions and the area allocated to each tree. The effective fraction of ground covered or shaded by the trees (f_{ceff}) was calculated from f_c and other variables as described by Allen and Pereira (2009) and Allen *et al.* (1998).

The stomatal resistance (r_l) was measured at monthly intervals using the infrared gas analyser (Model: LI-6400, Li-COR, Inc., Lincoln, Nebraska, USA). Data were collected on two healthy sun exposed leaves from ten tagged trees per orchard around midday from 12:00 to 14:30. The midday xylem water potential (ψ_x) was measured on the same ten trees using a pressure chamber (Model: 615, PMS Instrument Company, Albany, Oregon, USA). Two healthy and fully expanded leaves per tree, located close to the stem, were enclosed in the morning using zip-lock silver reflective stem water potential bags (prune bags) (PMS Instrument Company, Albany, Oregon, USA) to allow the leaf water potential to equilibrate with stem water potential for measurements at midday.

Weather data

Weather variables namely the maximum and minimum air temperature, maximum and minimum relative humidity, wind speed (at 2 m height), wind direction, solar radiation, and rainfall were monitored hourly using automatic weather stations situated close to each of the study sites. The stations were installed on open spaces with uniform short grass cover in order to derive the short grass reference evapotranspiration.

3.3 CALCULATION OF CROP COEFFICIENTS

3.3.1 Basal crop coefficients (K_{cb})

According to Allen *et al.* (1998), the basal crop coefficient (K_{cb}), also referred to as the transpiration crop coefficient, is given by:

$$K_{cb} = \frac{T}{ET_o} \qquad (3.1)$$

where T is the tree transpiration (in mm d^{-1}) derived from the sap flow measurements. Orchard level transpiration was calculated as the sum of the products of the sap flux density (U) and the orchard sapwood area index (SAI = m^2 of sapwood per m^2 of ground area) for trees in different stem diameter classes as:

$$T = \sum_{i=1} SAI_i \times U_i \qquad (3.2)$$

where U_i is the average sap flux density in a specific stem size class and each of the sap flow instrumented trees was assigned to an appropriate stem diameter class. Equation (3.1) assumes that the orchards did not suffer significant water stress. This was a reasonable assumption based on the measurements of tree water status as the orchards were generally well-watered. Sustained periods with water stress were excluded from the analysis.

Given that K_{cb} is dependent on the amount of vegetation, and also to ensure that the basal crop coefficients are transferable between fields, Allen and Pereira (2009) proposed a density coefficient (K_d) which they defined as:

$$K_d = \frac{K_{cb} - K_{c\min}}{K_{cbfull} - K_{c\min}} \qquad (3.3)$$

where K_{cmin} is the minimum basal coefficient for bare soil, K_{cbfull} is the estimated basal crop coefficient under conditions of nearly full ground cover (LAI ≥ 3.0). According to the A&P method, the density coefficient is estimated from the effective vegetation cover (f_{ceff}) and mean tree height (h) as:

$$K_d = \min(1, M_L fc_{eff}, fc_{eff}^{\left(\frac{1}{1+h}\right)}) \tag{3.4}$$

where M_L is a multiplier on f_{ceff} describing the effect of canopy density on shading. We used values of M_L=2.0 for mature orchards, and 1.5 for orchards with low and medium canopy cover, respectively. In situations where K_{cbfull} is not measured, it can be estimated from

$$K_{cb\,full} = F_r\left(\min(1.0 + 0.1h, 1.20) + [0.04(u_2 - 2) - 0.004(RH_{\min} - 45)]\left(\frac{h}{3}\right)^{0.3}\right) \tag{3.5}$$

where u_2 is the mean daily wind speed measured at 2.0 m height and RH_{min} is the minimum relative humidity (%) for the day. According to Allen and Pereira (2009), the parameter F_r, which can be considered as a K_{cb} adjustment factor through crop stomatal control and has values in the range 0 to 1, was estimated using the following equation:

$$F_r = \frac{\Delta + \gamma(1 + 0.34u_2)}{\Delta + \gamma(1 + 0.34u_2 \frac{r_l}{100})} \tag{3.6}$$

where Δ is the slope of the saturation vapour pressure vs temperature curve (Pa°C^{-1}), and γ is the psychrometric constant (Pa°C^{-1}). r_l is the mean leaf resistance for the vegetation in question (s m^{-1}). According to the A&P method, values of r_l for apple orchards were suggested as 140 s m^{-1} for the initial and midseason periods and

370 s m^{-1} at the end of the season. The resistance value of 100 s m^{-1} in the denominator of equation 3.6 is the mean resistance for annual crops and this could be a source of uncertainty for perennial crops like most fruit trees. Using the suggested parameters on apple orchards led to significant over-estimates of K_{cb} for orchards of all age groups as will be discussed in detail in the results section. Consequently, we replaced the 100 s m^{-1} in equation 3.6 with a resistance parameter α which can be considered to represent the minimum unstressed canopy resistance for apple trees. We then inverted equation 3.6 using measured values of the climatic variables, the K_{cbfull} in equation 3.5 derived from sap flow measurements of transpiration at the mid-season stage of a mature well-watered apple orchard (LAI ~ 3.6). The measured average leaf resistance (r_l) for all the 12 orchards at the mid-season stage was about 202 s m^{-1}. We then solved the A&P equation for α and obtained a mean value of about 37 s m^{-1}. This value is very close to the unstressed canopy resistance of a well-watered apple tree. For example, the minimum stomatal resistance of a well-watered Golden Delicious tree with a leaf area index of about 3.6 was around 37 s m^{-1}. This translates to a canopy resistance of about 38 s m^{-1} which is similar to the value obtained above.

The micro-sprinkler irrigated orchards had cover crops and weeds of varying densities between the tree rows. These ranged from exotic species such as the tall fescues (*Festuca arundinacea*) to various indigenous grasses such as the heart-seed love grass (*Eragrostis capensis*), etc. and one orchard even had fynbos. To account for the cover crop transpiration, the whole orchard K_{cb} was estimated according to A&P as:

$$K_{cb} = K_{cb\text{cover}} + K_d\left(\max\left[K_{cb\,full} - K_{cb\text{cover}}, \frac{K_{cb\,full} - K_{cb\text{cover}}}{2}\right]\right) \tag{3.7}$$

where $K_{cbcover}$ is the basal crop coefficient due to the cover crop. The dynamics of the cover crop LAI were monitored in at least five orchards at regular intervals throughout the season using a destructive sampling technique. In this method, plants in several

50 cm x 50 cm quadrants were harvested and their leaf area measured manually using a leaf area meter (Model: LI-3000, Li-COR, Inc., Lincoln, Nebraska, USA). Estimates of cover crop transpiration (T_c) were obtained using three to four miniature stem heat balance sap flow gauges (Model: SGA2, Dynamax, Houston, USA) installed on straight portions of individual grass blades. The sensors were installed during short window periods lasting a few days at a time to avoid damage by farm machinery. The transpiration data to determine the maximum basal coefficient for the cover crops ($K_{cbfullc}$) was collected in winter (July 2017) when the trees were leafless and there was no shading of the cover crops.

To convert the sap flow gauge readings to transpiration expressed over the entire orchard floor (T_c, in mm/h) first we normalised the sap flow (SF, in cm^3 h^{-1}) of each instrumented plant with the leaf area (A, in cm^2). Then we multiplied the average of the normalized sap flow with the understorey leaf area index (LAI_c) and the fraction of the orchard floor occupied by the understorey vegetation (f_g).

$$T_c = \frac{\overline{SF}}{A} \times LAI_c \times f_g \times 10 \quad (3.8)$$

The maximum cover crop basal crop coefficient ($K_{cbfullc}$) was then determined using:

$$K_{cbfullc} = \frac{T_c}{ET_o} \quad (3.9)$$

The density coefficient for the cover crops (K_{dc}) was subsequently derived according to Allen and Pereira (2009) as:

$$K_{dc} = 1 - e^{-0.7 \times LAIc} \quad (3.10)$$

$K_{cbcover}$ was then determined by combining equations 3.3, 3.9, and 3.10 assuming K_{cmin} of about 0.15 (Allen and Pereira, 2009).

3.3.2 Determining orchard crop coefficients (K_c)

The whole orchard K_c values were determined also using the density coefficient as proposed by Allen and Pereira (2009) as:

$$K_c = K_{soil} + K_d\left(\max\left[K_{cfull} - K_{soil}, \frac{K_{cfull} - K_{soil}}{2}\right]\right) \tag{3.11}$$

where K_{cfull} represents K_c from a fully covered soil with some background evaporation and it was calculated as:

$$K_{c\,full} = \max\left(\left\{1.2 + \left[0.04(u_2 - 2) - 0.004(RH_{\min} - 45)\right]\left(\frac{h}{3}\right)^{0.3}\right\}, \{K_{cb} + 0.05\}\right) \tag{3.12}$$

K_{soil} in equation 3.11 represents the average K_c from the non-vegetated (exposed) portion of the surface and reflects the impact of wetting frequency, and soil type. This was determined taking into account evaporation from the wet and dry portions of the orchard floor as:

$$K_{soil} = K_{ewet} + K_{edry} \tag{3.13}$$

where K_{ewet} was calculated following Allen *et al.* (2005) as:

$$K_{ewet} = \frac{TEW - (TEW - REW)\exp\left(\frac{-(t_w E_{so} - REW)}{TEW - REW}\right)}{t_w ET_o} f_w \tag{3.14}$$

where *TEW* is the total evaporable water which represents the depth of water that can be evaporated from the surface soil layer when the layer has been initially completely wetted. *REW* represents the readily evaporable water which represents the cumulative evaporation during stage 1 drying (Allen et al., 1998). t_w is the average time between independent wetting events which was calculated to be on average 2.7 days for wetting due to irrigation. E_{so} is the potential evaporation rate from a wet soil surface as described in equation (3.17), and f_w represents the fraction of the orchard floor that is wetted by irrigation or rain [0-1].

K_{edry} in this study was taken as a constant at 0.06 based on microlysimeter measurements of soil evaporation, and also given that the study area receives very little rainfall during the fruit growing season.

TEW was estimated as:

$$TEW = 1000(\theta_{FC} - 0.5\theta_{WP})Z_e \qquad (3.15)$$

where θ_{FC} and θ_{WP} represent the volumetric soil water content at field capacity and permanent wilting point, respectively ($cm^3\ cm^{-3}$) and Z_e is the effective depth of soil evaporation which was taken as 0.15 m (Allen *et al.*, 1998).

REW was calculated from soil texture data according to Ritchie *et al*. (1989) as:

$$REW = 20 - 0.15(Sa) \qquad \text{for } Sa \geq 80 \qquad (3.16)$$

$$REW = 11 - 0.06C = (Cl) \qquad \text{for } Cl \geq 50$$

$$REW = 8 + 0.06(Cl) \qquad \text{for } Sa < 80 \text{ and } Cl < 50$$

where *Sa* is the percentage fraction of sand in soil and *Cl* is the percentage fraction of clay in the soil which were determined for the twelve orchards at a commercial laboratory.

To account for the presence of tree cover on soil evaporation (E_{so}) used in equation (3.14), we used the expression proposed by Allen *et al.* (2005) wherein:

$$E_{so} = \left(K_{c\max} - K_{cb}\right)ET_O \qquad (3.17)$$

where K_{cmax} is the maximum crop coefficient for the surface under full vegetation and it is equal to K_{cfull} (equation 3.12); K_{cb} is the basal crop coefficient calculated according to equation (3.7).

3.4 MEASURED VS CALCULATED BASAL CROP COEFFICIENTS

The major advantage of the Allen and Pereira (2009) method is that the crop factors can be calculated from readily available information which makes the method very appealing for practical irrigation scheduling. The K_{cb} for example, can be calculated from estimates of the fractional vegetation cover, tree height and microclimatic data using equations 3.3 to 3.7. In this way, different crop coefficients for mature and young orchards are derived leading to more accurate irrigation decision making.

However, using the parameters published by Allen and Pereira (2009) for apple orchards to derive the K_{cb} values led to significant over-estimates. Figure 3.2 illustrates typical trends of K_{cb} for entire growing seasons for young, medium, and high canopy cover orchards. In these examples, the A&P method over-estimated K_{cb} by 103, 69 and 47% for the young, medium, and high canopy cover orchards, respectively. Similar trends were observed for the remaining nine orchards whose data are not shown.

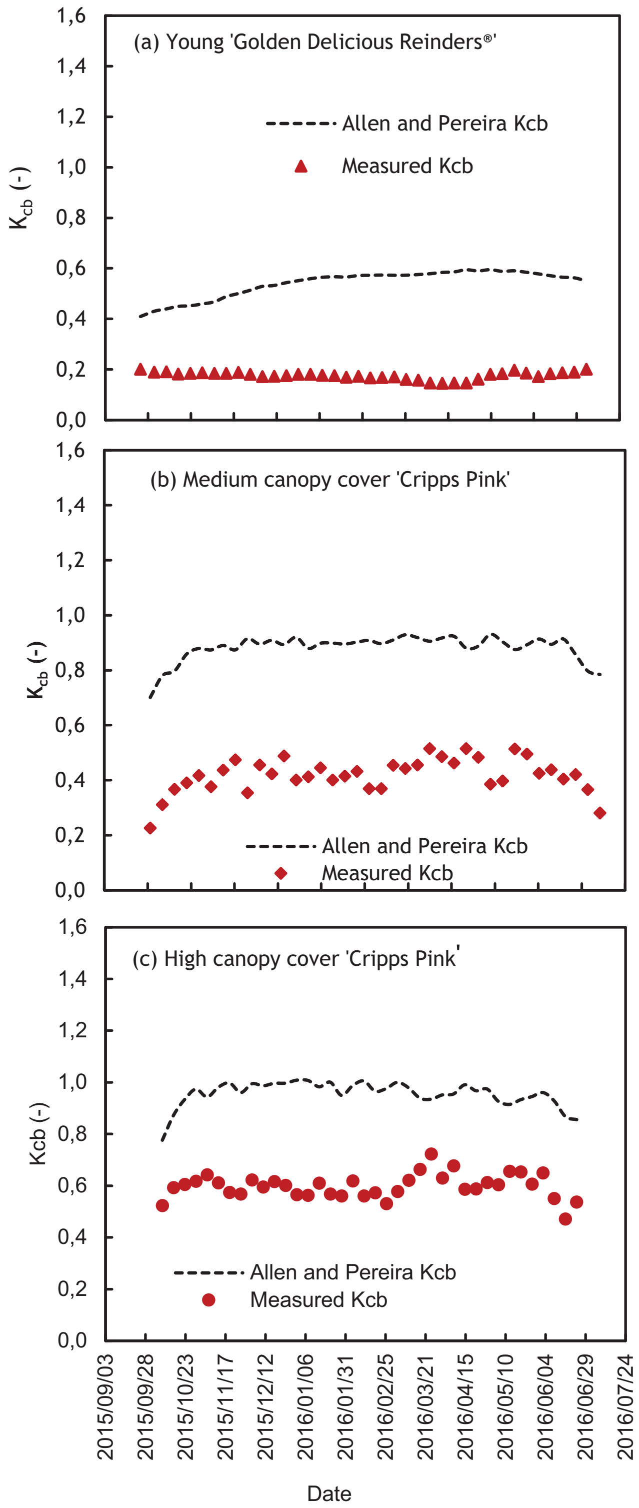

Figure 3.2: ***Comparison of the sap flow derived basal crop factors (open dots) with those determined using the original Allen and Pereira (2009) method (black line) for apple orchards with: a) low, b) medium, and c) high canopy cover orchards in the Western Cape Province.***

A possible source of uncertainty causing the poor fit resides in equation 3.6 in which the ratio of the leaf resistances is used to adjust K_{cb} through the adjustment factor, F_r, as proposed by Allen and Pereira (2009). For this reason, we collected detailed data to further investigate how the tree water status and environmental factors influenced the leaf resistance of apple trees as detailed in Mobe *et al.* (2020b). The measured stomatal resistance for the 12 apple orchards ranged from 100 to just over 500 s m^{-1}. The average resistance for the irrigation season (November to April) for all the orchards was around 202 s m^{-1}. An extremely high resistance of about 2 446 s m^{-1} was observed once in the young 'Rosy Glow' orchard when the irrigation system malfunctioned (Figure 3.3a). But this value was excluded in our analysis.

Over the course of all the growing seasons, the mean leaf resistance showed an exponentially decreasing trend with the rising midday stem water potential (ψ_x) as shown in Figure 3.3a. This confirms that the stomata opened as the tree water status decreased (i.e. less negative ψ_x). Using the leaf resistance measured for apple orchards, and also using the value of α = 37 s m^{-1} led to improved estimates of K_{cb} for all the 12 orchards. Figures 3.4 a-f show examples of six orchards with different cultivars and canopy cover classes. The improved A&P approach predicted the K_{cb} quite accurately for all the orchards. This result suggests that using crop-specific information improves the accuracy of the estimated crop coefficients derived using the A&P approach. This appears to be particularly the case especially for fruit trees whose physiology differs quite substantially from annual crops and the poor fit of the original A&P in orchards has been quite consistent across fruit tree types.

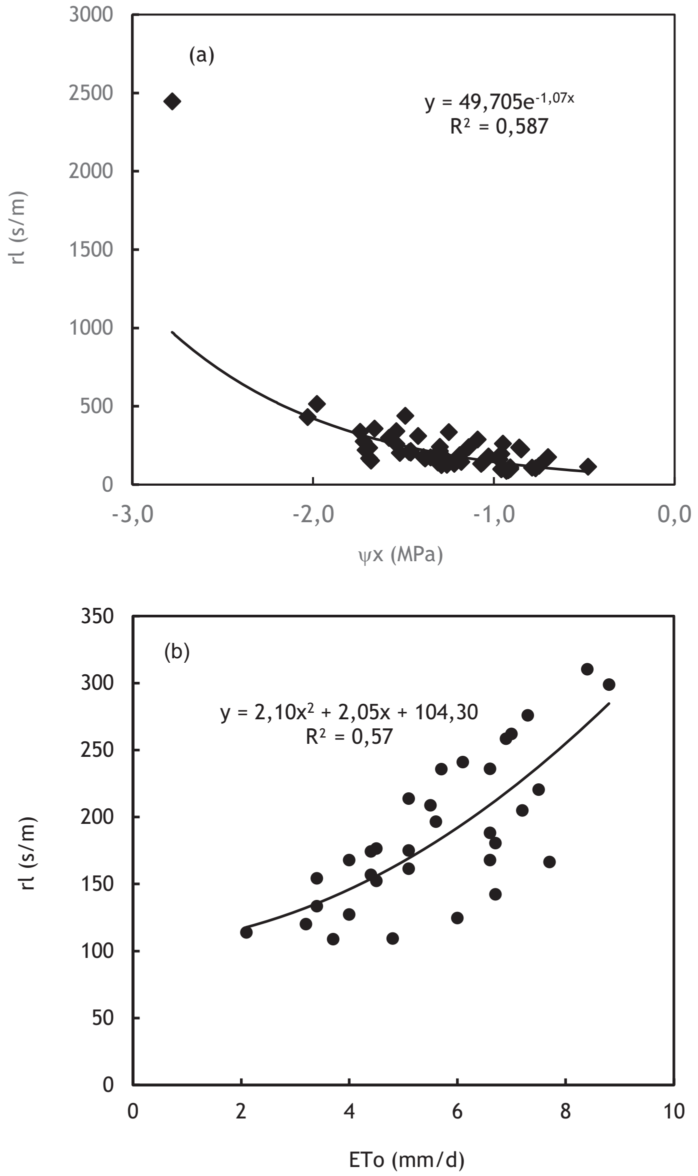

Figure 3.3: ***Effect of: a) the midday xylem water potential, and b) the daily total reference evapotranspiration on the average midday stomatal resistance of 12 apple orchards over three growing seasons (2014-2017).***

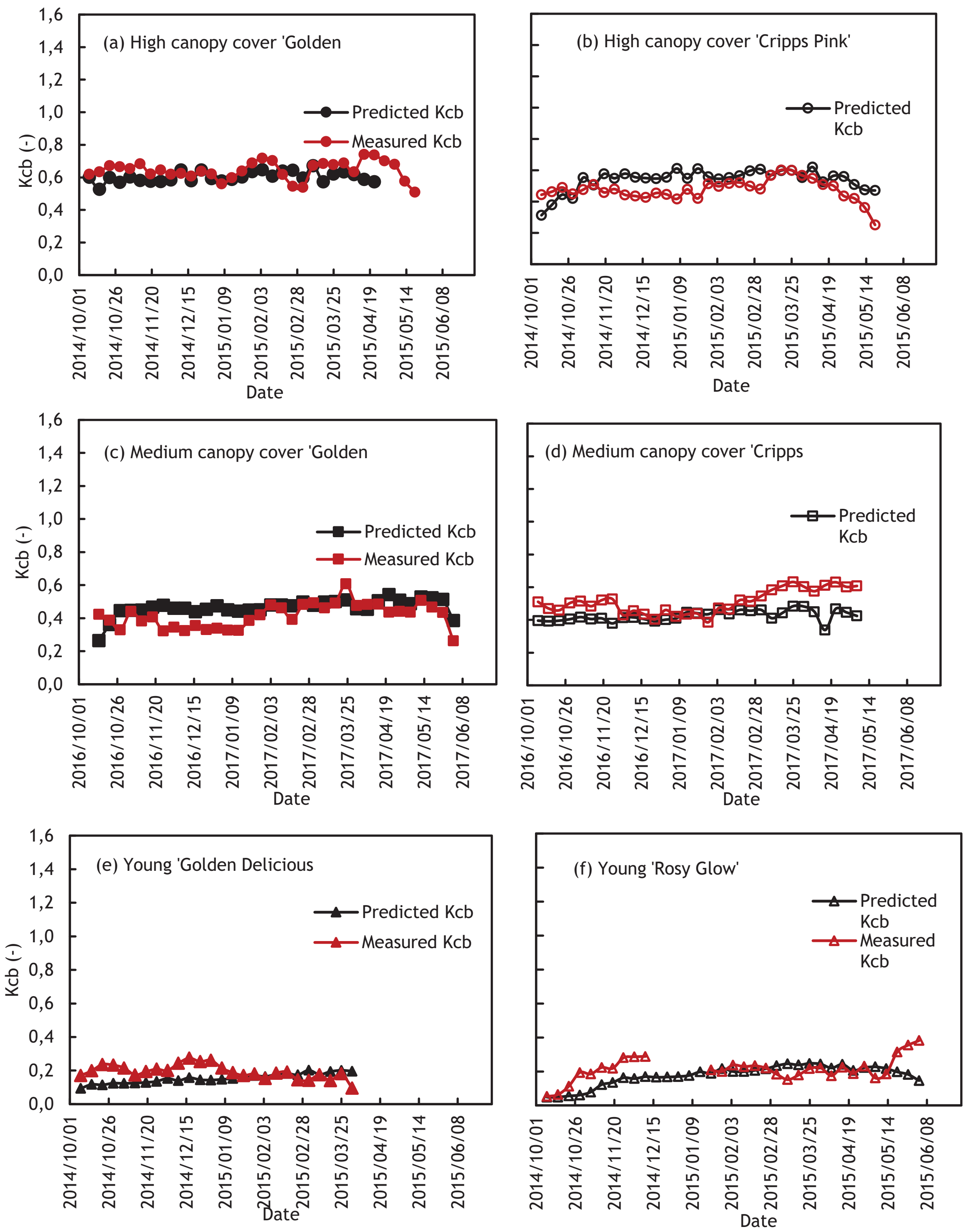

Figure 3.4: ***Illustration of the performance of the improved Allen and Pereira basal crop factor calculation method on 'Golden Delicious' and 'Cripps' Pink apple cultivars in: (a-b) – high canopy cover, (c-d) – medium canopy cover, and (e-f) – low canopy cover orchards.***

3.5 ESTIMATING ORCHARD TRANSPIRATION USING IMPROVED K_{cb}

The improvements in K_{cb} above were obtained by inverting data from only one orchard, i.e. a mature full-bearing 'Golden Delicious' in Villiersdorp. To confirm the accuracy of the K_{cb} for the rest of the orchards, we used the calculated values to derive the monthly total orchard transpiration as T = K_{cb} x ET_o. Figure 3.5 shows that the predicted transpiration was similar to the sap flow measured values for orchards with low, medium and high canopy cover. A summary for all the 12 orchards is shown in Table 3.3. In the high canopy cover 'Cripps' Pink' orchard the monthly transpiration was slightly underestimated in October, but marginally overestimated from November to the end of the growing season (Figure 3.5a). The good performance of the model was however, confirmed by the statistical parameters (MAE = ±12.9 mm $month^{-1}$, RMSE = ±7.84 mm $month^{-1}$, NSE = 0.68 and R^2 = 0.92). NSE is the Nash-Sutcliffe Efficiency calculated according to Dzikiti *et al.* (2018a) and Mobe *et al.* (2020b). In the medium canopy cover 'Cripps' Pink' and young 'Golden Delicious Reinders' orchards, the monthly measured transpiration was slightly underestimated throughout the growing season, except for the month of May and April, respectively. Nevertheless, the model performance was still satisfactory with an MAE of ±5.36 and ±5.07 mm $month^{-1}$, RMSE of ±6.46 and 6.36 mm $month^{-1}$, NSE of 0.86 and 0.47 and R^2 of 0.94 and 0.81 for medium canopy cover 'Cripps' Pink' and young 'Golden Delicious Reinders' orchards, respectively (Figure 3.5 b-c).

3.6 ESTIMATING ORCHARD ET USING IMPROVED K_c

The eddy covariance energy balance closure varied with orchard canopy cover – see Mobe *et al.* (2020b). The closure ratio was higher for the mature (0.95) than the young (0.77) orchards. These differences can be explained by, among other things, the more uniform vegetation cover in mature orchards while the orchard surface was more heterogeneous in young orchards.

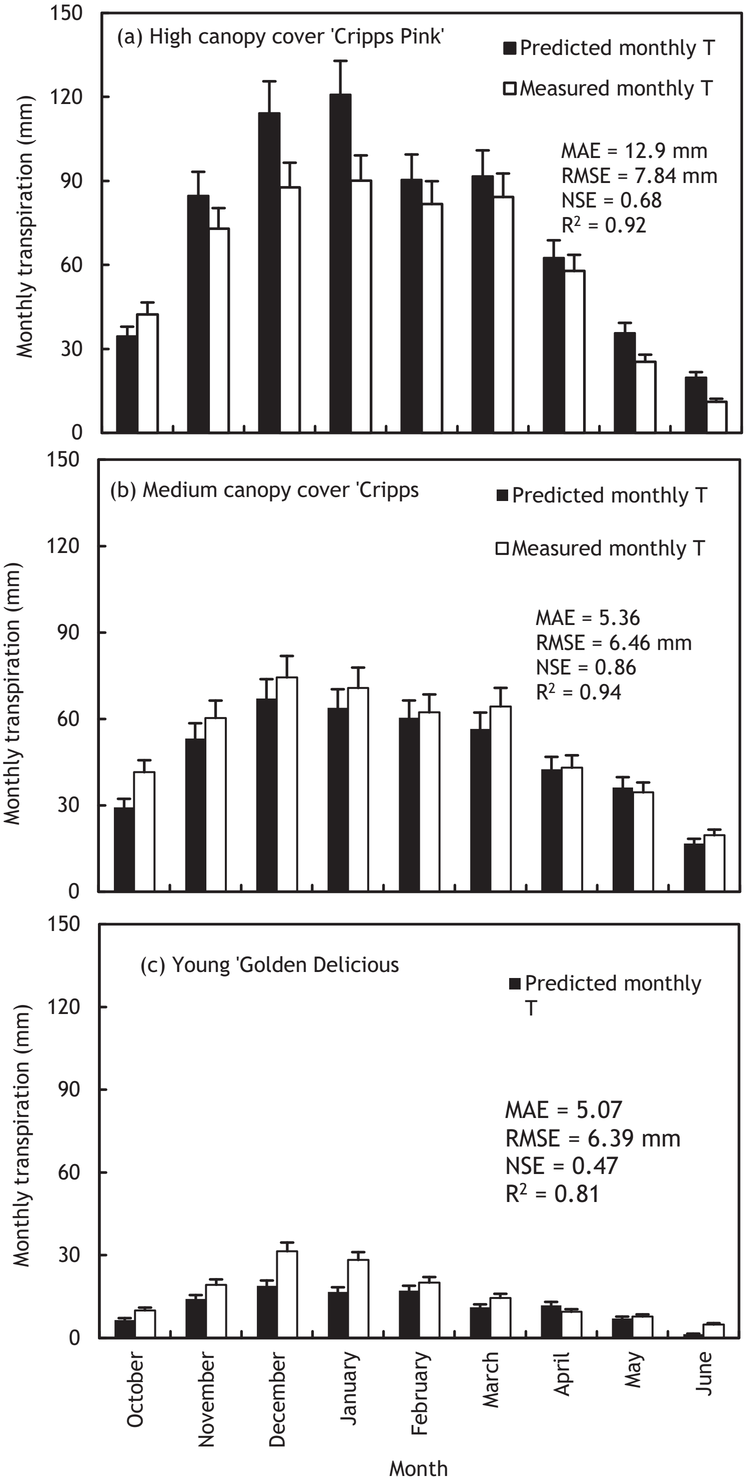

Figure 3.5: ***Comparison of the measured and calculated monthly total transpiration rates of orchards with high (a), medium (b) and low canopy cover (c). NSE represents the Nash-Sutcliffe Efficiency.***

The crop coefficients (K_c) for all the orchards were fairly well predicted by the improved A&P method and Figure 3.6a shows the data only for clear days. Cloudy days were excluded as these produced unrealistically high measured K_{cb} values due to the low reference evapotranspiration. The contribution of the cover crop to the orchard K_c was also included in this analysis. The average leaf area index of the cover crops (LAIc) was about 0.24 which gave a density function (K_{dc}) of ~0.15. The daily total transpiration for a typical clear day in winter expressed over the full orchard surface was around 0.9 mm while the corresponding reference evapotranspiration was around 4.0 mm d^{-1}. This gave a full-cover K_{cb} for the cover crops of about 0.225 and an average $K_{cbcover}$ of approx. 0.034 as detailed in the methodology. The maximum observed leaf area index for the cover crops was around 1.0 and, following the above procedure, this gave a $K_{cbcover}$ of about 0.08. Therefore, the following cover crop threshold values were used for estimating the K_{cb} of micro-sprinkler irrigated apple orchards in the APP: i.e. $K_{cbcover}$ = 0, for bare orchard floor (LAIc < 0.1); $K_{cbcover}$ = 0.03 for moderate density cover crop (0.1 < LAIc < 0.8) which was the most common cover type, and $K_{cbcover}$ = 0.1, for orchards with tall and dense cover crops (LAIc ≥ 0.8).

The crop coefficients for the mature orchards in Figure 3.6a tended to be high because most of the ET data were collected when canopy cover had reached its maximum in summer. The larger spread of the Kc values in the young orchards is a result of the high ET observed early in the growing season when the orchards had dense cover crop and weeds while the atmospheric evaporative demand was still comparatively low.

Orchard ET, calculated as ET = K_c x ET_o where K_c is the crop coefficients derived from the improved A&P method, closely matched the eddy covariance derived ET values in Figure 3.6b. The data shown in Figure 3.6b is for all the orchards measured during the three year study period wherein the eddy covariance ET were collected during selected window periods. The calculated orchard ET for the pooled data from all the orchards was within 10% of the eddy covariance measured values.

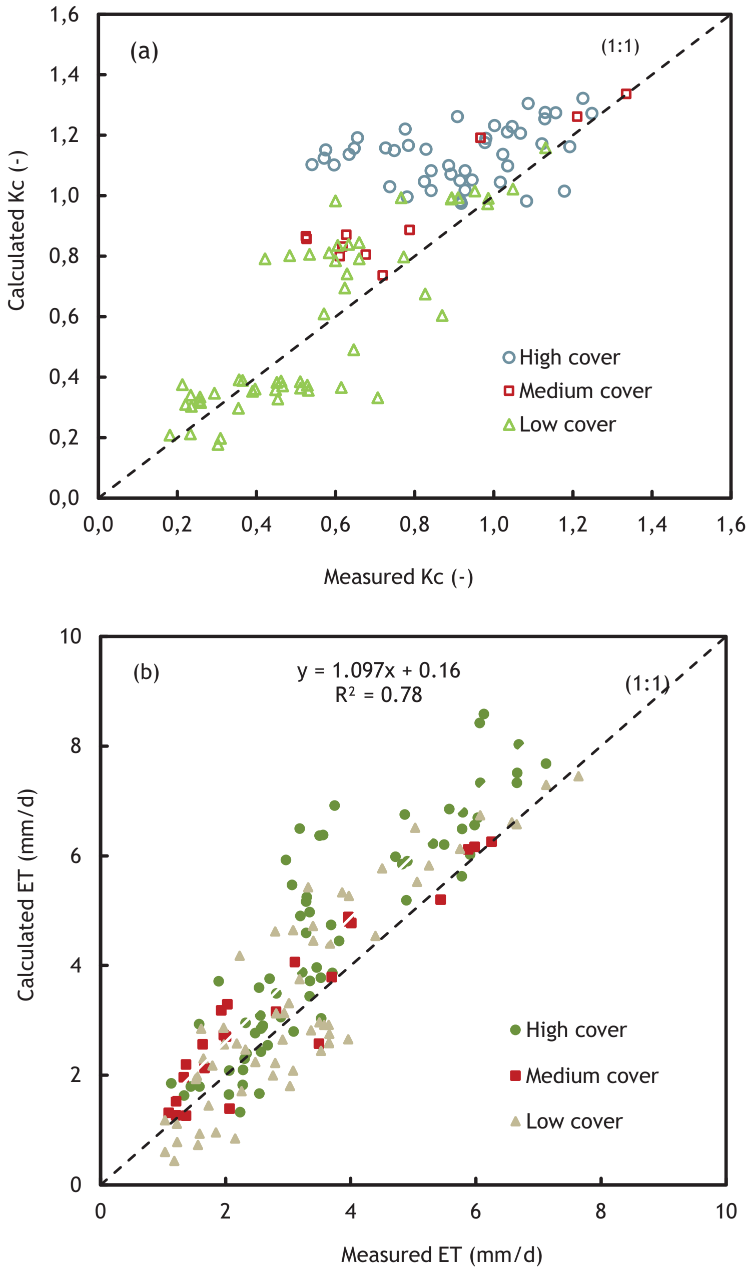

Figure 3.6: ***(a) Comparison of the crop coefficients determined with the improved A&P method with measured values for 12 apple orchards. (b) Evapotranspiration predicted using the improved crop factors and measured by the eddy covariance system.***

Table 3.3: **Comparison between monthly predicted and measured transpiration for orchards with varying canopy cover. R^2 is the coefficient of determination, RMSE is the root of the mean square error, MAE is mean absolute error and N is the number of observations.**

	Full canopy cover					Medium canopy cover					Low (young) canopy cover					
Month	**T_predicted (mm)**	**T_measured (mm)**	**R^2**	**RMSE (mm)**	**MAE (mm)**	**T_predicted (mm)**	**T_measured (mm)**	**R^2**	**RMSE (mm)**	**MAE (mm)**	**T_predicted (mm)**	**T_measured (mm)**	**R^2**	**RMSE (mm)**	**MAE (mm)**	**N**
October	47.61	59.22	0.52	14.35	11.61	25.13	38.43	0.43	17.32	13.30	5.01	11.37	-	7.25	6.36	4
November	90.88	89.78	0.37	9.74	8.33	51.92	53.11	0.68	9.71	8.78	15.03	26.71	0.77	12.43	11.68	4
December	116.18	107.66	0.36	14.36	10.96	62.69	61.21	0.55	13.81	12.21	22.23	34.87	0.75	12.65	12.64	4
January	118.01	107.57	0.41	15.68	10.45	61.19	57.88	0.72	10.12	8.43	23.62	33.09	0.80	10.30	9.48	4
February	92.29	92.31	0.62	8.49	7.95	56.68	53.40	0.94	4.94	4.23	21.01	23.83	0.83	4.14	2.94	4
March	82.33	85.57	0.12	8.19	7.00	51.60	54.25	0.93	6.05	5.53	18.65	18.77	0.69	4.34	3.78	4
April	59.62	63.22	0.64	6.72	5.96	36.76	39.66	0.61	10.35	7.20	15.49	14.24	0.68	2.49	2.47	4
May	39.03	45.71	0.12	13.96	11.85	28.63	30.95	0.44	9.43	6.72	9.69	11.46	0.72	2.72	2.33	4

3.7 DISCUSSION: IMPROVED Kc ESTIMATING ALGORITHM

The FAO-56 crop coefficient approach for estimating crop water requirements under well-watered conditions is a standard approach that has been widely adopted and used for irrigation management, particularly irrigation scheduling (Girona *et al.*, 2011; Dzikiti *et al.*, 2017; Volschenk, 2017; Gush *et al.*, 2019). However, accurate estimates of crop water requirements with this method require accurate crop factors and this is the major limitation of the method as the published FAO crop coefficients are not readily transferable between fields and growing regions (Casa *et al*., 2000; Allen, 2000; Lascano, 2000). To address this challenge, Allen and Pereira (2009) have advanced the original FAO-56 approach by proposing a method whereby crop coefficients (K_{cb} and K_c) are estimated using readily available crops data such as the fraction of ground cover, and crop height.

This method has a very high potential for improving irrigation management through improved crop coefficients given the simple inputs that are required to calculate the K_c values. For this reason, the A&P method has been the subject of research interest and several studies have evaluated its performance, albeit with mixed results (Jiang *et al*., 2014; Paço *et al.,* 2019; Taylor *et al*., 2015). For example, Jiang *et al.* (2014) applied the A&P method on maize in the Great Plains of China. They observed a close fit between the measured and calculated crop coefficients using the parameters published by Allen and Pereira (2009) for the maize crop. Observations from the present study indicate that the A&P method significantly over-estimates the crop coefficients for apple orchards under the Mediterranean-type growing conditions consistent with the conclusions by Taylor *et al.* (2015) on citrus orchards in South Africa. Taylor *et al.* (2015) however, proposed using a variable leaf resistance term in equation 3.6 instead of a fixed one to improve the K_{cb} estimates. This was a logical step given that citrus trees are known to have a very strong stomatal control of leaf gas exchange (Cohen and Cohen, 1983; Dzikiti *et al.*, 2007; Dzikiti *et al*., 2011). They noted a strongly linear relationship between the leaf resistance and the reference evapotranspiration. The leaf resistance for citrus had a much wider range than for apple trees varying from around 500 to close to 3 000 s/m. In contrast to citrus trees, the r_l-ET_o relationship for apple trees was in fact non-linear as shown in Figure 3.3b. These data exclude instances when the orchards were experiencing water stress. The orchards were deemed to be under water stress when the midday stem water potential was lower than -2.0 MPa following Dzikiti *et al.* (2018a,b). With no water stress, the rl-ETo relationship for apple trees suggests that the stomatal resistance increases sharply with the increasing atmospheric evaporative demand. This trend is due to the high sensitivity of apple trees to high vapor pressure deficits (Ntshidi *et al.*, 2018; Gush *et al.*, 2019; Mobe *et al.*, 2020a).

Applying the r_l-ET_o relationship to the A&P method as proposed by Taylor *et al.* (2015) also did not yield satisfactory results in this study likely because of the differences in the physiology of citrus and apple trees (data not shown). Apple trees, in this study had a narrower range of leaf resistance (100-515 s m^{-1}) than citrus which lead to a higher F_r ratio causing high K_{cb} values. The fact that Jiang *et al.* (2014) obtained satisfactory results on an annual crop (maize) using the A&P parameters as published, yet applications on three different perennial crops (citrus, olive, and apples) required adjustments for stomatal sensitivity suggests that there is need to differentiate between annual and perennial crops in the A&P approach. Here we demonstrate that using the r_l for apple trees and replacing the leaf resistance of an annual crop (~100 s m^{-1}) with the canopy resistance of well-watered apple trees gave accurate results for 12 different orchards. Findings in this study support the use of an appropriate tree reference resistance in the A&P method for fruit trees rather than the grass reference (~100 s/m) being used for all crop types.

3.8 CONCLUSIONS

In this chapter, we provide information that forms the back bone of the APP to be described in the next chapter. Accurate forecasts of the apple orchard water requirements is dependent on accurate ET_o forecasts and the crop coefficients. A detailed review of various online weather forecasts was done. In Chapter 6 we present comparisons between the forecast and measured weather variables including ETo in the apple producing regions.

While the need for a method to derive accurate crop coefficients using readily available information is essential for precise water resources management, this study demonstrates that there is also a need for a detailed understanding of the physiology of the specific crops. Different crops regulate their stomatal aperture in response to environmental stresses in different ways to balance CO_2 gain and transpiration losses. For apple trees in a semi-arid Mediterranean-type climate typical of the Western Cape Province of South Africa, replacing the annual crop resistance (= 100 s m^{-1}) with the unstressed canopy resistance for apple trees of 37 s m^{-1} gave accurate estimates of crop factors for apple orchards. This information has subsequently been used to develop the APP described in the next chapter.

CHAPTER 4

DEVELOPMENT AND FUNCTIONS OF THE APPLICATION

4.1 DESCRIPTION OF THE SMARTPHONE APPLICATION

The current Orchard Water Use Application (APP) has been developed only for apple orchards because of the limited resources. Other crop types will be added in future subject to the availability of resources. The APP is coded using Python so it can work on smartphones with both Android and IOS operating systems. Earlier versions of the APP were extensively tested on Android, and we expect the APP to also work on the IOS platform without problems. The APP can also be configured to run on most computers (Microsoft, Linux, etc.) although we have not attempted this.

There are two important steps in the running of the APP. The first is the calculation of the daily reference evapotranspiration (ET_o) done according to the FAO 56 guidelines (Allen *et al.*, 1998). The second is the derivation of the crop coefficients and all the complex calculations are done at the back end of the APP. A schematic representation of the APP is shown in Figure 1.1. Cell phone connectivity is required to run the application. The APP requires about 50 MB on the smartphone and data bundles are required to run the application. Installation of the APP on older smartphones can be difficult, so it is best to install on newish phones.

4.2 NAVIGATING THE APPLICATION

Once the APP has been successfully installed an icon appears on the smartphone – see red circle shown in Figure 4.1. Next the user is prompted to complete a short form with information that is specific to each orchard (Figure 4.2). The required inputs are:

1) Orchard coordinates
2) Fractional vegetation cover
3) Average tree height (in metres)
4) Soil texture
5) Irrigation system, and;

6) Cover crop status.

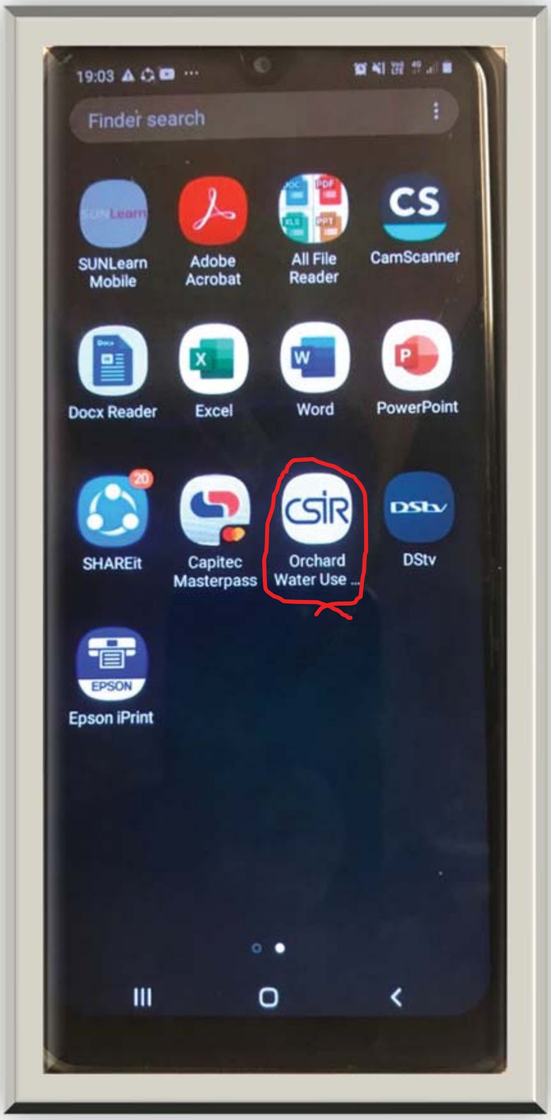

Figure 4.1: ***The CSIR Orchard Water Use APP icon highlighted in red.***

The orchard coordinates are entered as decimal degrees in the format indicated by the greyed figures. Please note that the greyed figures are not real numbers. They just illustrate the accepted format, otherwise they should be replace by real numbers. The latitude is negative in the southern and positive in the northern hemisphere.

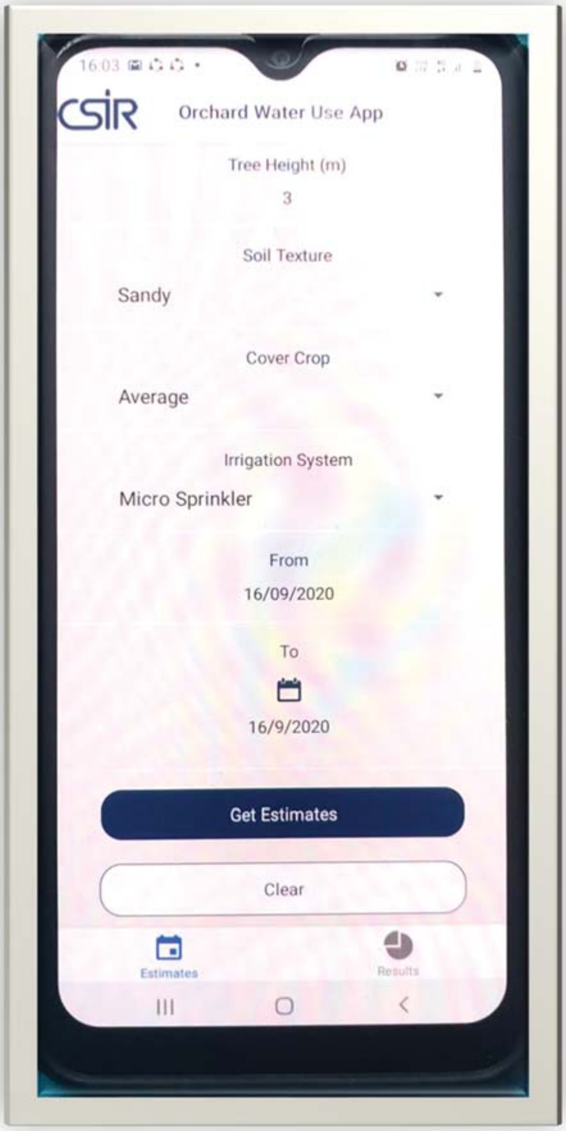

Figure 4.2: ***Landing page showing the required inputs.***

Should the user make a mistake and enter information incorrectly, the system flags the error as illustrated in Figure 4.3.

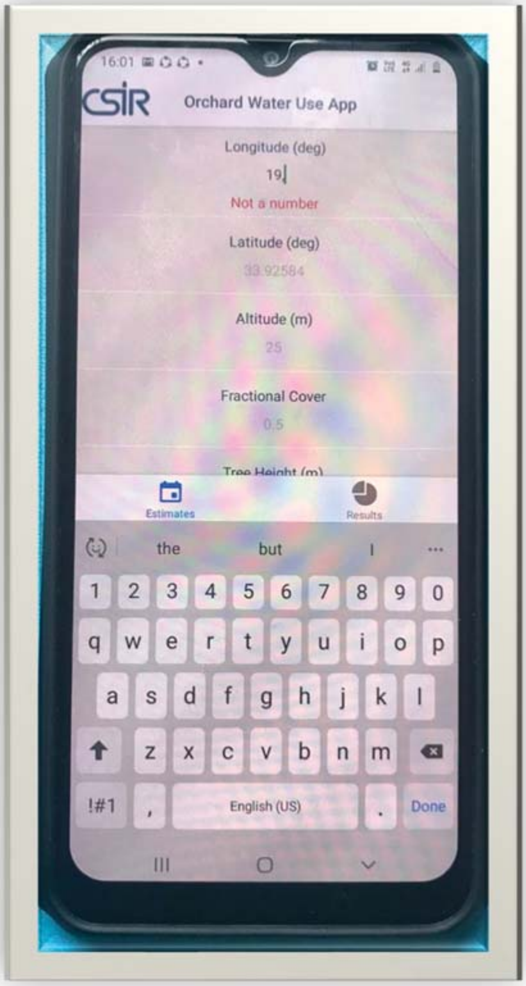

Figure 4.3: Warning for incorrectly entered information.

The procedure for determining the fractional vegetation cover (f_c), which should be a fraction between 0 and 1 is slightly more complicated and requires more care. Figure 4.4 illustrates the procedure according to Allen and Pereira (2009). f_c is the fraction of the surface allocated to each tree that is covered by vegetation as measured from directly overhead. During the peak irrigation season (late November to March/April), this quantity remains more or less constant for apple orchards as new flashes rarely occur during the fruit growing period. The effective fractional cover (f_{ceff}) is calculated internally by the APP from the information provided by the user.

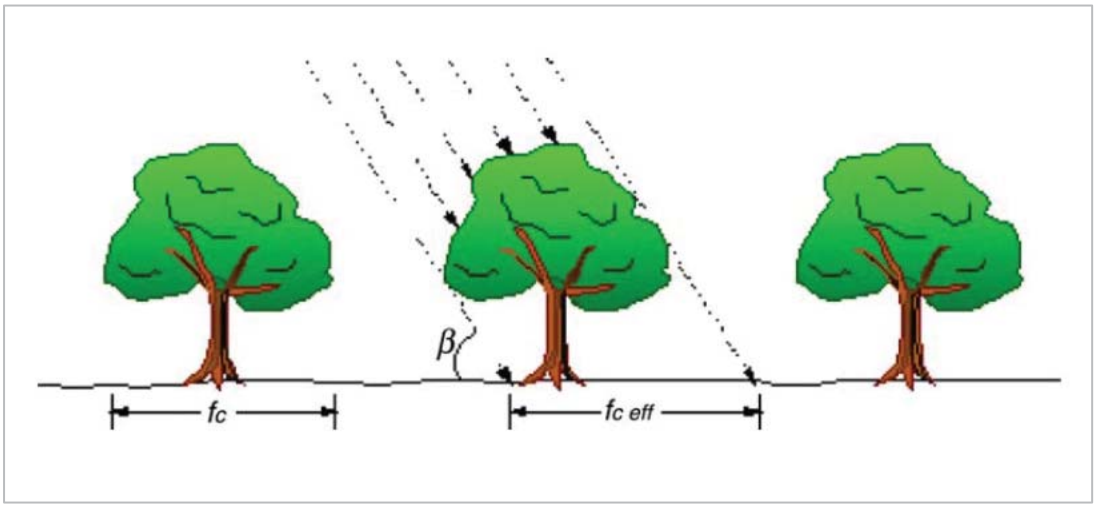

Figure 4.4: Schematic diagram illustrating the fractional vegetation cover (f_c) and the effective vegetation cover (f_{ceff}) (after Allen and Pereira, 2009).

There are three drop down menus to select the soil type, cover crop status and irrigation system (Figures 4.5 to 4.7) and a further option to select how far ahead the user wants to run the forecast. Although the system does not physically restrict the user from choosing a longer forecasting period, we strongly recommend a maximum of seven days (one week) ahead as the accuracy of weather forecasts become poorer the longer forecasting period. At present, the user can only select one of three soil types, i.e. sandy, loam and clay. The irrigation system is restricted to only drip and micro sprinkler which are the dominant systems currently in use. The user also enters information on the cover crop, i.e. whether there exists a tall and dense cover crop (typical of a poorly managed orchard floor), whether there exists a uniform, short cover crop or there is bare ground. The cover crop option does not distinguish between species, we only consider green vegetation cover on the orchard floor including weeds. In addition, orchard management practices such as mulching are not taken into account in the current APP.

Figure 4.5: Drop down menu to enter the dominant soil type.

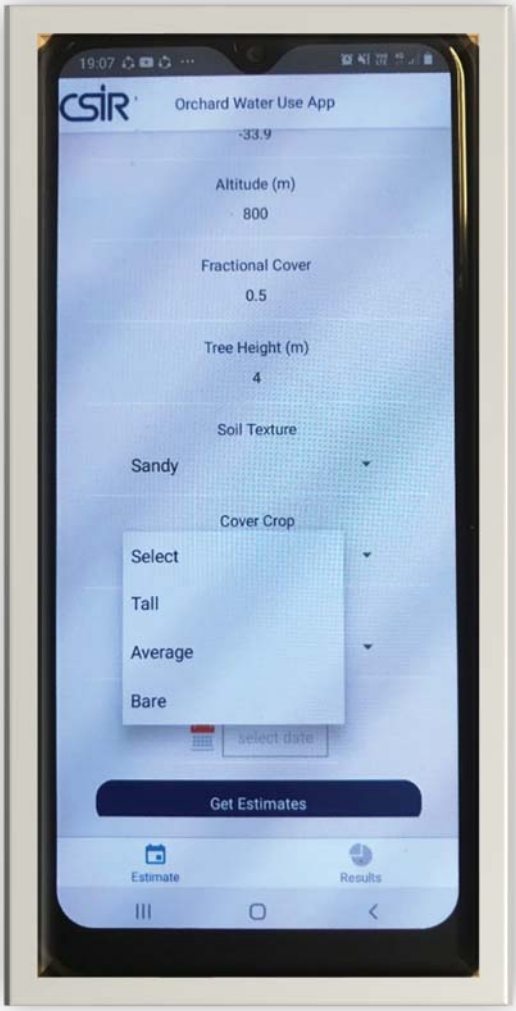

Figure 4.6: Cover crop status.

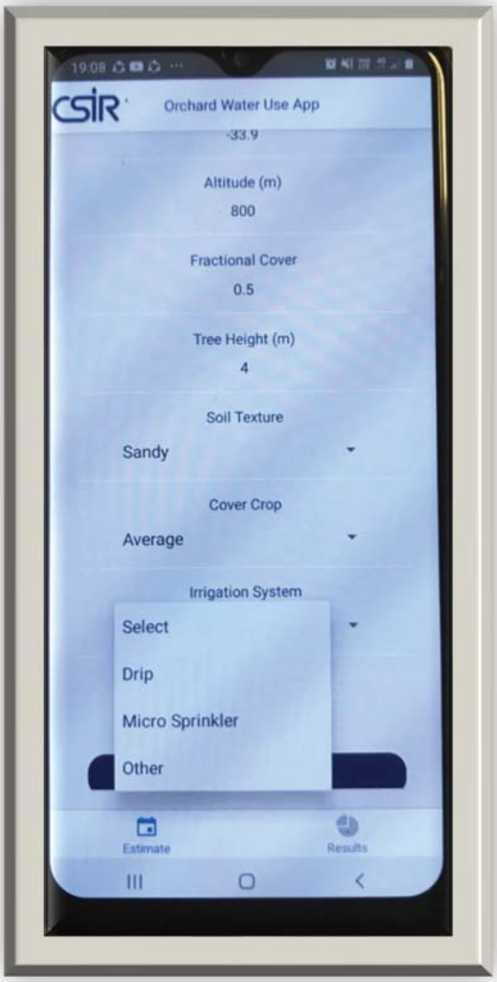

Figure 4.7: Selecting the irrigation system.

Figure 4.8: Selecting the forecasting period.

4.3 VIEWING OUTPUTS

Once the input form is fully populated, the next step is to run the APP (Figure 4.9). This is achieved by hitting the “Get Estimates” button and the screen will be as shown in Figure 4.9.

Figure 4.9: Get estimates to run the APP.

This action pulls into the APP the online weather data from the “DarkSky” website for the requested forecasting period. Several outputs are then generated which include:

1) Daily ET_o (in mm)
2) Daily orchard transpiration (in mm)
3) Daily orchard evapotranspiration (in mm)
4) Basal crop coefficient (K_{cb});
5) Orchard crop coefficient (K_c), and;
6) Various weather variables used to calculate ETo.

These variables are displayed either in graphical (Figure 4.10) or Tabular form (Figure 4.11). In addition, a weekly summary is also produced of the following variables:

1) Total transpiration
2) Total evapotranspiration
3) Total reference evapotranspiration
4) Weekly average K_c and K_{cb}, respectively.

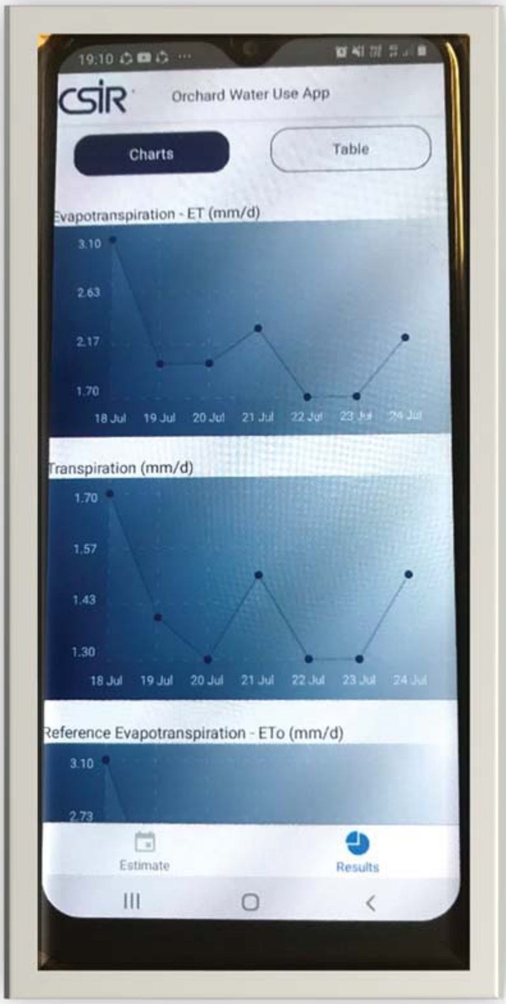

Figure 4.10: Graphical outputs of actual orchard evapotranspiration, transpiration, and the reference evapotranspiration.

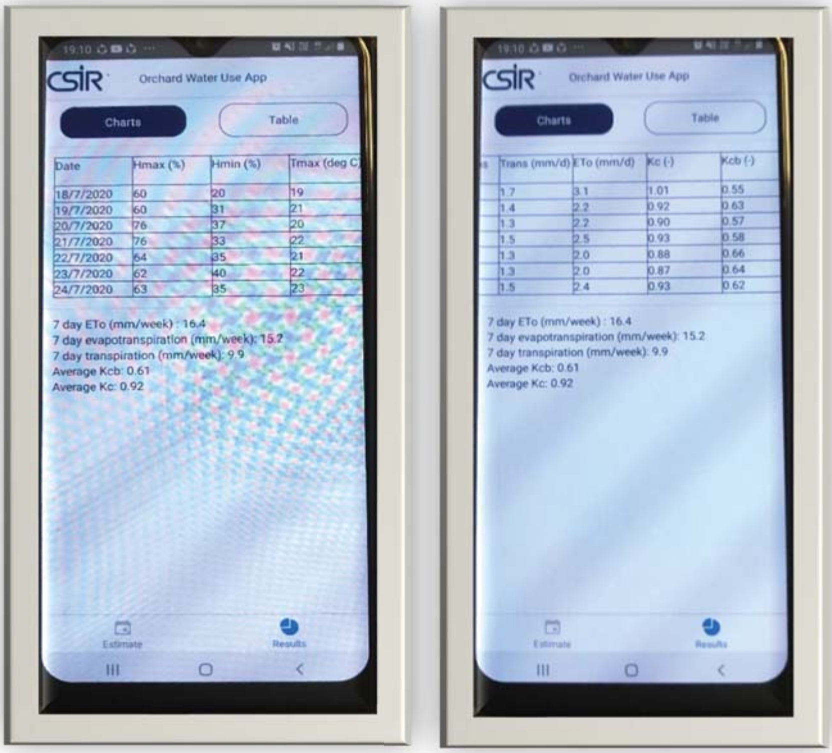

Figure 4.11: Tabular outputs of the driving weather variables, actual ET, transpiration and the crop factors.

CHAPTER 5

FIELD VALIDATION OF THE APPLICATION

5.1 INTRODUCTION

The next step following the completion of the development phase was to validate the APP. This was done by comparing the APP predictions of daily ETo, evapotranspiration (ET), and transpiration with actual measurements including of the actual irrigation in selected orchards. The orchards were in three microclimatic regions in the Koue Bokkeveld, Villiersdorp and Grabouw, respectively. Given that the intention of this study was to develop a pilot rather than a fully operational product, our validation was therefore not exhaustive. We recommend interested users to further conduct their own in-field tests to ensure that the product performs to their expectations. Other fruit tree species will be added subject to the availability of research funds.

A free version of the APP will be launched on Play Store and Google Store, respectively before October 2020 for ready access. We will solicit feedback from potential users to get information to improve the APP where possible. Because the participating farmers in the validation exercise were using other commercial products for their decision making, some of them recommended that we use proxy rather than real names of the study sites to avoid conflicts or to give the perception that they are endorsing this application. So we refer to Koue Bokkeveld, Villiersdorp, and Grabouw orchards, respectively to refer to the study sites located in each of these regions. These study sites were selected because these regions have somewhat different microclimates. In addition, we also chose orchards with different attributes, e.g. cultivar, training system, irrigation system, and canopy cover to evaluate the application over a range of conditions. Unfortunately, the quality of the measured data, e.g. in the young orchard in Grabouw was poor for a variety of reasons. So we exclude these data in the final analysis.

5.2 VALIDATION SITES

5.2.1 Koue Bokkeveld orchard

The study orchard in the Koue Bokkeveld was planted to ‘Rosy Glow’ on MM109 rootstock with an M9 interstem (MM109/M9). ‘Rosy Glow’ is a late-season, high-coloured spontaneous single limb mutation of ‘Cripps Pink’ which can also be marketed under the Pink Lady® brand when it meets the quality criteria. It is thought to give better fruit colour under less than optimal climatic conditions. The orchard was about 0.56 ha, planted in 2010 on ridges with a north-south orientation. Planting density was high (3.5 x 1.25 m), giving 2 285 trees per hectare (see Figure 5.1). The pollinator is ‘Royal Gala’ at 10%, i.e. every 10th tree in the row arranged as a diamond across rows. At this site, the trees achieved maximum canopy cover in early to mid November. Tree height was maintained at about 3.5 m.

The trees were under micro-sprinkler irrigation and each sprinkler had a delivery rate of about 30 L/h. Irrigation scheduling was done via neutron probes. An assortment of online products (i.e. iLeaf and Pulse) were also being used to forecast the weekly crop water requirements. The daily iLeaf forecasts were obtained every Monday for the week ahead. For this specific orchard, the farm used a crop factor of about 0.60 from November to January raising it to 0.95 during the hottest month in February. Because of the narrow row spacing, the sprinklers wetted most of the orchard floor thereby sustaining a vibrant cover crop between the rows. The cover crop strip was about 1.0 m wide comprising mostly of the exotic tall fescue grasses and a number of indigenous species. The cover crop was mostly kept low through regular mowing (Figure 5.1). The soils are deep sandy soils of the Fernwood soil form with very few stones. This orchard is a typical high yielding orchard producing between 120 and 140 t/ha during the 2017/18 and 2018/19 seasons.

Figure 5.1: A mature Rosy Glow apple orchard used for validating the APP in Koue Bokkeveld.

5.2.2 Villiersdorp orchard

This farm was located about 2.0 km south of Villiersdorp town close to the eastern edge of the Theewaterskloof dam. The study orchard was about 2.36 ha planted to the Royal Gala cultivar on the MM106 rootstock. The orchard was planted in 1998 and the trees were trained with a V-trellis system with about 2 500 trees per ha. Irrigation was via a drip system with emitters spaced about 0.75 m apart along the length of each drip line. Each emitter delivered about 2.3 L h^{-1}. There were two irrigation lines with one drip line per tree line (Figure 5.2). Some of the drip lines were buried in places.

There were no ridges in the orchard which was on flat terrain. The soils were deep sandy soils with no stones. Irrigation scheduling at the farm was done using DFM profile probes. The farm also used iLeaf for ETo forecasts and the daily forecasts were obtained every Monday for the week ahead.

Figure 5.2: Drip irrigated Royal Gala orchard on V-trellis training system in Villiersdorp.

The farm used a crop factor of 1.0 throughout the irrigation season although there were uncertainties surrounding this figure. There was an active cover crop that mostly grew close to the tree lines that received irrigation. The rest of the inter-row spaces were bare.

5.2.3 Grabouw orchard

Data were collected in two orchards in Grabouw. These included a mature ‘Golden Delicious’ orchard on M793 rootstock. The orchard was 5.13 ha and it was planted in 1992 with a spacing of 4.25 x 2 m giving 1 176 trees per hectare (Figure 5.3a). The orchard was on an uneven terrain irrigated with a medium range micro-sprinkler system.

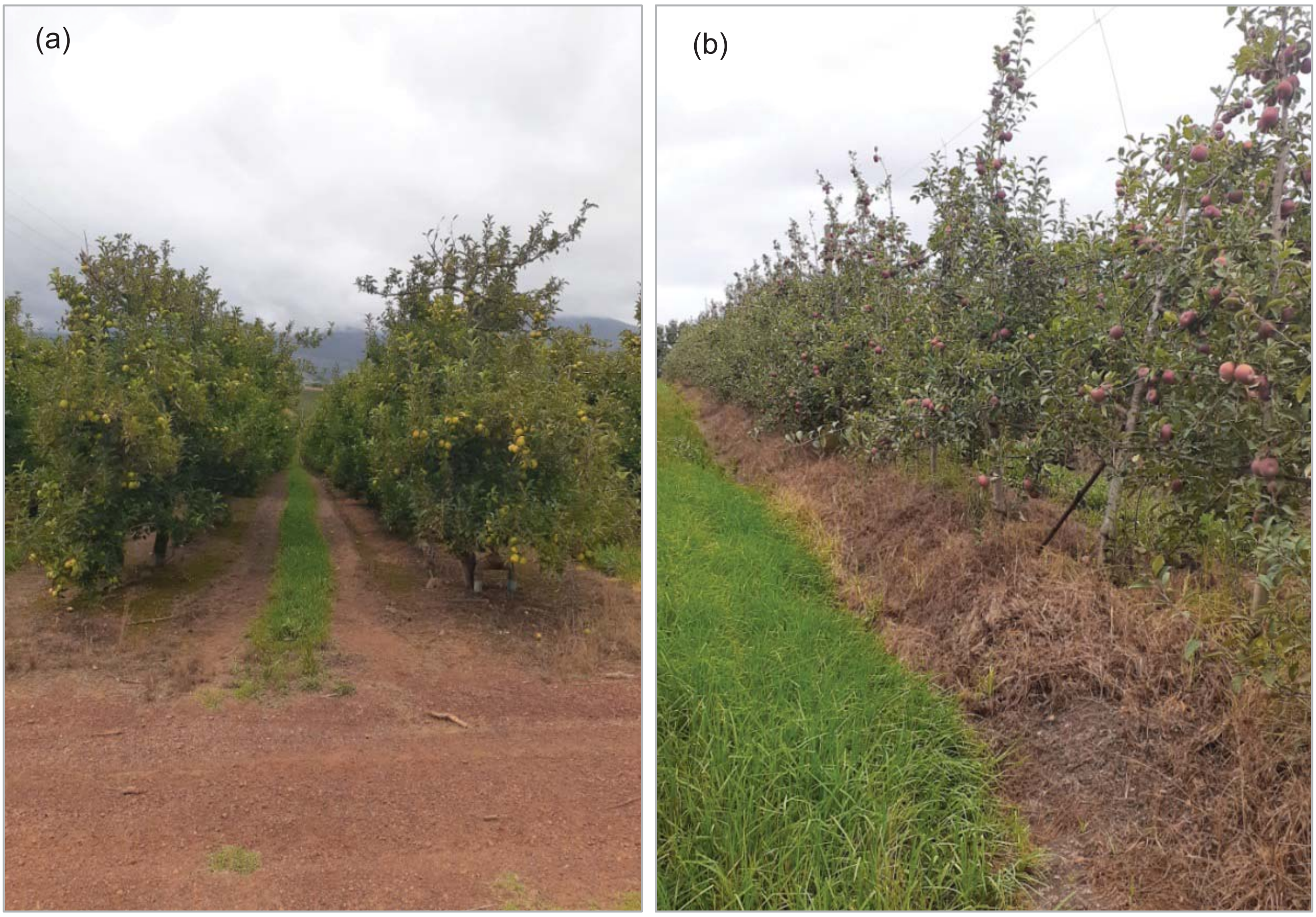

Figure 5.3: (a) Full-bearing Golden Delicious, and (b) young Fuji orchard in Grabouw.

There was a thin strip of cover crop between the tree rows mainly the kikuyu species which was kept low partly because of mowing and also because of the heavy shading by the larger canopies (Figure 5.3a).

The second orchard in Grabouw was a young Fuji orchard which was in the second year of bearing planted in 2015 (Figure 5.3b). The Fuji trees were on the vigorous and high yielding MM109 rootstock. This orchard was about 1.84 ha in extent and irrigation was via a micro-sprinkler system. Trees were on raised ridges oriented in a north-south direction and there was a dense cover crop of tall fescue which occupied almost the entire orchard floor (Figure 5.3b). The soils in both orchards were heavy clayey soils with a high stone content. Average yield in the mature Golden Delicious orchard was between 90 and 100 t/ha in most years.

5.3 DATA COLLECTION

The same type of data were collected in all the orchards during the 2019/20 growing season. The orchard microclimates were measured using automatic weather stations located close to the orchards install by the project team or operated by the ARC. In the Koue Bokkeveld, the weather station was located within the orchard as part of another ongoing Water Research Commission/Hortgro funded project on shade nets (WRC K5 2815//4). Therefore the weather station at this site was not a standard weather station. The wind speed was measured within the canopy, so we used a daily average of 2.0 m/s. At the Villiersdorp site, the weather data was collected from the Agricultural Research Council (ARC) weather station located about 7 km away. At Grabouw, we also used the ARC weather station but which was located about 3.0 km away from the study site.

Transpiration data were measured in all the orchards using the HRM method described in Chapter 3 on between three and four trees per orchard. Thermal dissipation probes were used in the young orchard, but the sensors never worked optimally. So these data are not reported here. The volumetric soil water content was monitored at various depths using time domain reflectometer probes (Model: CS616, Campbell Scientific, USA). The actual volumes of irrigation applied were measured using electronic water flow meters that are installed along the irrigation lines (Figure 5.4). Actual orchard evapotranspiration was estimated using the soil water balance approach only for the Koue Bokkeveld and Villiersdorp orchards. It was difficult to use this technique in Grabouw because of the stony soils and the sloping terrain of the orchards.

Figure 5.4: Electronic water flow meter measuring irrigation volumes.

5.4 GROWER PARTICIPATION IN THE VALIDATION

Every Monday morning the APP was run for each test orchard for the week ahead (Monday to Sunday). The information was immediately sent to the farm. The farm in turn sent back to the researchers their own irrigation forecasts for the week. This approach ensured that both the researchers and the farms had similar data sets for later engagements. Only the Koue Bokkeveld and Villiersdorp farms returned the data as they were also using other forecasting tools as discussed earlier. Grabouw farms did not provide their irrigation forecasts as they use DFM probes for irrigation scheduling and generally they do not forecast their irrigation. However, we were still able to compare the APP's performance with the actual transpiration and the applied irrigation. The APP was run in collaboration with the growers from 18 November 2019 to around 23 March 2020.

5.5 VALIDATION RESULTS

5.5.1 Koue Bokkeveld orchard

5.5.1.1 Reference evapotranspiration for Koue Bokkeveld

The Orchard water use application uses online weather forecasts from the DarkSky web site. For brevity, instead of validating the DarkSky forecasts variable-by-variable here we chose to rather compare the measured and the forecast reference evapotranspiration (ET_o) values (Figure 5.5). The ET_o integrates the effects of the key weather variables, i.e. maximum and minimum temperature, maximum and minimum relative humidity, wind speed and the solar irradiance. The short grass reference ET_o was used both in the APP and with the measured data according to Allen *et al.* (1998).

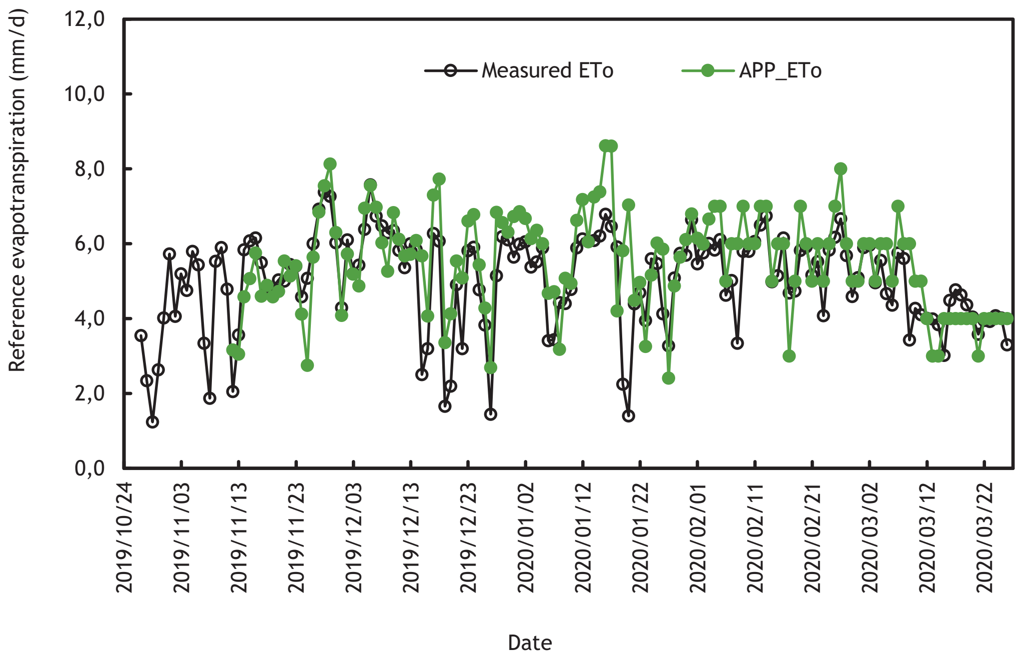

Figure 5.5: Comparison of the actual measured ET_o and those forecast by the APP in the Koue Bokkeveld.

According to Figure 5.5, the forecast ET_o closely tracked the measured values in most instances. However, there was a slight tendency to overestimate the reference evapotranspiration when evaporation rates were high. It is not clear whether this was a result of the tendency of DarkSky to slightly overestimate the minimum temperature or this was due to our assumptions on the wind speed which we fixed at 2.0 m s^{-1}. Correlating the predicted against measured ET_o produced a graph with a slope of 0.82, intercept of 1.26 and R^2 of 0.56. The root mean square error was ±0.96 mm d^{-1} over a period of 138 days. The daily ET_o forecasts by the APP at the Koue Bokkeveld can be described as fair. More accurate wind speed data would possibly have led to more accurate forecasts, therefore further validations will be necessary.

5.5.1.2 Water requirements of a Rosy Glow orchard in the Koue Bokkeveld

Comparisons between the forecast transpiration and evapotranspiration with actual measurements of the two fluxes in the Rosy Glow orchard are shown in Figures 5.6 and 5.7. The crop parameters used in the APP were: fractional vegetation cover (f_c) ~ 0.60, average tree height ~ 3.5 m. The constant APP values during March 2020 for both fluxes (including ET_o in Figure 5.5) were a result of rounding these fluxes to the nearest 1.0 mm. The rationale for this was that since the outputs could not possibly be more accurate than 1.0 mm d^{-1} given the uncertainties with weather forecast. However, this created another problem. For example, forecast daily transpirations of 1.4 mm d^{-1} for one day and 0.5 mm d^{-1} for the next day all appeared in the tables as 1.0 mm d^{-1} leading to the flat portions in the graphs. The graphical outputs in the APP were also affected in the same way showing step changes as the tables and graphs seem somewhat linked in the background. So we reinstated one decimal place in the water use outputs to get realistic outputs. By this we do not claim a higher degree of accuracy in the water use predictions, rather we seek to display outputs which are as close to reality as possible and we leave it to the user to round off as they see fit.

As with the ET_o, the trend in the predicted transpiration closely followed that of the measure transpiration on most occasions (Figure 5.6).

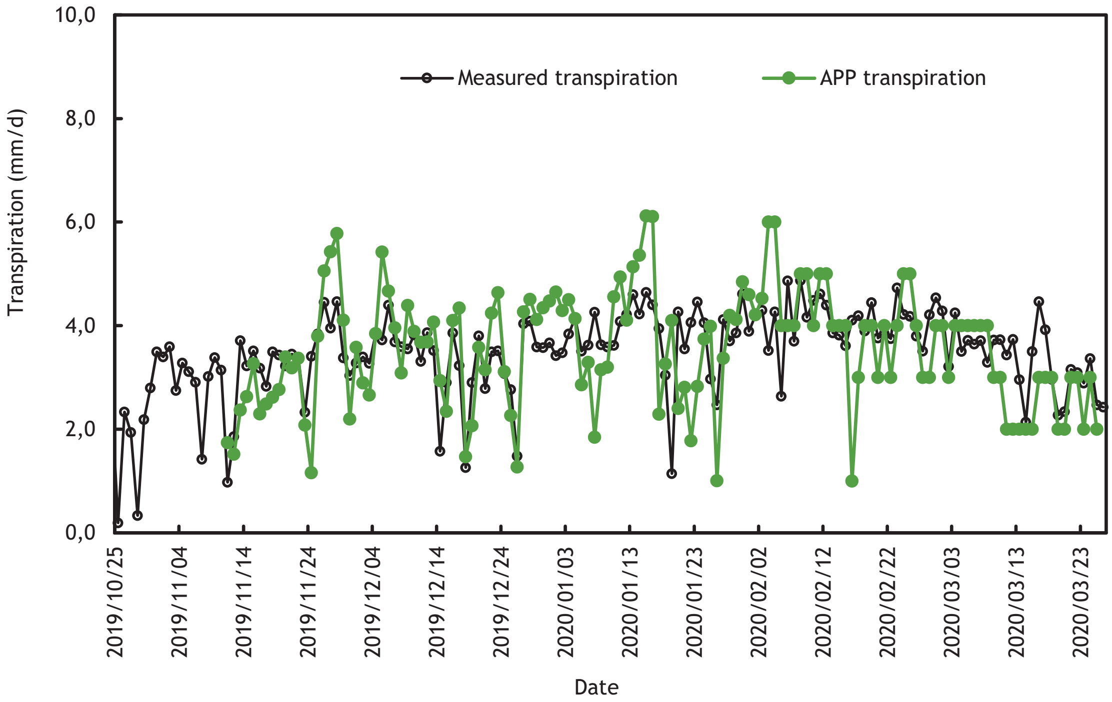

Figure 5.6: Forecasting the Rosy Glow orchard transpiration at the Koue Bokkeveld.

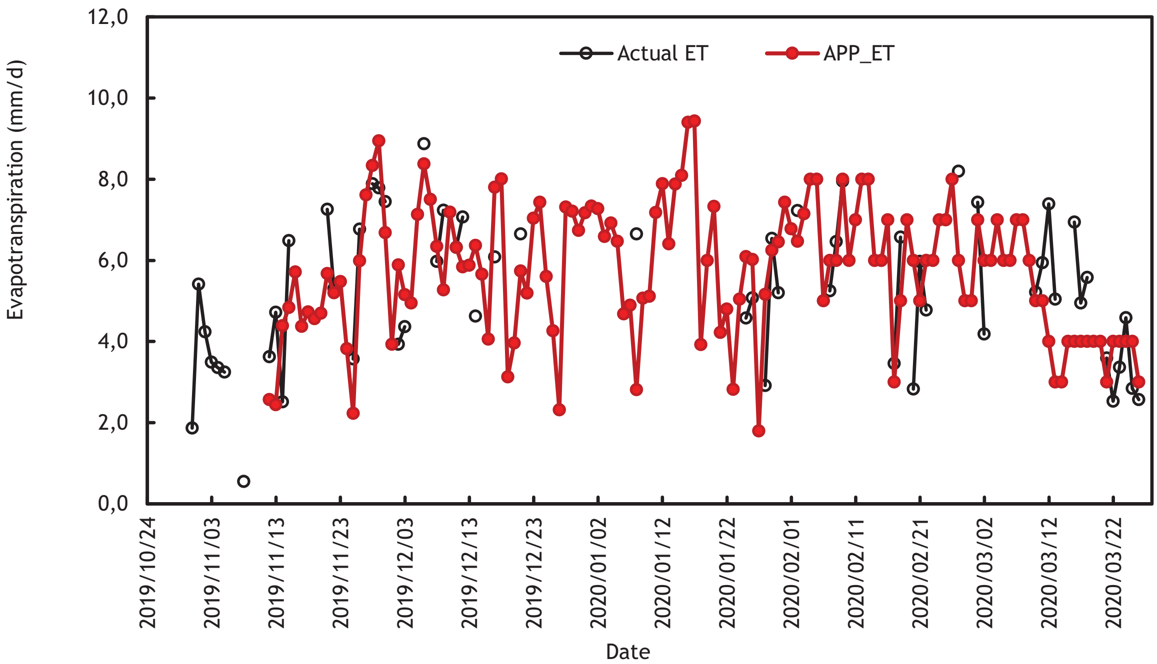

Figure 5.7: Forecasting the actual evapotranspiration of a Rosy Glow apple orchard in the Koue Bokkeveld using the smartphone APP.

The slope of the predicted vs measured transpiration was 0.86, with an intercept of 0.44, albeit with a much larger scatter, i.e. R^2 = 0.32. The root mean square error in the transpiration forecast for the mature high density Rosy Glow orchard was about ±0.94 mm d^{-1}. Comparing the weekly transpiration forecasts improved the R^2 to about 0.46, but the slope was worse at 1.25 (i.e. different from 1.0) with a slope of -6.6 mm/week. The actual ET was determined using the universal soil water balance approach, but accounting for the drainage flux proved to be difficult. As a result, days with substantial irrigation or rainfall were left out leading to the relatively fewer points shown in Figure 5.7. Nevertheless, the predicted daily ET were of the same order of magnitude as that determined with the soil water balance approach, but again validation with more continuous measured data will be very useful.

5.5.1.3 Weekly forecast vs actual applied irrigation in the Rosy Glow orchard

The irrigation scheduling strategy for the Rosy Glow orchard was to replace 100% of the water lost via ET.

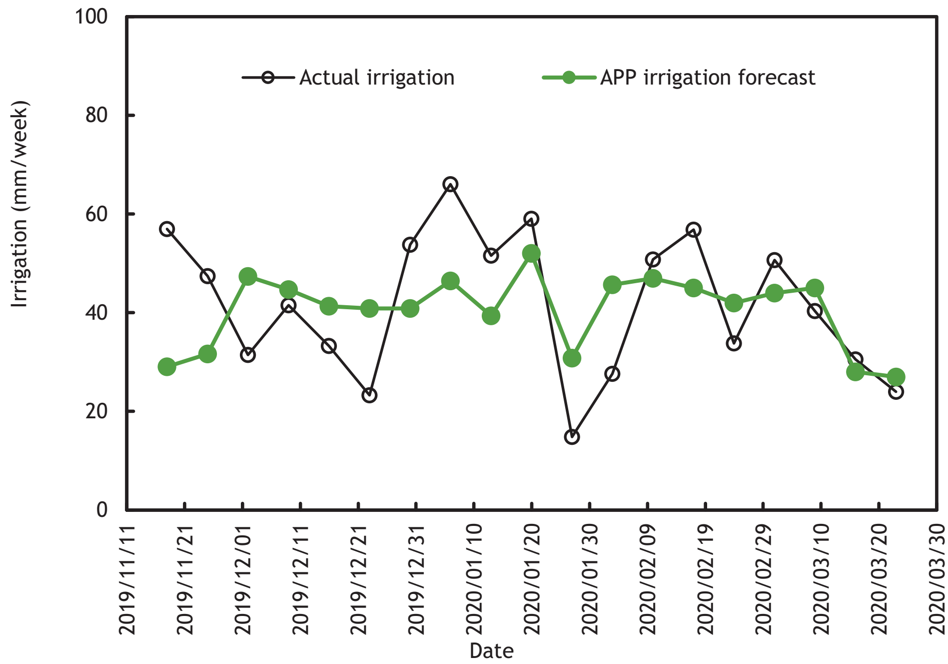

Figure 5.8: Comparison of the actual applied with the forecast weekly irrigation by the APP.

So weekly forecasts of ET were obtained using other online tools. Irrigation scheduling was done using a combination of the ET forecasts and neutron probe data and Figure 5.8 shows a comparison of the irrigation requirement forecast with the APP against the actual applied irrigation measured using online flow meters. The irrigation forecast in Figure 5.8 was estimated from the forecast weekly total ET similar to the approach adopted by the farm. While we did not expect an exact match between the forecast and the applied irrigation, it is clear from Figure 5.8 that these were of the same order of magnitude. For example, the total irrigation applied for the period 17 November 2019 to 25 March 2020 was about 794 mm. Total estimated irrigation from the APP for the same period was about 768 mm, which was less than 10% of the applied irrigation.

The weekly crop coefficients derived by the APP for the Rosy Glow orchard in the Koue Bokkeveld are summarized in Table 5.1. For the period November to January, these are clearly different from those used by the farm which used 0.6 for this period. We are uncertain to what extent this contributed to the large discrepancy between the applied irrigation and that forecast by the farm using online tools. The farm and APP's crop coefficients were within 10% of each in February 2020 when the farm raised their crop factors to about 0.90. Perhaps the crop coefficient should be increased much early in the season, but again further validation work will help to clarify this.

Table 5.1: **Weekly crop coefficients for a mature Rosy Glow orchard in the Koue Bokkeveld determined by the orchard APP.**

Date	K_c	K_{cb}
17-Nov-19	0.92	0.52
24-Nov-19	0.97	0.56
01-Dec-19	1.06	0.67
08-Dec-19	1.04	0.61
15-Dec-19	1.03	0.62
22-Dec-19	1.02	0.57
29-Dec-19	1.03	0.60
05-Jan-20	1.07	0.67
12-Jan-20	1.03	0.66
19-Jan-20	1.05	0.65
26-Jan-20	0.93	0.56
02-Feb-20	1.08	0.71
09-Feb-20	1.06	0.77
16-Feb-20	1.12	0.65
23-Feb-20	1.05	0.62
01-Mar-20	1.02	0.65
08-Mar-20	1.10	0.66
15-Mar-20	1.00	0.58
22-Mar-20	1.00	0.70
29-Mar-20	0.96	0.62
05-Apr-20	1.10	0.65
12-Apr-20	1.15	0.68
19-Apr-20	0.93	0.68
26-Apr-20	0.83	0.60

5.5.2 Villiersdorp orchard

5.5.2.1 Reference evapotranspiration for Villiersdorp

As in the Koue Bokkeveld, the forecast ET_o for the period November 2019 to March 2020 closely matched the measured values in Villiersdorp as shown in Figure 5.9. At Villiersdorp, all weather variables (including wind speed) were measured. Again the APP showed a tendency to slightly over estimate the ET_o suggesting that this is likely an artefact of the DarkSky weather forecasts. Fitting a linear relationship between the predicted and the measured daily ET_o yielded a slope of 0.79, an offset of +1.69 and R^2 of 0.59. The root mean square error was slightly larger at about ±1.21 mm d^{-1}.

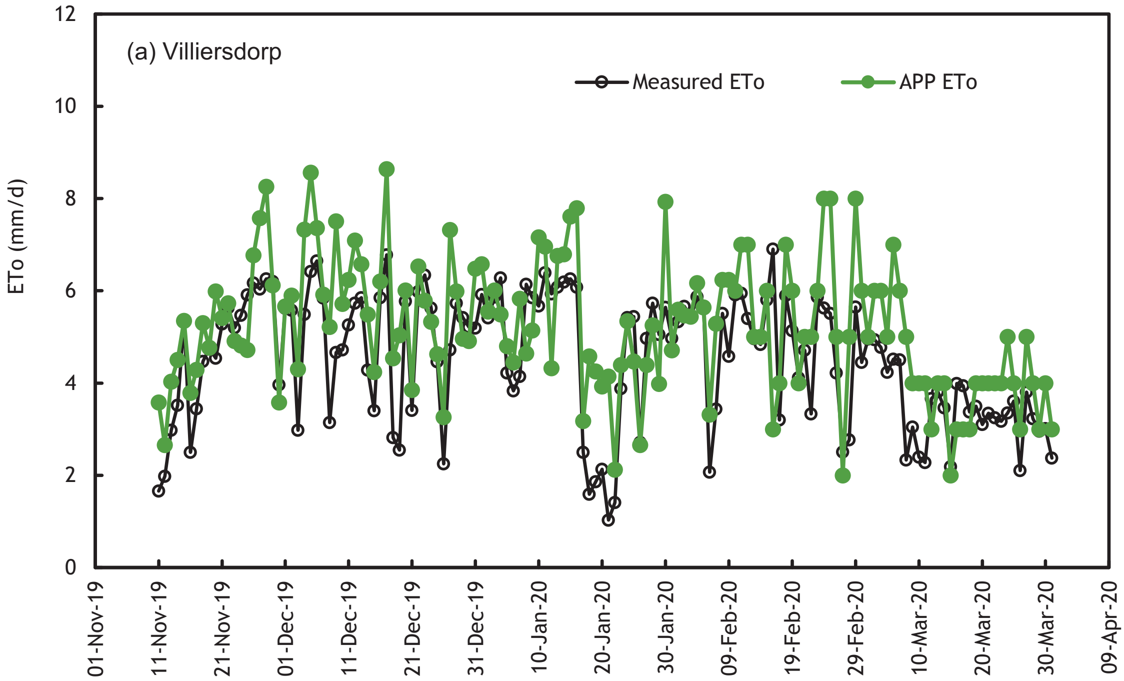

Figure 5.9: Comparison of the measured and APP predicted reference evapotranspiration in Villiersdorp.

5.5.2.2 Water requirements of a Royal Gala apple orchard in Villiersdorp

Forecasting of the transpiration dynamics by the APP for the Royal Gala orchard under drip and V-trellis training system at Villiersdorp is shown in Figure 5.10. The input orchard parameters used included a fractional vegetation cover (f_c) of 0.50, and average tree height of about 4.0 m.

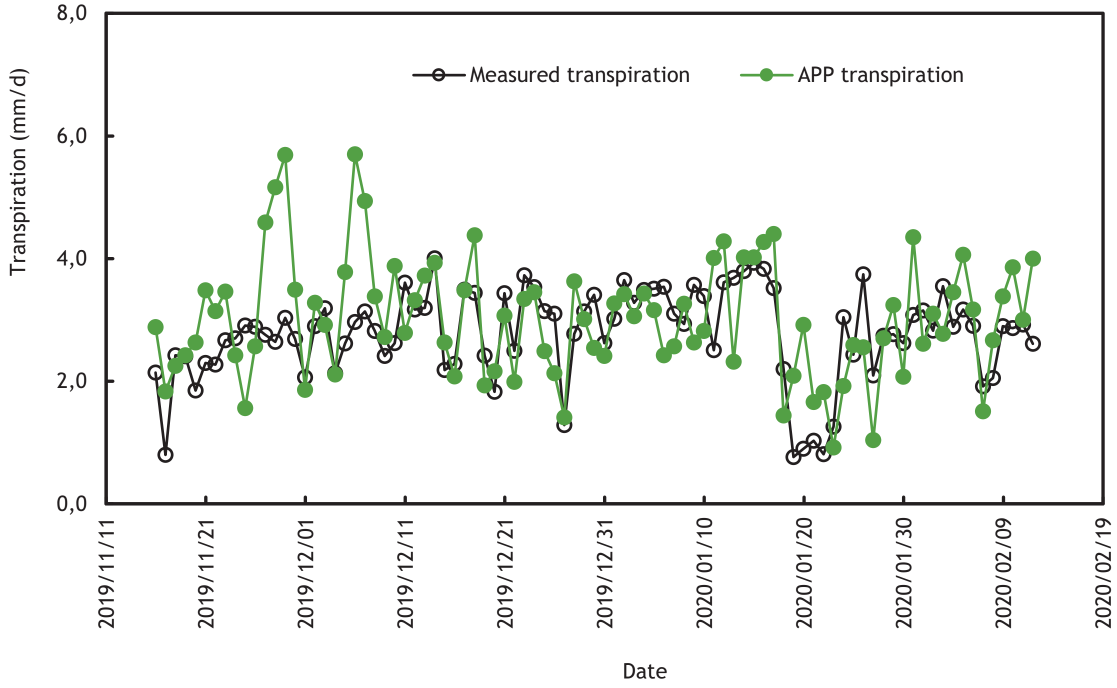

Figure 5.10: Forecasting the Royal Gala orchard transpiration under drip irrigation and a V-trellis training system at Villiersdorp.

There were significant errors in the transpiration forecasts between November and December 2019 related to the spikes in the ET_o forecasts (Figure 5.9) which we cannot explain. If we remove the outliers, the slope of the predicted versus measured transpiration was around 0.71, offset of +0.88 and a low R^2 of 0.34. The root mean square error was ±0.68 mm d^{-1}. Comparison of the ET forecasts with the actual measurements are shown in Figure 5.11 while the irrigation forecast is shown in Figure 5.12. As with the Koue Bokkeveld orchard, we removed data for periods when there was irrigation or rainfall as we could not accurately account for drainage. However, the APP's predictions were of the same order of magnitude as the measured variables.

Total applied irrigation between November 2019 and February 2020 was 368 mm while the APP forecast 385 mm.

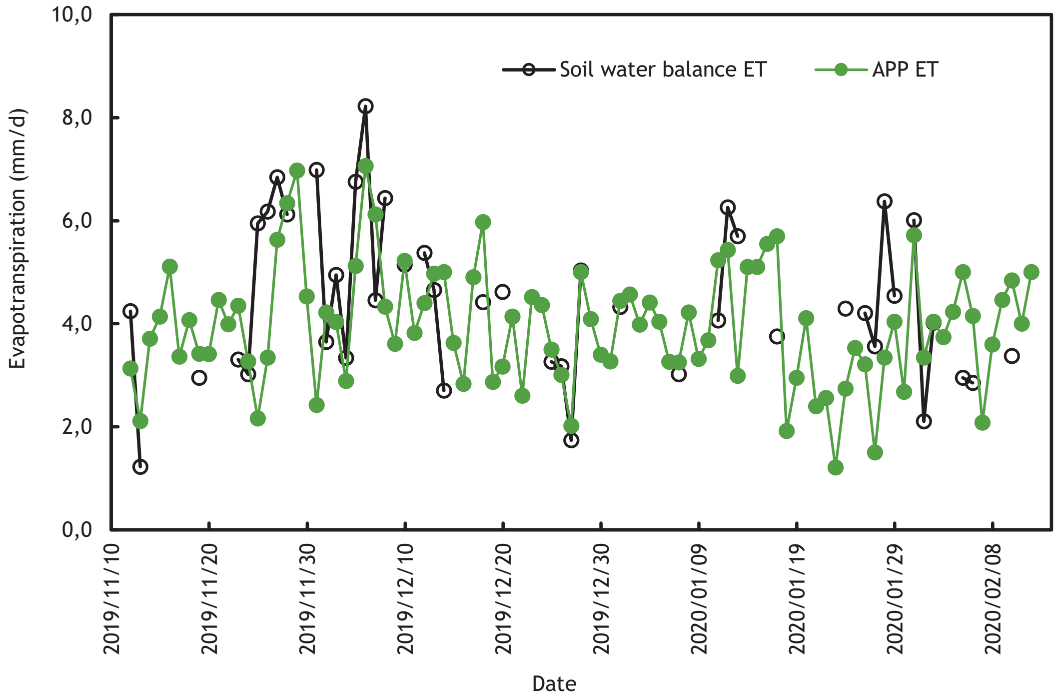

Figure 5.11: Forecasting the actual evapotranspiration of the Royal Gala orchard in Villiersdorp using the smartphone APP.

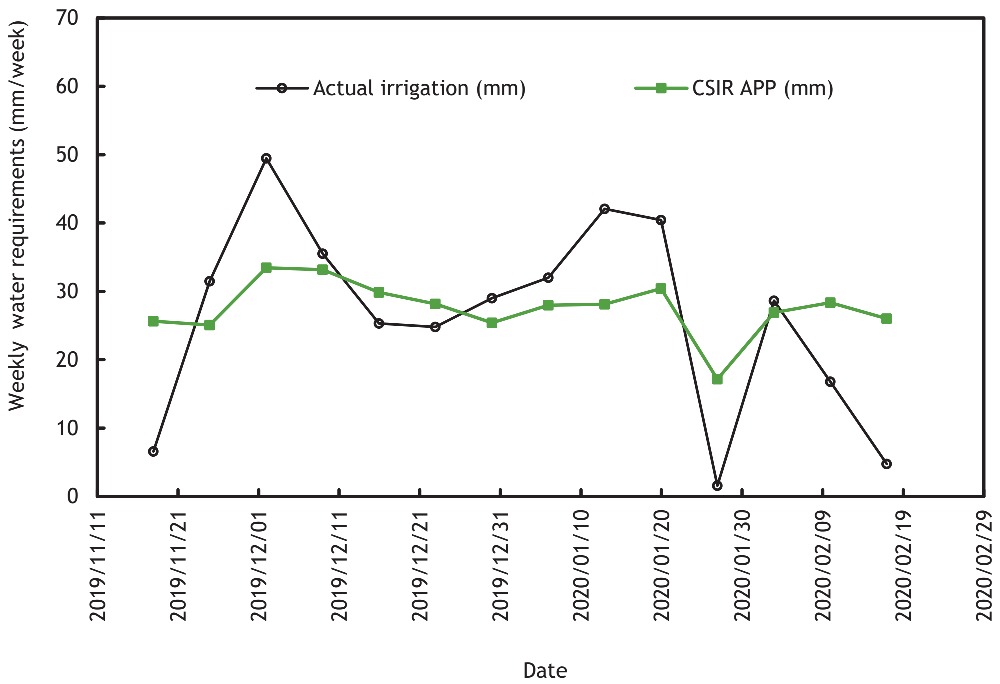

Figure 5.12: Comparison of the actual applied with the forecast weekly irrigation for the drip irrigated Royal Gala orchard by the APP in Villiersdorp.

A summary of the weekly crop coefficients for the Royal Gala orchard under drip derived using the application are shown in Table 5.2.

Table 5.2: **Weekly crop factors for the drip irrigated Royal Gala orchard on a V-trellis training system in Villiersdorp**

Date	K_c	K_{cb}
17-Nov-19	0.90	0.52
24-Nov-19	0.70	0.53
01-Dec-19	0.77	0.61
08-Dec-19	0.73	0.56
15-Dec-19	0.69	0.52
22-Dec-19	0.69	0.49
29-Dec-19	0.68	0.50
05-Jan-20	0.70	0.53
12-Jan-20	0.73	0.57
19-Jan-20	0.70	0.53
26-Jan-20	0.62	0.45
02-Feb-20	0.72	0.56
09-Feb-20	0.73	0.57
16-Feb-20	0.66	0.53
23-Feb-20	0.64	0.49
01-Mar-20	0.67	0.51
08-Mar-20	0.75	0.60
15-Mar-20	0.52	0.48
22-Mar-20	0.64	0.57
29-Mar-20	0.65	0.45
05-Apr-20	0.69	0.51
12-Apr-20	0.80	0.60
19-Apr-20	0.81	0.48
26-Apr-20	0.61	0.48
03-May-20	0.71	0.56

The average crop coefficient for this drip irrigated orchard was predicted to be between 0.70 and 0.75 for the peak irrigation season. Again independent verification of these predictions are recommended.

5.5.3 Grabouw orchard

5.5.3.1 Reference evapotranspiration forecasts for the Grabouw orchards

The forecast ET_o trend in Grabouw was consistent with that at the other two sites (see Figure 5.13). The APP systematically over-estimated the reference evapotranspiration albeit by some margin. The slope of the predicted versus measured ET_o was about 0.70 with an offset of +2.21 mm d^{-1}. The root mean square error was about ±1.7 mm/d which was higher than at the other two sites.

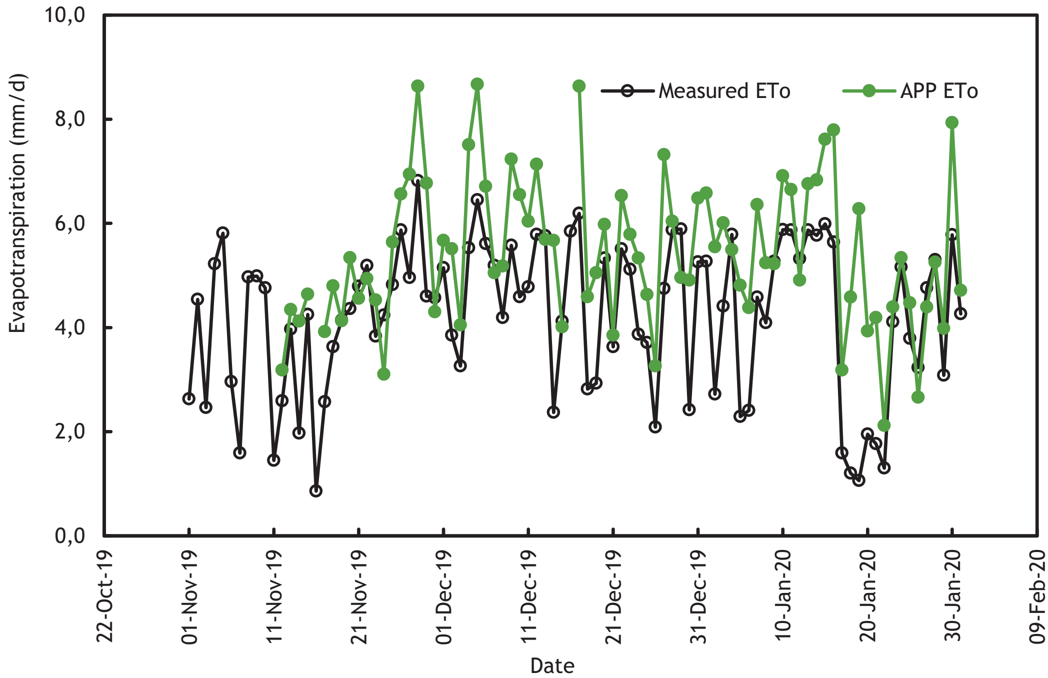

Figure 5.13: Comparison of the measured and APP predicted reference evapotranspiration in Grabouw.

5.5.3.2 Forecasting the water requirements of a mature Golden Delicious orchard in Grabouw

The trend of the forecast transpiration with respect to the measured values was the opposite of that displayed by ET_o (Figure 5.14). The predicted transpiration was consistently lower than the actual measurements, and we suspect that this we underestimated the fractional vegetation cover of the orchard which was taken as 0.65. Another feature of this orchard is the large canopy volume compared to the other orchards, so careful estimation of the fraction cover, e.g. based on the leaf area index is warranted.

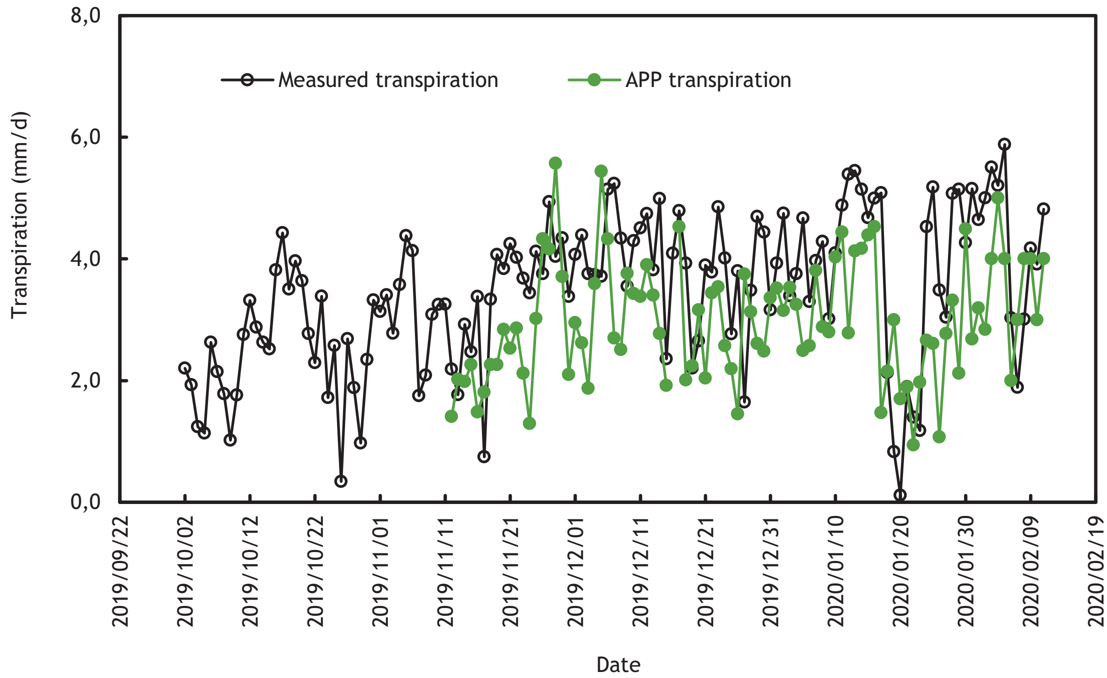

Figure 5.14: Forecasting the transpiration dynamics of a mature Golden Delicious orchard under micro-sprinkler irrigation at Grabouw.

On average the APP underestimated the daily transpiration by about 0.85 mm between 12 November 2019 and 11 February 2020. The measured total transpiration during this period was about 351 mm while the APP predicted 271 mm, representing a 23% difference. Similarly, the forecast irrigation (455 mm) was lower than the applied irrigation (517 mm) as shown in Figure 5.15.

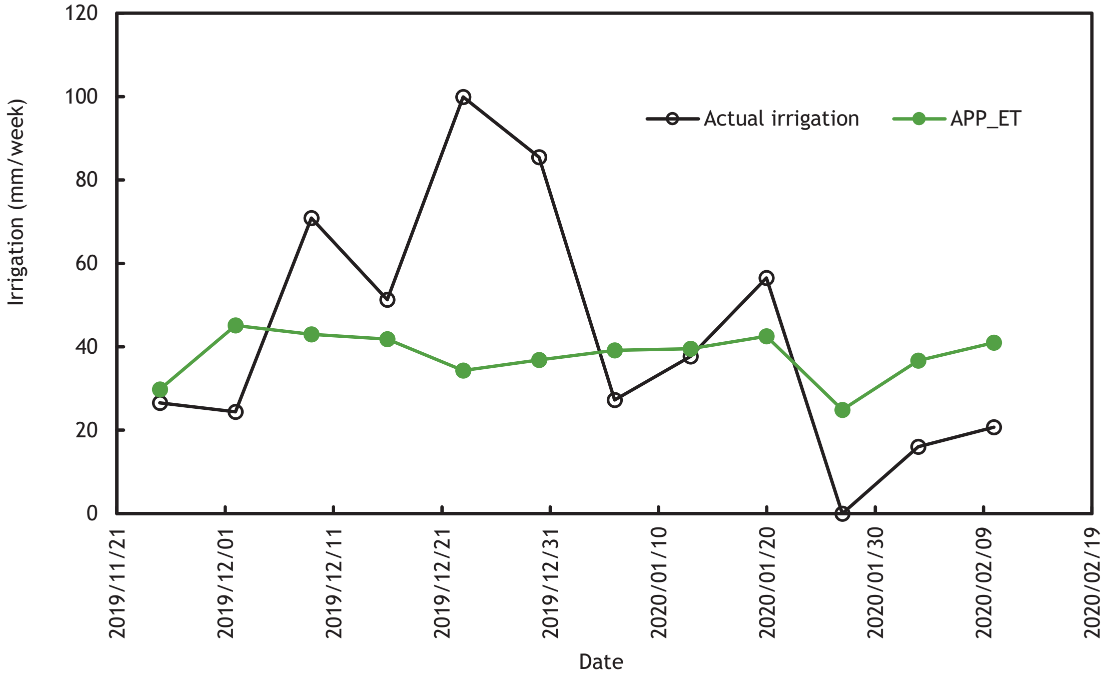

Figure 5.15: Comparison of the actual applied with the forecast weekly irrigation for the mature Golden Delicious orchard in Grabouw.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 VALUE ADDITION IN COMPARISON TO SIMILAR ONLINE PRODUCTS

In this study we have conceptualised, developed, and tested a pilot version of a smartphone application for forecasting the water requirements of apple orchards a few days in advance. There is a clear need for such a tool to improve water allocation planning and irrigation scheduling. While the fruit industry already has similar online tools, the APP developed here adds value to the existing tools. Unique features that differentiate this APP from the existing online products are its ability to forecast, not only the reference evapotranspiration (ET_o), but also the crop coefficients (K_c and K_{cb}) derived using a scientifically validated algorithm whose details are published in an internationally peer reviewed journal (Mobe *et al.*, 2020b). In this way, the expected actual orchard transpiration and evapotranspiration components can be forecast. Existing online products in the country do not provide both these components which are critical for identifying opportunities to save water, e.g. by reducing non-beneficial orchard floor evaporation.

The algorithm used to derive the crop coefficients takes into account both the amount of transpiring vegetation through a density coefficient and a stomatal sensitivity function. In this way, the amount of irrigation applied will be different between orchards of different age groups (and hence different canopy cover). This distinction is important as there is currently limited information on how the crop coefficients vary with canopy cover (Dzikiti *et al.*, 2018a,b). Because of the stomatal function, different crop species will have different crop factors even if they may have the same fractional vegetation cover. Another important aspect to note is that in the APP, the reference evapotranspiration (ET_o) and crop coefficient modules are independent. So inaccuracies in one variable do not affect the other variable, although the water use forecasts will be affected. The implication of this is that, if for example, a better online tool is available to forecast ET_o, this APP will still be useful in providing realistic crop coefficients which most growers struggle to access. Lastly the method used to develop the APP relies on readily available information which users can easily access. Only the fractional vegetation cover may be complicated, this is a variable that most farmers are used to.

6.2 PERFORMANCE ASSESSMENT AND RECOMMENDATIONS.

The performance of this application against actual field measurements can be described as mixed. It is encouraging to note that, overall, the trend in ET_o forecasts matched the observed values at the three sites where the APP was evaluated. However, there appears to be a tendency for the APP to slightly over-estimate the ET_o and the reason for this is unclear. It could be related to the quality of the online weather forecasts from the DarkSky, but there could also be other causes. In two of the three orchards (Koue Bokkeveld and Villiersdorp), the forecast seasonal total irrigation was within 10% of the actual applied irrigation. However, proper interpretation of these data against the seasonal measured ET was not possible due to issues with our soil water balance based ET estimation approach.

Development of version 1 of the APP has been completed. Even if several aspects of the APP still need to be improved, this version will be posted online on Apple Play Store and Google Play Store before October 2020.

In view of the above, the following recommendations can be made:

1) By design, this study is a pilot study. So the APP developed here should be viewed as such and we recommend further evaluations by interested users;
2) There is need to establish why the APP tends to over-estimate ET_o in some cases. If for instance, this is a result of the quality of the Darksky data, then the APP should be configured to source this data from several rather than from a single online source;

3) More accurate guidelines should be given for estimating the fractional vegetation cover as this can introduce significant uncertainties in the water use estimates.

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DATA STORAGE

Data from this project is stored on the I drive at the CSIR in Stellenbosch.

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1) At least two meetings were held with irrigation managers, two in the Koue Bokkeveld, the third in Villiersdorp and the fourth in Grabouw. Two of the farms subsequently actively participated in the evaluation of the application. Further engagements were interrupted by the covd-19 pandemic.
2) Two publications were produced as follows:
    a. Mobe NT., S. Dzikiti., T Zirebwa., SJE Midgley., W von Loeper., D Mazvimavi., Z Ntshidi., NZ Jovanovic. 2020. Estimating crop coefficients for apple orchards with varying canopy cover using measured data from twelve orchards in the Western Cape Province, South Africa. **Agricultural Water Management Journal. 233, 106103.**
    b. Dzikiti S., Lumsden T, Ntshidi Z, Mobe NT, Gush MB. 2020. A new application can predict apple orchard water requirements up to a week in advance. Water Wheel. July/August edition.