WATER USE OF HIGH-PERFORMING FULL-BEARING JAPANESE PLUM (PRUNUS SALICINA) IN TWO MAJOR PRODUCTION REGIONS OF THE WESTERN CAPE (SOUTH AFRICA)

FINAL REPORT

by

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This is the final report of WRC project No. C2019.2020-00093 on 'Water use of high-performing full-bearing Japanese Plum (*Prunus salicina* (Lindl.) in two major production regions of the Western Cape (South Africa)'.

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EXECUTIVE SUMMARY

BACKGROUND

Previous studies funded by the Water Research Commission (WRC) and various growers' associations have established the water requirements of fruit trees such as apples, citrus, macadamia nuts and avocados. The water use of plum orchards is not known, and research is needed to close this important information gap in order to improve water productivity and to maintain South Africa's global competitiveness with respect to the production and export of plums. Specifically, information is required on the most productive high-performing plum orchards in order to establish the maximum water requirements.

As with other commercial fruit types in South Africa, plum production is reliant on irrigation. The recent drought in the Western Cape has focused the sector on the need for water security and increased resilience to water shortages, and increased orchard water demand as projected under changing climatic conditions. One year of serious drought impacts on the trees can damage the entire future production potential of a long-term investment. Water availability is the most important risk to sustainable fruit production in South Africa given the increased frequency of droughts in regions such as the Western Cape, the rapid expansion of urban areas, and the growing competition for the limited water resources between irrigated agriculture, commercial and industrial use. Information on plum water requirements is therefore critical for planning orchards, water licensing and allocations, irrigation scheduling and catchment water management. This also ensures that fruit growers adhere to best practices in water management.

This project addressed the knowledge gap on water use of high-performing plum orchards in major production regions of South Africa, how it varies with growth stages and the impacts on fruit yield and quality.

RATIONALE

In South Africa, the Japanese plum (*Prunus salicina* Lindl.) fruit industry is well-established and primarily aimed at supplying plums to the export market. Plums in South Africa are cultivated on 5,319 ha and the plum industry employs 5,904 labourers and 23,616 dependents (HortGro, 2019). The Western Cape is the dominant Province with the main producing areas being the Klein Karoo (1602 ha), Wolseley/Tulbagh (664 ha), Franschoek (531 ha), Wellington (474 ha) and Paarl (400 ha), representing more than half of the production area in South Africa.

The total production of plums has been generally increasing in the last 10 years with a peak of 86,715 t achieved in 2016/17. The total value of production has also been generally increasing with a peak of R 1.4 billion achieved in 2018/19. Exports of plums show a steady trend in the last 10 years, with an average annual price of nearly R19,000 t^{-1} in 2018/19. The most exported cultivars in 2018/19 were African Delight, Angeleno/Sumplumsix and Fortune (HortGro, 2019).

Intensive cultivation of orchards is associated with increased water requirements, in particular in view of projected climatic changes in the main production areas. Therefore, the availability of adequate water is critical for sustainable production. However, little information is available on plum water use and crop water requirements. The project proposed to contribute novel scientific knowledge to fill this gap in the water and science sectors. Comparing the actual volumes of water consumed by plum orchards with the irrigation volumes applied would provide an indication on whether plum farmers are over- or under-irrigating, in support of improved irrigation planning and scheduling.

OBJECTIVES AND AIMS

The overarching objective of the project was to establish the water use of high-performing Japanese plums (*Prunus salicina* Lindl.) in the major plum production regions of South Africa with four aims as listed below.

AIM 1

To determine the water use of high performing full-bearing Japanese plum orchards under micro- and drip-irrigation.

AIM 2

To relate the water use of high performing full-bearing Japanese plum orchards to physical and economical water productivity.

AIM 3

To determine crop coefficients (Kc) and basal crop coefficients (Kcb) of Japanese plums to serve in the calculation of crop water requirements and water allocations.

AIM 4

To develop models of orchard water use in order to extrapolate the research results to other production regions.

METHODOLOGY

The approach used in this research was to quantify consumptive water use of high-performing, full-bearing Japanese plums in the major plum production regions of the Western Cape:

Robertson and Wellington. Based on the growers' interests and market demand, the focus was on two high-yielding cultivars, namely the early-maturing Fortune (30-35 t ha^{-1}) and late-maturing African Delight (40-45 t ha^{-1}). These accounted for about 7.5 and 6.8%, respectively, of the area planted to plums in 2019. Two sites were selected for the research with two suitable African Delight and Fortune orchards each, namely Sandrivier Estate near Wellington practising micro-jet irrigation and Smuts Brothers near Robertson under drip irrigation. The Fortune orchard in Wellington was uprooted after season 2021/22 due to declining yields, and it was replaced in the experiment by a Ruby Sun orchard under micro-jet irrigation. Intensive experiments and data collection programmes were conducted at these farms from season 2021/22 to season 2023/24. The experiments were designed to monitor all components of the soil-plant-atmosphere continuum: the weather conditions, plant water status and soil.

The following data were collected during the course of the experiments:

- Weather data with automatic weather stations of the Agricultural Research Council.
- Volumetric soil water contents at different depths in the soil profile (10, 20, 30, 40, 60 and 80 cm), in-row and between rows, with AquaCheck probes on a half-hourly basis.
- Gravimetric soil water content sampling for site-specific calibration of AquaCheck probes.
- In-house made micro-lysimeters for measurement of soil evaporation across the tree rows at specific days during the stage of full canopy development in the orchards.
- Leaf Area Index (LAI) and canopy cover (fc) with the LAI-2200C plant canopy analyser on a monthly basis for the purpose of calculating basal crop coefficients Kcb with the method of Allen and Pereira (2009).
- Logged data of stem water potential with Saturas sensors to ascertain that the orchards were properly irrigated and no water stress occurred during the growth season (February to July 2023).
- Irrigation volumes and crop yields were obtained from the farm managers on a regular basis.
- An eddy covariance flux tower was installed in the drip-irrigated African Delight orchard at Klipboschlaagte farm in Robertson. This site was selected as it was the largest study orchard (>4 ha), it is surrounded by other irrigated orchards of similar age and canopy structure, and this mitigated the assumptions around the required fetch distance from the border of the orchard. Half-hourly surface energy balance data were collected from May 2023 to August 2024.

Data collected in the field were used to populate the HYDRUS 2D model to determine the soil water balance of each orchard. The HYDRUS 2D/3D model (Simunek et al., 2020) is a well-known software package that can be used to simulate water, heat and solute transport in two-and three-dimensional (2D and 3D) saturated and unsaturated porous media. In this specific research, HYDRUS 2D was used for the following reasons: i) it is suitable to describe a two-dimensional water balance system with micro-irrigation, where a portion of the land is wetted (along tree rows) and another portion is non-wetted (between tree rows); ii) it uses Richards' equation (Richards, 1931) to calculate soil water redistribution that gives a more physically-based representation of the system; and iii) it calculates accurately the volume of water that passes the root system and ends up recharging groundwater due to over-irrigation. The model was run on a daily time step to calculate soil water contents, evapotranspiration (soil evaporation + root water uptake) and drainage (deep percolation) for each orchard and season. The model was validated using soil water content measurements with AquaCheck probes, soil evaporation measurements with micro-lysimeters and evapotranspiration flux measured using the eddy covariance system.

In order to determine plum water requirements for all study orchards, evapotranspiration data were derived from two remote sensing models, namely Surface Energy Balance System (SEBS) and FruitLook (https://fruitlook.co.za/ accessed on 5 June 2024, underpinned by SEBAL and ETLook). Data were validated against eddy covariance evapotranspiration fluxes.

Remote sensing data (FruitLook) were also used to compare evapotranspiration from 135 plum orchards (11 farms) across the Western Cape under micro-jets and drip irrigation. The orchards were selected from the CapeFarmMapper platform (www.gis.elsenburg.com accessed on 01 June 2022) of the Western Cape Department of Agriculture, and ground-truthed. The main purpose was to investigate the water use of plums under micro-jets and dripper in order to determine which irrigation method is more water use efficient.

Crop coefficients (Kc) of plums were calculated as the ratio of evapotranspiration measured with eddy covariance and reference evapotranspiration (ETo) from the weather station, whilst basal crop coefficients (Kcb) were determined from LAI and fc measurements with the Allen and Pereira (2009) method. Crop coefficients are key parameters in determining crop water requirements and irrigation planning according to the FAO56 approach.

Biophysical water productivity was calculated as the ratio of crop yield and evapotranspiration and economic water productivity was determined as the ratio of gross income and evapotranspiration. These two indicators are key in terms of recommending agricultural practices under water scarcity conditions.

RESULTS AND DISCUSSION

During the course of the project, season 2021/22 was drier and wetter than season 2022/23. Reference evapotranspiration ranged 1129-1196 mm a^{-1} in Wellington and 1188-1214 mm a^{-1} in Robertson. In 2021/22, rainfall was 462 mm a^{-1} in Wellington and 184 mm a^{-1} in Robertson.

Season 2022/23 was particularly wet causing floods in the Western Cape, with 665 mm a^{-1} in Wellington and 518 mm a^{-1} in Robertson.

Plum evapotranspiration in 2023/24 (from 1 September 2023 to 31 August 2024) in the African Delight orchard in Robertson was measured to be 1026 mm with eddy covariance, 1076 mm modelled with HYDRUS 2D, and 1023 mm with FruitLook. These figures gave confidence that both HYDRUS 2D and FruitLook gave reliable estimates of seasonal evapotranspiration compared to the reference method (eddy covariance).

Plum water requirements calculated with HYDRUS 2D for the full year were 958-1170 mm for African Delight in Wellington, 1094-1149 mm for Ruby Sun in Wellington, 1076-1267 mm for African Delight in Robertson and 1190-1285 mm for Fortune in Robertson. As a result of annual rainfall, more irrigation was applied in season 2021/22 compared to 2022/23, and irrigation volumes were higher in Robertson than in Wellington. The highest annual irrigation was delivered to the African Delight orchard in season 2021/22 (1152 mm a^{-1}). Drainage volumes calculated with HYDRUS 2D depended on rainfall distribution and irrigation management. The highest drainage (bottom boundary flux) was in the African Delight orchard in Robertson (73-148 mm a^{-1}). This orchard appeared to be slightly over-irrigated, however it excelled in terms of crop yields. Plum water requirements estimated with FruitLook were generally lower than those calculated with HYDRUS 2D, ranging from 837 mm a^{-1} (Robertson, Fortune in 2021/22) to 1144 mm (Wellington, Ruby Sun in 2022/23). Some weekly records in FruitLook were occasionally missing. Evapotranspiration estimated with FruitLook for 134 micro-sprinkler and drip-irrigated orchards across the Western Cape were in the range of those recorded at the experimental orchards, spanning from 810 to 1077 mm a^{-1}.

The average LAI in the initial stage varied between 0.55 (African Delight in Wellington) and 1.22 (Ruby Sun in Wellington). The average LAI in the mid-stage ranged between 2.35 (Fortune in Robertson) and 3.37 (Ruby Sun in Wellington). The canopy cover in the initial stage varied between 0.34 and 0.59 (Ruby Sun in Wellington), whilst in the mid-stage it was between 0.82 (Fortune in Robertson) and 0.91 (Ruby Sun in Wellington). LAI and fc did not vary much during the growing season as the vegetation growth was controlled by pruning.

The crop coefficient Kc, calculated for the African Delight orchard in Robertson as the ratio of evapotranspiration measured with eddy covariance and ETo, ranged between 0.49 (July and August) and 1.20 (January). Basal crop coefficients in the initial stage ranged between 0.84 (African Delight in Wellington) and 0.98 (African Delight in Robertson). In the mid-stage, average Kcb varied between 1.14 (Fortune in Robertson) and 1.20 (Ruby Sun in Wellington).

By far, the highest yields were obtained in the African Delight orchard in Robertson (51.0-52.0 t ha^{-1}), followed by Fortune in Robertson (39.8-42.0 t ha^{-1}). An exception was the final season of the experiment, when a poor fruit set occurred. Crop yields were higher in Robertson than in Wellington, where African Delight produced 32.0-36.0 t ha^{-1} and Fortune 37.9 t ha^{-1} (season 2021/22). Ruby Sun produced the lowest yields of 28.4-33.0 t ha^{-1}.

Crop water productivities for the full year were the highest for African Delight in Robertson (4.03-4.51 kg m^{-3}) because the crop yields were by far the highest of all orchards. This was followed by African Delight in Wellington (2.97-3.34 kg m^{-3}). African Delight (4.03-4.51 kg m^{-3}) used water more efficiently than Fortune (3.10-3.31 kg m^{-3}) in Robertson, possibly because of large irrigation volumes applied with three irrigation drip lines in the latter orchard. Ruby Sun had a comparable CWP (2.87-3.59 kg m^{-3}) to African Delight in Wellington (2.97-3.34 kg m^{-3}) because less irrigation volumes were applied, however the yields were lower. Economic water productivity depended greatly on crop yield, fruit quality, cultivar, season and market prices. Early-maturing cultivars (Fortune and Ruby Sun) in Wellington were economically comparable to the late-maturing African Delight. Economic water productivity at Robertson (estimated based on historic averages) appeared to be less compared to Wellington.

The comparison between plum orchard water consumption under micro-jets and drip-irrigation with FruitLook over five seasons (135 orchards on 11 farms) indicated that micro-jets use on average 9% more water (968 mm a^{-1}) than drippers (879 mm a^{-1}). However, they experience less ET deficit as manifestation of water stress. Nevertheless, instances were recorded where drip-irrigation used more water than micro-jets on the same farm. This suggests that site-specific conditions largely impact the performance of drip and micro-sprinkler irrigation systems at orchard scale.

CONCLUSIONS

The project achieved the set objectives of quantifying crop coefficients, evapotranspiration of well-irrigated, healthy plum orchards (representing crop water requirements), crop water and economic productivities by using different methods. The figures measured/estimated in the current study were generally well within the range of those reported in the literature, which gives confidence that realistic and accurate values are provided that can be used in practice to allocate water to farms for irrigation of plums.

HYDRUS 2D generally simulated well the general trends of soil wetness, seasonal evapotranspiration and the full profile soil water content. However, it was less successful in capturing the details of soil water dynamics in individual layers, possibly due to variabilities in soil properties and the inconsistency between the daily time step and the timing of irrigations. The model can be used to estimate yearly evapotranspiration and water allocations across a range of climates and conditions, as long as it is parametrized correctly.

Plum water requirements were higher for African Delight and Fortune in Robertson compared to Wellington because of the different climatic areas (warmer summers and drier winters in Robertson). Plum farmers practice irrigation after harvesting to keep trees healthy and this substantially increases crop water requirements for the full year compared to the main irrigation season, so water allocations for the full season need to be planned.

Remote sensing estimates of ET were in good agreement with eddy covariance, with FruitLook ET showing a better correlation than SEBS. On average, eddy covariance ET was under-estimated by both remote sensing methods, especially during periods of low water use in winter.

An analysis of plum water consumption in micro-sprinklers and drip-irrigated orchards across the Western Cape was also conducted with the use of remote sensing information (FruitLook). It indicated that, on average, orchards under micro-jets use 9% more water than drip irrigation. However, exceptions were recorded on the same farm, so the choice of the irrigation method will depend on site-specific conditions.

RECOMMENDATIONS FOR FUTURE RESEARCH AND WAY FORWARD

In order to calculate water allocations for plum orchards, maximum yearly evapotranspiration estimated with HYDRUS 2D was reduced by the average annual rainfall in Wellington and Robertson. These values, representing irrigation water requirements, were recommended for annual plum water allocations (rounded off to the nearest hundred in $m^3 ha^{-1}$):

- Wellington
  - African Delight: 7,800 $m^3 ha^{-1}$ (780 mm)
  - Ruby Sun: 7,500 $m^3 ha^{-1}$ (750 mm)
- Robertson
  - African Delight: 10,000 $m^3 ha^{-1}$ (1000 mm)
  - Fortune: 10,200 $m^3 ha^{-1}$ (1020 mm)

These water allocations would have to be increased during years of below-average rainfall and because winter rainfall replenishes the soil profile, but not all of it is available during peak water demand.

Canopy size is an important driver of water use in plum orchards. The practice of pruning to control vegetative growth is beneficial to reduce water consumption while maintaining high crop yields.

The economic water productivity (EWP) may be considered a more influential factor in orchard irrigation management than biophysical water productivity. It is recommended that differential irrigation treatment experiments be conducted with deficit irrigation targeting the less water stress sensitive stages of plums (stage II - pit hardening and post-harvest). This irrigation strategy could reduce water use and possibly improve yield quality.

A parametrized HYDRUS 2D model proved to be useful to run simulations of the soil water balance for different orchards and under different conditions. It could be applied to other orchards in the area.

Despite promising results, the continual validation of remote sensing-based ET estimates is required to improve model accuracy and operational capabilities as more high-resolution (spatial and temporal) open-source satellite images become available.

FruitLook under-estimated evapotranspiration mainly in the winter season, when cover crops are actively growing and providing lavish biomass that transpires. It is possible that remote sensing methods do not detect/calculate properly the contribution of cover crops to transpiration and this could be addressed to improve FruitLook outputs. The LAI outputs with FruitLook should be validated with ground measurements.

Remote sensing could be used for the identification and monitoring of highly productive regions/cultivars and conversely the identification of regions with sub-optimal yield and water use efficiency.

The potential of using sensors for logging stem water potential as water stress indicator for irrigation scheduling should be investigated (measurements of osmotic potential or water potential with a pressure transducer).

Surface energy balance methods such as eddy covariance proved to be crucial as a reference method to quantify evapotranspiration, despite the high cost and complexity of the equipment. Long-term monitoring (at least one full year) can provide answers to research questions and it can be used to validate other modelling approaches that are more transferable.

Although remote sensing data showed that micro-jets use on average 9% more water than drip irrigation, further field research on water use and efficiency of micro-jets and drip irrigation should be pursued as results were not entirely conclusive.

There is an increasing trend of orchards grown under agricultural nets, both locally and internationally, to prevent adverse weather conditions, sunburn of fruits, pests and birds, to reduce water use (improved water use efficiency), increase yields and induce an earlier harvest. There is a need to develop new methodologies for crop growth and water use monitoring under agricultural nets.

Holistic studies for long-term planning on water use of plums should be conducted from young age to full-bearing trees.

The findings and recommendations of this research were built into the "Guidelines for Irrigation of Japanese Plum" that is appended as a separate document to this report, along with an Excel Kcb calculator to calculate Kcb of specific orchards based on LAI and canopy cover. A database of photos of orchards with different LAI and canopy cover is also provided.

NEW KNOWLEDGE CONTRIBUTION

The project contributed new knowledge on the seasonal crop water requirements of high density Japanese plum orchards (Fortune and African Delight) in two main production regions (Wellington and Robertson), their water balance, crop coefficients and water productivities. These data did not exist in South Africa, hence they informed plum water requirements, water allocations to plum farms and irrigation management in the main production regions. The main drivers of water consumption of plums were determined to be the length of the growing season, irrigation volumes and canopy cover (pruning). Water consumption patterns can be predicted using a soil water balance model based on measurements of LAI or canopy cover.

In addition, ground-truthing of evapotranspiration estimated with remote sensing methods (FruitLook and SEBS) was conducted by means of soil water balance modelling and an eddy covariance flux tower. The validation provided confidence in the accuracy of estimations of seasonal evapotranspiration by FruitLook. FruitLook was then applied to compare water consumption of Japanese plum orchards under drip- and micro-irrigation across the production regions (150 orchards). Micro-jets used 9% more water than drip-irrigation on average, although results were site-specific.

The research led to the compilation of guidelines for irrigation of Japanese plums and the development of a Kcb calculator to calculate basal crop coefficients (Kcb) for specific orchards based on LAI or canopy cover. The project and products were designed around the explicit needs of farmers, practitioners, the growers' association as well as the water authority for the purpose of scientifically-sound water allocations to plum farms.

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2D – Two-dimensional

3D – Three-dimensional

ABA – Abscisic acid

ARC - Agricultural Research Council

b_0 and b_1 - Coefficients of linear calibration

b1, b3, b4, b5 and b7 - Landsat 8 bands

CHIRPS - Climate Hazards Group InfraRed Precipitation with Station data

C_p - Specific heat of dry air

CS100 - Barometric pressure sensor

CS655 - Water content reflector

CSAT3B – Three-dimensional sonic anemometer

CV – Coefficient of variation

CWP - Crop (biophysical) water productivity

DEM – Digital elevation model

DMC - Disaster Monitoring Constellation

E, Es – Soil evaporation

EC – Eddy covariance system

EF - Evaporative fraction

ET – Actual evapotranspiration

$\overline{\mathrm{ET}_{\mathrm{EC}}}$ - Mean of evapotranspiration measurements from the eddy covariance tower

ETc – Crop evapotranspiration; Crop water requirements

ET_{EC} - ET measurements from the eddy covariance tower

$ET_{estimate}$ - Satellite-derived ET estimate (SEBS or FruitLook)

ETo – Reference evapotranspiration

EWP - Economic water productivity

F_a – Electromagnetic frequency reading in air

fc – Canopy interception of radiation; Canopy cover

f_{IPAR} – Fraction of intercepted photosynthetically active radiation

F_r - Downward adjustment ($F_r \leq 1.0$) if the plant species exhibits more stomatal control on transpiration than is typical of most annual agricultural crops

FRD - Frequency domain reflectometry

F_s – Electromagnetic frequency reading in the soil

f_{shad} – Ground-shaded fraction of radiation

F_w – Electromagnetic frequency reading in distilled water

FW05 - Thermocouple type

g - Acceleration due to gravity

G – Soil heat flux

GUI - Graphic user interface

h – Crop height

H – Sensible heat flux

H_a – Alternate hypothesis

hBot - Cumulative flux at the bottom boundary layer, representing deep percolation in the HYDRUS 2D model

HFP - Soil heat flux plate

H_o – Null hypothesis

hVar1 - Cumulative irrigations in the HYDRUS 2D model

HygroVUE10 - Temperature and humidity sensor

I – Canopy interception of water

k - von Karman's constant

Kc – Crop coefficient

$K_{c\ end}$ – Crop coefficient at end stage

$K_{c\ mid}$ – Crop coefficient at mid-stage

Kcb – Basal crop coefficient

$K_{cb\ cover}$ – Kcb of the ground cover in the absence of tree foliage

$K_{cb\ end}$ - Basal crop coefficient at end stage

$K_{cb\ full}$ - Estimated Kcb during peak plant growth for conditions having nearly full ground cover (or LAI = 3)

$K_{cb\ mid}$ - Basal crop coefficient at mid-stage

K_d – Canopy density coefficient

Ke – Soil evaporation coefficient

K_s - Saturated hydraulic conductivity

l - Empirical parameters affecting the shape of the hydraulic functions (pore-connectivity parameter)

L - Obukhov length

LAI – Leaf area index

LAS - Large aperture scintillometer

LE – Latent heat flux

LULC - Land use/land cover

LW – Long-wave infrared radiation

MAE - Mean absolute error

METRIC - Mapping Evapotranspiration at High Resolution with Internalized Calibration

MOST - Monin-Obukhov similarity theory

n - Empirical parameter affecting the shape of the hydraulic functions (pore-size distribution index); Number of measurements

NDVI – Normalized difference vegetation index

NDVImax – Maximum normalized difference vegetation index

NDVImin - Minimum normalized difference vegetation index

NIR - Near infrared band (Landsat 8 band 5)

NR01 - Four-component net radiation sensor

NSE - Nash-Sutcliffe model efficiency coefficient

OECD - Organisation for Economic Co-operation and Development

PAR – Photosynthetically active radiation

Pbias – Percentage bias

PRD – Partial root-zone drying

R - Red band (Landsat 8 band 4)

R^2 – Coefficient of determination

$r_{a,canopy}$ - Aerodynamic resistance for canopy

$r_{a,soil}$ - Aerodynamic resistance for soil

r_{canopy} - Resistance of canopy

RDI – Regulated deficit irrigation

RF – Radio frequency

RH – Relative humidity

RH_{min} – Minimum daily relative humidity

RH_{max} - Maximum relative humidity

r_l - Mean leaf resistance for a plant species

RMSE – Root mean square error

Rn – Net radiation

$R_{n,canopy}$ – Net radiation at canopy

$R_{n,soil}$ - Net radiation at soil

RS – Remote sensing

Rs - Solar irradiance

r_{soil} - Resistance of soil

SCP - Semi-Automated Classification Plugin

SEB - Surface energy balance

SEBAL - Surface Energy Balance Algorithm for Land

SEBALI - Surface Energy Balance for Land – Improved

SEBI - Surface Energy Balance Index

SEBS - Surface energy balance system

SFU - Scaled frequency unit

SPAC - Soil-plant-atmosphere continuum

SR - Surface renewal

S-SEBI - Simplified Surface Energy Balance Index

StDev - Standard deviation

SW - Short-wave radiation

T - Transpiration

T_{avg} - Daily average temperature

Tc – Crop transpiration

TCAV - Averaging soil thermometer

TDR - Time domain reflectometry

T_{max} - Maximum temperature

T_{min} - Minimum temperature

TSS - Total soluble solids

T_v - Virtual temperature near the surface

u_* - Friction velocity

u_2 – Wind speed at 2 m height (m s^{-1})

USGS - United States Geological Survey

UWC1, 2, 3 … – Number of AquaCheck soil water content probe

VIIRS - Visible Infrared Imaging Radiometer Suite

vRoot - Cumulative actual root water uptake in the HYDRUS 2D model

WRC - Water Research Commission

α - Empirical parameter affecting the shape of the hydraulic functions (inverse of the air-entry value or bubbling pressure)

γ – Psychrometric constant (kPa °C^{-1})

Δ – Slope of the saturation vapour pressure-air temperature curve (kPa °C^{-1})

Δ_e – Vapour pressure deficit

θ_r - Residual volumetric soil water content

θ_s - Volumetric soil water content at saturation

θ_v – Volumetric soil water content

ρ - Air density

1. INTRODUCTION

1.1 Background

South Africa is a major exporter of various types of fruit that include apples, peaches, nectarines, pears, plums, citrus etc. All these fruits are grown under irrigation and therefore the availability of adequate water is critical for the sustainability and growth of the fruit industry in the country. Previous studies funded by the Water Research Commission (WRC) and various growers' associations have established the water requirements of fruit trees such as apples, citrus, macadamia nuts and avocados. The water use of plum orchards is not known and research is needed to close this important information gap in order to improve water productivity and to maintain South Africa's global competitiveness with respect to the production and export of plums. Specifically, information is required for the most productive high-performing plum orchards in order to establish the maximum water requirements and to understand how water use relates to yield quality and quantity.

As with other commercial fruit types in South Africa, plum production is reliant on irrigation. Therefore, the availability of adequate water is critical for sustainable production (National Agricultural Marketing Council, 2013). Water availability is the most important risk to sustainable fruit production in South Africa given the increased frequency of droughts in regions such as the Western Cape, the rapid expansion of urban areas, and the growing competition for the limited water resources between irrigated agriculture, commercial and industrial use. It is therefore imperative that the fruit industry be provided with tools and information on maximum water use that would inform water licensing and allocations.

Securing water availability is also important for mitigating climate variability impacts in order to reduce the risks to sustained production and exports of plums. One of the key research focus areas of HortGro Science which oversees research for the deciduous fruit industry, is to increase water use efficiency and productivity in line with the vision of the Orchard of the Future (OoF). As part of this research programme, HortGro requires accurate quantitative information on the water use in relation to yield of early and late season high-performing plum cultivars in production areas with contrasting microclimates. This information is critical for planning orchards, water allocations, irrigation scheduling and catchment water management. This also ensures that fruit growers adhere to best practices in water management to drive other water productivity initiatives.

The recent drought in the Western Cape has focused the sector on the need for water security and increased resilience to water shortages, and increased orchard water demand as projected under changing climatic conditions. One year of serious drought impacts on the trees can damage the entire future production potential of a long-term investment. Water scarcity, increasing frequency of drought in the Western Cape and the rising competition for the limited water resources between different sectors of the economy makes it imperative to find sustainable development solutions. Addressing the paucity of data on plum water requirements will contribute to fair water allocations and sustainable development.

Sustainable development is critically dependent on sustainable management of natural resources (e.g. water) and the transition to a low-carbon economy through reduced use of coal-derived electricity. Technologies which increase water use efficiency and water productivity of intensively irrigated fruit orchards can deliver both. Additional water resources made available can then be used for development and sector growth, especially for small-holder and emerging farmers, and help to drive job creation in the sector.

Accurate quantitative information on plum orchard water use based on actual measurements is essential for irrigation scheduling, irrigation system design and for water allocation purposes. Information on the biophysical and economic water productivity of plum orchards is also essential for planning purposes. This project, therefore, addressed the knowledge gap on water use of high-performing plum orchards in major production regions of South Africa, how it varies with growth stages and the impacts on fruit yield and quality. The research questions to be answered were:

1) How do the diurnal and seasonal water use trends of plums vary with cultivar and with production region?
2) What are the main drivers of water use and productivity in plums?
3) What are the biophysical and economic water productivity of plums and how is this affected by cultivar, growing regions, and management (e.g. crop loads, canopy size, irrigation practices etc.)?
4) Can the water use patterns of plums be modelled using readily available information?

1.2 Project objectives

The overarching objective of the project was to establish the water use of high-performing Japanese plums (*Prunus salicina* Lindl.) in the major plum production regions of South Africa. The specific objectives of the project were:

1) To determine the water use of high performing full-bearing Japanese plum orchards under micro- and drip-irrigation.
2) To relate the water use of high performing full-bearing Japanese plum orchards to physical and economical water productivity.

3) To determine crop coefficients (Kc) and basal crop coefficients (Kcb) of Japanese plums to serve in the calculation of crop water requirements and water allocations.
4) To develop models of orchard water use in order to extrapolate the research results to other production regions.

1.3 Scope of the project

The main scope of the project was to quantify the maximum crop water requirements, crop coefficients and water productivities of Japanese plums, for the purpose of recommending water allocations to plum farms in the Western Cape (objectives 2) and 3)). For this reason, dedicated experiments were established in the two main production regions (Wellington and Robertson), on farms that are distinguished for high-performing yields (Sandrivier in Wellington and Smuts Bros in Robertson), and on full-bearing orchards with cultivars of particular interest to the Growers' Association, namely African Delight and Fortune (subsequently replaced by Ruby Sun in Wellington). The HYDRUS-2D finite-difference unsaturated zone model (Simunek et al., 2020) was used to calculate the soil water balance in the four experimental orchards (African Delight and Fortune/Ruby Sun in Wellington and Robertson). The results of the HYDRUS-2D are transferable to other orchards provided the model is parametrized for soil properties, orchard characteristics (tree density, tree pruning) and irrigation management (objective 4)). As dedicated experiments are not feasible in a large number of orchards, satellite resources were used to investigate consumptive water use of plums over a large area. After ascertaining the accuracy of remote sensing seasonal evapotranspiration estimated with FruitLook ((https://fruitlook.co.za/ accessed on 5 June 2024), a comparison of water use of plums under drip- and micro-jets irrigation was conducted with satellite-derived evapotranspiration for a total of 150 orchards (objective 1)).

2. LITERATURE REVIEW

2.1 Plum production

2.1.1 Deciduous fruit cultivation

The production of deciduous fruits is widespread in the world. The dominant species include pome fruits (apple *Malus domestica* Borkh.; pears *Pyrus communis* L.) and stone fruits (apricots *Prunus armeniaca* L.; peaches and nectarines *Prunus persica* L.; European plums *Prunus domestica* L. and Japanese plums *Prunus salicina* Lindl.; cherries *Prunus avium* L.). Stone fruit species are temperate zone deciduous, drupe fruit trees with relatively high water requirements. The deciduous fruit cultivation in South Africa is practiced on a total of 54,294 ha (Figure 2.1).

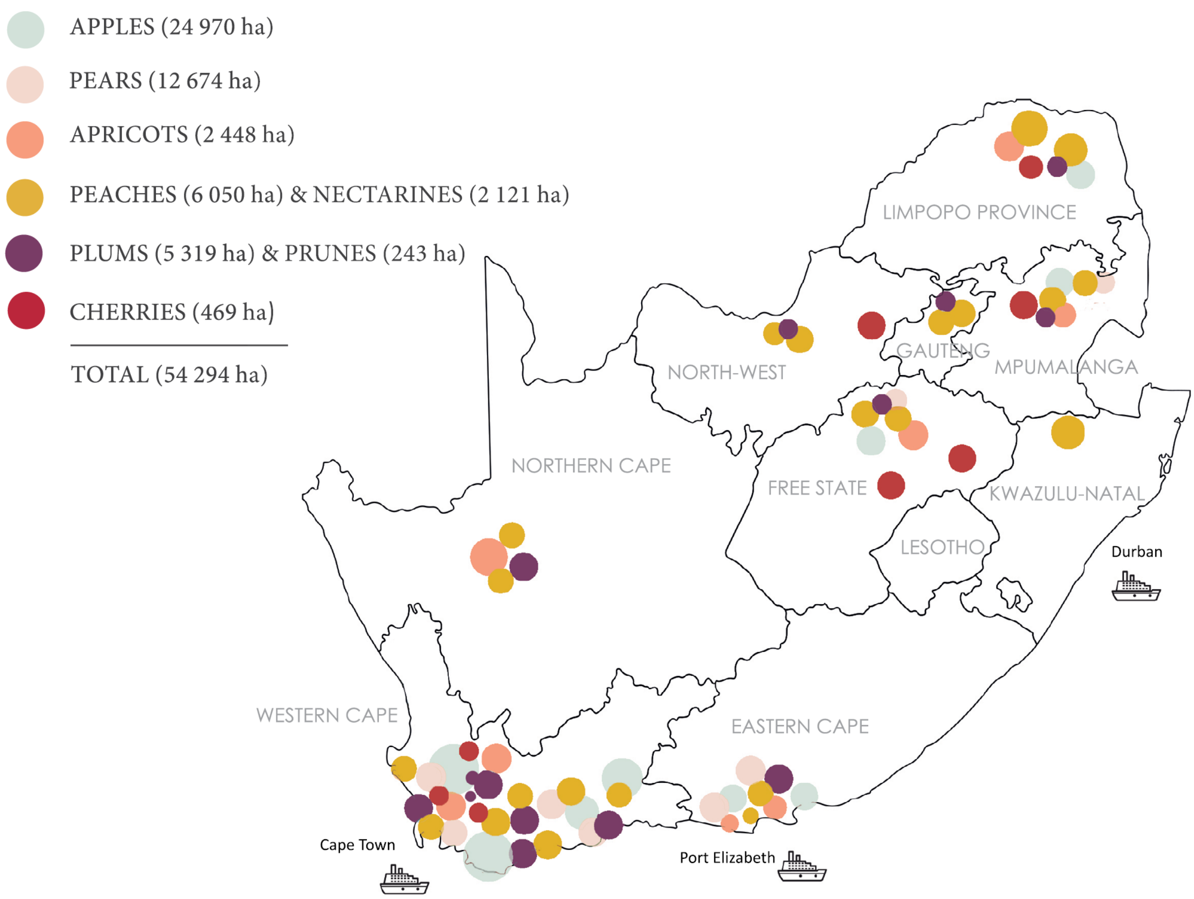


Figure 2.1 *Cultivation areas per deciduous fruit species in South Africa (HortGro, 2019).*

Figure 2.1 depicts the main production areas in the country. Apples and pears are produced throughout the year depending on the geographical region, whilst production seasons for stone fruits depend on the species: apricots from October to January, peaches from October to mid-April, nectarines from November to mid-April, plums from November to mid-May and cherries from October to January.

The pome and stone industry in South Africa includes 1152 producers; it creates 1.25 permanent jobs per ha (63,145 labourers and 252,579 dependents) with an average wage of R18.68 h^{-1} (R3,699 $month^{-1}$). It has a total turnover of R11,430M a^{-1} and it exports 45% of the products (HortGro, 2019).

2.1.2 Plum characteristics

Amongst the numerous species of plums, the hexaploid *Prunus domestica* (European plum originating in Europe around the Black Sea) and the diploid *Prunus salicina* (Japanese plum originating in the Far East) are known to be the most commercially feasible. Prunes are generally referred to dried plums, produced to a lesser extent than fresh plums. Whereas European plums are typically temperate species, Japanese plums grow in warmer regions, they require less chilling temperatures and flower early (Torrecillas et al., 2018).

The plum fruit is a fleshy one-seeded drupe produced on terminal or short shoots. Most commercial plum cultivars require pollinating varieties and thinning to obtain commercial fruit sizes due to the abundance of flowering.

Plum trees produce fruits suitable for fresh consumption, drying (prunes) and processing into different products. Japanese plums are mainly grown for fresh fruit, whilst European plums for dried fruit. Plum fruits contain high contents of bioactive compounds such as dietary fibre, sorbitol, antioxidants, vitamins and minerals. Thanks to the high sugar content (glucose, sorbitol, sucrose and fructose), plums are an excellent source of energy (Stacewicz-Sapuntzakis, 2013; Tomic et al., 2019).

The phenological stages are commonly divided into four stages, namely the first rapid fruit growth (stage I), pit hardening (stage II), the second rapid fruit growth (stage III), and post-harvest (stage IV) (Figure 2.2) (Torrecillas et al., 2018). Vegetative growth occurs mainly in the first two stages, when plant vigour can be manipulated to control fruit size and quality. A different response to water stress occurs at different phenological stages, which length depends on cultivars and degree days. Fruits grow exponentially during the cell division phase (stage I, 30 days or less), followed by a lag growth phase during pit hardening and embryo development (stage II). A second period of rapid cell enlargement occurs prior to harvest (stage III). After harvest, photosynthesis continues to produce shoot growth and store reserve carbohydrates until leaves are shed.

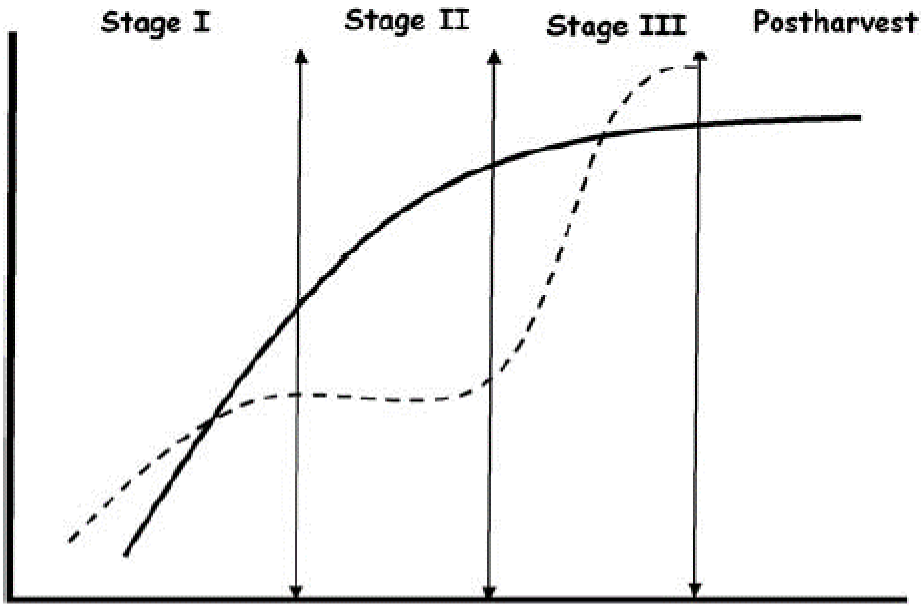


Figure 2.2 *Developmental stages in plums from flowering to rest, where the solid line represents vegetative growth and the dashed line represents fruit growth (Torrecillas et al., 2018).*

2.1.3 Plum production requirements

Plums are an attractive stone fruit thanks to the expanding market, early fruit-bearing (3-4 years after planting), high production and long life of trees, easy propagation by seed and grafting on common rootstocks. Plums generally have modest requirements and they are well-adapted to different types of soil, climate, crop management and environmental conditions (Oltenacu et al., 2015). They are particularly suited to deep, well-drained soils, but able to withstand a certain level of waterlogging (Amador et al., 2012).

Intensive plum orchards are usually planted at densities of 1 m (within row) x 4.5 m (between rows) depending on variety, rootstock and training system. Plum cultivars originally introduced in the country were not well-adapted to the South African environmental and climatic conditions, and research and development programmes had to be conducted to select more productive varieties. Plums require moderately low winter temperatures during the period of dormancy (2.5-12.5°C for 850 to 1000 hours), and they are, therefore, particularly adapted to the Western Cape (DAFF, 2010). In the Western Cape, the production season usually spans from November (early-maturing varieties) to mid-May (late-maturing varieties).

According to production guidelines given by the South African Department of Agriculture (DAFF, 2010), optimal soils are sandy loams to sandy clay loams, >60 cm in depth with a pH between 5.5 and 6.5. Plums may be sensitive to rainy and windy conditions during flowering, and to the development of pathogenic root nematodes. Selection of cultivars is based mainly on chilling requirements, resistance to diseases, and especially market demand and exportable yields. Common pests are banded fruit weevil, scale (red and pernicious), thrips, American bollworm, fruit fly and codling moth.

2.1.4 World production of plums

Total world production of plums amounted at 12,581,907 metric tons in 2018, with China accounting for more than half, and a slightly increasing trend worldwide (HortGro, 2019). Torrecillas et al. (2018) reported an increase in world plum production from 1993 to 2013 by 17%, mainly due to the increase in surface area of cultivation (21%) and a slight decrease in crop yield from 4.5 to 4.3 t ha^{-1} (-3%).

Top world exporters of plums in 2019 were Chile, Spain and Hong Kong-China (South Africa was placed 6th in the world). Top importers of plums in 2019 were Hong Kong-China, China and Russia. Tortajada et al. (2017) reported overall plum yields in California to vary between 8.9 and 20.8 t ha^{-1} (1990-2015), especially in response to droughts, and they discussed policy interventions to build resilience in the production of fruit trees.

Chile and South Africa are two major producers of deciduous fruits in the southern hemisphere (67%) with the major export destinations being the European Union, Far East and Asia (HortGro, 2019). In the southern hemisphere, South Africa is the third largest producer of plums (74,254 metric tons in 2018) behind Chile and Argentina, and the second exporter of plums (47,269 metric tons in 2019) behind Chile.

2.1.5 Plum production in South Africa

In South Africa, the Japanese plum fruit industry is well-established and primarily aimed at supplying plums to the export market. Even though South Africa is a relatively small plum grower in terms of area planted, the country is a major exporter by volume in global terms. Plums sold to the export markets generate a greater unit price than that achieved on the local market. South African peak production was achieved in 2016 (87,746 metric tons), whilst exports were slightly declining in the last 6 years (HortGro, 2019). Europe and Russia are the main South African markets for plums, followed by the UK, Middle East, Africa, and Far East and Asia. Out of the total plum production in South Africa, 73% is exported, 23% of the fruit is sold locally and a further 3% is processed into various products.

Plums in South Africa are cultivated on 5,319 ha and the plum industry employs 5,904 labourers and 23,616 dependents (HortGro, 2019). Total sales for 2019 amounted at R1.4

billions. Total costs of establishment of a plum orchard are estimated to be R378,531 ha^{-1}, whilst the total operational costs of a full-bearing plum orchard producing 30 t ha^{-1} at a density of 1524 trees ha^{-1} (spacing 3.3 m x 2 m) are estimated to be R343,355 ha^{-1} a^{-1}. Out of this amount, total pre-harvest operational costs of production are estimated to be R91,848 ha^{-1} a^{-1}, mainly for seasonal labour, fertilizer, repairs and maintenance, and fuel. Harvest and post-harvest costs amount at R170,165 ha^{-1} a^{-1}, mainly for packaging, transport and seasonal labour. Water costs are estimated to be R2,258 ha^{-1} a^{-1} (HortGro, 2019). These figures are average estimates and they change depending on the orchard and conditions.

Kritzinger (2015) reported that out of the approximately 5,000 ha cultivated to plums, the most dominant cultivars were traditionally Laetitia, Songold and Sapphire, which contributed 12%, 11% and 7%, respectively, to the total planted area (HortGro, 2014). Plum production in 2013/14 amounted at about 74,054 tons, including 1,881,125 cartons of Laetitia, with a net export income of R15,390 per ton (Kritzinger, 2015).

The most recent production report by HortGro (2019) shows the split per production area of the 5,319 ha of plums and 243 ha of prunes currently planted in South Africa. The Western Cape is the dominant Province with the main producing areas being the Klein Karoo (1602 ha), Wolseley/Tulbagh (664 ha), Franschoek (531 ha), Wellington (474 ha) and Paarl (400 ha), representing more than half of the production area in South Africa. The total production area was steady in the past 6 years (>5,000 ha) with the most represented cultivars in 2019 being Angeleno/Sumplumsix (542 ha or 10% of the total area), Laetitia (493 ha or 9%), Fortune (400 ha or 8%), Ruby Sun (368 ha or 7%) and African Delight (363 ha or 7%). The most represented cultivar of prunes in 2019 was Van der Merwe (188 ha or 78% of the total area). The dominant age of plum trees is 6-15 years (2135 ha or 40% of the total area), with tree ages of cultivar Fortune and African Delight being predominantly 3-15 years.

The total production of plums has been generally increasing in the last 10 years with a peak of 86,715 t achieved in 2016/17. The total value of production has also been generally increasing with a peak of R 1.4 billions achieved in 2018/19. Total sales were steadily increasing in each of the past 10 years, with local market sales reaching R8,315 t^{-1} and export net realization of R18,799 t^{-1} in 2018/19. Local and export market sales are the highest in-season (January-March) and the lowest off-season (June-August) (HortGro, 2019).

Exports of plums show a steady trend in the last 10 years, with an average annual price of nearly R19,000 t^{-1} in 2018/19. The most productive months of plums passed for export are January-March. Records indicated that 45% of plums are exported to Europe and 23% to the UK (HortGro, 2019). The most exported cultivars in 2018/19 were African Delight (1,114,010 cartons), Angeleno/Sumplumsix (1,088,105 cartons) and Fortune (994,863 cartons), where a carton is equivalent to 5.25 kg.

2.2 Irrigation water use and productivity of plums

The production of plums in South Africa is reliant on irrigation. Intensive cultivation of orchards is also associated with increased water requirements, in particular in view of projected climatic changes in the main production areas. Therefore, the availability of adequate water is critical for sustainable production (National Agricultural Marketing Council, 2013). Irrigation is one of the largest expenses involved in fruit production. Efficient irrigation management reduces operational costs and water-related risk to fruit production. This Section reviews irrigation methods, irrigation management, water use and crop water productivity with particular focus on Japanese plums.

2.2.1 Irrigation methods

Water applied to agricultural fields (water use) is consumed by crops through evapotranspiration (ET) or it is non-consumed, but may be reusable. Non-consumed water such as runoff (overland flow) and deep percolation (water that flows beyond the crop's effective root zone) can potentially be recovered by downstream users or contribute to recharge the groundwater, but it can also be non-recoverable. Water consumption can be beneficial when consumed by crops through transpiration, or non-beneficial if consumed by weeds, cover crops or as soil evaporation. As reduction in crop transpiration usually implies unwanted reduction in crop yield, water saving and conservation must logically first target components of the water balance such as the non-beneficial water consumption (e.g. reducing soil evaporation) and non-consumptive water use (e.g. reducing deep percolation to conserve water and nutrients) (Jovanovic et al., 2020). Micro-irrigation methods (e.g. micro-jets, drip-irrigation) are therefore widely adopted in high-intensive orchards to minimize the wetted portion of the ground and non-beneficial water consumption.

Due to the relatively high water demand of plum orchards, micro-irrigation methods are the most preferred options. Traditionally, micro-jets are used to irrigate plum trees in South Africa. This is because of a relatively large wetted area under micro-sprinklers and micro-jets, which is necessary for the development of an extensive root system and healthy trees. This irrigation method has proved to produce high fruit yields and high economic returns. Drip-irrigation is not always suitable to certain soil types and it can produce lower fruit yields, if improperly managed. However, the proportion of beneficial water consumption under micro-jet irrigation is relatively smaller than drip-irrigation. A recent study by Dzikiti and Schachtschneider (2015) indicated that drip may be more efficient than micro-jet irrigation, and that potential water savings are possible up to 20% by improving irrigation methods and crop coefficients for the calculation of water requirements. In addition, irrigation methods should be evaluated for improvements of fruit quality, e.g. fruit sunburn.

2.2.2 Irrigation management

In previous work, Jovanovic et al. (2018) reviewed methods for the determination of crop water requirements. They stressed the importance of an integrated approach for measurement of atmospheric, plant and soil variables in order to accurately interpret plant-water relations for improved irrigation management and scheduling. Jovanovic et al. (2018) provided a case study example describing a “close-to-ideal” methodology and equipment for collecting research data to determine crop water requirements and FAO56 crop coefficients (Allen et al., 1998). The approach is based on monitoring all components in the Soil-Plant-Atmosphere Continuum (SPAC) and the case study example was provided for an intensive apple orchard in the Western Cape (Jovanovic et al., 2018). This approach was also proposed in this project to determine water consumption of plums.

In this Section, we report on the latest research advances achieved adopting atmospheric, plant and soil measurements for irrigation management of Japanese plums. The section also reviews international applications of different irrigation strategies, in particular deficit irrigation studies that were conducted on Japanese plums.

<u>Atmospheric measurements and crop coefficients</u>

The estimation of water requirements in orchards (ETc) is traditionally accomplished with the FAO56 approach (Allen et al., 1998). The FAO56 approach uses the Kc-ETo method combining the grass reference evapotranspiration (ETo) with a crop coefficient (Kc). ETo represents the evaporative demand of the atmosphere, driven by climate, and it can be calculated from weather data using the Penman-Monteith equation (Allen et al., 1998). Kc is the ratio ETc/ETo representing the primary characteristics that distinguish the crop from the grass reference: the crop height, the crop–soil surface resistance and the albedo of the crop–soil surface.

The dual-Kc approach provides for the partition of ETc into crop transpiration (Tc) and soil evaporation (Es), the former estimated through the basal crop coefficient (Kcb) and the latter through the soil evaporation coefficient (Ke), thus with Kc = Kcb + Ke.

Little research experimentation was done in South Africa on crop coefficients of plums. Yet, accurate crop coefficients based on the dual-Kc approach for plum orchards are required taking into account the cultivar, growth stage, climatic conditions and irrigation methods. Such crop coefficients can be directly used to inform real-time irrigation scheduling. They can also be used to develop robust orchard water use models that distinguish between the plant transpiration and soil evaporation components of the orchard water balance. The water balance models could then be used for extrapolating the study results to other growing regions in the country and for planning purposes.

Standard Kc and Kcb values for many crops and their phenological stages were reported by Allen et al. (1998). Recently, Pereira et al. (2021) reviewed the work done in the past 20 years on the FAO56 method to produce a Special Issue on “Updates and advances to the FAO56 crop water requirements method” published in Agricultural Water Management. The Special Issue includes updates to crop coefficients for vegetables, field crops, trees and vines. In particular, updated crop coefficients for tree crops were published in the Special Issue paper by Rallo et al. (2021). The information extracted from Rallo et al. (2021) for plums is summarized in Tables 2.1 and 2.2.

In other published research, crop coefficients of around 1 at mid-season were recommended for stone fruits by Steduto et al. (2012). Higher crop coefficients may occur in high-density orchards and when using cover crops according to Fereres and Goldhamer (1990). Naor et al. (2004) proposed an optimum Kc between 0.6 and 0.8 in the month prior to harvest, based on a multi-level irrigation and crop load experiment conducted on cv Black Amber. Intrigliolo et al. (2014) estimated Kc to be between 0.29 in March and 0.57 in June in 10-years old Japanese plum cv Black Gold cultivated in Spain (average seasonal Kc was 0.46).

In South Africa, Dzikiti and Schachtschneider (2015) found the Kc coefficient to be between 0.9 and 1.0 for an African Delight plum orchard in Robertson during peak irrigation season. However, they also recommended further research to update crop coefficients for plums to increase the accuracy of irrigation scheduling thereby saving significant amounts of water and reducing water risk.

Table 2.1 Published Kc and Kcb for the mid and end-season of plums (Rallo et al., 2021)

Author	Age (years)	Density (plants/ha)	Training system	Height (m)	f_c*	$K_{c\ mid}$	$K_{c\ end}$	$K_{cb\ mid}$	$K_{cb\ end}$
Samperio et al. (2014)	4-9	417	Vase	2.50-4.60	0.65+ 0.90++	0.95 1.10-1.20	0.60 0.75-0.90	-	-

*includes the ground cover fraction (f_c), the fraction of intercepted PAR (f_{IPAR}), and the ground shaded fraction (f_{shad});
+ Red Beaut (early-maturing); ++ Angeleno (late-maturing)

Table 2.2 Updated values for single (Kc) and basal crop coefficients (Kcb) for stone fruit tree crops, previously tabulated Kc and Kcb values, and indicative values proposed in various focused studies (Rallo et al., 2021).

Crop	Density	Fraction of ground cover observed or indicative	Tree height observed or indicative (m)	Ranges of literature reported K_c and K_{cb} for the mid- and end-seasons				Ranges of previous tabulated standard K_c and K_{cb} for the mid- and end-seasons				Indicative standard values (±10%) of K_c and K_{cb} for the mid- and end-seasons			
				$K_{c\ mid}$	$K_{cb\ mid}$	$K_{c\ end}$	$K_{cb\ end}$	$K_{c\ mid}$	$K_{cb\ mid}$	$K_{c\ end}$	$K_{cb\ end}$	$K_{c\ mid}$	$K_{cb\ mid}$	$K_{c\ end}$	$K_{cb\ end}$
Stone fruit trees															
Apricot, Cherry and Plum	Young	0.15-0.30	1.5-2.0	-	-	-	-	0.60-0.70	0.55-0.65	0.45-0.55	0.40-0.50	0.55	0.50	0.40	0.30
	Low	0.30-0.40	2.0-3.0	-	-	-	-	0.60-0.70	0.55-0.65	0.45-0.55	0.40-0.50	0.60	0.55	0.45	0.35
	Medium	0.40-0.50	2.5-3.5	-	-	-	-	0.90	0.85	0.65	0.60	0.80	0.75	0.55	0.50
	High	0.50-0.60	2.5-4.0	-	0.80-0.85	-	-	1.00-1.05	0.95-1.00	0.70-0.75	0.65-0.70	0.90	0.85	0.60	0.55
	Very high	>0.60	2.5-5.0	0.95-1.20	1.05-1.10	-	-	1.15-1.20	1.10-1.15	0.80-0.85	0.75-0.80	1.05	1.00	0.70	0.65

Crop coefficients (Kc and Kcb) provided by Allen et al. (1998) and revised by Pereira et al. (2021) represent values under standard climatic conditions. However, different cultivation strategies, methods and technologies may require adjustments of Kc and Kcb to account for environmental stresses and specific management practices. Many water-saving and conservation measures and practices (crop, soil and irrigation management) were reviewed and described by Jovanovic et al. (2020), as part of the Special Issue on FAO56 updates. This review paper includes summary Tables of benefits and impacts of different practices on water consumption, crop water productivity and crop coefficients, i.e. how to adjust crop coefficients for non-standard conditions under different management practices. The practices were grouped according to the following:

- Irrigation methods (surface, sprinkler and micro-irrigation)
- Irrigation management and scheduling (deficit irrigation, regulated deficit irrigation and partial root-zone drying)
- Crop management (crop selection, planting dates, nutrient supply, plant density and canopy size, intercropping)
- Use of plant conditioners (anti-transpirants, biostimulants and plant growth regulators)
- Mulching (organic mulching, plastic mulching, combination of mulching, deficit irrigation and other practices)
- Soil management (soil tillage, land preparation and in-field water harvesting, soil additives and conditioners)
- Micro-climatic conditions (sheltered cultivation, windbreaks and wind shields, CO_2 and water vapour concentrations).

Plant-water relations

Knowledge on plant-water relations is fundamental in identifying the onset of water stress and for irrigation scheduling, i.e. deciding the timing and volume of irrigation. This is particularly important in intensive high-yielding orchards to sustain high productivity and secure stable income. Published international research on plum water stress indicators is reviewed below.

Intrigliolo and Castel (2004) assessed the fitness of plant water status indicators for irrigation scheduling in a five-years old Japanese plum (cv Black Gold) orchard. They evaluated trunk diameter variation (maximum daily shrinkage and trunk growth rate) and stem water potential against soil matric potential under different levels of regulated deficit irrigation. They concluded that stem water potential was the most sensitive and least variable indicator, maximum daily shrinkage is not uniquely correlated to stem water potential, whilst trunk growth rate requires a reference full-irrigation control for comparative purposes. Soil water potential is useful in the dry soil range, however it is variable in the wet range and a large number of sensors are required to remedy the uncertainty for irrigation scheduling. In a subsequent study, Intrigliolo and Castel (2006) confirmed the finding of the fitness of pre-dawn and midday leaf water potential as indicators of water stress in Japanese plum cv Black Gold.

Fernandez and Cuevas (2010) provided a review on the use of plant water stress indicators for irrigation scheduling, comparing in particular stem diameter variations that can be recorded automatically with stem water potential, for which laborious manual measurements have to be carried out. They found that stem diameter-based measurements (maximum daily shrinkage and trunk growth rate) are sufficiently sensitive indicators for peach and lemon, whilst stem water potential measurements are more feasible for irrigation scheduling of plums, apple and grapevine.

Blanco-Cipollone et al. (2017) conducted an experiment on cv Angeleno in Spain to investigate the anisohydric behaviour of Japanese plum through measurements of the soil water balance, stem water potential and sap flow under different irrigation treatments. They confirmed that stem water potential is a better indicator of water stress compared to predawn leaf water potential in anisohydric species (the effects of water stress are more prominent when stem water potential is measured at noon/early afternoon compared to measurements of leaf water potential before dawn). A threshold midday stem water potential of -1.5 MPa was recommended by Blanco-Cipollone et al. (2019) to avoid fruit size losses of cv Angeleno, in combination with tree crop load adjustment.

Torrecillas et al. (2018) reviewed research work done on water stress response in different phenological stages (McCutchan and Shackel, 1992; Intrigliolo and Castel, 2012; Samperio et al., 2015a), recommending that plant water stress be limited to phase II of fruit development and the post-harvest stage to avoid impacts on fruit size. The resulting practical recommendation was to maintain midday stem water potential >-0.7 MPa in stage I, >-1.5 MPa in stage II, >1.0 MPa in stage III and >-1.65 MPa at post-harvest in mid-season and late-ripening plum trees.

Opazo et al. (2020) investigated the fitness of rootstock to remedy water deficit in Japanese plum cv Angeleno. The experiment was carried out in pot trials in Chile, and it consisted in measuring root hydraulic conductivity, stomatal density, water use efficiency, growth and yield of different scion/rootstock combinations under well-watered and water deficit conditions. The study underlined the potential of using genotypes that confer water deficit tolerance to the grafted species, as well as the capacity of recovery from temporary drought conditions.

Another review on the fitness of trunk diameter measurements for irrigation scheduling was provided by Ortuno et al. (2010). Naor (2004) reported the relationships between soil water potential, midday-stem and leaf water potential, stomatal conductance and yield indicators (fruit weight, fruit per tree, relative yield) for Black Amber grafted on Mariana rootstock.

Additional literature on plant-water relations of relevance to irrigation scheduling can be found in Ton et al. (2004) on phytomonitoring techniques; Grappadelli et al. (2019) on fruit growth dynamics as a function of vascular flows in Japanese plum cv Angeleno; Intrigliolo and Castel (2005a) on maximum diurnal trunk shrinkage and midday stem water potential; Kathner et al. (2017) on spatial applications of crop water stress index and intrinsic water use efficiency for fruit quality and precision agriculture.

Considering response to salinity stress, Torrecillas et al. (2018) cited work by Ziska et al. (1984) where higher water salinity induced a reduction in stomatal conductance and transpiration during the season, while a reduction in leaf water content occurred only during the last stage of fruit growth.

<u>Soil water balance studies</u>

The soil water balance approach is commonly used in irrigation management and scheduling. In order apply the soil water balance equation to estimate the amount and timing of irrigation, an accurate measurement of changes in soil water content is required (Jovanovic et al., 2018).

Torrecillas et al. (2018) drew attention to the variability of plum responses to water stress, especially in early-maturing cultivars. In addition, the mechanisms of recovery of trees following water stress through rehydration are crucial in terms of final yield. More severe and longer water stress may cause slower rehydration and affect the water stress-sensitive stages of the plant, especially when such recovery is limited by the irrigation system design and water availability. This may commonly occur in commercial orchards where it would be therefore prudent to maintain soil and sub-soil sufficiently wet throughout the growing season, as shortfalls in soil water content may not easily be replenished with micro-irrigation systems.

Paltineanu et al. (2016) demonstrated the soil physical properties are more variable (soil bulk density, macro-porosity, saturated hydraulic conductivity and penetration resistance) in orchards compared to arable soils with homogeneous tillage, and less favourable to plants in the inter-row soil volume compared to intra-row, mainly due to mechanization traffic. This should be taken into account in irrigation management as soil physical properties determine the soil water retention capacity and ultimately root water uptake. Paltineanu et al. (2016) also recommended the management of root systems at a distance of 0.5–0.7 m away from tree rows for increased control of the irrigation regime and wetted soil volume with drip irrigation.

Millan et al. (2019) successfully tested an automated irrigation system that uses capacitance soil sensors for measurement of soil water content with a feedback adjustment mechanism for scheduling irrigation. The two-year experiment was conducted in an early-maturing Japanese plum orchard (cv Red Beaut) in Spain. Millan et al. (2020) also investigated correct sensor positioning and interpretation of measurements done with frequency domain reflectometry probes installed at different positions in relation to the tree and irrigation drippers. The soil water content measurements were compared to plant water stress indicators, namely midday stem water potential, sap flow, leaf stomatal conductance, net leaf photosynthesis and daily fraction of intercepted photosynthetically active radiation. The experiment exhibited high variability in soil water extraction pattern by drip-irrigated Japanese plum (cv Red Beaut) across the row cross-section. Using the midday stem water potential, photosynthesis rate and stomatal conductance as indicators of plant water stress, Millan et al. (2020) proposed that the most suitable sites for measuring soil water content are close to the drippers under full-irrigation, and further away from the drippers under medium and severe deficit irrigation.

Deficit irrigation

Although deficit irrigation was not a specific objective of this project, this irrigation strategy appears to be of particular interest to tree crops and a vast body of literature was found on the topic. This practice was specifically introduced to allow some degree of crop water stress and yield reduction to reduce soil evaporation, water and chemical losses, whilst maintaining economically viable yields. Deficit irrigation can be applied throughout the crop season or targeted to some non-critical phenological stages. Regulated (or controlled, managed) deficit irrigation (RDI) targets certain phenological stages during which plants are less sensitive to water stress. Partial (or alternate) root-zone drying (PRD) targets the production of the plant hormone abscisic acid (ABA), which reduces leaf expansion and stomatal conductance by stressing one portion of the roots, whilst the other portion of the roots sustains transpiration. To be a sustainable practice, reduction of water consumption in deficit irrigation should be proportionally higher than the reduction in yield. This is often not the preferred strategy by farmers due to the risk of yield loss. Exceptions are tree crops for which lower yield may result in better quality fruit and higher profits, as discussed by Torrecillas et al. (2018).

Maatallah et al. (2015) conducted research on improving the fruit quality through moderate water deficit in three plum cultivars (Black Diamond, Black Gold and Black Star) in Centre-West Tunisia. The results showed that water restriction reduced the diameter and weight of the fruit, though the extent depended on the cultivar. However, other measures of fruit quality were improved. It was concluded from the study that regulated deficit irrigation may save water in semi-arid regions and improve fruit quality with a moderate impact on productivity. This was also reported by Intrigliolo and Castel (2012). No effect on fruit quality was observed in the subsequent season when water stress was applied at post-harvest (Samperio et al., 2015b).

Intrigliolo and Castel (2010) evaluated the yield and water consumption of seven-years old Japanese plum (cv Black Gold grafted on Mariana GF81 rootstock) in Spain under regulated deficit irrigation and low to medium crop load. They observed a tendency of lower yield under deficit irrigation, but improved fruit quality with thinning to low crop load. Gennai et al. (2017) demonstrated the ability of plum fruit growth recovery after mid-season regulated deficit irrigation in high-density cv Angeleno on Mariana 2624 rootstock in Spain.

Research was also conducted on the effects of long-term deficit irrigation and possible carry-over impacts on subsequent seasons. Intrigliolo et al. (2013) warned about carry-over effects of deficit irrigation after conducting an eight-year experiment on Japanese plums cv Black Gold in Spain. The carry-over effects manifested in smaller trees compared to a control fully-irrigated treatment, which led to 29% yield reduction. Therefore, they recommended slight water restrictions (up to 9%) to avoid long-term carry-over effects of deficit irrigation on tree performance. Intrigliolo and Castel (2011) and Intrigliolo et al. (2014) proposed a strategy for recovery of vegetative growth (tree size) after a prolonged deficit irrigation (seven years) of young Japanese plum trees drip-irrigated in Spain. Measured yields were between 13.9 and 41.8 kg tree^{-1} of cv Black Gold (10-years old trees), depending on irrigation treatments. The recovery strategy consisted in increasing the wetting zone by adding drippers with water application up to 133% of crop water requirements, in combination with lowering the crop load. This strategy allowed recovery of tree size after two years compared to a well-irrigated control, and it was proposed for cases when full water availability follows a prolonged drought period.

The post-harvest period until leaf fall is characterized by reduced crop water requirements of plums, however physiological processes are still required to be supported because they affect the following year's production. Pre-harvest and post-harvest deficit irrigation of plums was frequently the topic of international research investigations.

Intrigliolo and Castel (2005b) applied 4 years of regulated deficit irrigation to a four-year old Japanese plum cv Black Gold before and after harvest. Drought before harvest affected fruit growth and size. Although drought after harvest did not affect fruit growth and yield in the short term, there was indication that the cumulative effects of deficit irrigation may manifest in the long term through smaller tree size, which can be considered in cases of water scarcity or as a tool to control vegetative growth.

Samperio et al. (2015a) conducted a five-year experiment on four-year old Japanese plum trees (cv Angeleno on Mariana 2624 rootstock) in Spain, where they investigated crop physiological responses, tree growth and economic returns under deficit irrigation. They concluded that moderate regulated deficit irrigation applied in stage II and post-harvest reduced water use, controlled tree vigour, increased yield and economic return compared to well-irrigated trees. Mild water stress of short duration during fruit growth did not affect fruit size. Samperio et al. (2015b) confirmed similar findings in a five-year experiment on cv Red Beaut, where post-harvest water deficit appeared an effective way to save water as well as to control vegetative growth (reduce total pruning), whilst maintaining fruit yield, quality and economic return without any carry-over effects of water stress from year to year.

Blanco-Cipollone et al. (2019) carried out an eight-year study on cv Angeleno and compared full-irrigation practice with deficit irrigation in the middle of the fruit growth stage as well as post-harvest. They found that the intensity of water stress was more important than the timing of deficit irrigation in terms of fruit growth pattern, with no carry-over effects on crop yield; however, this depends on cultivar and specific environmental conditions.

Monino et al. (2020) carried out a three-year experiment on cv Angeleno to investigate the effects of regulated deficit irrigation at pre- and post-harvest stage. They found that moderate pre- and post-harvest water stress leads to greater crop water productivity compared to other timing of water deficit, as water savings can be achieved (23% on average) with no observed carry-over effects.

Other literature on the effects of deficit irrigation on growth, yield and quality was published by Hajian et al. (2020) for cv Methly.

The effects of water stress and deficit may not only reflect on vegetative and fruit growth and quality, but also on the development of the root system. Cochavi et al. (2019) investigated the effects of different irrigation regimes on the root system of young cherry plum (*Prunus cerasifera* Ehrh.) trees in a pot trial. They found an escalating response under different water stress levels: root biomass decreased under moderate stress compared to the full-irrigated control, but finer roots were not affected; under severe stress, both total root biomass and finer roots were inhibited.

2.2.3 Water use of plums

Little detailed information was found in the literature on the seasonal water use of plums, not only in South Africa but globally. Dzikiti and Schachtschneider (2015) investigated the water consumption of five-year old Japanese plum cv. African Delight budded on the GF-677 rootstock in a 3 ha orchard at Robertson. The orchard was trained on a V-Haag trellis system with dual rows running in an East-West direction, and irrigated with a drip system. Spacing was about 5 m between rows and 1.5 m within rows. The results showed that maximum transpiration during the peak irrigation season, determined with heat pulse velocity sap flow measurements, exceeded 20 L tree^{-1} d^{-1} (2.7 mm d^{-1} by accounting for the planting density), with plants exhibiting midday depression in the diurnal transpiration trend due to partial stomatal closure under conditions of high atmospheric evaporative demand. The seasonal total evapotranspiration, determined through eddy covariance measurements, was about 921 mm for this long-season cultivar harvested in March-April, and retaining leaves until mid- to late June. The recorded leaf area index in this high-density plum orchard was about 1.1 and the measured yield was 55 t ha^{-1}.

Internationally, Samperio et al. (2014) parametrized the CropSyst model for Japanese plum. The calibrated parameters were crop coefficient at full canopy, the hydraulic conductance to predict the orchard crop coefficient (Kc) at any time of the year, and the stem water potential. They used the soil water balance method to determine the orchard water use, but no seasonal total water use results were reported.

In another work by Samperio et al. (2015a) on Japanese plums cv Angeleno in Spain, average water input over five years was estimated to be between 962 and 1211 mm a^{-1} (irrigation + rainfall) depending on well-irrigated and deficit irrigation treatments. Samperio et al. (2015b) also reported average irrigation of 639 mm a^{-1} in a control full-irrigation treatment and average annual rainfall of 520 mm a^{-1} (total of 1159 mm a^{-1}) in a five-year experiment on cv Red Beaut.

Monino et al. (2020) estimated annual water input (irrigation + rainfall) to be between 895 and 1287 mm a^{-1} for cv Angeleno (nine-year old trees), depending on the deficit irrigation strategy, in an experiment conducted in Spain over 3 years.

Intrigliolo and Castel (2010) used an adjusted Kc for canopy size (average value of 0.5 for the season) to estimate crop water requirements of Japanese plum cv. Black Gold in Spain. Seasonal evapotranspiration, calculated as the sum of irrigation and effective rainfall from April to October, was between 409 and 558 mm, depending on the irrigation water treatment and crop load. Intrigliolo et al. (2014) also reported irrigation water requirements to be between 250 and 311 mm $season^{-1}$ (from April to September) for cv Black Gold in Spain.

Iancu (1997) measured evapotranspiration of plums using non-weighing lysimeters in Romania. Actual evapotranspiration was measured to be 622 mm for the period from April to October, with daily values ranging from 1.69 mm d^{-1} in April to 4.24 mm d^{-1} in July, and with the soil evaporation component from bare-soil lysimeters being quite high.

Chootummatat et al. (1990) researched the effects of different trellis systems (Lincoln, Vase, Palmette and Tatura) on water use of six-year old plum trees (cv Laroda and Santa Rosa) in Western Australia. Differences in water use between cultivars and trellises were not large, however Tatura and Palmette systems used more water than the Lincoln trellis under water stress, which was attributed to the ability of their root system to extract water from deeper soil layers. Soil water balance calculations indicated that average water consumption under irrigation practices commonly adopted on commercial farms in the area varied between 7.2 and 8.2 mm d^{-1} in the period of rapid fruit growth (mid-December).

Estimates of evapotranspiration were also conducted using remote sensing information. Mhawej and Faour (2020) used the SEBALIGEE system, a Google Earth Engine-based platform adopting the Surface Energy Balance for Land – Improved (SEBALI) model, to estimate seasonal actual evapotranspiration in California between 2017 and 2019 at 30 m spatial resolution. The USDA NASS Cropland Data (https://developers.google.com/earth-engine/datasets/catalog/USDA_NASS_CDL, accessed on 13 January 2021) were used to identify crops at 30 m spatial resolution. Average plum evapotranspiration was estimated to be 994 ± 188 mm a^{-1}.

2.2.4 Water productivity of plums

Although it is widely recognized that improving water use efficiency at farm level is fundamental to improve irrigation management and crop economic return, it is often found in the literature that the terminology and methods to calculate water use efficiency and crop water productivity are used inconsistently and interchangeably. Recently, Fernandez et al. (2020) published a study where they discussed and evaluated critically the terminology and calculation methods. They recommended that, in order to improve decision-making in on-farm irrigation, both biophysical and economic water productivity indicators should be used. Under conditions of non-limiting water, full irrigation is likely to be the most profitable option. However, when water is limited, deficit irrigation strategies may be considered to improve crop water productivity.

Crop water productivity is usually expressed as crop yield (or economic yield) divided by crop water consumption (or evapotranspiration). Lack of measurements or estimates of seasonal evapotranspiration precludes the use of this definition of crop water productivity. As evapotranspiration was seldom measured/estimated in the plum experiments reviewed in the literature, little reliable information was found on crop water productivity.

Dzikiti and Schachtschneider (2015) reported a water productivity of 5.97 kg plums m^{-3} of water transpired. They suggested that Western Cape fruit farming is already quite advanced in its water productivity, compared to stone fruit farmers worldwide. However, they noted that there is room for further improvement through the adoption of irrigation scheduling tools and guidelines. They found that a limited number of farmers schedule their irrigation based on soil moisture probes and weather data, whilst most farmers make use of moisture pits, intuition and experience.

Intrigliolo and Castel (2010) calculated crop water productivities between 4.2 and 7.5 kg m^{-3} for Japanese plum cv Black Gold grown in Spain, depending on the irrigation water treatment and crop load. Yields were between 36.1 and 56.7 kg $tree^{-1}$ (20.6 and 32.4 t ha^{-1}).

Monino et al. (2020) estimated plum water productivity (nine-year trees cv Angeleno) to be between 5.6 and 13.38 kg m^{-3} depending on the deficit irrigation strategy, with yields ranging from 27 to 166 kg $tree^{-1}$ (11.3 and 69.2 t ha^{-1}).

2.2.5 Plum fruit quality

Improving and maintaining fruit quality is an essential condition to satisfy market demand. Common attributes of fruit quality are firmness and weight, total soluble solids, titratable acidity, sugar-to-acid ratio and fruit mineral content (Rato et al., 2008; Louw and Theron, 2010). Crisosto et al. (2007) described the development of a fruit quality index based on chemical characteristics as well as sensory attributes (sweetness, sourness, plum flavour intensity, plum aroma intensity). Jaroszewska (2011) investigated the differentiation of macro- and micro-nutrients, as well as dry matter and sugars in stone fruits resulting from irrigation and different mineral fertilization levels.

Lufu et al. (2020) provided a review of factors that affect water loss in fresh fruits, where irrigation was listed as one of the pre-harvest factors determining post-harvest fruit weight loss. Kritzinger (2015) discussed the classification of plum fruits destined for export based on internal and external quality indicators (e.g. shape, development, colouring etc.) and adopted by the Organisation for Economic Co-operation and Development (OECD) (OECD, 2002). Some of the main challenges to producers in the Western Cape related to fruit quality and irrigation management are sunburn, fruit size and broken stones.

Dzikiti and Schachtschneider (2015) reported that much water in the Western Cape is used to minimize sunburn as an estimated 15% of some fruit types are lost due to sunburn annually. Farmers use spurts of extra irrigation to cool the micro-climate and the trees as a measure to reduce sunburn. Alternative methods of sunburn control are shade-netting and applying kaolin sprays.

Intrigliolo and Castel (2010) demonstrated that appropriate irrigation management and fruit thinning may result in improvement of fruit grade and increase in total soluble solids (TSS).

Kritzinger (2015) reported that techniques such as fruit thinning and shoot pinching are practices to promote fruit growth, however these practices can also reduce fruit quality due to the occurrence of split stones. The risk of stone splitting is particularly high at crop stages when fruits are enlarging and stones are still too weak to resist to the pulling forces of the growing mesocarp. Kritzinger (2015) found that stone splitting is controlled not only by genetic differences between cultivars, but also by environmental factors. Initial results showed that fruit characteristics (size and fresh weight) and weather conditions (air temperature and relative humidity within the orchard early in the growing season) could control stone splitting. Similarly, high soil water contents and incidence of spring rainfall may also be conducive to high turgidity of fruit cells resulting in stone splitting. Proper irrigation management could therefore reduce this risk to fruit quality.

2.3 Crop modelling

Two main modelling streams are adopted in the calculation of evapotranspiration and water requirements of tree crops. These are commonly known as one-step and two-step approach. In the one-step approach, crop evapotranspiration is directly calculated with the Penman-Monteith combination equation by using the aerodynamic and bulk surface resistances of the crop. The one-step approach is more direct and it does not require the soil water balance because water stress is implicitly accounted for in the canopy resistance terms, however the latter are difficult to parametrize because they change over time depending on crop height and variety, canopy architecture, leaf age and area, water availability and weather conditions, amongst others.

The two-step approach makes use of the FAO56 method where crop evapotranspiration is calculated as the product of the grass reference evapotranspiration (ETo) multiplied by the crop coefficient (Kc). The two-step approach is more intuitive, however the crop coefficient may vary under non-standard conditions, i.e. it needs to be determined for a specific orchard. Pereira et al. (2020) provided and extensive review and theoretical discussion of modelling approaches.

One modelling paper on plums was found in the literature (Samperio et al., 2014). The study made use of the CropSyst model to predict water use and crop coefficients of cv Angeleno and cv Red Beaut with different pruning over three years (2010-2012). The main conclusion was that different Kc values at full canopy and maximum plant hydraulic conductance were required as input in order to simulate accurately evapotranspiration, depending on canopy sizes and different tree vigour exhibited by the two cultivars.

2.4 Main findings and research gaps

The review indicated that, although plums are produced in intensive and high-technology systems in many parts of the world, little information is available on their water use and crop water requirements. Crop coefficients for the calculation of plum water requirements are available in the literature for standard conditions (Allen et al., 1998; Pereira et al., 2021), however it is uncertain whether they are entirely transferable as adjusted values were reported for non-standard conditions.

Extensive research on plant water stress indicators was conducted internationally, in particular in Spain. The midday stem water potential was often demonstrated to be a good indicator of water stress to describe the anisohydric behaviour of plums, with reported threshold values around -1.5 MPa.

Although deficit irrigation was not a specific objective of this project, a vast body of literature originating mainly from Spain was found on this strategy. Similarly to South Africa, semi-arid climate and water scarcity appear to be major challenges in Spanish agriculture. Deficit irrigation was demonstrated as a potential practice to reduce water use and improve fruit quality, whilst still maintaining commercially acceptable crop yields. In particular, research was directed towards investigating the effects of deficit irrigation in stage II and the post-harvest stage in order to reduce water use during less critical periods and, at the same time, to ensure control of vegetative growth and no carry-over effects on crop yields in successive years. Stage III of rapid fruit growth before harvest is considered the most sensitive crop stage. Water stress at this stage could lead to severe yield loss and reduced fruit size. Similarly important is the recovery speed of trees following water stress through rehydration.

The quantification of water use of high-performing Japanese plums (*Prunus salicina* Lindl.) in the major plum production regions of South Africa was the overarching objective of this project. As little is known on the water requirements of plum orchards, the project proposed to contribute novel scientific knowledge to fill this gap in the water and science sectors. Commercial irrigation uses the bulk of South Africa's run-off water. Comparing the actual volumes of water consumed by plum orchards with the irrigation volumes applied would provide an indication on whether the fruit farmers are over-irrigating or not. Only one modelling study on plums was found in the literature. This made it therefore imperative to develop robust orchard water use models to facilitate irrigation planning and scheduling.

3. STUDY SITES DESCRIPTION

According to statistics from the Deciduous Fruit Industry, the total area under plums (*Prunus salicina* Lindl.) in South Africa in 2019 was about 5,319 ha (HortGro, 2019). Most of the fruit is grown in the Western Cape and more than 30% of the production regions are in the Klein Karoo area around Robertson and Ashton. The Wellington and Paarl regions are also important production areas with a combined total planted area of around 874 ha (roughly 16% of the total area). Besides the Western Cape, there are smaller plum production areas in the Northern Cape, Eastern Cape, and in parts of the Free State Province. As with pome fruit, e.g. apples and pears, plums also require cold winters to induce dormancy for optimal flowering and growth to occur. It is for this reason that conditions in the Western Cape are particularly suited for the growth and production of plums.

More than 20 different cultivars of both the European and Japanese plum varieties are planted in South Africa (HortGro, 2019). The choice of cultivar primarily depends on production conditions, and especially the requirements of the target market (market demand and yield expectations). Angeleno is the most widely planted cultivar accounting for close to 10.2% of the planted cultivars according to HortGro (2019). Angeleno is an American variety that has the best shelf life, but the fruits are not the biggest in terms of size and neither are they very tasty (S. Strauss, Sandrivier Estate, personal communication).

According to the proposal of this project and based on the growers' interests and market demand, the focus in this research was on two high-yielding, full-bearing Japanese plum cultivars, namely Fortune and African Delight. These accounted for about 7.5 and 6.8% of the planted area, respectively, in 2019. The African Delight is a late maturing cultivar with a range of harvesting dates between mid-January and March. Its major advantage is that the fruit can stay for longer on the trees, and the fruits tend to have high sugar content and good size. In well-managed orchards with optimal irrigation, fertilization, weeding, pest and disease control etc., maximum yield of African Delight can reach about 40 t/ha in the Wellington area and up to 45 t/ha in Robertson.

Fortune, on the other hand, is a light red coloured mid-season cultivar that is commonly harvested during the January to February window. It is one of the cultivars that has experienced the most rapid rate of expansion in recent years with annual growth in the planted area of up to 11% in some years. In well-managed orchards, the maximum yield of this cultivar can peak at about 30 t/ha in the Wellington area. The yield can be as much as 35 t/ha in the Robertson area. Consistently high yields were an important consideration in the selection of study sites.

The goal of this study was to establish the maximum unstressed water use of the African Delight and Fortune plum cultivars in regions with somewhat different growing conditions. According to the Stems Fruit website, Robertson is a low rainfall region that receives between 175 and 300 mm rainfall per annum (www.stemsfruit.co.za/our-growers, accessed on 26 February 2021). Summer temperatures are quite hot as a result of the Du Toitskloof and Riviersonderend Mountains blocking cooling oceanic breezes from reaching the valley. Winter temperatures, however, are often colder than other seaward regions and snow is a regular occurrence on the surrounding mountains. Wellington, on the other hand, has a long-term annual rainfall of around 450 mm which is about double that in Robertson and the surrounding areas. The daily average temperatures range from about 16 °C in July to around 28 °C in February. The milder climate in Wellington is ideal for growing plums.

Selection of study orchards was done based on the recommendations of the growers' associations and field site visits, and it was constrained by the unusual circumstances of the COVID-19 pandemic that necessitated to limit contacts with people and prevented a wider search due to restrictions of movement. Following discussions with industry experts, it became clear that there were few plum orchards with the desirable attributes. For example, an essential consideration related to the orchard size (>4 ha) to ensure adequate fetch especially when micrometeorological techniques such as the eddy covariance are used to quantify orchard evapotranspiration. The plum orchards tend to be <4 ha in size. Another consideration was the soil type to avoid stony soils that are problematic in terms of the calculation of the soil water balance. The study approach being followed in this project implied that four orchards had to be investigated simultaneously over a period of three years per site. This approach ensured that at least two seasons of data were obtained per orchard and water productivity variations as a result of, for example, alternate bearing are captured.

Two sites were eventually selected for the research with two suitable African Delight and Fortune orchards each, namely:

- Sandrivier Estate near Wellington
- Smuts Brothers near Robertson

This Chapter of the report describes the study sites that have been identified to establish the water use dynamics of African Delight and Fortune plum orchards and to determine how the water use relates to fruit yield. It includes attributes of all four orchards, some baseline data of soil physical and chemical properties, leaf nutrition practices, pesticide programs, irrigation programs and historic yields.

3.1 Wellington study site: Sandrivier Estate

Sandrivier Estate (Figure 3.1) is located less than 10 km to the West of Wellington. Along with Broodkraal, which is in the vicinity of Piketberg, it forms part of the Le Roux Group. Sandrivier Estate was historically a table grapes and cattle farm. In 1995/96, it was planted to fruit trees for the export market and accompanying infrastructure was built. It is currently planted to 195 ha of stone fruit, predominantly plums (85%) and nectarines (15%).

Sandrivier Estate draws its water from the Berg River (Figure 3.1) using two pumps. The pumps deliver water to a holding dam with a capacity sufficient to supply water to the farm for one week (~40,000 m^3) during periods of equipment breakdown or maintenance of pumps. Pumping takes place also during the night when electricity tariffs are lower. The dam is located at the highest point of the farm and it can potentially supply water to a third of the farm by gravity. The pumps operate at 35 kW. In addition to irrigation, if excess water is available, this is used for cooling the micro-climate with pulse irrigation to reduce sunburn damage especially on susceptible varieties.

The irrigation system is computerized and water delivery is measured using 15 water flow meters installed across the farm. Irrigation is via narrow range micro-jet sprinklers delivering about 32 L h^{-1} with an operating pressure of about 3 bars. The farm does not use drip-irrigation because of the clay soil and difficulties in irrigation management, e.g. pipe water pressure requirements, water volumes and timing, dissolving calcite/dolomite amendments etc. Each block has its own valve, so micro-jets irrigation can be applied independently from the other blocks. Initially, a computerized Motorola irrigation system was used, but this was subsequently replaced, and the current irrigation system operates with Motorola, DFM and Irrigator, approximately on 1/3 of the area each. AquaCheck probes are installed to monitor soil water content and to activate irrigation when the soil water content depletes below set threshold levels. The AquaCheck data are downloaded manually by an operator using a radio link, stored to a PC, and irrigation decisions are made. There are about 50 AquaCheck probes across the farm. The soil on most of the farm is shallow on shale.

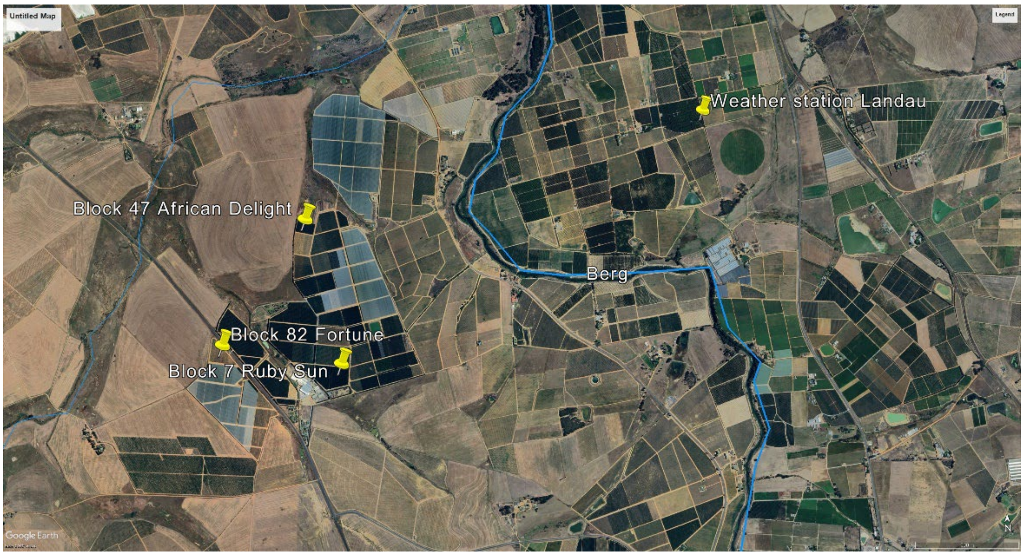


Figure 3.1 *Top: Entrance to Sandrivier Estate (top). Bottom: Google Earth map of Sandrivier Estate with the African Delight (Block 47), Fortune (Block 82) and Ruby Sun (Block 7) orchards. The location of the weather station in Landau (Agricultural Research Council) is also indicated on the Google Earth map.*

The three biggest plum cultivars on the farm are Fortune, African Delight and Angeleno. The following varieties are planted in order from early to late varieties:

- Select 21 (October)
- Alpine (November)
- African Rose (early November)
- Black Splendor (end November- early December)
- Ruby Sun (before Christmas)
- Suplum 11 (Black Diamond series) (mid to end of December)
- Fortune (November-December)
- Sun Supreme (this variety is the biggest in fruit size) (end of January)
- Laetitia (January)
- Songold (yellow variety with severe alternate bearing tendencies and often used as a pollinator)
- Afrigold (latest yellow plum, small in size, being taken out)
- African Delight (beginning of February, but harvest can span from mid-January to mid-March because the ripe fruit can stay long on trees)
- Suplum 50 (black plum with red flesh)
- Angeleno (variety with the longest shelf-life)
- Ruby Star
- Other varieties include cross-pollinators.

Full bloom occurs from mid-August to mid-September for the plums. Thinning is done about 35 days after bloom (in October-November). Spacing for plum trees is usually at 3 ½ m x 1.0 m giving an average tree density of about 2857 trees per ha. Older trees grow to about 3.5 m tall and 80% of the orchards on the farm are oriented North to South with a maximum deviation of about 30° from North to maximize radiation interception. In more recent plantings, trees are much shorter growing to, on average, 2.4 to 2.8 m high to facilitate manual harvesting with a small ladder. Trees in most orchards are planted in ridges in a zig-zag layout along the ridge to favour root development and to reduce competition between plants.

The recommended blocks for the water use experiment were Block 47 for African Delight (1.4 ha in size) and Block 82 for Fortune (2.4 ha in size) (Figure 3.1). Block 47 was planted in 2010 and Block 82 in 2003. The maximum yield for African Delight was as high as 50 t ha^{-1} (Figure 3.2). However, crop load management usually targets around 40 t ha^{-1} for good quality fruit and to improve fruit size. Fruit size ranges from 40-45 mm diameter for C grade to 55-60 mm for the AA grade. The farm measures the diameter of 50 fruits per week to get the growth curves in order to compare the current year performance of the crop against previous seasons and to inform decision-making. Block 82 (cultivar Fortune) showed a declining trend in yields (Figure 3.2). The cause of the decline was unclear although the steepest decline (2015-2016) appeared to coincide with the severe drought that affected the Cape Province. The Fortune orchard was subsequently uprooted at the end of the 2021/22 season and it was replaced in the project by Block 7 cultivar Ruby Sun. Plates of the three experimental orchards are shown in Figure 3.3.

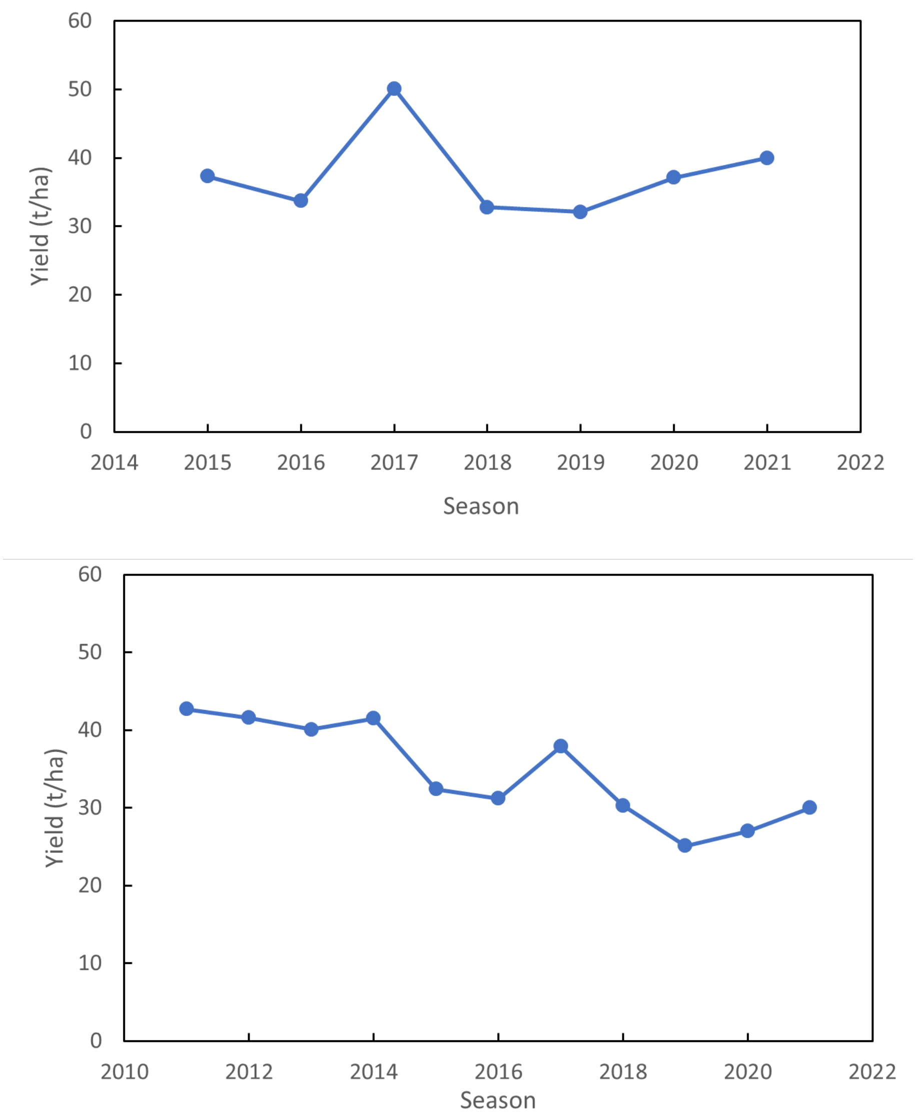


Figure 3.2 *Historical yields of Block 47 (African Delight) and Block 82 (Fortune) at Sandrivier Estate.*

Figure 3.3 *African Delight (left), Fortune (middle) and Ruby Sun (right) plum experimental orchards at Sandrivier Estate.*

At Sandrivier Farm, plums are affected by several diseases. The farm adopts an active spraying program throughout the season. They spray against 11 different pests and diseases during different times of the season using a range of chemicals. The types of pests and diseases appear to be similar for the African Delight and Fortune cultivars. Curl leaf, scale, blossom blight, thrips, bollworm and bacteria spot are being controlled early in the growing season from August to September. In the early stages of full canopy cover in October-November, the spray program shifts towards the fruit fly and red spider mite, with fruit fly being the most prevalent problem. The spray program receives international certification for export to international markets from various international bodies such as Global Gap. The farm keeps records of the type of chemicals applied, quantities and when the chemicals were applied during the growing season. Examples of pesticides programs can be found in Deliverable 2 of this project.

Pits are dug every few seasons and soil samples collected for detailed analysis of the nutritional status of the soils. Leaf samples are also collected each season and sent to a commercial laboratory in order to determine the fertilizer recommendation for the next season. Soil analyses for Blocks 47 (African Delight) and 82 (Fortune) are reported in Table 3.1. Examples of fertilizer programs can be found in Deliverable 2 of this project.

Table 3.1 Soil properties for the African Delight Block 47 and Fortune Block 82 orchards at Sandrivier Estate.

Orchard	Texture	pH (KCl)	Resistance (ohm)	H^+ (cmol/kg)	Stones (Vol. %)	P Bray II	K	Exchangeable cations (cmol(+)/kg)				Cu	Zn	Mn	B	Fe	S	C (%)	Na	K	Ca	Mg	T-value*
						mg/kg		Na	K	Ca	Mg	mg/kg							(%)				
African Delight (47)	Sandy	6.0	2470	0.25	63	32	227	0.10	0.58	3.20	0.67	0.32	0.20	1.50	0.32	34.77	-	0.76	2.11	12.09	66.67	13.92	4.80
Fortune (82)	Loam	5.6	1280	0.41	51	32	210	0.50	0.54	3.10	1.12	0.84	-	-	-	-	13.89	0.84	8.74	9.47	54.82	19.72	5.66

*Sum of base cations and H^+

3.2 Robertson study site: Smuts Brothers

Smuts Bros is located about 8 km to the East of Robertson town (Figure 3.4). The estate has several farms, amongst others the Lucerne Farm close to the office park on the R317 road and Klipboschlaagte on the R60 towards Montague. Smuts Bros farm tomato, butternut, avocado and stone fruits (peaches and plums). A variety of soil types with different textures occur on the farms. A shallow hard layer of conglomerates occurs frequently; ideally, this should be broken up through deep ripping. Soils were classified based on profile pits and lime requirements were established.

Water to the farm is supplied through releases from the Brandvlei Dam in Worcester into the Breede River. Canals divert water from the Breede River to the Lucerne Farm covering a distance of 28 km. Canal diversion occurs through a canal sluice and water is conveyed to a balancing dam before distribution to the orchards. The annual water allocation is 10000 m^3 ha^{-1} (7450 m^3 ha^{-1} in summer from November to May, and 2550 m^3 ha^{-1} in winter). The water allocation to the farm was cut by 50% during the drought of 2016 and 2017. Lesser amounts of irrigation water that were applied resulted in the build-up of salinity in the root zone.

The irrigation method used on the entire farm is drip-irrigation. It was found that drip-irrigation can provide better fertigation, less water use and cheaper maintenance of the irrigation system compared to micro-jets. A continuous logging Irricon system is used for irrigation scheduling by a provider that supplies Internet services and software. Irrigation scheduling is based on soil water probes that are installed at 10, 20, 30 and 40 cm soil depth. Particular attention is given not to dry out the soil below the root zone during the dormant season, as it has been observed that a dry subsoil may not be able to refill during the full irrigation season and this may consequently cause a reduction in yield. Data are collected by the farm managers and irrigations are scheduled three times per week.

For the water use experiment, the recommended blocks were a Fortune orchard at Lucerne Farm (Block L17) and an African Delight orchard at Klipboschlaagte (Block K35) (Figure 3.4). The Fortune orchard is 1.65 ha in size and 8 years old (Figure 3.5). The orchard produced on average about 44 t ha^{-1} (32.5 t ha^{-1} in 2019, 53.7 t ha^{-1} in 2020 and 45.4 t ha^{-1} in 2021). The growing season usually starts at the end of August; blooming begins in the beginning of September and full bloom is achieved by mid-September. Harvest is generally in the beginning of January. Fortune is irrigated with three dripper lines per row to ensure a bigger area is wetted and larger soil water retention. The root system is estimated to be 2 m wide across the row and about 90 cm deep. Drippers operate with a discharge of 2.3 L h^{-1} and they are spaced 0.5 m apart. Harry Pickstone pollinator trees are planted every 8 trees in the row.

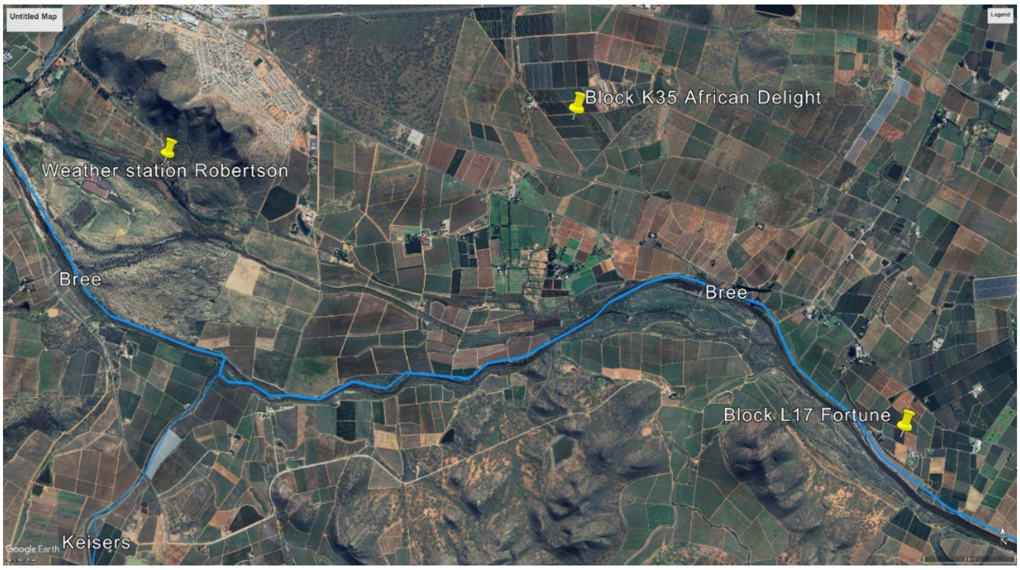


Figure 3.4 *Top: Entrance to Klipboschlaagte Farm – Smuts Bros (top). Bottom: Google Earth map of Sandrivier Estate with the African Delight (Block K35) and Fortune (Block L17) orchards. The location of the weather station in Robertson (Agricultural Research Council) is alo indicated on the Google Earth map.*

The African Delight orchard is grown on 4 ha in Block K35 at Klipboschlaagte and it is 7 years old (Figure 3.5). Current seasonal production is around 45-50 t ha^{-1} (37 t/ha in 2019, 34 t/ha in 2020 and 40 t/ha in 2021). Harvesting starts in February. The African Delight orchard was initially established without pollinators. It was observed that higher yields occurred at one edge of the orchard compared to the rest of the area. This was attributed to an adjacent orchard planted to African Rose cultivar that acted as a pollinator. African Rose trees were then planted within the African Delight orchard to improve pollination. This increased yields for about 3-4 years, however after this time flowering of the two cultivars started mismatching, which worsened the effectiveness of pollination. Pioneer seedlings were recently grafted to branches of African Delight. The branches are left to grow and flower to improve pollination.

Both Fortune’s and African Delight’s rootstocks are Mariana. The predominant pruning system on the farm is Palmette and the plant spacing is 4 m x 1.5 m giving 1667 trees per hectare. Pruning is performed to keep tree height at 3 m. Planting in ridges is not used, except for younger orchards on the farm.

Figure 3.5 *African Delight (left) and Fortune (right) plum experimental orchards at Smuts Bros.*

The suite of insects and pests that afflict plums in the Robertson area appears to be similar to that in Wellington. In the Fortune orchard at Lucerne Farm, pest and disease control is applied for thrips, bollworm, red spider, pernicious scale, false coding moth, fruit fly, rust and botrytis/brown rot. At Klipboschlaagte, pesticides are applied to treat bollworm, blossom blight, false codling moth and powdery mildew among others in early to late spring. In summer, the false codling moth is the major pest that has to be controlled while red scale and fruit fly become a problem towards fruit maturity. An example of the pest and disease prevention and treatment program for the African Delight orchard can be found in Deliverable 2 of this project.

The fertilization program is planned based on soil analyses done by a commercial lab. Recent soil analyses (February 2018) for the Fortune orchard are shown in Table 3.2.

Table 3.2 Soil properties of the Fortune orchard (Block L17) at Lucerne (Smuts Bros).

Orchard	Depth (cm)	Texture	pH (KCl)	Resistance (ohm)	Stones (Vol. %)	P* Bray II	K	Exchangeable cations (cmol(+)/kg)				Cu	Zn	Mn	B	Fe	S	C (%)	Na	K	Ca	Mg	T-value**
						mg/kg		Na	K	Ca	Mg	mg/kg							(%)				
Fortune (L17)	40	Clay	7.2	490	31	94	611	0.37	1.56	10.94	3.45	18.8	4.4	95.4	0.79	49	11.48	1.19	2.29	9.58	67.00	21.14	16.33

*P with Olsen method was 30 mg/kg

**Sum of base cations and H^+

4. METHODOLOGY AND DATA COLLECTION

4.1 Experimental set up

In order to achieve the objectives of the project, intensive experiments and data collection programmes were established in four orchards at Sandrivier Estate and Smuts Bros Farms. Two orchards were selected at each farm with African Delight and Fortune cultivars that are of particular interest to the growers' association and popular on the markets. Fully-bearing, high-yielding and well-managed orchards were selected to determine the maximum plum water consumption for water allocation purposes. Intensive data collection took place from September 2021 to August 2024, comprising three plum growing seasons, namely 2021/22, 2022/23 and 2023/24. The Fortune orchard at Sandrivier Estate was used only in the 2021/22 season, after which it was uprooted and replaced by Ruby Sun (Block 7) in this project (Figure 3.1). Field data collection included measurements on the soil, plant and atmosphere, thereby characterizing the soil-plant-atmosphere continuum. This Chapter describes the experimental design, methods, instruments and tools used for data collection in order to quantify the soil water balance, crop water consumption and crop water requirements.

4.2 Weather data

Daily weather data were outsourced from two standard automatic weather stations of the ARC from January 2011 until February 2024:

- Weather station No. 30049 in Robertson (Lat: -33.8284; Long: 19.88534; Alt: 156 m)
- Weather station No. 31016 at Diemerskraal, Landau, in the vicinity of Wellington (Lat: -33.5778; Long: 18.96795; Alt: 126 m)

The locations of the weather stations are indicated in the Google Earth maps in Figures 3.1 and 3.4 in relation to the experimental farms and orchards. The Robertson weather station is located about 6 km from Klipboschlaagte Farm and about 10 km from Lucerne Farm. The Landau weather station is about 5 km from Sandrivier Estate.

The weather data served primarily for the calculation of the reference evapotranspiration for use in the HYDRUS model and the calculation of crop coefficients with various methods.

4.3 Soil water content measurements

Amongst many different principles of measuring soil water content (Hillel, 1982; Klute, 1996), measurements based on electromagnetic waves emitted in the soil have become one of the most common approaches in research because they allow to collect and log frequent data at different soil depths. The approach is based on the measurement of the dielectric properties of the bulk soil that depend on soil water content. The most commonly used electromagnetic techniques are Time Domain Reflectometry (TDR, measuring the time of travel/propagation of electromagnetic waves), Frequency Domain Reflectometry (FRD, measuring the frequency of reflected electromagnetic waves) and capacitance. In the capacitance measurement technique, two or more electrodes (metal rods, spikes or rings) are inserted in the soil to form an electrical capacitor. The soil is the dielectric medium and the charging time of the emitted electromagnetic field is a function of its dielectric constant (Hajdu et al., 2019).

The AquaCheck Basic II soil water probes used in the current study are capacitance sensors that measure the dielectric constant of the bulk soil by measuring the voltage between two electric plates (sensor rings). The electromagnetic frequency measured by the rings depends on the dielectric constant and it can be used to calculate the water content of the soil. The probes are positioned at various depths in a 32 mm diameter column inserted in the soil. Different column lengths are provided by the manufacturer for measurement of soil water content in the profile. In this experiment, 800 mm probes were deemed to be suitable to cover the root zone depth of plums, logging data at 10, 20, 30 40, 60 and 80 cm soil depth (Figure 4.1).

The output of the moisture sensors is in Scaled Frequency Unit (SFU). The SFU is calibrated to return 0 for air and 100 for water readings. The range of the moisture sensor is between -5 and 120 SFU. The resolution of the moisture sensor is 0.01 SFU. The temperature sensor range is between -20 and 50°C and the resolution is 0.1°C (AquaCheck, 2019). The sphere of influence of the sensor is about 60 mm in height and 20-45 mm in radius.

AquaCheck probes are calibrated in the factory in controlled air bath and water bath. The output of the AquaCheck probes needs to be calibrated against soil water content for soil- and site-specific conditions. The calibration against soil water content is not linear depending on the characteristics of capacitance in different soils. Calibration equations provided by the manufacturer are expected to provide 5% to 7% accuracy without further calibration. However, for very accurate volumetric soil water content readings, the manufacturer recommends in-field calibration using soil water depletion cycles to identify at least two calibration points, preferably permanent wilting point and field capacity.

In a performance evaluation of AquaCheck probes conducted in silt loam soils on rangeland in New Zealand (Hajdu et al., 2019), it was demonstrated that the accuracy of volumetric soil water content improved for single probe and sensor calibration depending on soil wetness, bulk density, clay and total organic carbon content. Hajdu et al. (2019) reported that the SFU formula used for calibration against open air and distilled water takes the form of:

$$SFU = \frac{F_a - F_s}{F_a - F_w} \qquad [1]$$

F_s – Electromagnetic frequency reading in the soil

F_a – Electromagnetic frequency reading in air

F_w – Electromagnetic frequency reading in distilled water

The SFU readings are automatically corrected by temperature, which is also measured with sensors. Factory calibration equations to convert SFU into volumetric soil water content (θ_v) take the generic form of:

$$\theta_v = b_0 + b_1 * SFU \qquad [2]$$

where b_0 and b_1 are coefficients of the linear calibration (intercept and slope) and they depend on soil texture. Additional calibration may, however, be required for specific sites and soils (Hajdu et al., 2019) by taking samples and determining soil water content with the gravimetric method.

Specific precautions need to be put in place in handling the installation of access tubes. A slurry is prepared that serves to fill air gaps between the access tube and the soil. The access tube needs to adhere properly to the surrounding soil as air gaps may distort the soil water content readings. The slurry must be representative of the soil textures and layers.

Soil water content data are stored in the probe for up to 6 weeks (30 min reading intervals) and they can be collected with a hand-held wireless data logger (AquaCheck Basic II data logger) through radio frequency (RF) telemetry (Figure 4.1). The data can then be downloaded to a PC and processed in a software for viewing trends (CropGraph/Plant-Plus). The battery pack of the probes lasts approximately 18 months, after which it can be replaced.

AquaCheck Basic II soil water probes were installed during July 2021 (Figure 4.1) according to guidelines (AquaCheck, 2010), for hourly measurements of soil water content. Table 4.1 summarizes the installation of AquaCheck probes in the four experimental orchards. The purpose was to measure soil water contents both in-row and half-way between rows in order to describe differences in wetness between the wetted and non-wetted areas by micro-irrigation. Two replicates were installed in each orchard to describe variability in soil water contents. Although precautions were taken by the research teams and farm managers, all probes installed between rows were damaged by machinery during the course of the three years of experimentation. The in-row probes operated and collected data throughout the three years of experimentation.

a) b)

c) d)

Figure 4.1 *a) AquaCheck probe (top left), b) hand-held wireless AquaCheck Basic II data logger (top right), c) installation of AquaCheck probes with a portable motor drill (bottom left) and d) installed AquaCheck probe (bottom right).*

Table 4.1 Installation positions of AquaCheck soil water probes in four plum orchards at Wellington and Robertson.

<table>
<tr><th>Farm</th><th>Variety</th><th>Orchard block</th><th>Position</th><th>Probe</th></tr>
<tr><td rowspan="6">Sandrivier</td><td rowspan="2">Fortune</td><td rowspan="2">82</td><td>Row 21, in-row</td><td>UWC1</td></tr>
<tr><td>Row 20-21, mid-row</td><td>UWC2</td></tr>
<tr><td rowspan="4">African Delight</td><td rowspan="4">47</td><td>Row 8-9 upper section, mid-row</td><td>UWC3</td></tr>
<tr><td>Row 8 upper section, in-row</td><td>UWC4</td></tr>
<tr><td>Row 8 lower section, in-row</td><td>UWC5</td></tr>
<tr><td>Row 8-9 lower section, mid-row</td><td>UWC6</td></tr>
<tr><td rowspan="8">Smuts Bros</td><td rowspan="4">Fortune</td><td rowspan="4">L17</td><td>Row 14 upper section, in-row</td><td>UWC7</td></tr>
<tr><td>Row 14-15 upper section, mid-row</td><td>UWC8</td></tr>
<tr><td>Row 25 lower section, in-row</td><td>UWC9</td></tr>
<tr><td>Row 24-25 lower section, mid-row</td><td>UWC10</td></tr>
<tr><td rowspan="4">African Delight</td><td rowspan="4">K35</td><td>Row 20 lower section, in-row</td><td>UWC11</td></tr>
<tr><td>Row 20-21 lower section, mid-row</td><td>UWC12</td></tr>
<tr><td>Row 55 upper section, in-row</td><td>UWC13</td></tr>
<tr><td>Row 55-56 upper section, mid-row</td><td>UWC14</td></tr>
</table>

The main purpose of the AquaCheck probes was to monitor changes in soil water content as a result of root water uptake, rainfall and irrigation. These data were used in the platform provided by AquaCheck for irrigation scheduling. Soil water contents measured with AquaCheck probes were also used to calibrate the HYDRUS-2D model.

4.4 Soil sampling for calibration of AquaCheck probes

The output of the AquaCheck probes needed to be calibrated against soil water content for soil- and site-specific conditions. Probe calibration was therefore conducted by taking samples and determining soil water content using the gravimetric method. Undisturbed soil samples were taken with Kopecki cylinders (100 cm^3 in volume) at depths of 10 and 30 cm. Sampling took place in the vicinity of AquaCheck probes to obtain volumetric soil water content vs. SFU calibration points. Samples were sealed and dried in the laboratory at 105°C to determine gravimetric soil water content and soil bulk density. Volumetric soil water content was then calculated using soil bulk density values.

Soil samples were collected in replicates throughout the course of the experiment following extensive rainfall to determine volumetric soil water content values approximating field capacity, and during the dry seasons in particular in the non-irrigated portion of the field between the tree rows to determine lower limits of available soil water. The samples were collected to a depth of about 40 cm, where most of the root system was observed to occur (Figure 4.2).

Figure 4.2 *Plum root system observed in a 0.5 m deep soil pit in the Fortune orchard at Sandrivier Estate.*

4.5 Micro-lysimeters

A set of micro-lysimeters for measurement of evaporation from the soil surface were constructed in-house based on the model described by Facchi et al. (2017). The micro-lysimeters consist of a 90 mm PVC irrigation pipe about 120 mm in length and sealed at the bottom with a PVC end cap. Wider 110 mm PVC drainage pipes were cut out to a length of about 120 mm. The 110 mm PVC pipes were inserted in holes dug out in the soil to act as walls and provide stability so that the soil does not cave into the hole. The 90 mm diameter micro-lysimeters were then inserted in the external 110 mm PVC pipes and filled with soil representative of the measurement area. The micro-lysimeters were filled with soil and vegetation representative of the conditions in the field (Figure 4.3). In order to ensure representativity of the measurement, the micro-lysimeters were installed in the field immediately before measurement campaigns. The weight of the micro-lysimeters was measured using a portable weighing scale at 0.1 g resolution. The change in weight corresponded to soil evaporation. The micro-lysimeters were installed to measure soil evaporation at five positions across the tree row: tree row; ¼ distance from the tree row; ½ distance from the tree row; ¾ distance from the tree row; tree row (Figure 4.3). The weight of the micro-lysimeters was measured approximately at two-hour intervals to describe daily trends of soil evaporation and capture the effects of shading on soil evaporation. The dates of measurement campaigns lasting a full day were 20/10/2021, 08/12/2021 and 25/10/2022 at Sandrivier Estate, and 03/11/2021, 10/12/2021 and 28/10/2022 at Smuts Bros. The dates of measurement covered the period of full canopy development.

The main purpose of micro-lysimeter measurements was to determine the range of evaporation from the soil in the orchards, and compare these measurements to soil evaporation values simulated with the HYDRUS-2D model.

Figure 4.3 *Top: In-house manufactured micro-lysimeters installed in the field for measurement of soil evaporation. Bottom: Micro-lysimeters installed across the tree rows.*

4.6 Leaf Area Index (LAI) and canopy interception of radiation

The main purpose of measurements of LAI and canopy interception of radiation (fc) was to determine the seasonal growth curve of plums and to calculate basal crop coefficients (Kcb) as a function of LAI and fc using the method proposed by Allen and Pereira (2009).

Measurements of LAI and fc were carried out with an LAI-2200C plant canopy analyser (LI-COR, Lincoln, Nebraska, USA; https://www.licor.com/documents/ny34xgfry9ewxma8p97y accessed on 18 July 2021). The LAI-2200C plant canopy analyser is composed of a console (control unit) and a wand with the sensor (Figure 4.4). The LAI-2200C calculates fc and LAI (foliage area index) from light measurements using a “fish-eye” optical sensor. The “fish-eye” optical sensor includes five lenses oriented at different zenith angles. Light measurements are taken above and below the vegetation canopy to determine light attenuation through the crop canopy. A model of radiative transfer is then used to compute fc and LAI. Sampling sites can be geo-referenced with a GPS system incorporated in the instrument. The theory and operation of the LAI-2220C are described in the instruction manual (Li-Cor, 2015).

Figure 4.4 *Components of the LAI-2200C plant canopy analyser: console and wand (top left); close- up of the console (control unit); and close-up of the "fish-eye" light sensor installed on the wand.*

The Allen and Pereira (2009) method was used to determine Kcb as a function of canopy cover or LAI. For tree crops having grass or other ground cover, Kcb was calculated as follows:

$$K_{cb} = K_{cb\ cover} + K_d \left(\max \left[K_{cb\ full} - K_{cb\ cover}, \frac{K_{cb\ full} - K_{cb\ cover}}{2} \right] \right) \qquad [3]$$

$K_{cb\ cover}$ – Kcb of the ground cover in the absence of tree foliage

K_d – Canopy density coefficient

$K_{cb\ full}$ - Estimated Kcb during peak plant growth for conditions having nearly full ground cover (or LAI = 3)

$K_{cb\ cover}$ was estimated to be 0.7, based on the value reported by Allen and Pereira (2009 in Table 4) for the initial stage of fruits (apricots, peaches, pears, plums, pecans) with no killing frost.

The K_d coefficient can be calculated as follows (Allen and Pereira, 2009):

$$K_d = 1 - e^{(-0.7\,LAI)} \quad [4]$$

LAI and fc were measured with the LAI-2200 plant canopy analyser and they were found to be quite stable during the mid-stage because the trees were pruned to the required canopy size. Average LAI was therefore used in the equation to calculate K_d.

$K_{cb\ full}$ was calculated according to the following equation (Allen and Pereira, 2009):

$$K_{cb\,full} = F_r\left(\min(1.0 + 0.1\,h, 1.20) + [0.04(u_2 - 2) - 0.004\,(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3}\right) \quad [5]$$

F_r - Downward adjustment ($F_r \leq 1.0$) if the species exhibits more stomatal control on transpiration than is typical of most annual agricultural crops

h – Crop height (m)

u_2 – Wind speed at 2 m height (m s^{-1})

RH_{min} – Minimum daily relative humidity (%)

In the current study, crop height was 3 m at Smuts Bros and 3.5 m at Sandrivier Estate, whilst u_2 and RH_{min} were obtained from the weather stations. The adjustment F_r can be calculated as follows (Allen and Pereira, 2009):

$$F_r \approx \frac{\Delta + \gamma\,(1 + 0.34\,u_2)}{\Delta + \gamma\left(1 + 0.34\,u_2\,\frac{r_l}{100}\right)} \quad [6]$$

Δ – Slope of the saturation vapour pressure-air temperature curve (kPa °C^{-1})

γ – Psychrometric constant (kPa °C^{-1})

r_l - Mean leaf resistance for the species (s m^{-1})

The slope of the saturation vapour pressure-air temperature curve can be calculated with equation:

$$\Delta = \frac{4098\left[0.6108\,exp\left(\frac{17.27\,T_{avg}}{T_{avg}+237.7}\right)\right]}{\left(T_{avg}+237.3\right)^2} \quad [7]$$

where T_{avg} is the daily average temperature in °C. The psychrometric constant is approximately 0.0665 kPa °C^{-1} at standard atmospheric pressure. In the absence of measurements of stomatal resistance, r_l for plums was assumed to be 100 s m^{-1} resulting in F_r = 1.

In the current study, initial Kcb at the beginning of the season (1 September) was calculated from K_d and LAI measured during the period of dormancy (Allen and Pereira, 2009). The value of LAI was increased linearly until day 45 of the season (15 October), when full cover was reached at mid-stage, and Kcb was calculated accordingly. The value of Kcb for the mid-stage until harvest was calculated based on the average fc and average LAI measured with the LAI-2200C plant canopy analyser. Values of fc and LAI didn't change much during the full cover period because the trees were pruned to reduce vegetative growth and facilitate harvesting.

4.7 Stem water potential

Knowledge on plant-water relations is fundamental in identifying the onset of water stress and for irrigation scheduling, i.e. deciding the timing and volume of irrigation. This is particularly important in intensive high-yielding plum orchards to sustain high productivity and secure stable income. Extensive research on plant water stress indicators was conducted internationally, in particular in Spain. For example, Naor (2004) reported the relationships between soil water potential, midday stem and leaf water potential, stomatal conductance and yield indicators (fruit weight, fruit per tree, relative yield) for Black Amber grafted on Mariana rootstock. The midday stem water potential was often demonstrated to be a good indicator of water stress to describe the anisohydric behaviour of plums. This was the case of research conducted by Intrigliolo and Castel (2004) who assessed the fitness of plant water status indicators for irrigation scheduling in a five-years old Japanese plum (cv Black Gold) orchard. They concluded that stem water potential was the most sensitive and the least variable indicator. In subsequent studies, Fernandez and Cuevas (2010) and Blanco-Cipollone et al. (2017) confirmed stem water potential measurements are more feasible than other indicators for irrigation scheduling of anisohydric species such as plums. A threshold midday stem water potential of -1.5 MPa was recommended by Blanco-Cipollone et al. (2019) to avoid fruit size losses of cv Angeleno, in combination with tree crop load adjustment. Torrecillas et al. (2018) provided practical recommendations to maintain midday stem water potential >-0.7 MPa in stage I, >-1.5 MPa in stage II, >1.0 MPa in stage III and >-1.65 MPa at post-harvest in mid-season and late-ripening plum trees.

Although midday stem water potential was reportedly identified as a good indicator of plant water stress for irrigation scheduling, the measurement of this variable is destructive, time consuming and laborious. It involves the sealing of individual healthy and mature leaves in sun-reflecting envelopes and the measurement of water potential in those leaves at equilibrium with the stem. Measurements of water potential is commonly carried out manually with Scholander pressure chambers (Scholander et al., 1965). This makes the methodology time- and labour-intensive.

A new product available on the market was investigated that logs stem water potential data with sensors inserted directly in contact with the tree's xylem. The sensors are produced by Saturas (https://saturas-ag.com, accessed on 18 February 2023) and marketed in South Africa by Aquahaus (https://www.aquahaus.co.za, accessed on 18 February 2023). The Saturas technology consists of a humidity sensor that exchanges water vapour with the plant's xylem through an osmotic membrane. The relative humidity in the sensor's chamber is correlated with the water potential in the plant's stem. Half-hourly measurements are logged and relayed to a receiver that transmits data to an Internet platform. The half-hourly data are processed to produce midday stem water potential values that can be used as plant water stress indicators for irrigation scheduling.

Figure 4.5 depicts the sensor and the installation process in the tree trunk. Sensors are isolated from surrounding heat with a polystyrene shield and enveloped in reflective cover (Figure 4.5). A relay antenna (Figure 4.5) transmits the sensor's signal to a receiver installed in the vicinity of the measurement site and requiring a power supply (Figure 4.5). Data are then transmitted by the receiver to an Internet platform for processing and visualization. A pressure transducer is also installed in the water distribution pipeline of the measuring field to keep track of irrigation timing (Figure 4.5). Irrigation events can be correlated with the plant response and variations in stem water potential. The company sells the installation of the system and provision of irrigation scheduling data as a service.

In this project, three Saturas sensors were installed in three trees of each experimental orchard (a total of 12 sensors with required remote data collection systems) on 14-15 February 2023. The sensors were installed according to the pattern reported in Table 4.2. The main purpose of this installation was to keep track of the plant water status to ascertain that irrigation scheduling on the farm did not induce plant water stress that could have affected the determination of plum water requirements in the high-yielding, full-bearing orchards.

Sadly, the Saturas company declared bankruptcy in September 2023, stopped supplying services and closed the website for data retrieval. Notwithstanding the attempts of the research team and the South African representative from Aquahaus to retrieve the logging data, this was unsuccessful. Data remained recorded and available only from February to July 2023.

Table 4.2 Installation details of Saturas sensors.

Farm	Orchard	Sensors and rows	Notes
Sandrivier (Wellington)	Block 47 cv African Delight	3 sensors in row 8	Sensors installed in the row of AquaCheck probes
	Block 7 cv Ruby Sun	Sensors in rows 15, 18, 21	Sensors installed in the middle of the orchards
Smuts Bros (Robertson)	Block K35 cv African Delight	3 sensors in row 21	Sensors installed in the row of AquaCheck probes; middle sensor is on grafted pollinator
	Block L17 cv Fortune	Sensors in rows 14, 19, 25	Sensors installed in the rows of AquaCheck probes and to cover the gradient in soil texture

Figure 4.5 *From top left clockwise: Saturas sensor for measurement of stem water potential; Sensor mounting: a hole in the tree trunk is drilled until the appearance of soft tissue; Sensor installed in the trunk; Antenna relay that transmits the sensor's signal to a receiver; Saturas sensor installed in a plum tree trunk and covered with polystyrene; Reflective cover for isolation; and Pressure transducer installed to keep track of irrigation timing.*

4.8 Irrigation volumes and crop yields

Irrigation data measured with water meters were obtained from the farm in the following formats:

- Hourly irrigation volumes and dates for Fortune and Ruby Sun blocks at Sandrivier Estate.
- Volumes estimated from irrigation duration and irrigation frequency for African Delight block at Sandrivier Estate.
- Weekly volumes of irrigation for Fortune and African Delight blocks at Smuts Bros.

As a result, exact days of irrigation events for African Delight block at Sandrivier Estate, Fortune and African Delight blocks at Smuts Bros were identified based on the response of AquaCheck sensors (peaks in soil water content).

A verbal agreement was made with the farm managers to obtain crop yield data and fruit grading into the various market classes.

4.9 HYDRUS-2D modelling

4.9.1 Model description

The HYDRUS 2D/3D model (Simunek et al., 2020) is a well-known software package that can be used to simulate water, heat and solute transport in 2D and 3D saturated and unsaturated porous media. It consists of a computational program and a fairly sophisticated and user-friendly Graphic User Interface (GUI). While the computational program is written in FORTRAN, the GUI is written in C++. The computational program of HYDRUS solves Richards' equation for saturated/unsaturated water flow (Richards, 1931) and the convection-dispersion equation for heat and solute transport in porous media. Flow and transport in dual porous media can also be simulated by setting up zones with different water and solute mobility to simulate preferential flow processes, if sufficient input data and knowledge of the system are available. A detailed technical description of HYDRUS 2D/3D is given in Simunek et al. (2020).

The GUI of HYDRUS is used to define the computational domain and geometry, the inputs (pre-processing unit) and the outputs (post-processing unit). The pre-processing unit includes flow and transport input parameters (general information, water flow parameters, solute transport parameters, heat transport parameters, and root water uptake and growth parameters), and grid (mesh) generators. The pre-processing unit also includes a database of soil hydraulic properties and a program for generating soil hydraulic properties from textural information (Rosetta Lite). The post-processing unit consists of graphical presentations, contour maps and animations of outputs of the water, heat and salt balance. The GUI was described in detail by Sejna et al. (2020).

In this project, the HYDRUS 2D/3D version 3.04 (Simunek et al., 2020) was used to determine the soil water balance in each orchard. There were a number of reasons for using HYDRUS in this specific research. Firstly, the model is fit to describe a two-dimensional water balance system with micro-irrigation, where portion of the land is wetted (along tree rows) and another portion is non-wetted (between tree rows). Secondly, the HYDRUS model uses Richards' equation (Richards, 1931) to calculate soil water redistribution that gives a more physically-based representation of soil water redistribution as compared to traditional tipping bucket/cascading soil water balance models. It is, however, also more data-intensive. Thirdly, one of the main objectives of this project was to provide recommendations to farmers on efficient water use. To this effect, given the underlining physics of the 2D processes, it was deemed that the HYDRUS model would give realistic and accurate results of the field soil water balance, in particular the volume of water that passes the root system and ends up recharging groundwater due to over-irrigation. Some of the theory of the HYDRUS model relevant to the current research project (soil water flow, root water uptake, soil hydraulic functions, boundary conditions and numerical solution to Richards' equation for unsaturated flow) were described in Deliverable 3 of this project.

4.9.2 Input data

The HYDRUS numerical solution to the soil water balance can be applied in transient and steady-state simulations. It was envisaged that, for the purpose of this project, transient simulations were far more relevant because they account for variability of boundary conditions over time (e.g. atmospheric evaporative demand, root water uptake, rainfall and irrigation etc.).

In order to parametrize the model for the orchards at the study sites, two model domain geometries were constructed in HYDRUS-2D. The first model domain geometry had a rectangular shape to represent a row cross-section of the orchards in Robertson. The dimensions of the cross-section were 4 m (tree row width) x 1 m (depth of root zone) (Figure 4.6, top). The second model domain geometry was set up to represent realistically the row cross-section with tree rows planted in ridges at Wellington, with dimensions of 3.5 m (tree row width) x 0.8-1.1 m (soil depth at mid-row furrow – soil depth at ridge) (Figure 4.6, bottom). The light blue lines within the model domains represented the mesh connecting the nodes. The simulated processes were water flow and root water uptake at a time interval of 1 day with daily outputs for each growth season (September to January-March) and for each hydrological year (September to August). Default iteration criteria were used.

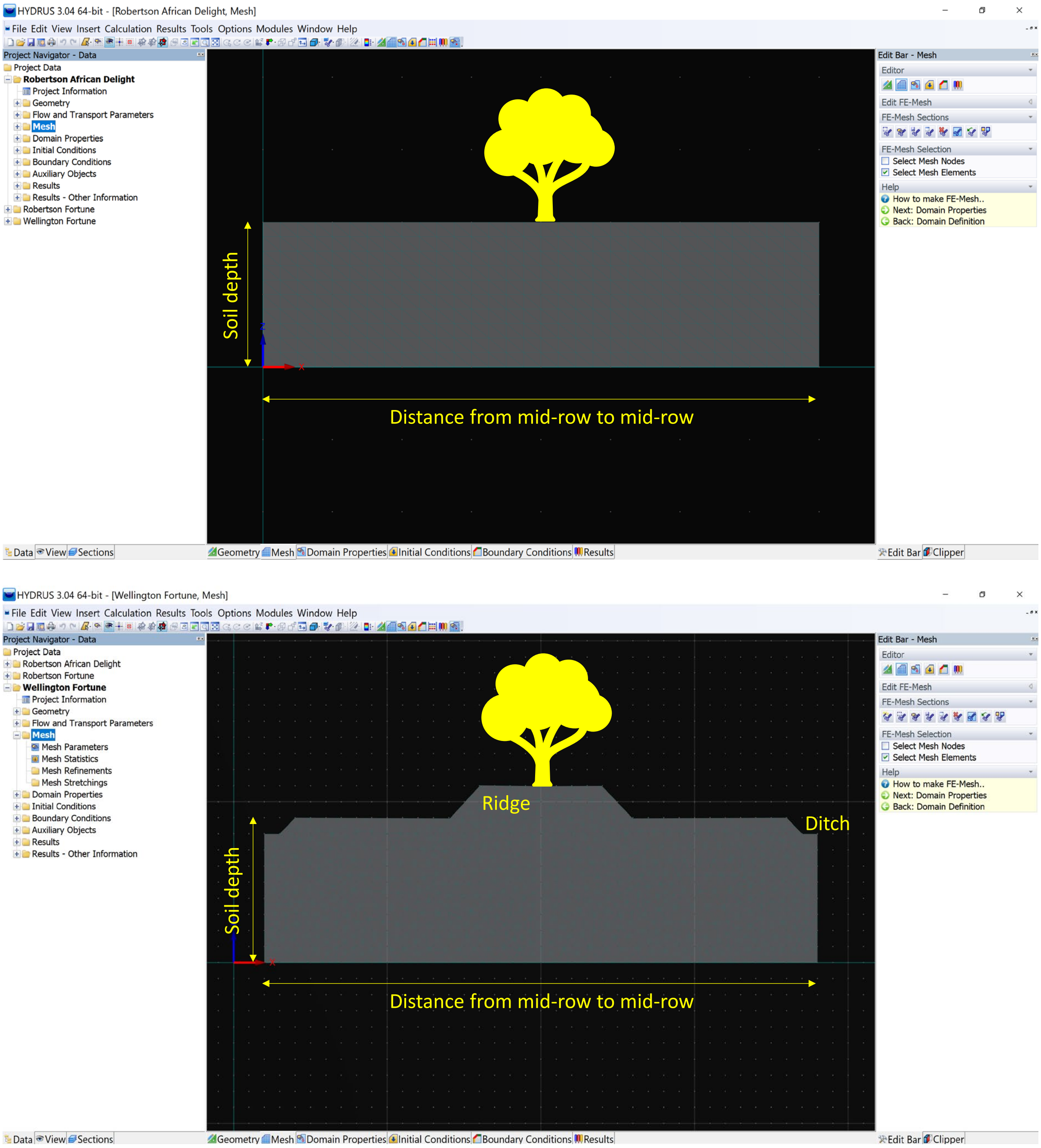


***Figure 4.6** Printscreen of HYDRUS-2D representing the model domain geometries with schematic representation. Top: Rectangular cross-section with dimensions 4 m (tree row width) x 1 m (depth of root zone) for orchards in Robertson. Bottom: Cross-section with ridge and furrow with dimensions of 3.5 m (tree row width) x 0.8 – 1.2 m (soil depth at mid-row furrow – soil depth at ridge) for orchards in Wellington. A small 10 cm deep ditch is established in the middle between rows.*

Soil hydraulic characteristics are key properties that serve the calculation of the soil water balance. Unsaturated soil water contents and hydraulic conductivities are calculated as a function of pressure head, residual volumetric soil water content θ_r, volumetric soil water content at saturation θ_s, saturated hydraulic conductivity K_s and the empirical parameters affecting the shape of the hydraulic functions, namely α (inverse of the air-entry value or bubbling pressure), n (pore-size distribution index) and l (pore-connectivity parameter). The Van Genuchten-Mualem soil hydraulic model was chosen to characterize unsaturated hydraulic conductivity vs pressure head. Soil hydraulic parameters were calculated with a neural network prediction incorporated in HYDRUS (Rosetta Lite), based on soil properties and calibrated against observed volumetric soil water contents obtained with AquaCheck probes (Section 4.3). The AquaCheck readings were calibrated with the gravimetric method (Section 4.4) to obtain observed volumetric water contents. The following soil hydraulic parameters were used as inputs for each experimental orchard:

- African Delight orchard in Robertson
  - Soil water content at saturation: 0.20 m/m
  - Field capacity: 0.14 m/m
  - Residual soil water content: 0.03 m/m
- Fortune orchard in Robertson
  - Soil water content at saturation: 0.40 m/m
  - Field capacity: 0.25 m/m
  - Residual soil water content: 0.04 m/m
- African Delight orchard in Wellington
  - Soil water content at saturation: 0.38 m/m
  - Field capacity: 0.20 m/m
  - Residual soil water content: 0.04 m/m
- Fortune orchard in Wellington
  - Soil water content at saturation: 0.36 m/m
  - Field capacity: 0.20 m/m
  - Residual soil water content: 0.04 m/m
- Ruby Sun orchard in Wellington
  - Soil water content at saturation: 0.36 m/m
  - Field capacity: 0.24 m/m
  - Residual soil water content: 0.04 m/m

According to textural analysis reported in Chapter 3 of this report, the soil in Robertson is predominantly clay and the soil in Wellington is predominantly loam. However, field observations with AquaCheck probes served to determine field capacity and residual soil water contents. For example, the African Delight orchard in Robertson is planted on a stony soil with an inherently low volumetric soil water content at field capacity ≈ 0.14 m/m. This was corroborated with field measurements with AquaCheck probes installed in-row, where it was found that volumetric soil water contents at field capacity lingered around 0.14 m/m after irrigation and rainfall (Section 5.2). Likewise, residual soil water contents were estimated from field observations with AquaCheck probes installed in mid-row, and they corresponded to the lowest recorded volumetric soil water contents (Section 5.2). In this way, soil hydraulic input parameters coincided with real field observations. Initial conditions were set with soil water content at field capacity for all orchards, as all simulations started on 1 September after the rainy season.

The root distribution functions in HYDRUS can be implemented in two or three dimensions, or as a function of root growth (Simunek et al., 2020). The latter is not required for tree orchards with established root systems. Root distribution in the orchards was set in the domain properties according to the patterns in Figure 4.7, based on discussions held with farm managers on the volume explored by tree roots. The root water uptake model of Feddes et al. (1978) was selected for the simulations with no solute stress. Root water uptake parameters of the Feddes' model for deciduous fruits were selected from the database incorporated in HYDRUS.

Observation points can be inserted at nodes in the mesh to write output variables in output files at the selected time-step intervals, e.g. soil water content. Data for these output variables can then be used for model validation by comparing HYDRUS output values with field measurements. Observation nodes were set according to Figure 4.8 to represent positions of measurements of soil water content with AquaCheck probes. Soil depths were 10, 20, 30, 40, 60 and 80 cm. The model writes soil water contents at these observation nodes in the output file for each time step. The simulated values of soil water content could then be calibrated against field measurements with AquaCheck probes.

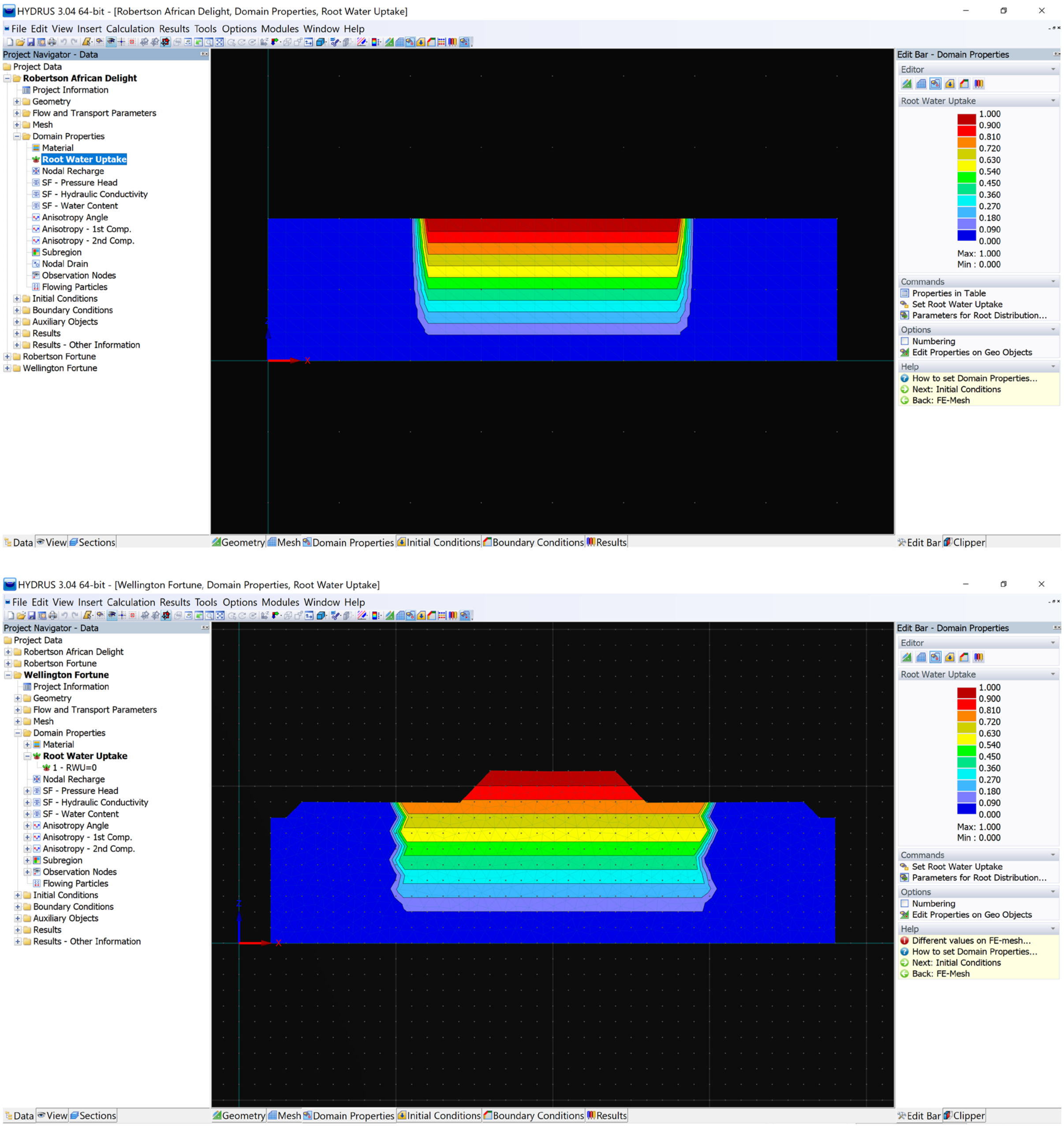


***Figure 4.7** Printscreen of HYDRUS-2D representing the root distribution at Robertson (top) and Wellington (bottom).*

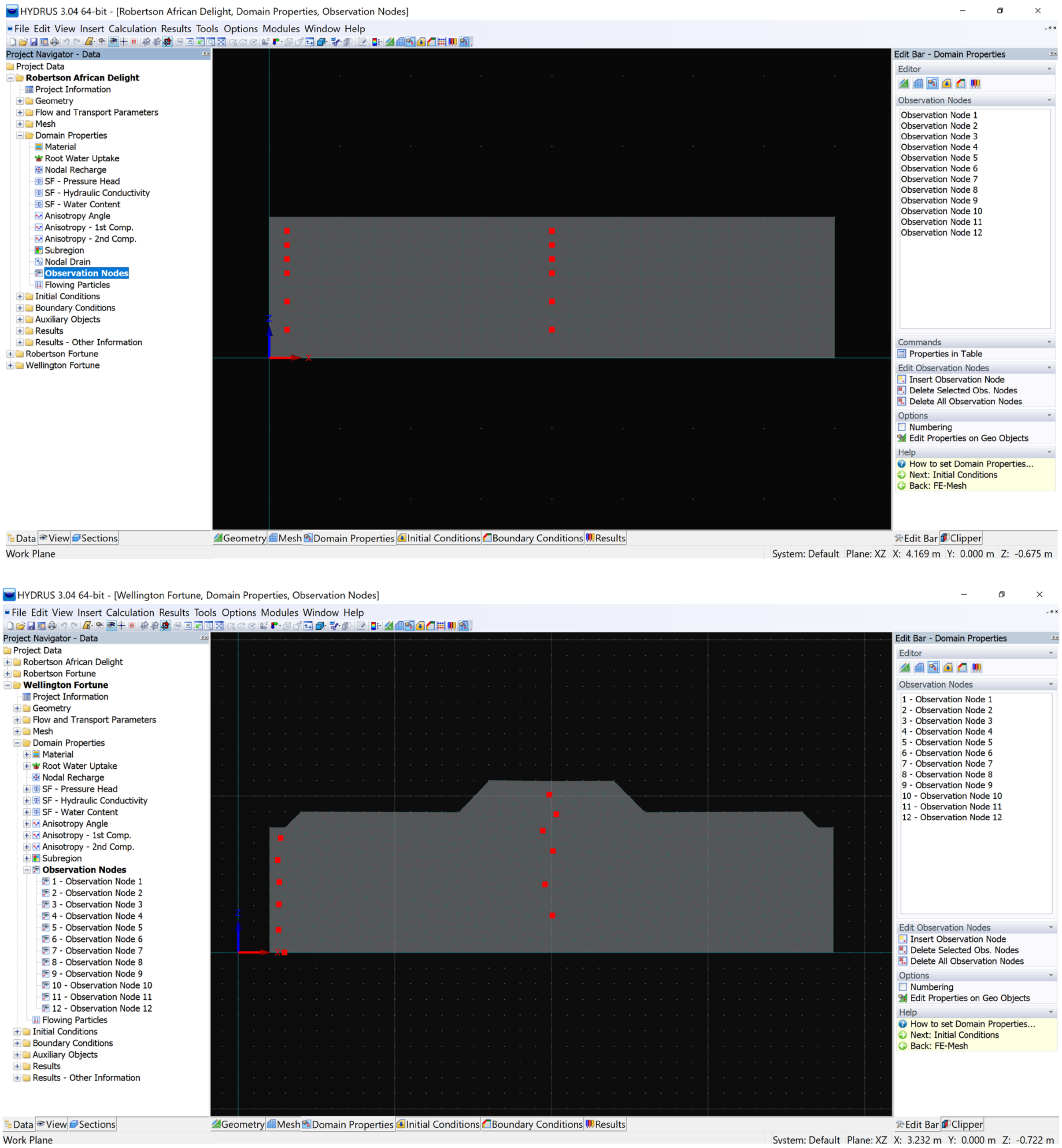


Figure 4.8 *Printscreen of HYDRUS representing observation nodes marked with red circles at Robertson (top) and Wellington (bottom).*

Time-variable or system-dependent boundary conditions need to be specified, such as atmospheric boundary conditions at the interface between soil and atmosphere (fluxes of evaporation, rainfall, infiltration, pressure head), seepage face, tile drains and others (Simunek et al., 2020). Notably, one option that can be selected as time-variable boundary condition is surface drip-irrigation with dynamic evaluation of the wetted area. This surface boundary condition allows one to simulate the practice occurring in irrigated tree orchards. The user needs to specify the irrigation flux to boundary nodes representing the drippers (e.g. placed at the left/right edge or in the middle of the surface boundary), and the time-variable boundary at the surface, which length needs to be sufficiently large to include the wetting zone. The HYDRUS model then calculates the radius of the dynamically increasing wetted area under the dripper for transient conditions.

Boundary conditions of the model domain were defined according to the patterns in Figure 4.9. The boundary nodes in light green represent the atmospheric boundary conditions. This is a time-variable boundary condition that requires precipitation, potential evaporation and potential transpiration values as inputs for transient simulations. Precipitation, potential evaporation and potential transpiration are entered in tabular format for the given modelling time step (daily). Potential soil evaporation and potential transpiration were partitioned using the reference evapotranspiration ETo (Allen et al., 1998) calculated from weather data and fractional interception of radiation measured with the LAI-2200C.

The purple boundary nodes represent a special time-variable boundary condition. It represents surface drip with dynamic wetting and it is used to simulate surface drip (or micro-jet) wetting of the surface. The specific equations used to simulate micro-irrigation and the wet bulb formation were described in detail by Simunek et al. (2020). The surface area associated with transpiration was set to be 2 m for the orchards in Robertson (three dripper lines) and 1.8 m for Wellington (micro-jet irrigation), which was confirmed through field observations.

The boundary nodes in white on the vertical faces of the domain represent no flux boundaries, assuming that no horizontal fluxes occur in the soil. The bottom boundary is a free drainage boundary (dark green boundary nodes) along which water percolation beyond the root zone is calculated.

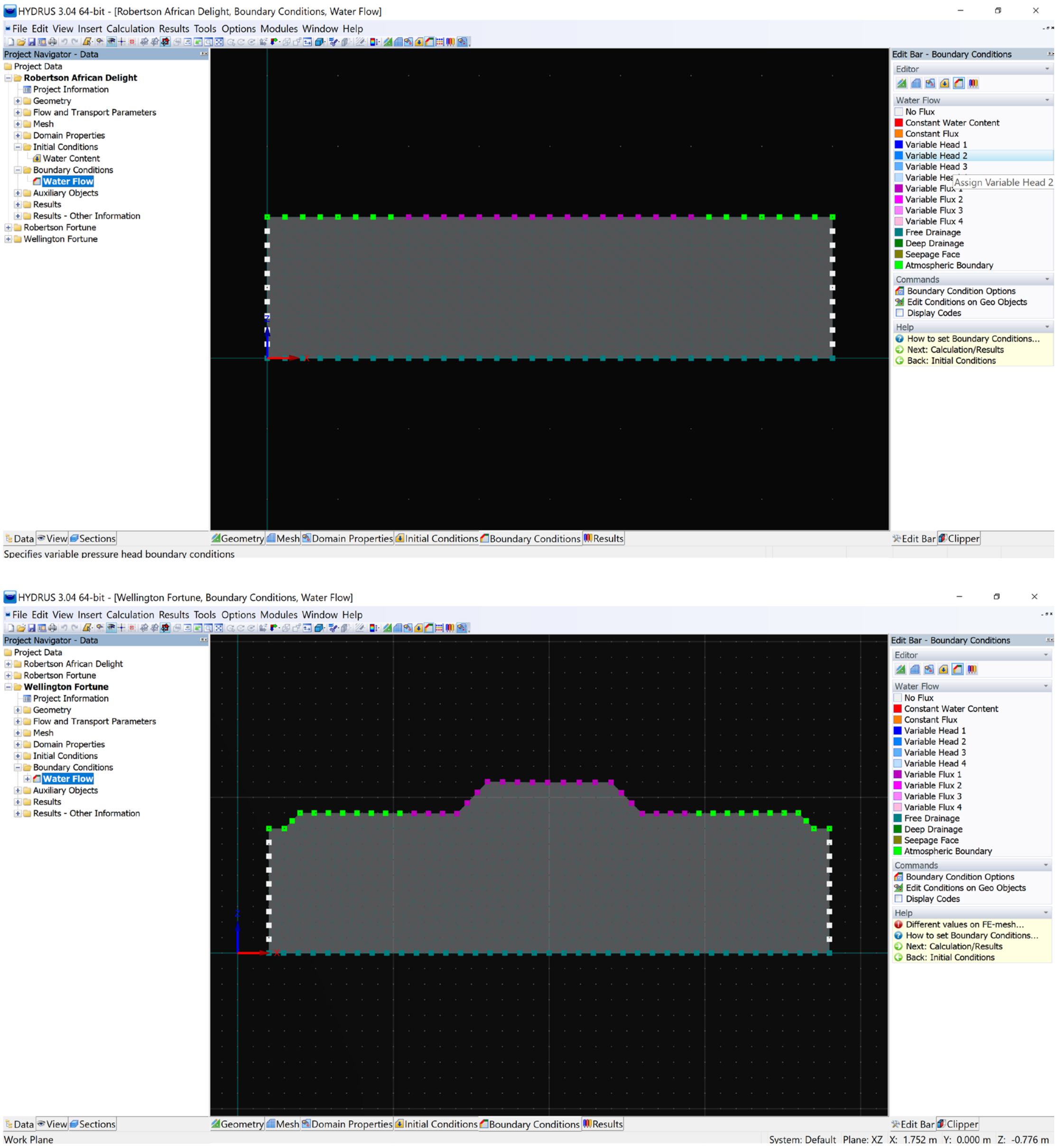


Figure 4.9 *Boundary conditions of the model domains (Robertson, top; Wellington, bottom) with boundary nodes represented with circles in different colours: Light green – atmospheric boundary conditions; Purple – Surface drip with dynamic wetting; White – No flux boundary; and Dark green – Free drainage boundary.*

4.10 Eddy covariance micrometeorological system

4.10.1 Introduction

Crop evapotranspiration (ETc) from a vegetated surface can be determined directly by using micrometeorological methods. Among these micrometeorological methods is the eddy covariance that allows measurements of gas exchange and emission rates, and measurements of momentum, sensible heat, and latent heat fluxes that are integrated over areas of varying sizes (López-Olivari et al., 2016). The eddy covariance method characterises fluxes of various gases such as CO_2, H_2O, NH_3, CH_4, N_2O and O_3 etc., above the soil and water surfaces, and plant canopies, from a single point measurement. The method is used in many applications that include scientific research, environmental and industrial monitoring, and production agriculture. The eddy covariance method is considered one of the most direct, defensible and accurate approaches for determining the emission of gases and consumption rates of water vapour (Jovanovic et al., 2018). It relies on a three-dimensional wind sensor that provides direct and fast measurements of actual gas transport. Measurement of gas fluxes in and out of the ecosystem, monitoring of gas emission rates and quantifying evaporative water losses from an agricultural field can, therefore, be done with an extensive variety of techniques (López-Olivari et al., 2016).

Modernised instruments and software have caused the eddy covariance method to be easily available and thus widely used throughout the world over the last two decades. The method has been used extensively in other disciplines beyond micrometeorology. However, the eddy covariance method comes with a main challenge of the complexity of the system design and implementation. The processing and analysis of large volumes of data cannot go unmentioned. Although modernised instruments and software can solve these complexities, there is a need to understand the underlying eddy covariance principles and resulting requirements for the lucrative implementation of the method.

Up to date, there are countless options for eddy covariance flux tower designs and considerably growing instrument and configuration options. Choosing from these options requires one to find an optimal solution that best attains the accuracy required to accomplish the respective scientific objectives while minimising installation and operational costs (Munger et al., 2019). The right location of the tower placement and the correct mounting of all the components that make up the eddy covariance system is essential for precise overall performance and reduced uncertainty levels.

Measuring scalar exchanges above the vegetation canopy is characterised by a unique set of challenges. Eddy covariance flux towers need to be designed in a way that best captures ecological drivers and various processes from different types of surfaces, i.e. from complex forest ecosystems to relatively simple homogenous grasslands (Munger et al., 2019). Towers that support the instrumentation and sensors need to be robust enough to withstand extreme weather. The stability of the tower can influence the measurement of winds and turbulent fluxes (Barthlott and Fiedler, 2003). Thus, any movement of the tower that may covary with either the scalar of interest or turbulence fluctuations of wind speed, may contribute towards uncertainty in the measurements or estimates (Munger et al., 2019).

This Section focuses primarily on the installation of the eddy covariance flux tower on an irrigated African Delight orchard at Klipboschlaagte farm in Robertson. The African Delight orchard in Robertson was selected for the installation of the eddy covariance system because it was the largest study orchard (>4 ha), it is surrounded by other irrigated orchards of similar age and canopy structure, and this mitigated the assumptions around the required fetch distance from the border of the orchard. The eddy covariance system recorded the energy balance from 11 May 2023 to 31 August 2024. This Section describes all the components and sensors of the tower, while explaining specific steps of mounting and installing all the components.

4.10.2 Installation of flux tower

The eddy covariance flux system was erected between rows 20 and 21 (33°49’33” S, 19°56’1” E), at the lower section of the Block K35 African Delight orchard in Robertson (Figure 4.10). The average canopy height of the African Delight plums was 3 m. The mounting was made up of a stainless steel CM120 tripod that held a 6-meter mast. To secure the mounting, the 6-meter-long mast was slid through the tripod leg junction and cemented 1 meter into the ground. A PWENC 16/18 pre-wired weather-resistant 16 x 16-inch enclosure containing a 12 V rechargeable battery (84Ah) and a SunSaver MPPT 15 A charge controller for the battery was mounted 0.23 m from the ground, on the tripod. A PWENC 16/18 pre-wired weather-resistant 16 x 16-inch enclosure containing a CR1000X measurement and control datalogger, and a VOLT116 Granite series 16- or 32-channel 5V analogue input module was mounted 1.70 m from the ground surface on the same tripod. Six spikes for the tripod feet were used to secure the stands to the ground. A stainless steel lighting rod was mounted on top of the mast, while a copper rod was dug halfway into the ground, approximately a meter from the tower.

Figure 4.10 *The eddy covariance flux tower mounted in an African Delight orchard at Klipboschlaagte farm.*

4.10.3 Sensors installation and configurations

All sensors and system components were installed according to their respective product manuals. Thus, instructions on the installation, configuration and mounting of all the sensors were according to the guidelines provided by Campbell Scientific (Logan, Utah, USA).

EasyFlux DL

The EasyFlux DL is a CRBasic program that enables a CR1000X data logger to collect fully corrected fluxes of CO_2, latent heat (H_2O), sensible heat, ground surface heat flux, and momentum from a Campbell Scientific open-path eddy covariance system. The program processes eddy covariance data using commonly used corrections. Because the number of analogue channels on the CR1000X is limited, the program also supports the addition of a VOLT116 analogue input module. The VOLT116 allows expansion to include a full suite of energy balance sensors, thus enabling the program to calculate the ground surface heat flux and energy closure. Specifically, EasyFlux DL supported data collection and processing from the following sensors: Three Dimensional Sonic Anemometer (CSAT3B), Thermocouple (FW05), Four-Component Net Radiation Sensor (NR01), Averaging Soil Thermometer (TCAV), Water Content Reflector (CS655), Soil Heat Flux Plate (HFP), Temperature and Humidity Sensor (HygroVUE10) and Barometric Pressure Sensor (CS100).

CSAT3B Three-Dimensional Sonic Anemometer

CSAT3B is an ultrasonic anemometer that measures sonic temperature and wind speed in three dimensions. Not only does the CSAT3B measure average wind speed and direction, but it also measures the turbulent fluctuations of horizontal and vertical wind and sonic temperature. Therefore, momentum flux and sensible heat flux can be calculated from turbulent and sonic temperatures. Computation of the covariance between the vertical wind measured by CSAT3B and various scalar quantities measured by other sensors can be used to determine the latent, sensible heat flux and the gas fluxes (Munger et al., 2019).

The LoggerNet 4.7 version, Build 4.7.0.15 software was downloaded and used to send a datalogger program to the data logger. The CSAT3B was configured using the Campbell Scientific Device Configuration Utility, version 2.28, and set in the default operating Mode 0, where the CSAT3B measurement and output were triggered by the CR1000X.

After configuration, the CSAT3B was mounted on a 3.33 cm outer diameter CM20X cross-arm to the 6-meter tripod mast mounting. Precisely, the CSAT3B was mounted at a height of 5.0 m above average 3 m tall plum trees. The CSAT3B pointed into the negative x-direction, in the direction of the prevailing wind. The anemometer therefore reported a positive u_x wind. The CM250 levelling mount was mounted to the end of the cross arm to level the CSAT3B while it pointed towards the North East (prevailing wind) direction to minimise the interference from support structures such as the tripod mast. Typically, the anemometer was mounted level to the ground, within a couple of considerably sufficient degrees. Lastly, the CSAT3B was grounded to the tower by attaching an AWG14 gauge wire to the copper grounding lug on the back of the CSAT3B block. Grounding the CSAT3B is critical as it ensures maximum electrostatic discharge protection and improves measurement accuracy.

FW05 Thermocouple

The FW05 is a type E thermocouple with a 0.0127 mm diameter. The fine-wire thermocouple, which measures atmospheric temperature fluctuations, was connected and mounted on the side of the CSAT3B block to directly calculate sensible heat flux. The FW05 was connected to the CR1000x using the FWC-L cable. The cable has a connector that mates with the connector on a FW05 and pigtail wires that are connected to a pair of differential voltage terminals on the data logger.

NR01 Four-Component Net Radiation Sensor

The NR01, manufactured by Hukseflux, is a research-grade net radiometer that measures the energy balance between incoming short-wave (SW) and long-wave (LW) infrared radiation versus surface-reflected short-wave and outgoing long-wave infrared radiation. The NR01 is a four-component net-radiometer consisting of two pyranometers of type SR01, two pyrgeometers of type IR01, a heater, and a PT100 temperature sensor. The pyranometer measures solar radiation (SW) while the pyrgeometer measures far infrared (LW) radiation. The CR1000x measures the NR01 output and controls its internal heater.

The NRO1 was horizontally mounted on a CM206 cross-arm which was then attached to the stainless-steel mast at a height and angle of 5.2 m and 180° from the true North, respectively. Given that the upward-looking sensors should not have any shading, the height of the sensor mounting was extended beyond the canopy. For the same reasons, the NR01 was mounted at 0.2 m above the CSAT3B to avoid shadows that may be cast by both the sensor and its cross-arm. Both sensors were above the plum orchard canopy of an average height of 3.0 m.

TCAV Averaging Soil Thermocouple Probe

The TCAV used with the eddy covariance system is a chromel-constantan with a typical output of 60 µV/°C, weight of 0.45 kg and a 15.24 m cable. Typically, it provides the average temperature of the soil for energy balance in flux systems. It parallels four thermocouples together into one 24 AWG wire. A voltage potential is generated when the measurement end of the thermocouple is at a different temperature than the reference end of the thermocouple. The magnitude of the voltage potential is related to the temperature difference. Therefore, temperature can be determined by measuring the differences in potential created at the junction of the two wires.

Typically, the TCAV is used to calculate the heat flux at the surface of the soil. The standard set of sensors that were used for measuring soil heat flux included (1) the TCAV Averaging Soil Thermocouple, (2) HFP01SC Soil Heat Flux Plates, and (3) CS655 water content reflectometer. Two sets of the thermocouples, heat flux plates, and the reflectometers were installed in the ground, 1.5 m on either side of the tower at different depths measured from the surface using a 30 cm ruler (Table 4.3).

Table 4.3 Sensor placement for the soil heat flux measurements.

Sensor	Depth (cm)
Thermocouple 1	0.5
Thermocouple 1	5.5
Thermocouple 1	10.5
Thermocouple 1	15.5
Soil heat flux plate	8.0
Water content reflectometer	8.0

A shovel was used to cut a vertical slice in the soil and remove the soil to one side of the cut. Although the ground had a shallow layer of conglomerates, the soil was kept intact such that its replacement was done with minimum disruption. A small knife was used to make horizontal cuts below the surface into the undisturbed face of the hole. The stainless-steel tubes encasing the thermocouple junctions were pressed into the soil, keeping the tubes horizontal. All sensors were completely inserted into the soil face before the hole was backfilled.

CS655 Water Content Reflectometers

The CS650 and CS655 are multiparameter smart sensors used to monitor soil volumetric water content, bulk electrical conductivity and temperature. They output an SDI-12 signal that the CR1000X data logger measures. The CS655 has 15 cm length rods. Volumetric water content is derived from the sensor sensitivity to the dielectric permittivity of the medium surrounding the sensor stainless-steel rods. The CS650 is configured as a water content reflectometer with the two parallel rods forming an open-ended transmission line.

The 15 cm sensor rods of the CS655 were inserted horizontally, 8.0 cm from the soil surface (Table 4.3). The main reason for inserting the CS655 at this depth was to avoid the inclusion of the air above the surface in its measurements, and therefore, underestimating the soil water content. Since the orchard has stony soils, a CS650G rod insertion guide tool was used to aid the insertion of the CS655. The CS650G helps to maintain the proper spacing and parallel orientation of the rods during sensor insertion. The sensor head was also carefully buried in the soil so that it was insulated from the diurnal temperature fluctuations.

HFP Soil Heat Flux Plate

The HFP01 Soil Heat Flux Plate uses a thermopile to measure temperature gradients across its plate. Operating in a completely passive way, it generates a small output voltage that is proportional to this differential temperature. Assuming that the heat flux is steady, that the thermal conductivity of the body is constant, and that the sensor has negligible influence on the thermal flow pattern, the signal of the HFP01 is directly proportional to the local heat flux. The HFP01 is placed and used together with the TCAV and CS655 to get the soil heat flux at the surface. The temporal change in soil temperature and soil water content is used to compute the soil storage term.

A small shovel was used to make a vertical slice in the soil. The soil was excavated to the side of the slice while keeping it intact so that it can be replaced with minimal disruption. The HFP01 was insert into a horizontal cut, 8 cm below the surface (Table 4.3), with the side of the red label facing the sky and the blue label facing the soil. The soil was excavated back into its original position after the HFP01 had been installed.

HygroVUE10 Temperature and Relative Humidity Sensor

The HygroVUE™10 Temperature and Relative Humidity (RH) Sensor is designed for general meteorological and environmental applications. The HygroVUE 10 sensor uses a single chip element that incorporates both a temperature and an RH sensor. Each element is individually calibrated with the calibration corrections stored on the chip. The HygroVUE 10 uses the SDI-12 communications protocol to communicate with any SDI-12 recorder, simplifying wiring and programming.

The HygroVUE10 sensor comes along with a radiation shield into which it was pushed so the tip of the sensor was approximately one-third of the way down from the top of the shield. The radiation shield was attached to the tripod mast, 3.5 m from the ground surface, using the supplied U-bolt. The connecting cable was routed to the CR1000X, and the cable was secured to the mounting structure using cable ties.

CS100 Barometric Pressure Sensor

The CS100 is a capacitive pressure transducer that uses Setra's electrical capacitor technology for barometric pressure measurements. The transducer is encased in a stainless steel and polyester case fitted with an 1/8-inch barbed fitting for pressure connection. The CS100 measures barometric pressure in the range of 600 to 1100 hPa. This range equates to from below sea level up to 3,658 m above sea level. Designed for use in environmental applications, the CS100 is compatible with all Campbell Scientific data loggers, including the CR1000X used in this study. CR1000x directly measures the analogue signal generated by the barometer.

The CR1000x and the CS100 were housed in the same enclosure. The CS100 was mounted directly onto the holes on the backplates of the Campbell Scientific enclosures. The sensor was mounted with the pneumatic connector pointing vertically downwards to prevent condensation collecting in the pressure cavity, and to ensure that water cannot enter the sensor. The CS100 was supplied in the triggered mode that allows the data logger to switch 12 VDC power to the barometer before the measurement. The data logger then powered down the barometer after the measurements to conserve power.

4.11 Remote sensing study

4.11.1 Introduction

The measurements of evapotranspiration fluxes with the eddy covariancee system provided the most direct estimation of water consumption of plum orchards. However, due to the cost and complexity of measurements, it was not possible to conduct eddy covariance measurements in all study orchards. The eddy covariance system was therefore installed in the most suitable orchard (African Delight in Robertson, >4 ha in size) to obtain continuous records of evapotranspiration from May 2023 to August 2024. However, these data were representative of one orchard only.

Van Niekerk et al. (2018) noted that remote sensing-based techniques are at present the only viable method of regional or national scale quantification of agricultural water use in South Africa. Remote sensing data were therefore adopted to quantify the seasonal water consumption of all study orchards and to compare water consumption from micro-jet and drip-irrigated plum orchards in the two main production regions of the Western Cape, namely Wellington and Robertson.

At present, there is no universal consensus on which remote sensing is the best as each approach has a set of assumptions and associated advantages and limitations (Zhang et al., 2016; Ayralekkshmi et al., 2021). However, through a comprehensive review of literature, Mohan et al. (2020) found that the Surface Energy Balance Algorithm for Land (SEBAL), Mapping Evapotranspiration at High Resolution with Internalized Calibration (METRIC), and Surface Energy Balance System (SEBS) models were the most "popular" (appeared the most in literature) among single-source ET estimation models, along with the S-SEBI (Simplified Surface Energy Balance Index) and SEBI (Surface Energy Balance Index) models, ranked 4th and 5th respectively, and the newly developed dual-source ETLook model. Figure 4.11 depicts a timeline of the publication of each model.

Two RS-based surface energy balance (SEB) ET estimation methods, i.e. the SEBS model and FruitLook (https://fruitlook.co.za/ accessed on 5 June 2024, underpinned by SEBAL and

ETLook), were used in the remote sensing study, mainly because of their accessibility and reported reliability. However, before adopting these two remote sensing products to estimate regional ET, it was necessary to validate them against ground-based measurements from the eddy covariance tower.

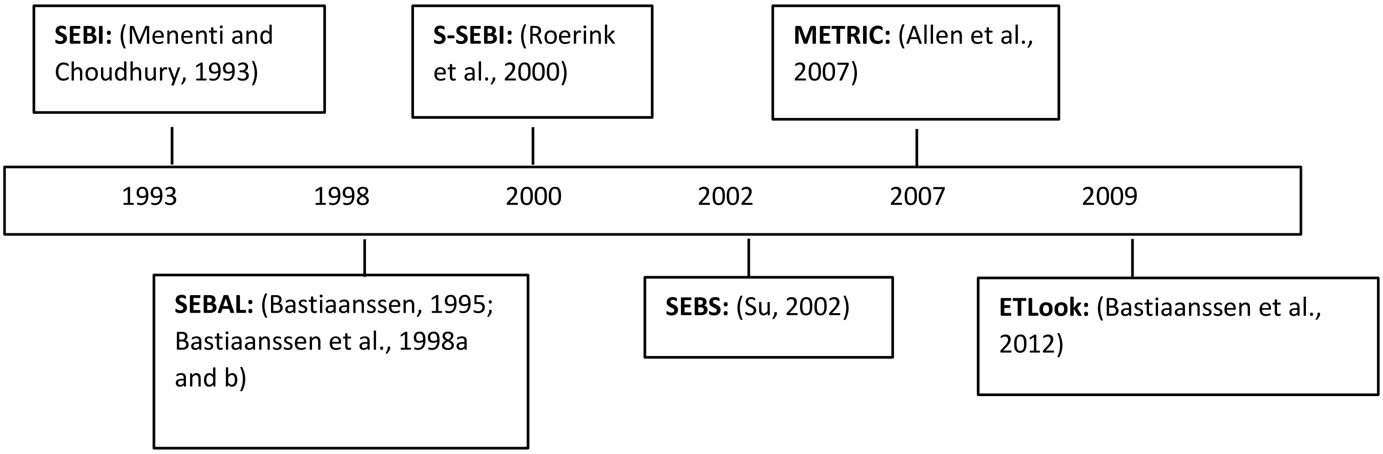


Figure 4.11 *Timeline of remote sensing models formulation and publication.*

4.11.2 Description of SEBS

The SEBS model was developed and formally published by Su (2002) from the University of Twente (ITC, The Netherlands). Over the years, it has gained international recognition for its universal applicability and accurate estimations of ET over a vast array of land cover types from agricultural land (Mengistu et al., 2014) to bare soil (Xin, 2006), wetlands and grassland (Jarmain et al., 2009). The model is open-source and freely available as part of the GIS software ILWIS. A commonly reported caveat of SEBS is its high input data requirements. The model estimates land surface fluxes using a set of remotely sensed biophysical parameters (surface temperature, albedo, emissivity, fractional vegetation cover, LAI and NDVI) and meteorological inputs (air temperature, wind speed, air pressure and relative humidity) along with ancillary datasets e.g., digital elevation model (DEM). In SEBS the derivation of the H term is based on the Monin-Obukhov Similarity Theory (MOST) and incorporates the wind speed, air, and surface temperature. The equation is expressed as:

$$L = \frac{\rho C_p u_*^3 T_v}{kgH} \qquad [8]$$

where L - Obukhov length

ρ - air density

C_p - specific heat of dry air

u_* - friction velocity

T_v - virtual temperature near the surface

k - von Karman's constant

g - acceleration due to gravity

Once H has been derived, latent heat of vaporization (LE) can be indirectly estimated by solving for the SEB equation. Su et al. (2007), using MODIS-satellite imagery, reviewed the robustness of SEBS in estimating ET over a diverse landscape and varying climatic regions. The SEBS-based ET estimates were validated against in-situ measurements at various sites. The results showed that estimated ET values were closely correlated to ground-based measurements. Gibson et al. (2010) and Gibson et al. (2011) evaluated the applicability of SEBS in estimating ET for water use compliance monitoring and catchment water balance estimation in South Africa. In both instances, SEBS overestimated ET, which was attributed to a myriad of reasons particularly the sensitivity of H to surface-air temperature gradient. A common theme from all three studies, which used MODIS imagery, was the importance of the spatial resolution of input satellite images. Sharma et al. (2016) noted that coarse satellite images may not adequately depict the spatial heterogeneity of the region of interest due to pixel mixing, resulting in either an over- or under-estimation of ET. The results of their study showed that Landsat images better depicted the spatial distribution and subsequently produced more accurate ET estimates (R^2 = 0.91) compared to coarse-resolution MODIS imagery (R^2 = 0.59). This coincides with findings by Shoko (2014).

4.11.3 Description of ETLook

ETLook (Bastiaanssen et al., 2012) is the latest iteration of SEBAL and was developed to address the shortcomings of SEBAL in estimating ET over extensive areas with widely variable topography and climate. The model, along with its predecessor, is owned and licensed by the Dutch company eLEAF. The model considers energy fluxes at the land surface, however unlike in single-source SEB models, ETLook does not compute LE (ET) as a residual term of the SEB equation. E and T (along with interception, denoted as I) are estimated separately using a two-layer Penman-Monteith equation and integrated transport resistances. The equation is written as:

$$E = \frac{\Delta\left(R_{n,soil} - G\right) + \rho c_p \left(\frac{\Delta_e}{r_{a,soil}}\right)}{\Delta + \gamma\left(1 + \frac{r_{soil}}{r_{a,soil}}\right)} \qquad [9]$$

$$T = \frac{\Delta\left(R_{n,canopy}\right)+\rho c_p\left(\frac{\Delta_e}{r_{a,canopy}}\right)}{\Delta+\gamma\left(1+\frac{r_{canopy}}{r_{a,canopy}}\right)} \quad [10]$$

where Δ: slope of the saturation vapor pressure curve

Δ_e - vapor pressure deficit

ρ - air density,

C_p - specific heat of dry air

γ - psychometric constant

$R_{n,soil}$ and $R_{n,canopy}$ - net radiations at soil and canopy, respectively;

r_{soil} and r_{canopy} - resistances of soil and canopy, respectively

$r_{a,soil}$ and $r_{a,canopy}$ - aerodynamic resistances for soil and canopy, respectively

Transport resistance for E (r_{soil}) is a function of topsoil water content whereas resistances for T (r_{canopy}) are a function of the leaf area index, incident radiation, air temperature, vapour pressure and subsoil water content (Guzinski and Nieto, 2022). The model requires a set of remotely sensed and meteorological data to run. The required remotely sensed data include NDVI, surface albedo, emissivity, land surface temperature, leaf area index and soil moisture whereas the meteorological inputs include precipitation, air temperature, relative humidity, wind speed and transmissivity (van Niekerk et al., 2018). In addition to this, various static inputs (single date) are also required. These include a digital elevation model (DEM), a latitude raster and a land use land cover (LULC) dataset.

The ETLook algorithm was first presented at the Remote Sensing and Hydrology Symposium in Wyoming, United States, in 2010 (Pelgrum et al., 2010). This was followed by a detailed validation study of the model which aimed to accurately estimate ET in the Indus Basin (Bastiaanssen et al., 2012). The estimated ET compared reasonably well with historical field-scale soil moisture and Bowen ratio measurements yielding R^2 and RMSE values of 0.70 and 0.45 mm d^{-1}. Samain et al. (2012) evaluated the performance of ETLook in estimating surface energy fluxes at point and catchment scale in the Dender catchment, Belgium. The derived estimates were validated with measurements from an eddy covariance system and large aperture scintillometer (LAS). At point scale, ETLook-derived estimates of the available energy, H and LE yielded R^2 values of 0.93, 0.65 and 0.63 respectively. At catchment scale the study concluded that ETLook produced LE and H estimates that were in good arrangement with the LAS system and physically based TOPLATS model.

Locally, van Niekerk et al. (2018) used ETLook (at 250 m resolution) to map the areal extent and quantify the water use of irrigated agricultural land for the whole of South Africa over a 12-month period (August 2014 – July 2015). A total of 1.33 million ha of irrigated agricultural land was delineated with an estimated consumptive water use of 10.22 billion m^3 a^{-1}. As in subsequent studies by Jovanovic et al. (2020) and van Niekerk et al. (2023), which used ETLook and WaPOR (a web-based platform based on ETLook), respectively, to estimate the water use of different land use classes (agricultural land, natural vegetation, and commercial forestry plantations), the ETLook-derived ET estimates compared well with historic measurements from previous studies.

4.11.4 Validation of remote sensing data

Acquisition of SEBS Data

Seven cloud-free Landsat 8 OLI images (cloud cover <10%) were acquired from the United States Geological Survey (USGS) earth explorer website (http://earthexplorer.usgs.gov) as atmospherically corrected Collection 2 Level 2 GeoTiff images from 10 May to 13 November 2023. This period was selected to overlap with available ground-based measurements from the eddy covariance tower. The downloaded satellite images were converted to surface reflectance (bands 2, 4, 5, 6 and 7) and surface temperature (band 10) values using the multiplicative and additive scaling factors summarized on the USGS website (https://www.usgs.gov/landsat-missions/landsat-collection-2-level-2-science-products accessed on 20 July 2022). The Semi-Automated Classification Plugin (SCP) tool, which is embedded in the QuantumGIS (QGIS) 3.4.15 software, was used to complete this task. The processed images were then imported into ILWIS to calculate the surface biophysical parameters (i.e., NDVI, LAI, fc, emissivity and albedo) required as remotely sensed inputs in the SEBS model. The formulae used to calculate these parameters are shown in Table 4.4. In addition to the remotely sensed inputs, meteorological data (solar irradiance, hourly air temperature and wind speed, and mean daily temperature) from a ground-based weather station and ancillary data (DEM, Julian day and solar zenith angle) (Table 4.5) were used to compute for daily ET estimates for each image. A simplified flow chart depicting the procedure followed to run the SEBS model was shown by Motsei (2024).

Table 4.4 Formulae for computing the SEBS remote sensing inputs.

Parameter	Equation	Reference
NDVI	NDVI = $\frac{\mathrm{NIR-R}}{\mathrm{NIR+R}}$	
fc	fc = $\left(\frac{\mathrm{NDVI-\ NDVI_{min}}}{\mathrm{NDVI_{max+}\ NDVI_{min}}}\right)^2$	Sobrino et al. (2004)
LAI	LAI = $\mathrm{NDVI}\sqrt{\frac{1+\mathrm{NDVI}}{1-\mathrm{NDVI}}}$	Timmermans et al. (2013)
Emissivity	ε = 0.004 fc + 0.986	Sobrino et al. (2004)
Albedo	a = $0.356_{b1} + 0.13_{b3} + 0.373_{b4} + 0.085_{b5} + 0.072_{b7}$ - 0.0018	Liang (2020)

NDVImin and NDVImax refer to the minimum and maximum NDVI values in the area of interest; NIR is the near infrared band (Landsat 8 band 5) and R is the red band (Landsat 8 band 4); b1, b3, b4, b5 and b7 refers to the respective Landsat 8 bands.

Table 4.5 Meteorological and ancillary inputs for the SEBS model.

Image acquisition date	Julian day	Solar zenith angle (°)	Radiation (W m^{-2})*	Temperature (°C)*	Wind speed (m s^{-1})*	Mean daily temperature (°C)
30-Jun-23	181	66	27	12.6	1.3	13.5
16-Jul-23	197	62	84	8.1	0.3	13.8
01-Aug-23	213	62	90	4.9	0.2	9.5
02-Sep-23	245	51	178	7.2	1.6	10.1
18-Sep-23	261	46	318	10.0	0.4	11.6
12-Oct-23	285	38	398	16.5	1.1	16.7
13-Nov-23	317	30	535	23.0	2.3	22.4

*Instantaneous meteorological data at time of satellite overpass (~08h30)

Acquisition of FruitLook Data

FruitLook, developed by Dutch company eLeaf, is an online platform which provides high quality, satellite-derived data on crop growth (LAI, NDVI and biomass production) and water usage (actual ET, ET deficit and biomass water use productivity) to farmers and agricultural business within the Western Cape. These variables are computed using the SEBAL and ETLook models, along satellite imagery from several platforms (i.e. Sentinel, Landsat, VIIRS, MODIS) and meteorological data from ground-based weather stations, at a 10 m x 10 m spatial resolution. At present (2022), FruitLook surveys about 9.5 million hectares of land, covering a large portion of the Western Cape. Although initially used in the grape industry, FruitLook currently provides data on a variety of crops from stone fruits to apples, pears, citrus etc. It provides farmers with a tool to monitor plant growth, health and water usage as well as identify spatial and temporal trends in crop characteristics. The temporal coverage of FruitLook varies from season to season as depicted in Table 4.6. Full-year (1 August – 31 July) water use (ET) estimates were only available from the 2018/19 season onwards. Therefore, weekly water use estimates for the selected study orchards at the Smuts Brothers (Robertson) and Sandrivier (Wellington) farms were extracted from the FruitLook portal and aggregated to monthly and seasonal estimates for each season from the 2018/19 to the 2022/23 season (5 seasons).

Table 4.6 Temporal coverage of FruitLook data in the Western Cape during different seasons

Season	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
2011/12 – 2014/15												
2015/16												
2016/17 – 2018/19												
2018/19 – Present												

Statistical Analysis

A statistical analysis comprising a coefficient of determination (R^2), Root Mean Square Error (RMSE) and percentage bias was employed to evaluate the performance of FruitLook and the SEBS model. The coefficient of determination (R^2) indicates the degree of correlation between the measured and estimated variables (Jierula et al., 2021). Therefore, it was used to determine the strength of the relationship between remote-sensing based ET estimates and ground-based measurements from the eddy covariance tower, where a value close to 1 (or -1) indicates a good correlation and a value close to 0 indicates poor correlation. On the other hand, RMSE and percentage bias (Pbias) provide a measure of the deviation of the estimated values from measured values. With these methods, values close to 0 indicate good model accuracy, whereas larger values indicate increasing model inaccuracy. Moreover, Pbias indicates the direction of the error i.e., whether the model over- or under-estimated values. The equations of the statistical indicators are:

$$R^2 = \frac{\sum (ET_{EC} - ET_{estimate})^2}{\sum (ET_{EC} - \overline{ET_{EC}})^2} \quad [11]$$

$$RMSE = \sqrt{\frac{\sum (ET_{EC} - ET_{estimate})^2}{n}} \quad [12]$$

$$Pbias = \frac{\sum(ET_{estimate} - ET_{EC})}{\sum ET_{EC}} \quad [13]$$

Where ET_{EC} - ET measurements from the eddy covariance tower

$\overline{ET_{EC}}$ - Mean of ET measurements from the eddy covariance tower

$ET_{estimate}$ - Satellite-derived ET estimate from SEBS or FruitLook

n - Number of measurements

4.11.5 Comparison of plum water consumption with micro-jet and drip- irrigation

Selection of orchards

Georeferenced spatial data depicting the distribution of Japanese plum orchards across the Western Cape Province along with the employed irrigation system were extracted from the CapeFarmMapper platform (www.gis.elsenburg.com accessed on 01 June 2022). A majority of the orchards were situated within the agriculturally prominent Cape Winelands District with the rest falling within the Central Karoo, City of Cape Town, Garden Route, Overberg and West Coast Districts. According to the metadata, the field boundaries were digitized (mapped) during the 2017/18 agricultural season using aerial photographs from 2016. There was no indication that the dataset had been updated since then, therefore it was assumed that some of the delineated orchards were likely outdated. This necessitated the ground-truthing of these orchards prior to their use in the study. Due to transport constraints, an extensive ground truthing campaign was not achievable, therefore a narrowed-down pool of orchards was selected for validation and use in the study. The primary considerations for orchard selection were their proximity to the Sandrivier (Wellington) and Smuts Brothers (Robertson) farms (due to the transport constraints) and farmer participation. The latter was unequivocally more important as we required access to the farms to verify the crop type and employed irrigation system. Several farm managers declined to participate in the study or did not respond to calls and emails, which further reduced the pool of selectable orchards. Additionally, orchards under agricultural nets, i.e. not under natural open field conditions, were omitted.

A ground-truthing campaign was carried out in the Wellington and Robertson regions from August to November 2022, highlighting multiple errors in the extracted dataset. Firstly, abandoned plots, fallow land and other crop types (i.e., citrus, nectarines, peaches etc.) were demarcated as plum orchards. In other instances, plum orchards present on the ground were not included in the spatial dataset. Additionally, the listed irrigation system at multiple orchards, particularly in Wellington, was incorrect, i.e. micro-sprinkler irrigated orchards were listed as drip-irrigated and vice versa. Lastly, the field boundaries of some orchards were not properly digitized (i.e. the digitized plots included bare soil and other land surfaces surrounding the orchards).

A total of 150 plum orchards, cultivated on 239.5 hectares of land and spread across 11 farms were validated at the end of the ground-truthing campaign. Twenty-four cultivars were planted to these orchards, with cv. Angeleno, Ruby Sun, Sunkiss and Fortune being the most prominent. The trees were trained on a single or dual row Palmette trellis system. The age of an orchard was used to determine its bearing status (bearing or non-bearing). Plum trees typically begin bearing fruit from 3 years. Therefore, orchards older than 3 years were considered as full-bearing. In instances where orchard age was not readily available, visual observations of tree features (tree height, stem thickness, canopy density and the presence of fruits) and communication with farm workers in comparison with features of known bearing trees were used to determine the bearing status of observed trees. Examples of trees used as benchmarks for comparison and selected orchards using this method are shown in Figure 4.12. A total of 49 orchards were selected using this method, 14 in Robertson and 35 in Wellington. A second shapefile was created, where the validated plum orchards were digitized, and the employed irrigation system was noted. Additional information on the selected orchards (cultivar, age, size and training system) can be found in Motsei (2024).

The selected orchards in Robertson were situated on 6 farms along the valley floor. These were the Smuts Brothers (Klipboschlaagte and Lucerne), Mon Don, Sonskyn, Rosedale and Ebendale farms (Figure 4.13). There were 76 orchards in total planted on 126.8 hectares of land, giving an average area of 1.67 ha (Table 4.7). The farms, except Ebendale, were within a 5 km proximity of each other. Ebendale is in Bonnievale, a neighbouring town approximately 20 km from Robertson. A majority of the farms in the area were drip-irrigated, with Mon Don being the only exception where 13 out of the 20 orchards on the farm are irrigated via micro-sprinklers. In terms of area under cultivation, the Klipboschlaagte farm was the largest (30.1 ha) followed by Mon Don (28.4 ha) and Ebendale (23.3 ha). In Wellington, the selected orchards were situated on 5 farms within a 4 km radius of each other. These were the Sandrivier, De Geode Hoop, Louisvale, Abendruhe and Welgemoed farms (Figure 4.14). In total, there were 74 selected orchards, cultivated on 112.7 hectares of land (Table 4.7). Orchards in the region were predominantly irrigated via micro-jets, with the Abendruhe farm being the only farm where both irrigation systems (drip and micro-jets) were employed.

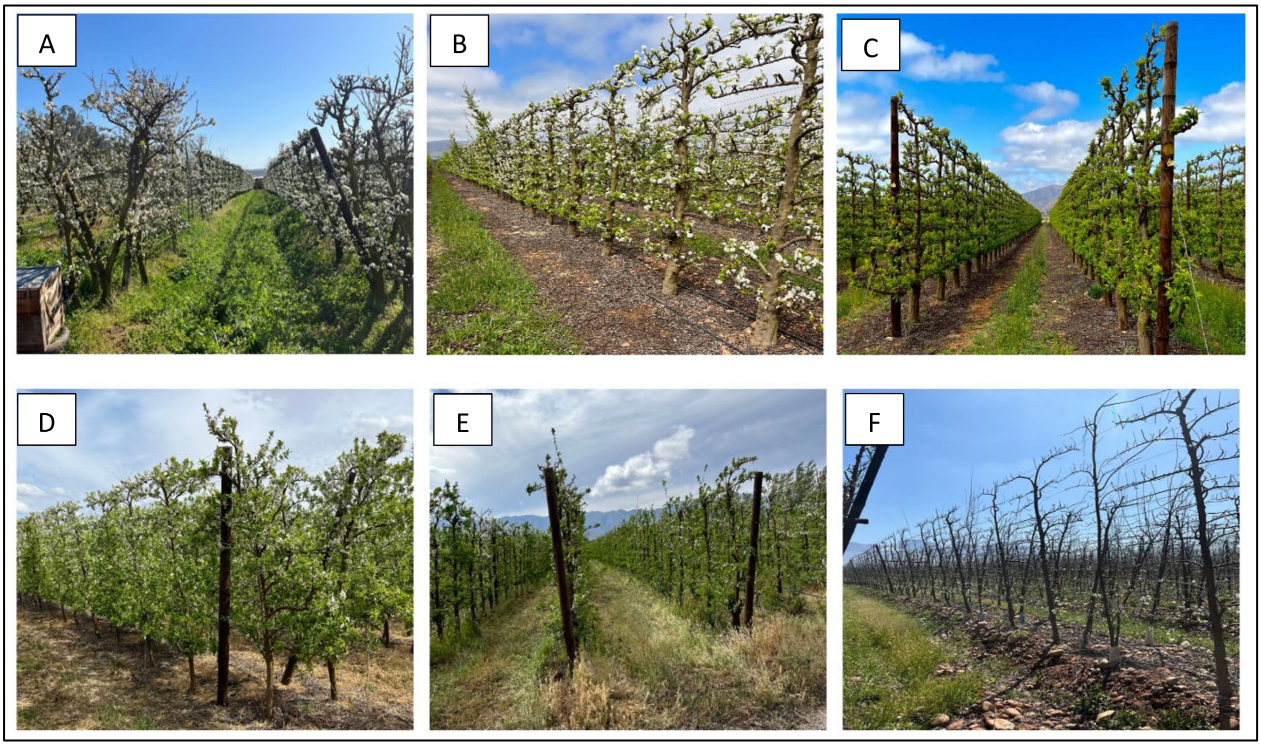


Figure 4.12 *Examples of benchmark orchards: (a) 12-year-old African Delight orchard, (b) 13-year-old African Delight orchard, (c) 12-year-old African Rose orchard and orchards selected through visual observations (d), (e) and (f).*

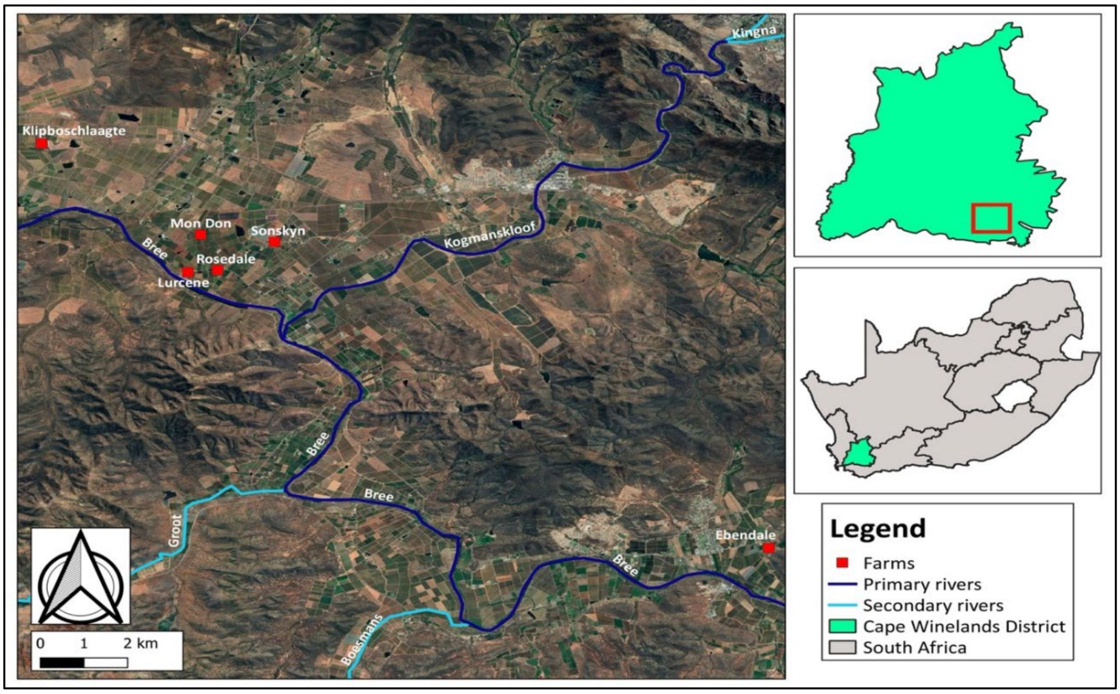


Figure 4.13 *Map of selected farms in Robertson for the comparison of plum water consumption between drip- and micro-jets irrigation.*

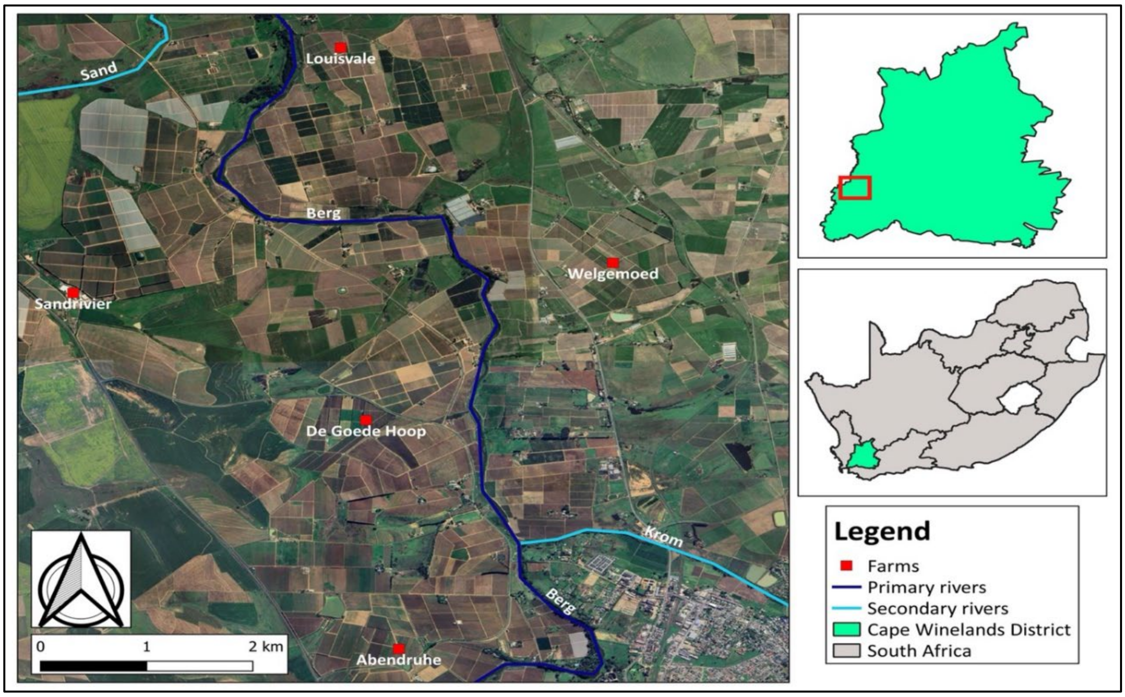


Figure 4.14 *Map of selected farms in Wellington for the comparison of plum water consumption between drip- and micro-jets irrigation.*

Table 4.7 Selected farms in Robertson and Wellington for the comparison of plum water consumption between drip- and micro-jets irrigation.

Region	Farm	No. of orchards	Area under cultivation (ha)	Irrigation type
Robertson	Ebendale	18	23.3	Drip
	Klipboschlaagte	9	30.1	Drip
	Lucerne	6	12.4	Drip
	Mon Don	20	28.4	Drip and micro-jets
	Rosedale	15	16.9	Drip
	Sonskyn	8	15.7	Drip
Wellington	Abendruhe	8	19.1	Micro-jets and drip
	De Goede Hoop	15	10.1	Micro-jets
	Louisvale	12	12.2	Micro-jets
	Sandrivier	32	57.2	Micro-sprinkler
	Welgemoed	7	14.1	Micro-jets
	Total	**150**	**239.5**	

Statistical Analysis

An independent Student's t-test, at a 5% confidence level ($\alpha = 0.05$), was performed to test if there was a statistically significant difference between the estimated water use (ET) of micro-jets and drip-irrigated Japanese plum orchards. The null (H_o) and alternate (H_a) hypotheses were:

- H_o ($p > 0.05$): There is no statistically significant difference between the estimated water use in micro-sprinkler and drip-irrigated Japanese plum orchards.
- H_a ($p < 0.05$): There is a statistically significant difference between the estimated water use in micro-sprinkler and drip-irrigated Japanese plum orchards.

The Student's t-test has four primary assumptions, these being: 1) the data are continuous, 2) the data were sampled from a random population, 3) the data are normally distributed (follow a bell-shaped curve) and 4) the sampled datasets have equal or similar variances. While the first 2 assumptions were satisfied, a normality test (Shapiro-Wilk) and f-test were conducted to test the validity of the third and fourth assumptions respectively. The assumptions of these tests are highlighted in Table 4.8.

Table 4.8 Assumptions of the Shapiro-Wilk (normality) and f-tests.

	Shapiro-Wilk test	**F-test**
H_o ($p > 0.05$)	The data is normally distributed	The datasets have similar or equal variances
H_a ($p <0.05$)	The date does not follow a normal distribution	The datasets have unequal variances
	If the alternative hypothesis is true, a non-parametric statistical test (i.e., Mann-Whitney U test) was used.	If the alternative hypothesis is true, an unequal variance t-test was used.

5. EXPERIMENTAL RESULTS

5.1 Weather data

Historical meteorological data outsourced from the Agricultural Research Council (ARC) were processed for the period 2011-2022. Annual meteorological averages were calculated based on the agricultural year (August – July) as opposed to the calendar year (January – December) to overlap with the deciduous fruit growing season (Figures 5.1 and 5.2). There were marked differences in annual rainfall between the two regions with Robertson having a considerably lower mean annual rainfall of 265 mm a^{-1} compared to 396 mm a^{-1} in Wellington (Table 5.1). The lower rainfall in Robertson was attributed to the orographic effect of the surrounding Du Toitskloof and Riviersonderend mountain ranges, which block off cool oceanic wind from reaching the valley. Wellington on the other hand is exposed seaward which allows an inflow of moisture-rich air into the region. Peak rainfall figures of 679 mm a^{-1} and 420 mm a^{-1} were recorded during the 2013/14 season in Wellington and Robertson respectively, whilst minimum rainfall was recorded during the 2017/18 (266 mm a^{-1}) and 2016/17 (125 mm a^{-1}) seasons (Table 5.1). There was a decline in rainfall from 2015/16 to the 2018/19 season and an increase thereafter, which coincided with the onset and cessation of a drought that plagued the Western Cape Province from 2015 to mid-2018 (Figures 5.1 and 5.2). Over the same period, ETo measurements were 4% – 24% higher than the long-term averages of 1360 mm a^{-1} (Wellington) and 1275 mm a^{-1} (Robertson).

Monthly total solar irradiance varied from 236 and 265 MJ m^{-2} $month^{-1}$ during winter (June) to a peak value of 926 and 839 MJ m^{-2} $month^{-1}$ during summer (January) in Wellington and Robertson. The average relative humidity, similar to rainfall, peaked during the winter months and was at its lowest during summer. Conversely, the mean monthly wind speed was the highest during summer, particularly between November and February ranging from 1.9 to 2.8 m s^{-1}. On average, Wellington experienced warmer summers (December – February) with an average maximum air temperature of 39.05 °C compared to 38.34 °C in Robertson. Winters (June – August) were significantly colder in Robertson where a minimum air temperature of -3.7 °C was recorded in July 2016. The average minimum air temperature in winter varied between -1.96 °C to 0.12°C in Robertson and 1.73°C to 3.58 °C in Wellington. Mean annual solar irradiance and wind speed were higher in Wellington whereas the average relative humidity was higher in Robertson. There was a noticeable decline in ETo, solar irradiance and wind speed, from the 2018/19 (Robertson) and 2019/20 (Wellington) seasons in both regions. Over the same period, there was an increase in the annual rainfall while temperature and relative humidity remained fairly constant. A statistical summary (mean, maximum, minimum, standard deviation and coefficient of variation) of the meteorological data over the 12 seasons is provided in Table 5.1. Annual rainfall measurements were highly variable (CV > 30%), while other meteorological factors showed minimal variability (CV < 15%).

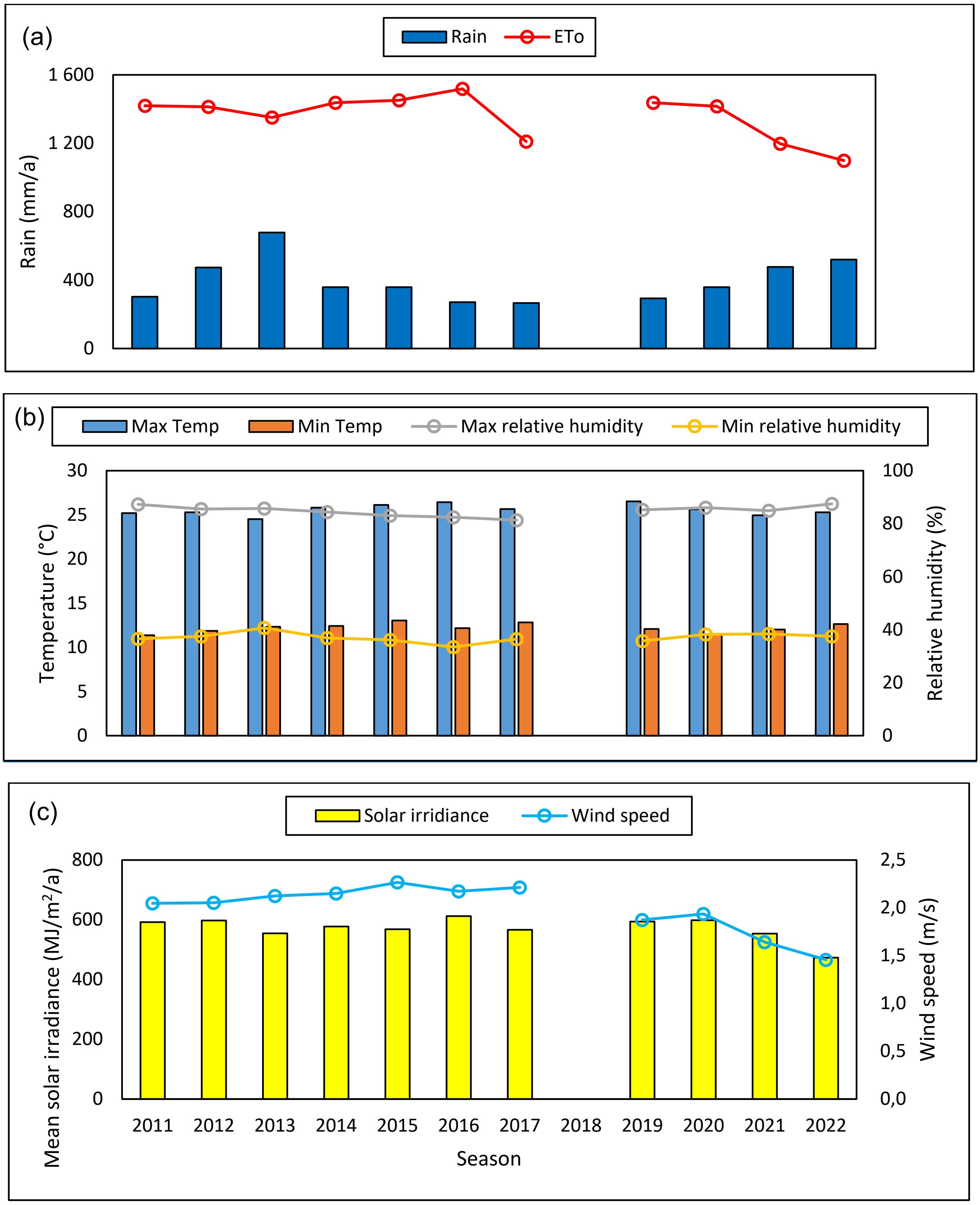


***Figure 5.1** Seasonal variation (August – July) of (a) rainfall and reference evapotranspiration; (b) max and min temperature, and max and min relative humidity; (c) total radiation and wind speed at the Diemerskraal (Wellington) weather station.*

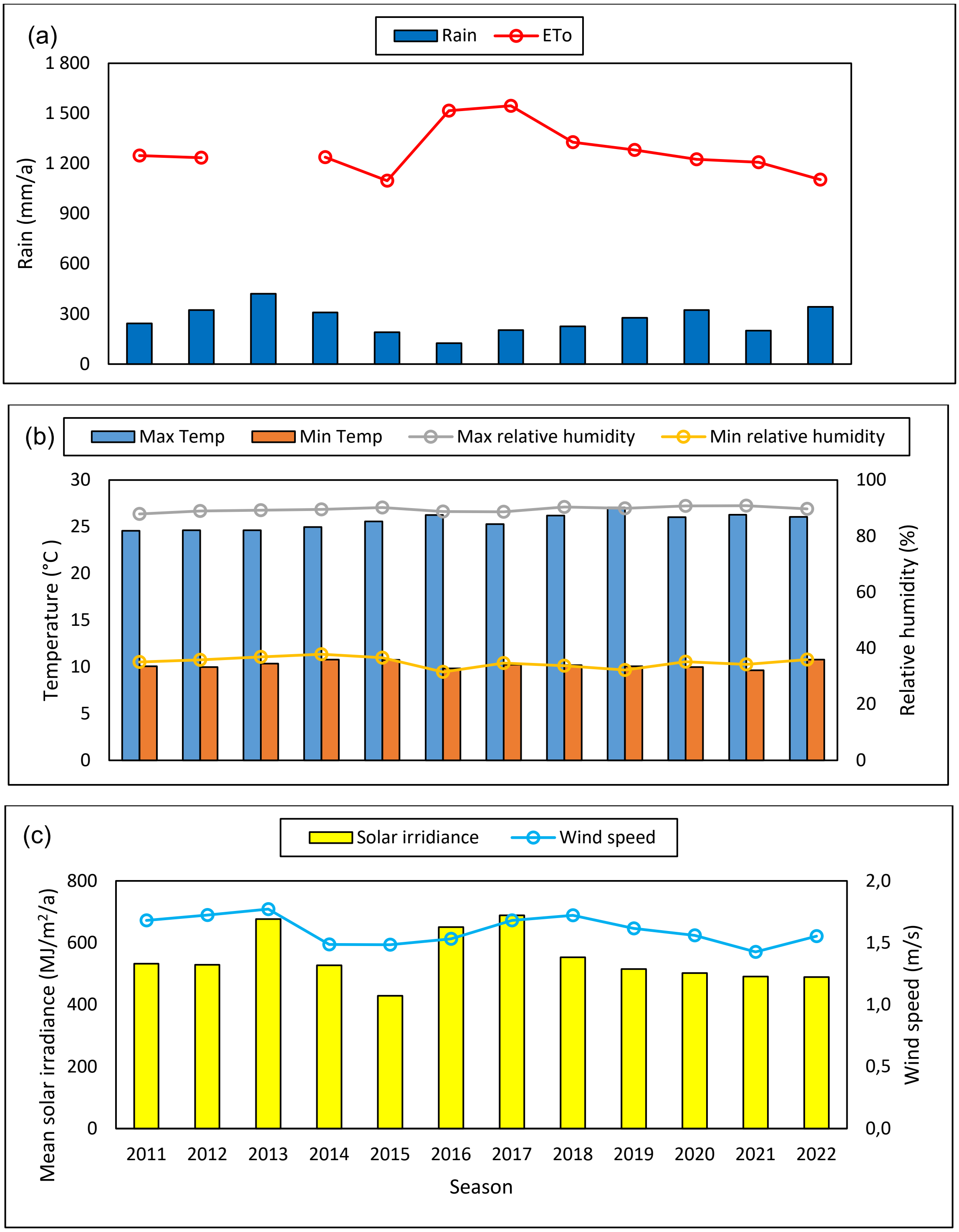


Figure 5.2 *Seasonal variation (August – July) of (a) rainfall and reference evapotranspiration; (b) max and min temperature, and max and min relative humidity; (c) total radiation and wind speed at the Robertson weather station.*

Table 5.1 Statistical summary of meteorological data from the Diemerskraal (Wellington) and Robertson weather stations from the 2011/12 – 2022/23 season.

Region		Rain ($mm\ a^{-1}$)	ETo ($mm\ a^{-1}$)	T_{max} (°C)	T_{min} (°C)	RH_{max} (%)	RH_{min} (%)	Rs ($MJ\ m^{-2}\ month^{-1}$)	U_2 ($m\ s^{-1}$)
Wellington	Average	396	1360	25.6	12.2	84.9	37.0	572	2.0
	Max	679	1518	26.5	13.0	87.5	40.7	612	2.3
	Min	266	1099	24.5	11.4	81.3	33.4	473	1.5
	StDev	128	131	0.6	0.5	1.9	1.8	38	0.3
	CV	32%	10%	2%	4%	2%	5%	7%	13%
Robertson	Average	265	1275	25.6	10.2	89.6	35.0	549	1.6
	Max	420	1546	27.1	10.8	90.8	37.9	689	1.8
	Min	125	1097	24.6	9.6	87.9	31.5	429	1.4
	StDev	82	143	0.8	0.4	0.9	1.9	81	0.1
	CV	31%	11%	3%	4%	1%	5%	15%	7%

T_{max} and T_{min} are the maximum and minimum temperature; RH_{max} and RH_{min} are the maximum and minimum relative humidity; Rs is average solar irradiance and U_2 is average wind speed.

Detailed daily weather data observed during the experimental years (2021-2024) can be found in Appendix A of this report.

Historic weather data (2011-2022) were used in the analyses of remote sensing data of ET (historic water uses of plum trees and comparison between orchards irrigated with micro-jets and drip-irrigation). Weather data collected during the experimental years (2021-2024) were used as inputs in the HYDRUS-2D model (precipitation and reference evapotranspiration) and in the interpretation of micro-lysimeters and eddy covariance data.

5.2 Soil water content measurements

Results of soil water content measurements obtained from AquaCheck probes for 3 seasons (from installation in 2021 until March 2024) are shown in Figures 5.3 and 5.4. Details on the installation of AquaCheck probes are given in Table 4.1. The probes were calibrated using volumetric soil water contents measured by sampling with the gravimetric method and bulk density. Probes 1 and 2 functioned in the Fortune orchard of Wellington until it was uprooted (Figure 5.3). The mid-row probes 8 and 10 in the Fortune orchard in Robertson were damaged by machinery soon after installation. The mid-row probes 12 and 14 in the African Delight orchard in Robertson were damaged by machinery during the course of the experiment (Figure 5.4). All other probes functioned and provided half-hourly data during the entire duration of the experiment.

The fluctuations in soil water contents in the graphs are due to irrigation and rainfall (Figures 5.3 and 5.4). This is particularly prominent in the upper soil layers in the probes installed in-row. Peaks in soil water content were usually stable around a value corresponding to field capacity, which is testimonial that scheduled irrigations were generally appropriate. Field capacity values were around 20% in Wellington (Figure 5.3). The highest field capacity values were recorded in the heavier soil of the Fortune orchard in Robertson (Figure (5.4). The lowest field capacity values were recorded in the stony soil of the African Delight orchard in Robertson (Figure 5.4). A remarkable difference in soil water content can be observed between the in-row and mid-row probes, the latter exhibiting a drying cycle during the summer season due to lack of irrigation water in the non-wetted portion of the ground. Large differences in soil water content at different depths may indicate the layering nature of the soils and vertical variability in soil hydraulic properties.

Soil water content measurements were used to calibrate the HYDRUS-2D model by comparing simulated and observed values.

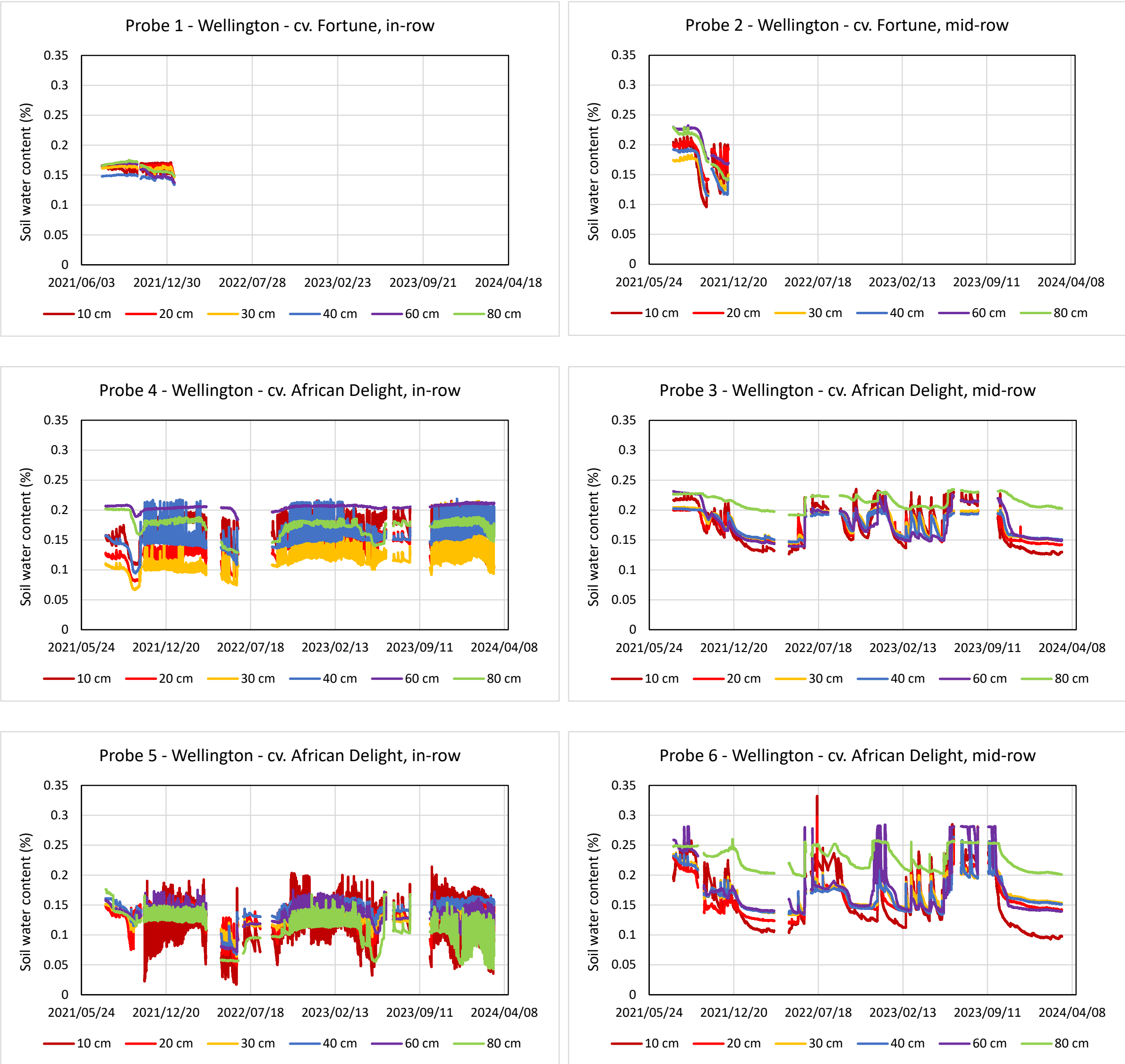


Figure 5.3 *Hourly data of volumetric soil water content measured with AquaCheck probes in Wellington from installation in July 2021 until March 2024. Data refer to measurements taken in Fortune (uprooted in January 2022) and African Delight orchards at different depths in the soil profile, in-row and mid-row (half way between tree rows).*

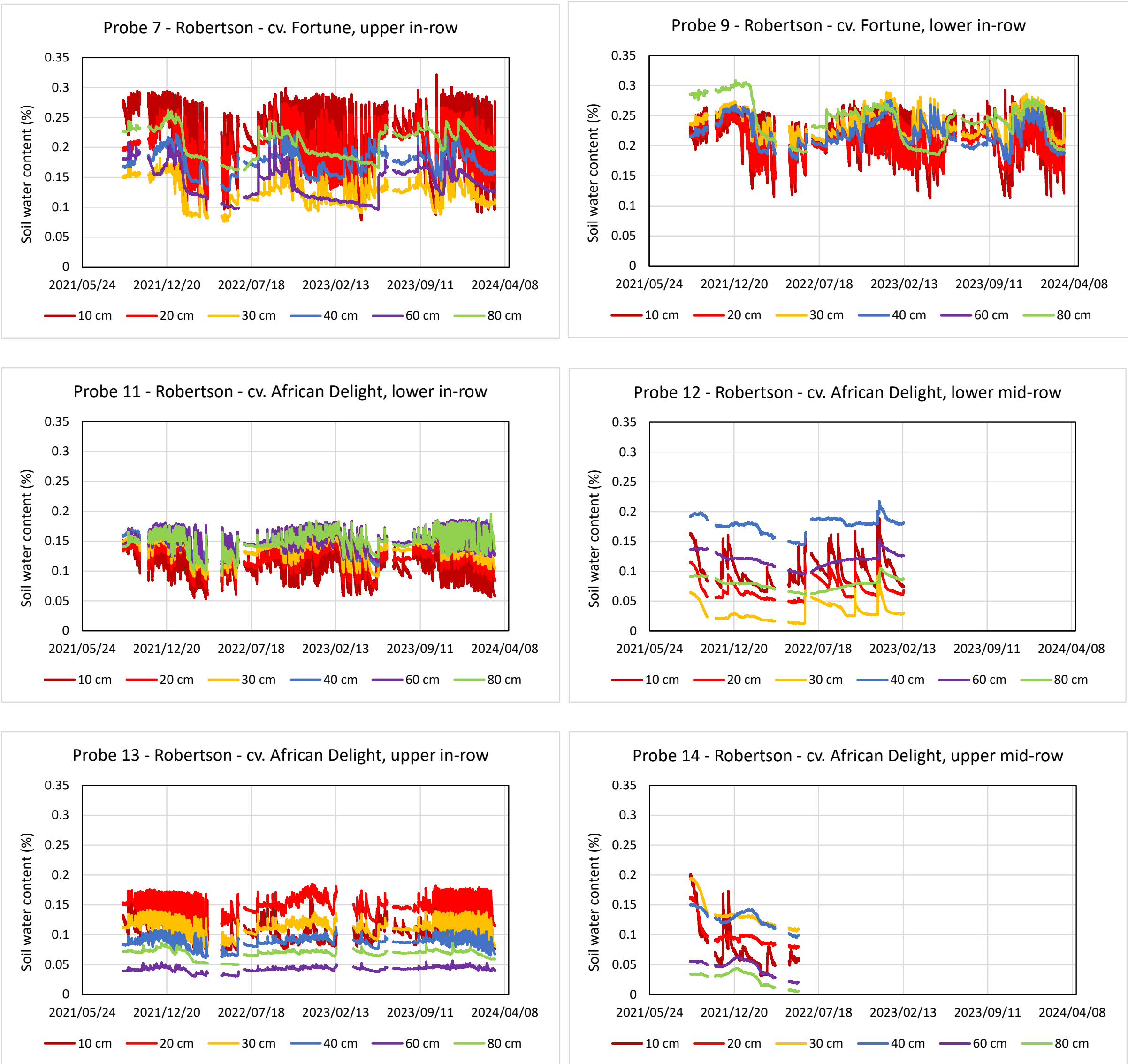


Figure 5.4 *Hourly data of volumetric soil water content measured with AquaCheck probes in Robertson from installation in July 2021 until March 2024.*

5.3 Micro-lysimeter measurements

The micro-lysimeters were installed in the field immediately before daily measurement campaigns to measure soil evaporation at different positions across the tree row. The weight of the micro-lysimeters was measured approximately every 2 hours to describe daily trends of soil evaporation and capture the effects of shading on soil evaporation. Data were plotted in graphs to represent the hourly changes in soil evaporation in transects across the row (tree row; ¼ distance from the tree row; ½ distance from the tree row; ¾ distance from the tree row; tree row) as well as the daily total evaporation.

The dates of measurement campaigns lasting a full day and atmospheric conditions are summarized in Table 5.2. Observed daily soil evaporation depended on daily weather conditions. Definite patterns in soil evaporation dependent on climatic region and cultivar were not discernible from the measurements taken, although more soil evaporation appeared to occur in Wellington than Robertson, and more from Fortune than African Delight orchards.

Table 5.2 Total daily soil evaporation measured with micro-lysimeters, maximum and minimum air temperatures and solar radiation measured on the day.

Farm	Orchard	Date of measurements	Minimum temperature (°C)	Maximum temperature (°C)	Solar radiation (MJ m^{-2} d^{-1})	Total daily evaporation (mm)
Sandrivier	African Delight	20/10/2021	14.5	36.9	22.4	1.1
		08/12/2021	17.1	31.7	24.5	2.1
		25/10/2022	14.3	23.9	17.9	1.6
	Fortune	20/10/2021	14.5	36.9	22.4	2.2
		08/12/2021	17.1	31.7	24.5	1.8
Smuts Bros	African Delight	03/11/2021	9.0	25.6	27.3	1.3
		10/12/2021	17.3	32.1	22.7	1.2
		28/10/2022	9.7	29.3	25.5	1.2
	Fortune	03/11/2021	9.0	25.6	27.3	1.8
		10/12/2021	17.3	32.1	22.7	1.8
		28/10/2022	9.7	29.3	25.5	1.2

Examples of data recorded at full canopy cover are shown in Figure 5.5 for African Delight in Wellington (08/12/2021) and for African Delight in Robertson (10/12/2021). Based on the measurements obtained, it is clear that soil evaporation varies across the row depending on the row orientation, time of the day and shading. The graphs show that Wellington had a higher total soil evaporation than Robertson. This could be due to the higher temperature and solar radiation on the day. Additionally, Wellington had a higher evaporation rate in the tree rows, whereas Robertson showed a flatter evaporation line across the row. This suggests that cultivation in ridges in Wellington exposes the soil to solar radiation, thereby increasing in-row soil evaporation. Conversely, Robertson has a flat terrain which exposes more the mid-row to solar radiation. Differences in evaporation rates can also be attributed to irrigation methods and duration of irrigation events, pruning practices etc.

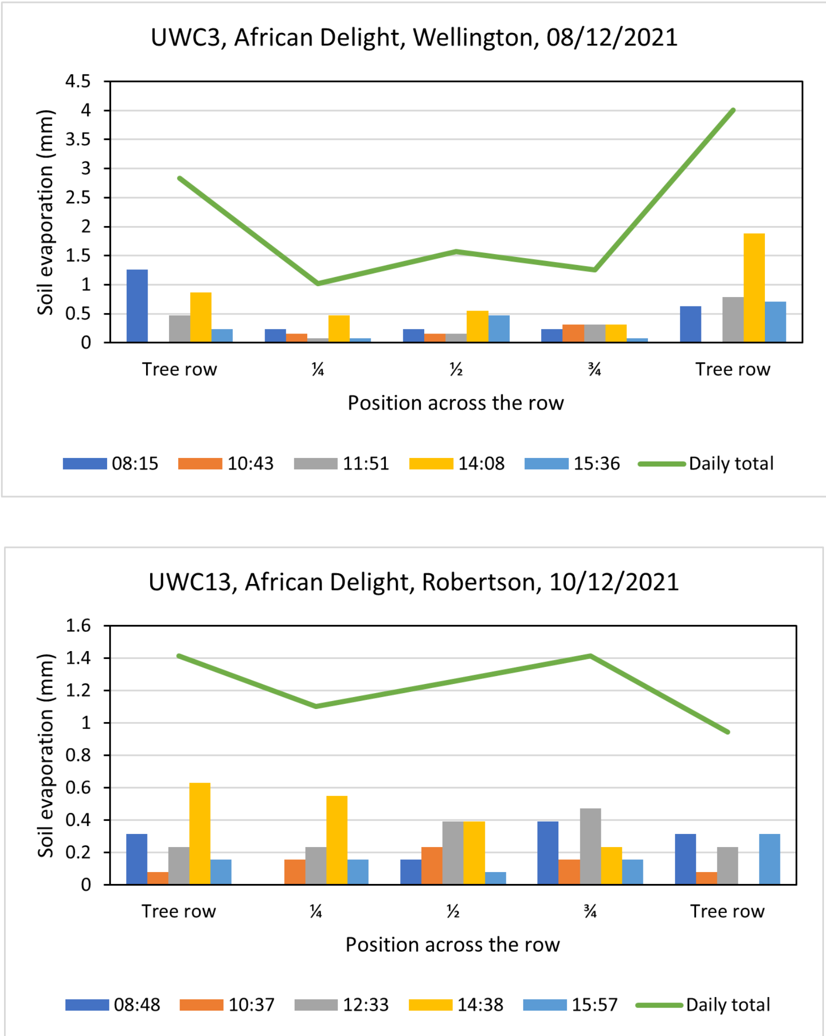


Figure 5.5 *Soil evaporation measurements in micro-lysimeters across the rows in African Delight plum orchards in Wellington and Robertson. The bars represent the time when the measurements were taken and the solid line represents the total daily values. Positions across the row are on the X-axis: tree row; ¼ distance from the tree row: ½ distance from the tree row; ¾ distance from the tree row; tree row. UWCn denotes the proximity of Aquacheck probes (Table 4.1).*

During data processing, some data were omitted when irrational values were recorded, such as unrealistically high soil evaporation or negative values, which occurred due to irrigations that took place during certain hours of the day while measurements were on-going. Both micro-jet irrigations at Wellington and drip-irrigation at Robertson affected some measurements. It was interesting to note that, under drip-irrigation in Robertson (African Delight orchard), saturation levels were reached close to the soil surface at the location of some micro-lysimeters, which caused groundwater to seep through the bottom cap of the micro-lysimeters (Figure 5.6).

Figure 5.6 *Image showing saturated conditions close to the soil surface during/following drip-irrigation in the African Delight orchard at Robertson.*

5.4 Leaf Area Index (LAI) and canopy cover

Measurements of LAI and fc are shown in Figure 5.7 for the Wellington orchards and Figure 5.8 for Robertson. The measurement period spanned from September 2021 to March 2024. The Fortune orchard that was uprooted after the first season in Wellington was replaced by the Ruby Sun orchard (Figure 5.7). From the observed measurements, it is clearly visible that a peak in LAI and fc occurs during the summer season and a low in winter. The LAI in winter (from June to August) represents rather the plant area index (shading of the LAI2200C sensor by the wooden pats of the tree trunk and branches) because all leaves are shed during that period of the year. It is also evident from the measurements that LAI and fc did not vary much during the growing season as the vegetation growth was controlled by pruning. The highest LAI reading over three seasons was 3.99 recorded in the African Delight orchard in Robertson. The lowest LAI reading was 0.52 in the Fortune orchard in Robertson and African Delight orchard in Wellington. The highest recorded fc was 0.93 (Fortune and African Delight in Robertson, and Ruby Sun in Wellington).

Table 5.3 summarizes the average LAI and fc measured during the initial and mid-stages in all orchards over three seasons. Fortune and Ruby Sun tended to have a higher LAI and fc in Wellington, whilst African Delight recorded higher values in Robertson. Fractional interception of radiation by plum canopies was above 0.82 throughout the mid-stage in all orchards. The canopy appeared to be the densest in the Ruby Sun orchard at Wellington. The average LAI in the initial stage varied between 0.55 (African Delight in Wellington) and 1.22 (Ruby Sun in Wellington). The average LAI in the mid-stage ranged between 2.35 (Fortune in Robertson) and 3.37 (Ruby Sun in Wellington). The canopy cover fc in the initial stage varied between 0.34 and 0.59 (Ruby Sun in Wellington), whilst in the mid-stage it was between 0.82 (Fortune in Robertson) and 0.91 (Ruby Sun in Wellington).

The results measured with the LAI-2200C plant canopy analyzer were processed according to the procedure reported by Allen and Pereira (2009) for LAI, fc, Kcb and Kd in high performing plum trees (see procedure in Section 4.6 of methodology). Calculated Kcb and Kd values for the initial and mid-stages are presented in Table 5.3. Kd in the initial stage ranged between 0.32 (African Delight in Wellington) and 0.57 (Ruby Sun in Wellington). In the mid-stage, the lowest Kd of 0.83 was measured in Fortune at Robertson, whilst Ruby Sun in Wellington appeared to have the densest canopy (Kd = 0.91). Kcb in the initial stage ranged between 0.84 (African Delight in Wellington) and 0.98 (African Delight in Robertson). In the mid-stage, average Kcb varied between 1.14 (Fortune in Robertson) and 1.20 (Ruby Sun in Wellington). These values of Kcb are close to those estimated by Allen and Pereira (2009; Table 3) and Rallo et al. (2021).

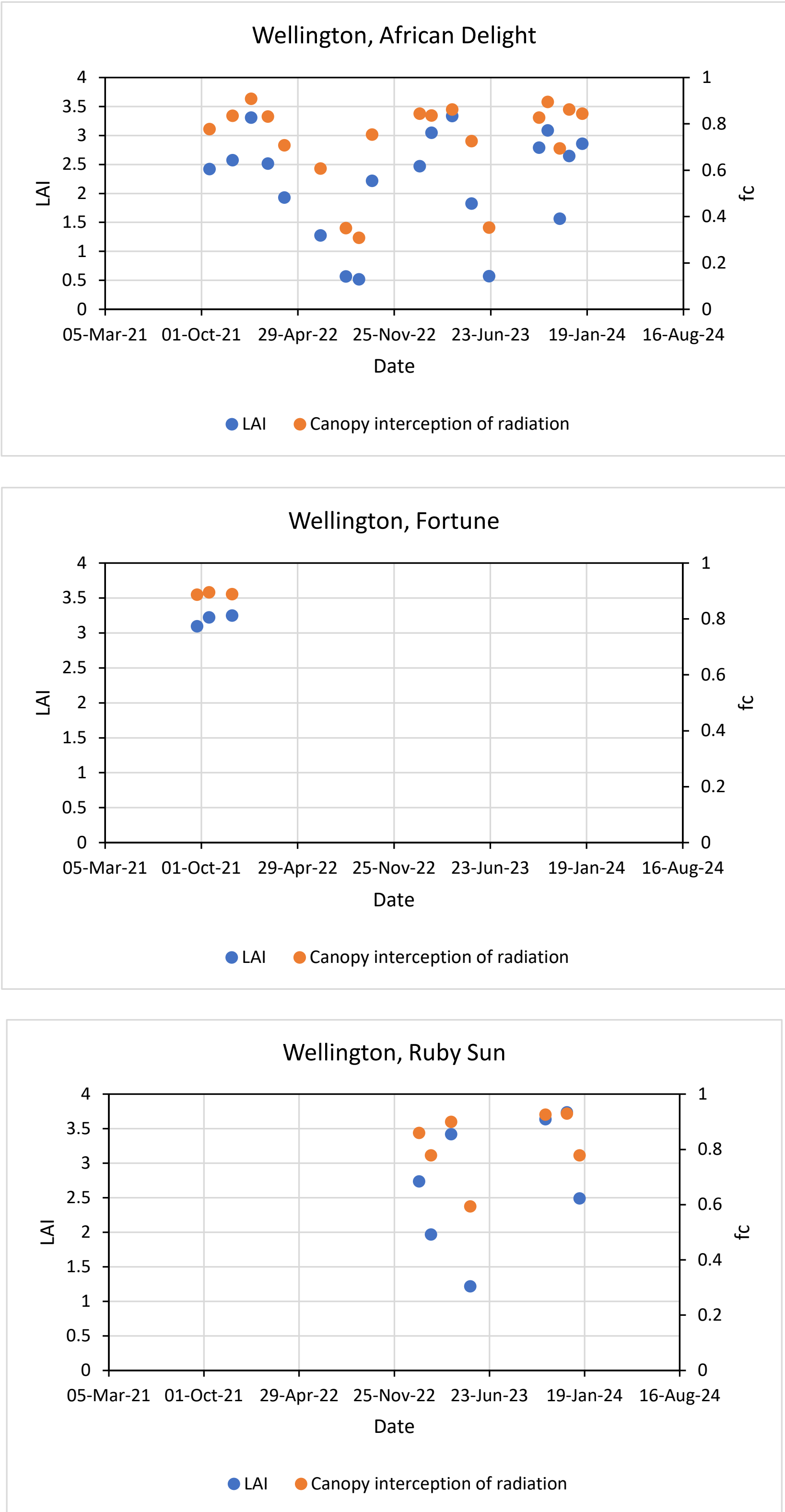
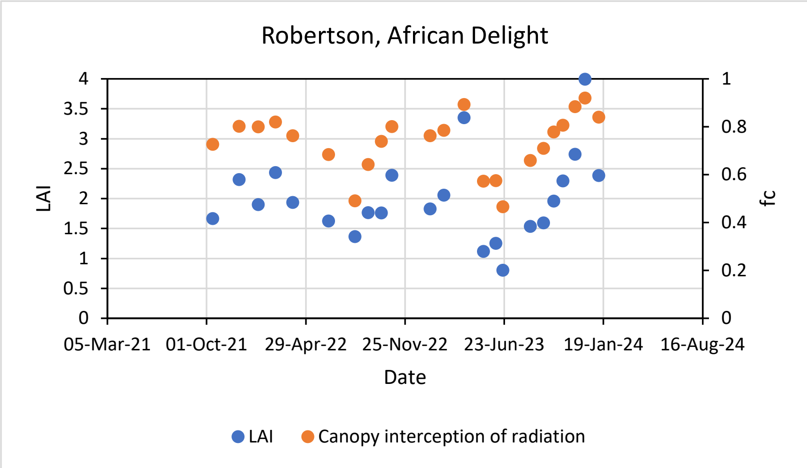


Figure 5.7 *Leaf Area Index (LAI) and fractional interception of radiation measured in 3 plum cultivars in Wellington.*



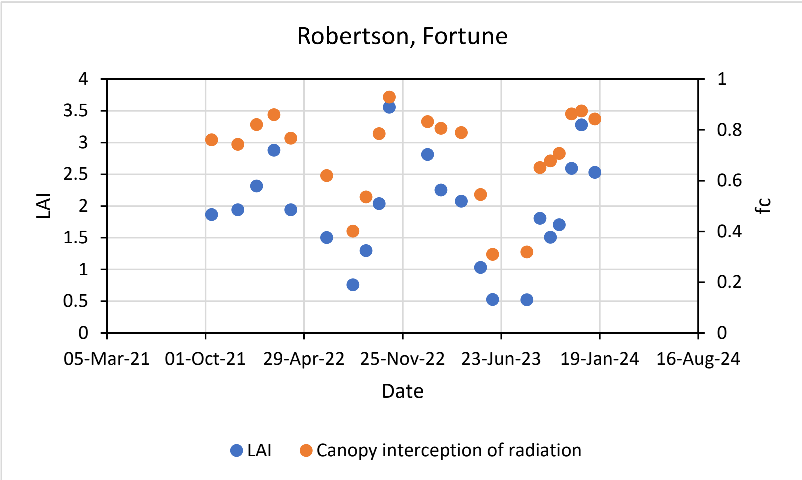


Figure 5. 8 *Leaf Area Index (LAI) and fractional interception of radiation measured in two plum cultivars in Robertson.*

Table 5.3 Fractional interception of radiation (fc), Leaf Area Index (LAI) measured with the LAI-2200C plant canopy analyser, Kcb readings and canopy density (Kd) calculated with the Allen and Pereira (2009) method for the initial and mid-stage in five orchards in Wellington and Robertson. Tree heights are also reported in the Table.

Cultivar and location	Initial stage				Mid stage				Crop height (m)
	fc	LAI	Kcb	Kd	fc	LAI	Kcb	Kd	
African Delight - Wellington	0.34	0.55	0.84	0.32	0.84	2.65	1.16	0.84	3.5
Fortune - Wellington	0.34*	0.60*	0.86	0.34	0.89	3.24	1.19	0.90	3.5
Ruby Sun - Wellington	0.59	1.22	0.94	0.57	0.91	3.37	1.20	0.91	3.5
African Delight - Robertson	0.48	1.09	0.98	0.53	0.84	2.72	1.15	0.85	3
Fortune - Robertson	0.34	0.60	0.88	0.34	0.82	2.35	1.14	0.83	3

*Estimated from Fortune in Robertson

5.5 Stem water potential measurements

Figures 5.9-5.12 present the midday stem water potential (average and three individual trees), rainfall and irrigations for the period February-July 2023. The midday stem water potential data were calculated from Saturas sensors' 20 min readings. Rainfall was obtained from the weather stations in Wellington and Robertson, whilst irrigation data were obtained from the farms. Originally, before Saturas services were discontinued, the Saturas platform made used of rainfall data obtained from Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) (https://chc.ucsb.edu/data/chirps, accessed on 14 June 2023), whilst irrigation data were obtained from pressure transducers (duration of pressure signals were used to calculate irrigation water applied in mm from delivery rates).

Data in Figures 5.9-5.12 indicate that the sensors responded well to rainfall or irrigation water applied as well as to periods of no water inputs, demonstrating the potential for use in irrigation scheduling. Dry periods, especially during summer, caused an increase in midday stem water potentials (measured in bars expressed as a positive number). Additions of water resulted in a drop in midday stem water potentials. Average midday stem water potentials were most of the time within the recommended range for irrigation scheduling (<16.5 b or >-16.5 MPa) at post-harvest stage (Torrecillas et al., 2018). According to data in Figures 5.9-5.12, mild water stress may have occasionally occurred from February to April 2023 during periods between irrigations, based on water stress thresholds reported in the literature by Torrecillas et al. (2018) (16.5 b at post-harvest stage). However, without differentiated irrigation treatments, it was difficult to ascertain these water stress threshold levels for Japanese plums in the Western Cape.

Substantial differences in midday stem water potential between individual trees (>5 b) were measured in some orchards during some periods (Figures 5.9-5.12). Stem water potential data and recommended ranges should be refined using manual measurements with a Scholander pressure chamber (Scholander et al., 1965). Data were available, however, only from February to July 2023, i.e. mostly during the dormancy season, after which the service provision was discontinued. The principles, functioning and reliability of these sensors should be tested during the peak water requirement and irrigation season in summer.

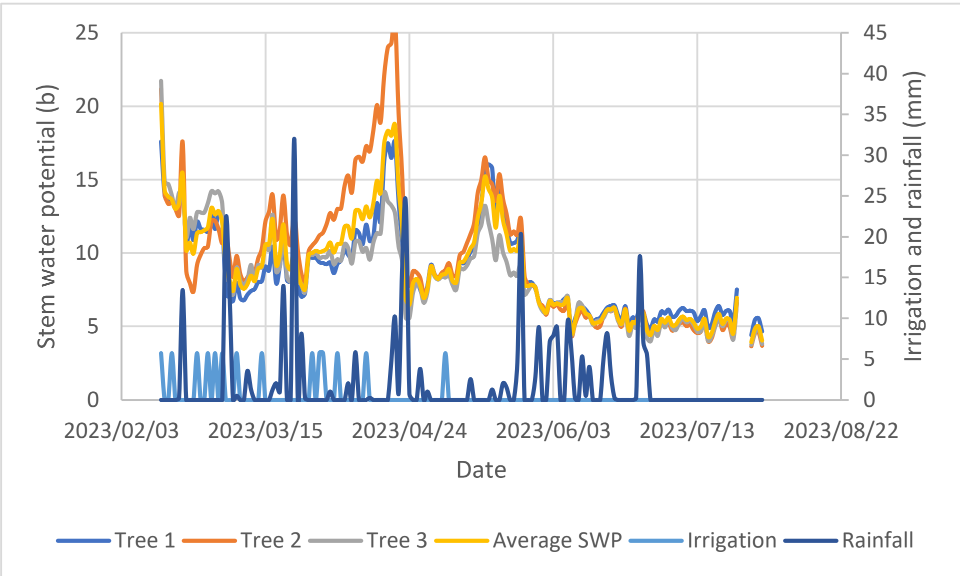


Figure 5.9 *Midday stem water potential (average and individual measurements on three trees), rainfall and irrigation in Block 47 cv African Delight in Wellington.*

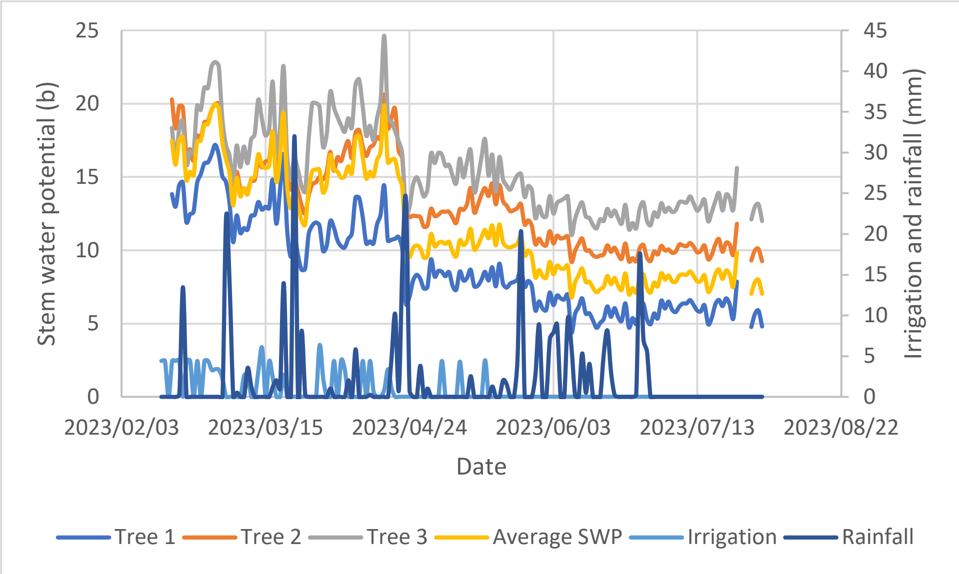


Figure 5.10 *Midday stem water potential (average and individual measurements on three trees), rainfall and irrigation in Block 7 cv Ruby Sun in Wellington.*

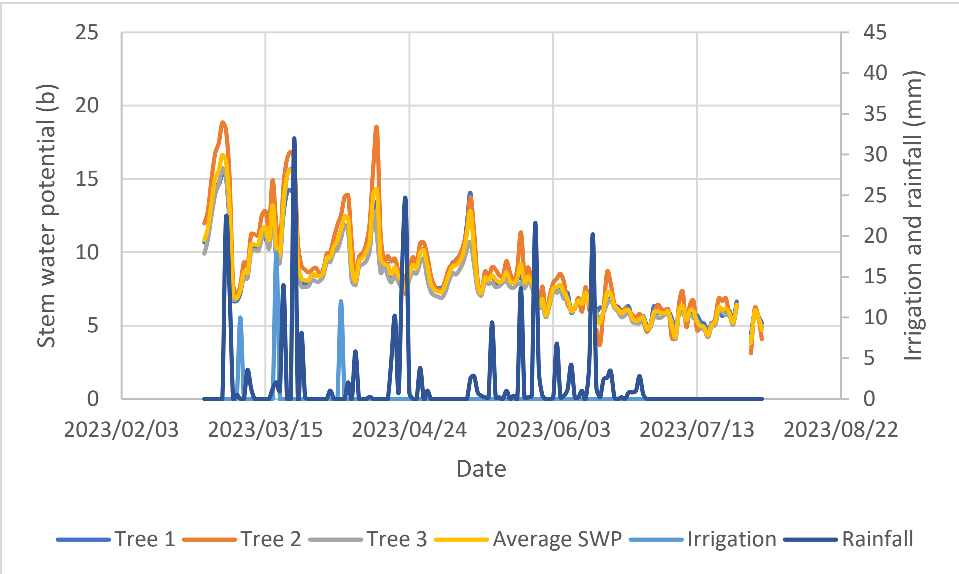


Figure 5.11 *Midday stem water potential (average and individual measurements on three trees), rainfall and irrigation in Block K35 cv African Delight in Robertson.*

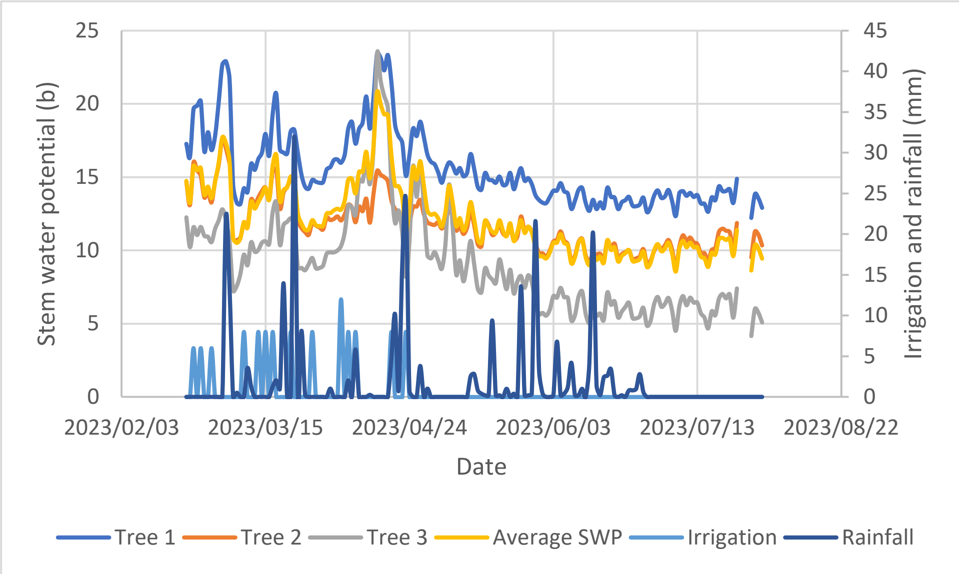


Figure 5.12 *Midday stem water potential (average and individual measurements on three trees), rainfall and irrigation in Block L17 cv Fortune in Robertson.*

5.6 Irrigation volumes and crop yields

A verbal agreement was made with the farm managers to obtain irrigation volumes, crop yield data and grading into the various market classes. Total crop yields and irrigation volumes are summarized in Table 5.4 for all orchards, along with rainfall and reference evapotranspiration. Income per ha was also obtained from the farms. Totals of irrigations, rainfall and reference evapotranspiration are reported for both the main irrigation season (1 September to 8 March) and for the whole year (1 September to 31 August) in order to record off-season irrigations that farms apply to keep the trees healthy and regulate carry-over effects.

Reference evapotranspiration was higher in Robertson than in Wellington, whilst rainfall was higher in the coastal area of Wellington compared to inland (Table 5.4). Season 2021/22 had below-average rainfall at both sites, whilst season 2022/23 was particularly wet characterized by floods in June 2023. Irrigations were applied in response to rainfall. The highest yearly irrigation was delivered to the African Delight orchard in Robertson (2021/22) and the lowest in the African Delight and Ruby Sun orchards in Wellington (2022/23).

Total yields were generally in the range of the expected yield for full-bearing high-density orchards (Table 5.4). By far the highest yields were recorded in the African Delight orchard in Robertson, except in the last year of experimentation when reduced yields were obtained due to a bad fruit set and small fruit numbers. Higher yields were generally recorded in Robertson compared to Wellington. Income in Wellington depended greatly on the market price. In Robertson, income for the last three years was estimated.

Table 5.4 Reference evapotranspiration (ETo), rainfall, irrigation, total crop yields and income for all experimental orchards in Robertson and Wellington.

Location	Orchard	Period	ETo (mm)	Rainfall (mm)	Irrigation (mm)	Total crop yield (t/ha)	Income (ZAR/ha)
Wellington	African Delight	01/09/2021-08/03/2022	791	179	575	36.0	228,669
		01/09/2021-31/08/2022	1162	462	759		
		01/09/2022-08/03/2023	810	184	413	32.0	495,092
		01/09/2022-31/08/2023	1129	665	453		
		01/09/2023-08/03/2024	809	132	754	34.8	-
		01/09/2023-31/08/2024	1196	559	912		
	Fortune	01/09/2021-01/09/2022	514	176	401	37.9	316,628
	Ruby Sun	01/09/2022-08/03/2023	810	184	542	28.4	439,117
		01/09/2022-31/08/2023	1129	665	615		
		01/09/2023-08/03/2024	809	132	608	33.0	-
		01/09/2023-31/08/2024	1196	559	733		
Robertson	African Delight	01/09/2021-08/03/2022	836	59	943	51.0	190,000-200,000
		01/09/2021-31/08/2022	1214	184	1152		
		01/09/2022-08/03/2023	829	140	777	52.0	190,000-200,000
		01/09/2022-31/08/2023	1188	518	817		
		01/09/2023-08/03/2024	825	224	543	20.0	-
		01/09/2023-31/08/2024	1179	454	618		
	Fortune	01/09/2021-08/03/2022	836	59	688	39.8	190,000-200,000
		01/09/2021-31/08/2022	1214	184	970		
		01/09/2022-08/03/2023	829	140	650	42.0	190,000-200,000
		01/09/2022-31/08/2023	1188	518	750		
		01/09/2023-08/03/2024	825	224	525	33.0	-
		01/09/2023-31/08/2024	1179	454	593		

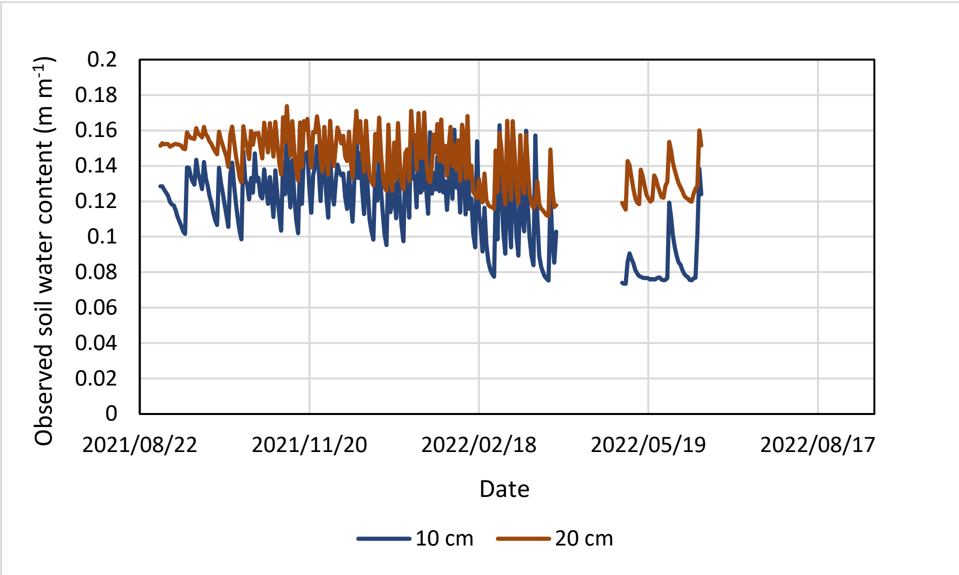
5.7 HYDRUS-2D modelling results

The HYDRUS 2D model (Simunek et al., 2020) was used to calculate the soil water balance for each experimental orchard. The physically-based soil water redistribution calculated in HUDRUS 2D with Richards' equation (Richards, 1931) allowed to calculate crop transpiration and soil evaporation separately, and soil percolation (the volume of water that passes the root system and ends up recharging groundwater due to over-irrigation). In this way, the irrigation management and crop water productivity could be evaluated for each orchard.

HYDRUS 2D simulations were run for the growth season until harvest (from 1 September until 8 March of the following year) and for the full year (from 1 September until 31 August of the following year). This was done in order to capture crop water requirements for the growth season as well as for the full year, given farmers continue to irrigate orchards after harvest to ensure healthy trees and remedy possible water stress and desiccation of trees. Simulations for Fortune at Wellington were run until 9 January 2022, after which the orchard was uprooted. Continuous simulations across the entire period of the experiment were not possible because the maximum number of time steps taken by the model is 500, corresponding to 500 days when the model is run on a daily time step.

The first step of the modelling exercise consisted in calibrating the model. This was done by comparing simulated soil water contents with those observed with the AquaCheck probes. Model inputs were modified (soil hydraulic properties, initial soil water content, boundary conditions, root depth and distribution) and the outputs of simulated soil water contents were extracted and compared to observed soil water content data. The purpose was to obtain the least possible errors in simulated soil water contents, thereby gaining confidence that the model is reliable in the simulation of the soil water balance.

An example of simulated and observed soil water content data are shown in Figure 5.13 for the African Delight orchard in Robertson at soil depths of 10 and 20 cm. The observed data refer to AquaCheck probe 13 (Table 4.1). It can be observed in Figure 5.13 that the general seasonal trends of soil water content are well replicated with the HYDRUS 2D model. The top layers of the soil are very dynamic in terms of water redistributions due to rainfall, frequent drip-irrigations and root water uptake. The mean absolute error committed by the model was 0.028 m m^{-1}. This could be due to several reasons such as spatial variability of soil properties, stony soil, soil layers impeding or enhancing water redistribution through preferential flow. Another possible source of error was that the model was run on a daily time step and for this reason the observed data refer to time 00:00 of each day, which may not be consistent with the irrigation timing, usually occurring during daytime. A more detailed analysis of observed and simulated water contents for the entire soil profile indicated that the errors committed by the model are very small, rendering it sufficiently reliable for the estimation of the soil water balance (Mathews, 2024). This analysis is summarized in Table 5.5.



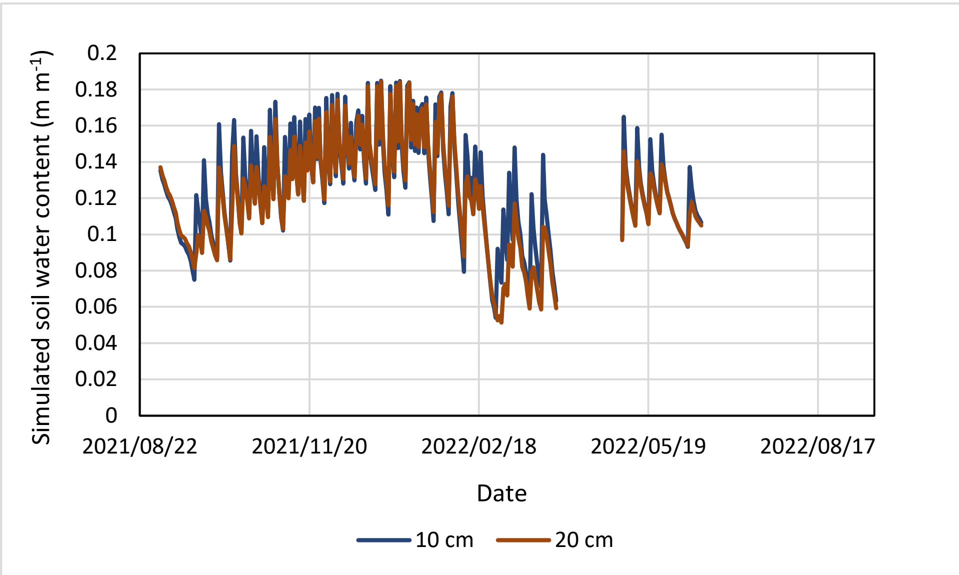


Figure 5.13 *Observed and simulated soil water contents in Block K35 cv African Delight in Robertson during season 2021/22 at soil depths of 10 and 20 cm. The observed data refer to AquaCheck probe 13 (Table 4.1).*

Table 5.5 Mean absolute errors (MAE) between observed and simulated water contents over the entire soil profile at the two experimental farms for the period from 01/09/2021 to 31/03/2023.

Farm	Cultivar	Measurement period	Observation probe (Table 4.1)	MAE (mm)
Smuts Bros (Robertson)	African Delight	01/09/2012-31/03/2023	11	3.82
			13	4.20
	Fortune	01/09/2012-31/03/2023	7	3.78
			9	3.65
Sandrivier (Wellington)	African Delight	01/09/2012-31/03/2023	4	1.49
			5	1.41

Once confidence was gained in the reliability of model results, simulations were run to calculate and interpret the soil water balance components. An example of HYDRUS 2D output is shown in Figure 5.14, showing the cumulative values of fluxes occurring at all model's boundaries. The simulations refer to the African Delight orchard in Robertson for season 2021/22 (full year from 1 September 2021 to 31 August 2022). The units of output graphs are unusual and the values were recalculated per unit length of the model domain according to the technical manual (Simunek et al., 2020).

The summary of soil water balance components and crop yields are presented in Table 5.6 for all experimental orchards and seasons. Reference evapotranspiration and rainfall were obtained from measurements at the weather stations. Irrigation amounts and crop yields were obtained from the farmers. Soil evaporation and actual root water uptake were simulated with HYDRUS 2D. Crop water requirements were calculated as the sum of soil evaporation and actual root water uptake.

Data in Table 5.6 indicated that ETo was substantially higher in Robertson than in Wellington with yearly maxima of 1214 mm a^{-1} and 1196 mm a^{-1}, respectively (periods from 1 September to 31 August). Yearly rainfall was substantially higher in Wellington than in Robertson. Year 2021/22 was dry in Wellington recording 462 mm a^{-1}, and particularly in Robertson where only 184 mm a^{-1} of rain fell from 1 September to 31 August. Year 2022/23 was wetter with 665 mm a^{-1} recorded in Wellington and 518 mm a^{-1} in Robertson. Widespread floods occurred in June 2023 across the Western Cape. Rainfall in 2023/24 was also above average with 559 mm a^{-1} in Wellington and 454 mm a^{-1} in Robertson.

As a result of weather conditions, more irrigation was applied in season 2021/22 compared to 2022/23 (Table 5.6). Irrigation volumes were generally higher in Robertson than in Wellington due to the higher atmospheric evaporative demand (ETo) and the irrigation management applied in specific orchards. In the Fortune orchard at Robertson, a third drip-irrigation line was added. This was done to ensure sufficient discharge rates especially in deeper alluvial soil and to refill the sub-soil that may have dried out during the dry season. The highest annual irrigation was delivered to the African Delight orchard in season 2021/22 (1152 mm a^{-1}). This orchard is particularly difficult to manage due to the stony soil. However, it produced by far the highest crops yields of 51 t ha^{-1} (2021/22) and 52 t ha^{-1} (2022/23). In 2023/24, the African Delight orchard in Robertson produced only 20 t ha^{-1}. This was an anomaly due to a bad fruit set and small fruit numbers, unrelated to irrigation management. The Fortune orchard in Robertson experienced the same challenge in 2023/24 producing only 33 t ha^{-1}, the least out of three seasons.

According to HYDRUS 2D model simulations (Table 5.6), soil evaporation from African Delight orchards in Robertson and Wellington was comparable, ranging between 249 and 264 mm a^{-1}. Calculated soil evaporation in the Ruby Sun cultivar was the lowest (158 and 164 mm a^{-1}), whilst the highest was calculated for cultivar Fortune in Robertson (310-339 mm a^{-1}). Simulated daily soil evaporation data were within range of those measured with micro-lysimeters (Mathews, 2024).

The highest actual root water uptake calculated with HYDRUS 2D occurred in the African Delight orchard in Robertson (822-1018 mm a^{-1}) and Fortune orchard in Robertson (866-975 mm a^{-1}) (Table 5.6). According to the model, trees in Wellington extract less water yearly, however the crop yields in Wellington are lower than in Robertson. The least root water uptake was calculated for the Fortune cultivar in Wellington, however these data refer from 1 September 2021 to 9 January 2022, after which the orchard was uprooted. As a result of irrigation volumes applied, HYDRUS 2D calculated that the highest drainage (bottom boundary flux) was in the African Delight orchard in Robertson (73-148 mm a^{-1}). This orchard appeared to be slightly over-irrigated, however, it excelled in terms of crop yields. Drainage volumes calculated in the orchards depended on irrigation management and rainfall distribution. The highest drainage was calculated for most orchards in year 2022/23 due to the high rainfall in winter 2023.

Finally, data generated with the HYDRUS 2D model were used to calculate crop water requirements as the sum of soil evaporation and actual root water uptake for both the main irrigation season and hydrological (calendar) year (Table 5.6). In this way, we obtained crop water requirements for fully-bearing high-performing Japanese plum orchards. Crop water requirements during the main irrigation season varied widely depending on the harvest period for early- and late-maturing cultivars. Important factors were also pruning that reduced the leaf area available for evapotranspiration and the management of the cover crop (regular cuttings to reduce the leaf area and evapotranspiration from mid-rows). The lowest crop water requirements for the main irrigation season were calculated for cultivar Fortune in Wellington (488 mm from 1 September 2021 to 9 January 2022) and the highest for cultivar Fortune in Robertson (921 mm from 1 September 2021 to 8 March 2022). As farmers continue to irrigate after harvesting to mitigate drought water stress and tree damage, the calculation of crop water requirements was also performed for the full calendar year from 1 September to 31 August (Table 5.6). The lowest crop water requirement of 958 mm a^{-1} was calculated for cultivar African Delight in Wellington. The highest yearly crop water requirement of 1285 mm a^{-1} was calculated for cultivar Fortune in Robertson irrigated with three drip laterals, which appeared the least pruned with generally lavish cover crop. Whilst yearly crop water requirements of African Delight and Fortune orchards in Robertson were similar, the water requirements of African Delight were less in the cooler climate of Wellington. Crop yields in Wellington were however consistently lower compared to Robertson.

A more detailed analysis of these data is provided in Chapter 6 of this report, where comparison is made between crop water requirements obtained with different methods, and crop water and economic productivities are calculated.

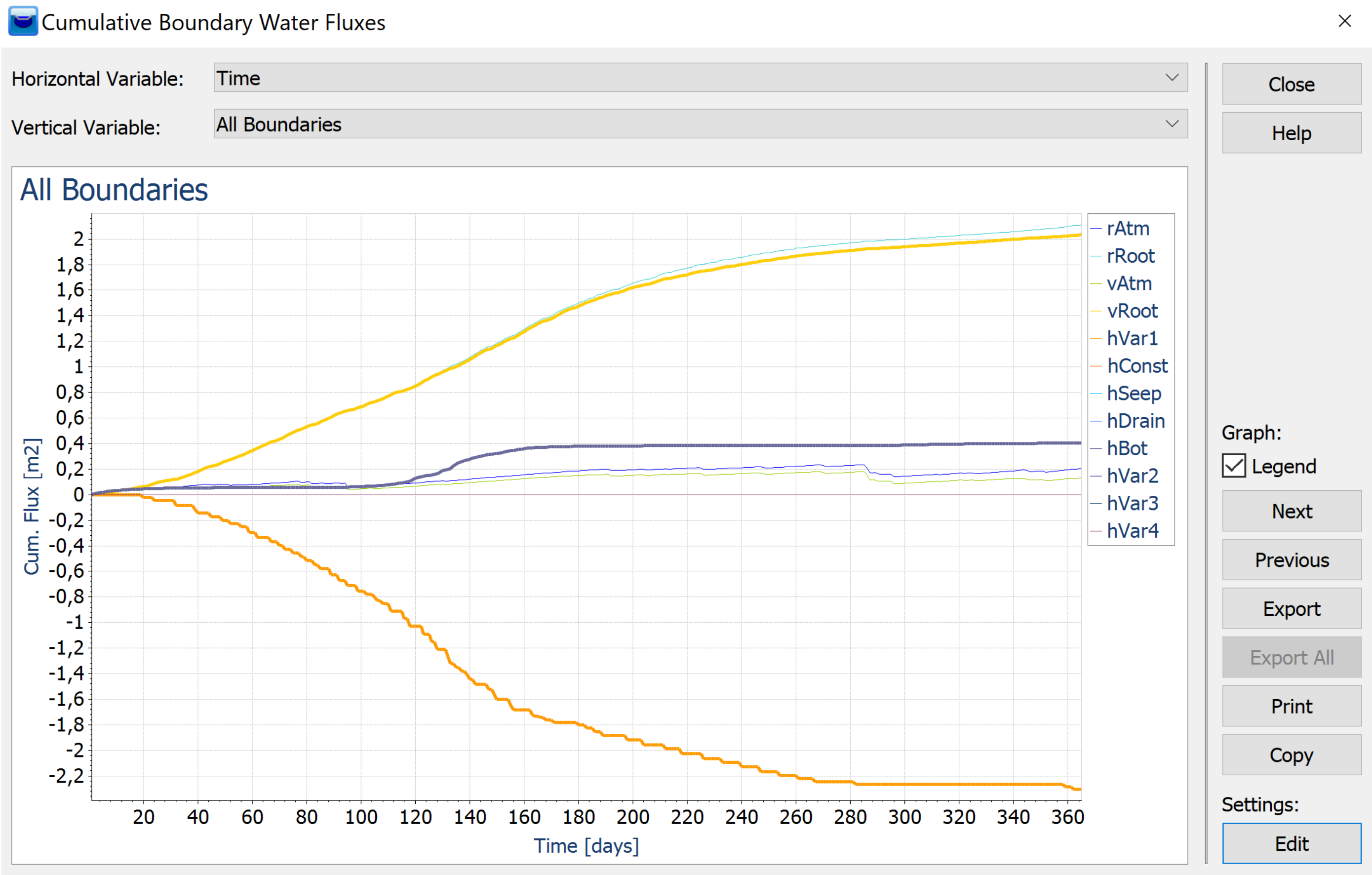


Figure 5.14 *Example of model outputs (cumulative boundary water fluxes) for African Delight orchard in Robertson for the simulation period from 1 September 2021 to 31 August 2022. The bold yellow curve represents the cumulative actual root water uptake (vRoot): the bold orange line is cumulative irrigations (hVar1); the bold purple line is the cumulative flux at the bottom boundary layer, representing deep percolation (hBot). Bottom graph: Cumulative soil evaporation represented by the bold blue line.*

Table 5.6 Summary of reference evapotranspiration (ETo), soil water balance components and crop yields for all experimental orchards and season

Location	Orchard	Period	ETo[1] (mm)	Rainfall[1] (mm)	Irrigation[2] (mm)	Soil evaporation[3] (mm)	Actual root water uptake[3] (mm)	Drainage[3] (mm)	Crop water requirements[4] (mm)	Yield[2] ($t\ ha^{-1}$)
Wellington	African Delight	01/09/2021-08/03/2022	791	179	575	134	646	19	780	36.0
		01/09/2021-31/08/2022	1162	462	759	264	859	39	1123	
		01/09/2022-08/03/2023	810	184	413	121	570	12	691	32.0
		01/09/2022-31/08/2023	1129	665	453	256	702	62	958	
		01/09/2023-08/03/2024	809	132	754	143	702	45	845	34.8
		01/09/2023-31/08/2024	1196	559	912	264	906	111	1170	
	Fortune	01/09/2021-09/01/2022	514	176	401	46	442	32	488	37.9
	Ruby Sun	01/09/2022-08/03/2023	810	184	542	81	709	28	790	28.4
		01/09/2022-31/08/2023	1129	665	615	164	930	98	1094	
		01/09/2023-08/03/2024	809	132	608	82	772	39	854	33.0
		01/09/2023-31/08/2024	1196	559	733	158	991	92	1149	
Robertson	African Delight	01/09/2021-08/03/2022	836	59	943	137	773	95	910	51.0
		01/09/2021-31/08/2022	1214	184	1152	249	1018	101	1267	
		01/09/2022-08/03/2023	829	140	777	130	704	58	834	52.0
		01/09/2022-31/08/2023	1188	518	817	253	901	148	1154	
		01/09/2023-08/03/2024	825	224	543	141	675	44	816	20.0
		01/09/2023-31/08/2024	1179	454	618	254	822	73	1076	
	Fortune	01/09/2021-08/03/2022	836	59	688	173	748	21	921	39.8
		01/09/2021-31/08/2022	1214	184	970	310	975	22	1285	
		01/09/2022-08/03/2023	829	140	650	182	733	36	915	42.0
		01/09/2022-31/08/2023	1188	518	750	339	928	66	1267	
		01/09/2023-08/03/2024	825	224	525	178	716	45	894	33.0
		01/09/2023-31/08/2024	1179	454	593	324	866	52	1190	

[1]Obtained from the weather stations [2]Obtained from the farms [3]Simulated with the HYDRUS-2D model [4]Sum of actual root water uptake and soil evaporation simulated with the HYDRUS 2D model

5.8 Eddy covariance energy balance fluxes

5.8.1 Surface energy balance in a plum orchard

Surface energy balance data were collected in the African Delight orchard at Robertson from 11 May 2023 to 31 August 2024. Data were collected and stored with a Campbell Scientific (CR1000X) logger on an half-hourly basis. For the purpose of this Section, surface energy balance data were analyzed from 11 May 2023 until 10 May 2024 (full hydrological year).

Figure 5.15 shows the seasonal variation of daily surface energy balance components: net radiation (Rn), sensible heat (H), soil heat (G), and latent heat (LE) fluxes. Rn represents the balance between the incoming shortwave (SW) radiation and the outgoing longwave (LW) radiation. H represents heat transfer between the earth's surface and the atmosphere through conduction and convection. G represents heat transfer through the soil profile. Lastly, LE represents heat transfer associated with phase changes primarily from the transpiration of water from plants and evaporation from the soil surface. In a well-irrigated and well managed crop field, the LE variation follows that of Rn. Both Rn and LE had the lowest values in the winter (June – July) before starting to increase gradually towards the beginning of the vegetative season in September. As the plum trees approached the full development stage, Rn and LE reached their single-peaks (21.8 and 19.6 MJ m^{-2} day^{-1}, respectively) in the summer season (January). H and G values were expected to be smaller than Rn and LE values in the irrigated orchard. However, these fluxes' seasonal trends were different. At the onset of the winter season, in May, the values of H were higher than those of G, which were primarily negative during that period. This period is associated with nocturnal cooling, suggesting that atmospheric boundary layer temperatures are cooler than soil temperatures. Negative values of H were observed during most days of June. Towards the end of winter, G slightly increased and stayed positive during most days of the growing season, excluding some isolated cases, as much solar radiation penetrated the soil. Negative H values are common in winter during strong conditions of radiation cooling (thermal inversion). The peaks of H and G peaks were 4.8 (November) and 2.1 (January) MJ m^{-2} day^{-1}, respectively. LE of the cv. African Delight was the main consumer of net radiation, followed by H and lastly G. These fluxes accounted for 83.5, 15.7 and 0.8% of Rn respectively.

The available energy for transpiration and biological processes is calculated as the difference between Rn and G, and is illustrated as Rn-G. Average flux ratios of H/LE (Bowen ratio), H/(Rn-G), LE/(Rn-G), and G/Rn were 0.23, 0.12, 0.85, and -0.02 respectively (Figure 5.16). Results show that LE/(Rn-G) was close to 1 throughout the plum growing season. H/LE, LE/(Rn-G) and H/(Rn-G) ratio were mostly positive over the season. This was not the case with G/Rn (Figure 5.16c), which had a substantial portion of negative values, particularly during the winter just before the beginning of the vegetative season.

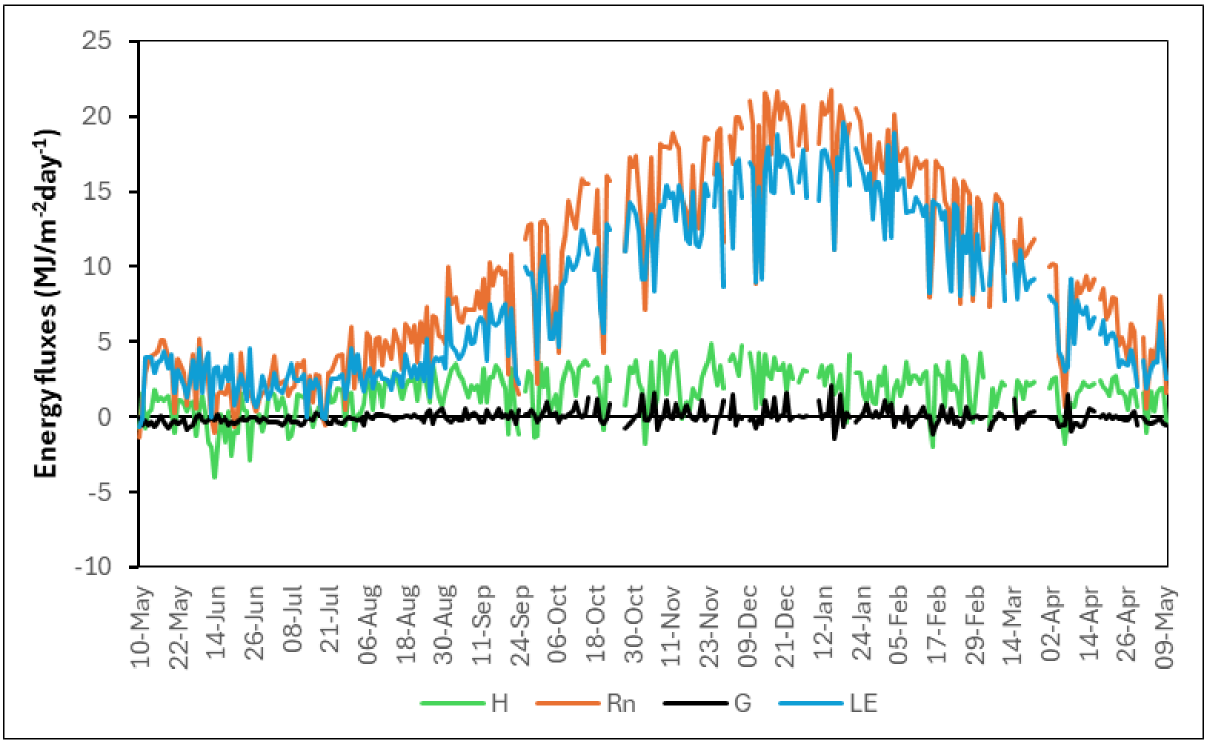


Figure 5.15 *Values of daily energy fluxes measured with an eddy covariance micrometeorological station in the African Delight orchard in Robertson from 11 May 2023 to 10 May 2024. H, Rn, G, and LE are the sensible heat, net radiation, soil heat flux, and the latent heat flux.*

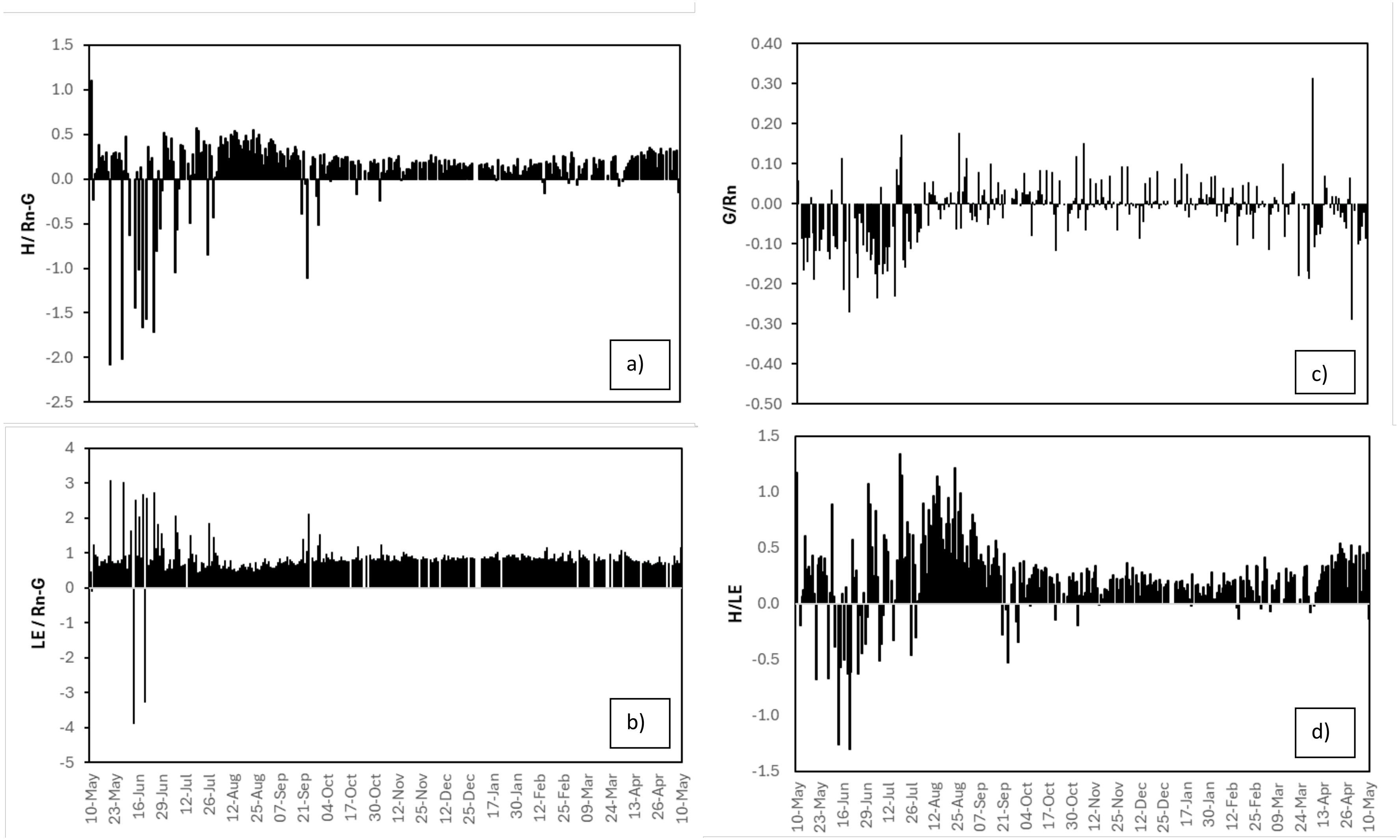


Figure 5.16 *Ratios of daily energy fluxes in the African Delight orchard in Robertson from 11 May 2023 to 24 March 2024. H, Rn, G, and LE are the sensible heat, soil heat flux, net radiation, and the latent heat flux.*

5.8.2 Plum evapotranspiration and crop coefficient

Figure 5.17 shows a seasonal curve of daily crop evapotranspiration (ETc) of cv. African Delight determined from daily LE. Results obtained show a sinusoidal growth curve: a trough (0.26 mm day^{-1}) in winter (June – July) before the onset of the vegetative season, and a high peak (7.99 mm day^{-1}) in summer (December-January) when there was full canopy cover, before ETc started to decline gradually towards harvest. The mean daily ETc over the period of the main irrigation season (from 1 September 2023 to 8 March 2024) was 4.86 mm d^{-1}, while the cumulative ETc for that period was 782 mm. The ETc value represented evapotranspiration from a fully-bearing, high-performing, well-irrigated African Delight orchard and the value of 782 mm can therefore be considered the crop water requirement for the main irrigation season. The total measured ETc for the entire year from 11 May 2023 to 10 May 2024 was 996 mm, which can be considered the crop water requirement for the hydrological year.

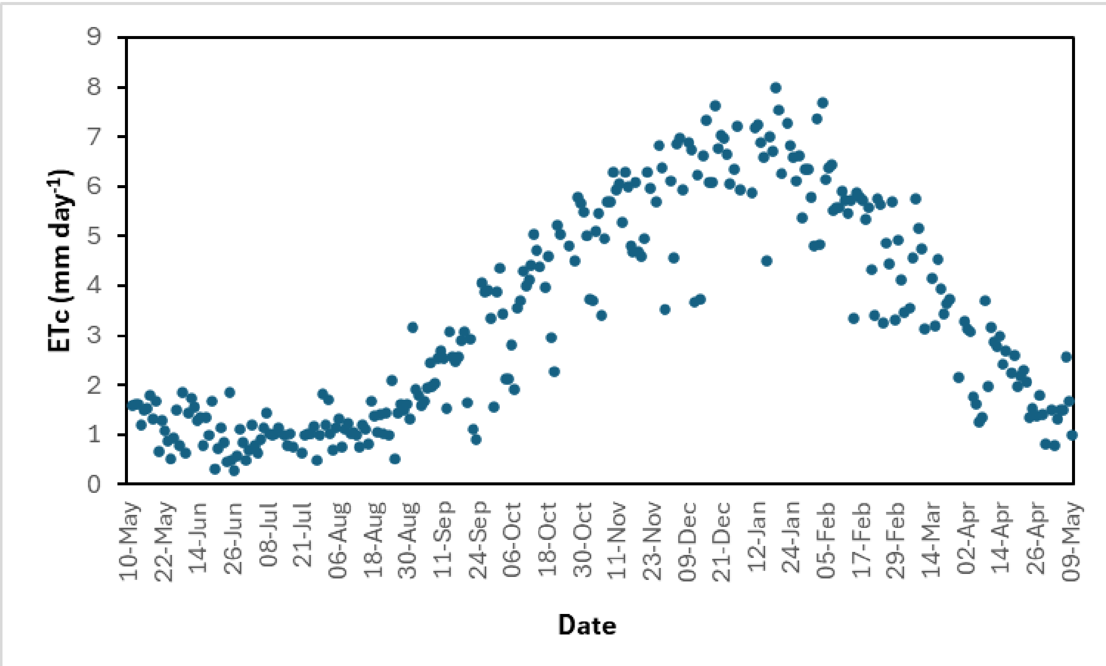


Figure 5.17 *Seasonal curve of the daily crop evapotranspiration (ETc) measured by the eddy covariance system (EC) in the 2023-2024 year for cv. African Delight.*

Crop coefficients Kc were obtained from the ratio of ETc and ETo, assuming that irrigation and soil water supply conditions were optimal, and no water stress occurred. Monthly crop coefficients (Kc) of cv. African Delight showed a seasonal curve similar to that of ETc (Table 5.7). A trough value of 0.49 was observed in July and August. However, high values >1.0 formed a plateau during the plums' full cover mid-stage from October to March. After March, the Kc curve started to decline.

Table 5.7 Monthly crop coefficients (Kc) of cv African Delight plum in Robertson.

Month	Kc
May	0.82
June	0.74
July	0.49
August	0.49
September	0.84
October	1.00
November	1.07
December	1.18
January	1.20
February	1.09
March	1.05
April	0.80

5.9 Remote sensing evapotranspiration

5.9.1 Validation of FruitLook

The eddy covariance system is considered the most direct method to determine evapotranspiration because it estimates directly evapotranspirative fluxes. However, it is a point measurement representing a homogeneous footprint of vegetation and it is expensive equipment. Remote sensing provides the opportunity to estimate spatial evapotranspiration over large scales, provided this method is validated against a trusted reference. In this project, weekly (FruitLook) ET estimates were validated against field measurements from the eddy covariance tower as reference.

Weekly FruitLook-based ET estimates were validated against field measurements from the EC system. Four commonly used statistical metrics (R^2, RMSE, NSE and Pbias) were employed to evaluate the performance of the model. FruitLook ET estimates showed a similar weekly single-peak temporal curve as that obtained from the EC system (Figure 5.18). The mean weekly, seasonal and annual ET volumes estimated by FruitLook were 20.6, 744 and 948 mm, respectively, compared to 21.8, 751 and 996 mm volumes measured by the EC system. FruitLook had good agreement with field measurements showing R^2 = 0.92 while having RMSE and MAE values of 4.11 mm week^{-1} and 2.95 mm week^{-1}, respectively (Figure 5.19). On average, FruitLook underestimated plum ET with a Pbias of 6.15%. The NSE statistical metric was 0.91, meaning that FruitLook has a predictive power, although it is less accurate than a perfect model. However, NSE = 0.91 also implies that FruitLook performs better than the mean of the field-measured data.

Figure 5.20 shows the percentage bias of the performance of FruitLook when estimating ET in an African Delight orchard in Robertson. Significant deviations between the measured and estimated ET values (up to 37% underestimation) were observed during the winter season (between May – early July). The remote sensing model overestimated ET values by up to 61% between mid-July and mid-August. Model accuracy increased thereafter (mid-September - November) as the crop canopy developed and orchard water use increased. This can be seen in Figure 5.20, where the percentage difference between estimated and measured ET decreases over time. FruitLook accurately depicted the seasonality of orchard water use, where minimum ET occurred during the winter months (4 mm week^{-1}) followed by a gradual increase towards peak consumption during the summer months (4.5 mm d^{-1} and 34 mm week^{-1}). During the latter part of the validation period (mid-September to November), FruitLook ET estimates were within 10% of field measurements on 3 instances (week of 18 – 24 October, 25 -31 October and 8 – 13 November). A leap in the underestimation of the ET values by FruitLook during the mid-summer season (mid-December and mid-January), as shown in Figures 5.18 and 5.20, can be attributed to missing field-measured data during the respective period. The model improved thereafter, with the estimated ET within 10% of the field data from mid-January to early-March 2024.

Validation of daily SEBS data was also conducted against eddy covariance measurements for the period May 2023-November 2024, and they were reported by Motsei (2024). Comparatively, SEBS performed less effectively than FruitLook, yielding an R^2 = 0.80, RMSE = 0.82 mm/day and Pbias = -14%.

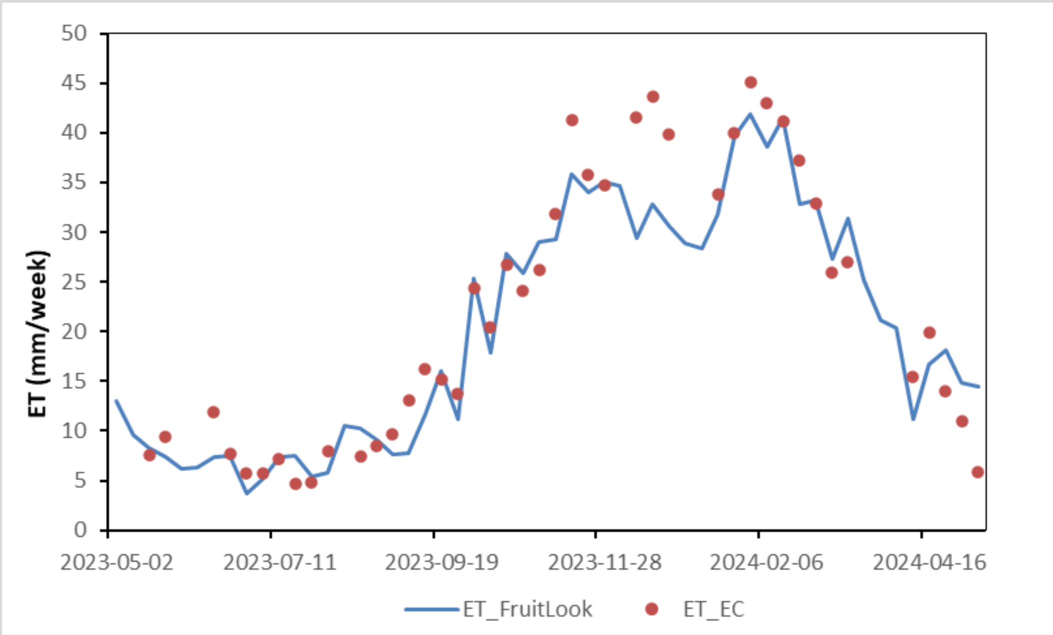


Figure 5.18 *Comparison between weekly FruitLook-based evapotranspiration and eddy covariance system measured evapotranspiration (ET_EC) in an African Delight orchard (Robertson) for the 2023-2024 hydrological year.*

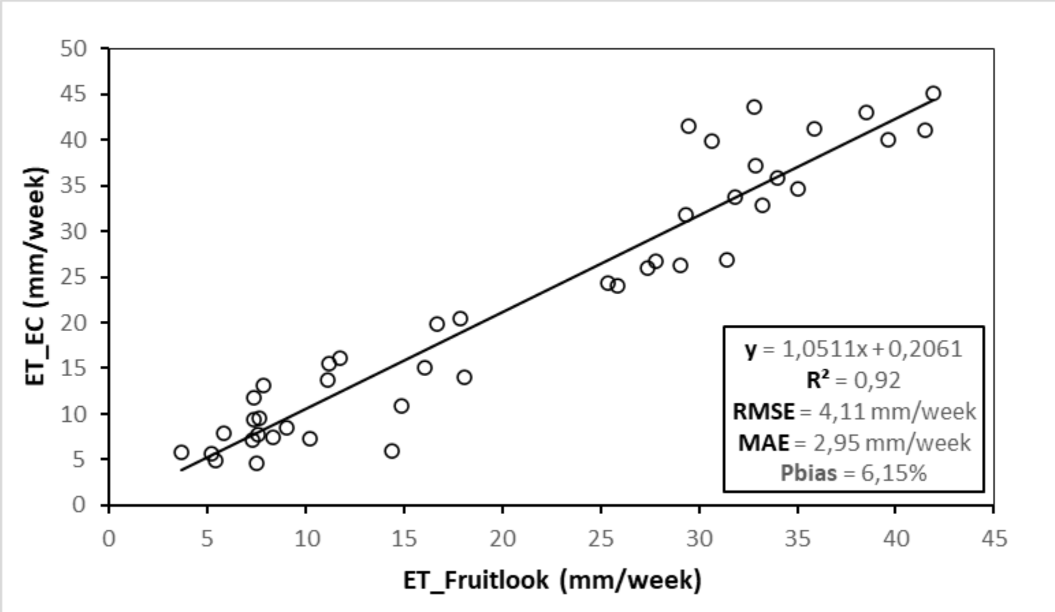


***Figure 5.19** A scatter plot showing the correlation between evapotranspiration (ET) measured by the eddy covariance (EC) system and estimated by FruitLook for the African Delight orchard in Robertson.*

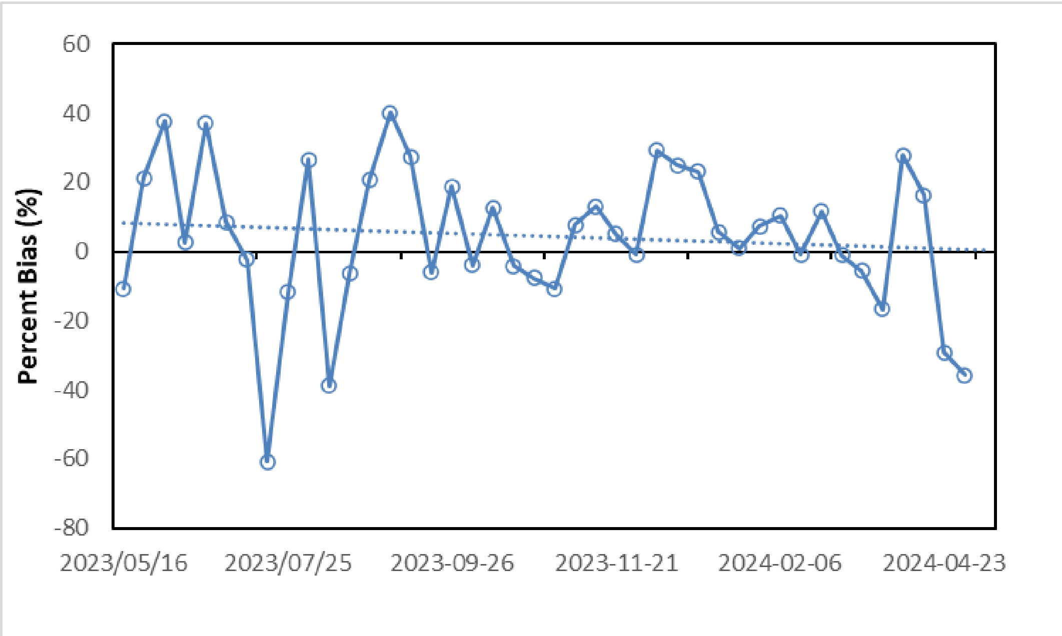


***Figure 5.20** Percentage bias of the performance of FruitLook when estimating evapotranspiration in an African Delight orchard in Robertson.*

An example of modelled weekly FruitLook ET is shown in Figure 5.21 for the week of 18 – 24 September 2023. The spatial variability of ET was adequately depicted in the high-resolution 10 m FruitLook image. ET at the edges of the field was considerably lower than in the middle of the field due to the field edge effect. In remote sensing, this is often a result of pixel mixing, where pixels at the edge of the field contain other landcover types (i.e. bare soil between orchards, different crop types), which decrease or increase the overall ET for the pixel.

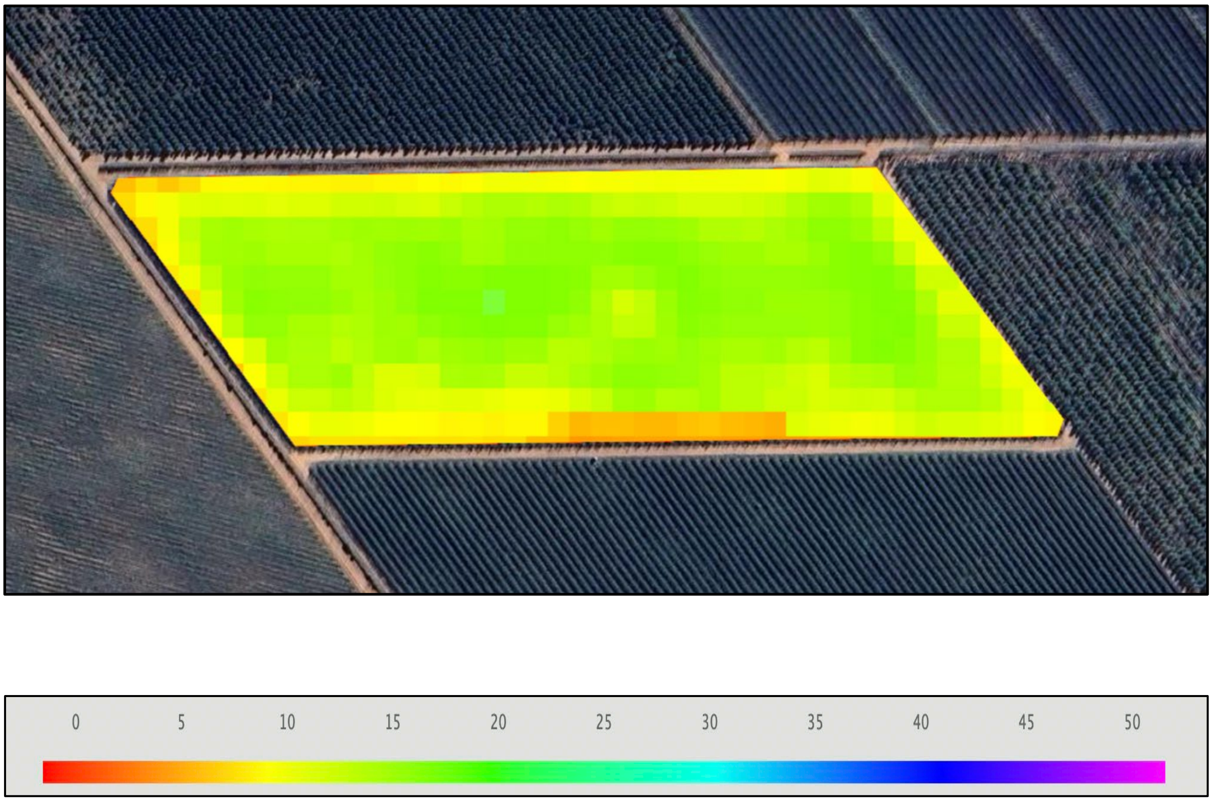


Figure 5.21 *Weekly FruitLook evapotranspiration (ET) (18 – 24 September 2023) for African Delight orchard (block K35) in Robertson. ET ranged between 3.5 and 19.9 mm week^{-1}, with a mean of 15.9 mm week^{-1}.*

To better evaluate the reported accuracies in this study, a literature search was conducted with a focus on the application of the SEBS model and FruitLook (SEBAL and ETLook model) for agricultural water use estimation in South Africa (Table 5.8). The search revealed that the SEBAL model has been extensively applied in South Africa across a diverse range of land cover types and climatic regions with a relatively high level of success (average R^2 > 0.65). First used by Kongo and Jewitt (2006) to access the hydrological response of the Pontshini catchment to rainwater harvesting, the model has since been used operationally for water use estimation of several crops types (Jarmain et al., 2009; Meijninger and Jarmain, 2014; van der

Laan et al., 2019; Rebelo et al., 2020), water use efficiency monitoring (Klaase et al., 2008; Hellegers et al., 2008; Jarmain et al., 2014; Singels et al., 2018a) and catchment-scale hydrological analysis (Kongo et al., 2011; Hellegers et al., 2011; Dzikiti et al., 2016) to support the management of water resources. The ETLook model (Bastiaanssen et al., 2012), the latest iteration of the SEBAL, has gained traction in recent years. However, limited studies were found where ET was validated against field measurements in South Africa. Brombacher et al. (2022) reported R^2 values of 0.75 and 0.78 for monthly and seasonal irrigation-based ET estimates when compared to water meter recordings in the Hex Valley, Western Cape. Jarmain (2020) and van Niekerk et al. (2018; 2023) found that ETLook ET estimates compared well with historic field measurements and RS-based estimates from previous studies.

SEBS, on the other hand, has historically performed poorly in South Africa in contrast to findings from international literature (Ma et al., 2013; Jamshidi et al., 2019; Acharya and Sharma, 2021; Xue et al., 2021), which reported higher model accuracy. Gokool et al. (2016) validated SEBS ET estimates against in-situ surface renewal measurements in a sugarcane field. They reported a coefficient of determination (R^2) of 0.33 and RMSE of 2.19 mm day^{-1} (81% of the observed mean). Jarmain et al. (2009) and Gibson (2013) reported similarly low model accuracy, where on average, SEBS ET estimates exceeded field measurements by 9 – 47%.

In the current study, FruitLook outperformed reported accuracies in previous studies ($R^2 \geq 0.8$ and relative RMSE < 30% of the observed mean). Another notable point is that estimated ET in previous studies typically exceeded field measurements whereas ET estimates in this study under-estimated eddy covariance measurements. This is likely due to a large portion of the validation period covering the winter months and early spring, which are associated with low water use and atmospheric demand. Additionally, the chosen spatial resolution has been reported to largely impact model accuracy (Shoko, 2014), particularly when investigating small agricultural fields, which is often the case in fruit orchards. Historic studies predominantly used coarse resolution MODIS (250 m – 1 km resolution) satellite images to compute for biophysical surface parameters and ET compared to the moderate resolution Landsat 8 (30 m) and high-resolution Sentinel 2 (10 m) images used to derive SEBS and FruitLook ET estimates in the current study.

Table 5.8 Example of studies in South Africa using the ETLook, SEBAL and SEBS models for agricultural water use estimation along with the reported accuracies.

Author	Model	Sensor (spatial resolution	Temporal resolution	Region (Scale)	Crop type	Reported accuracies
Brombacher et al. (2022)	ETLook	Sentinel 2 (10 m), Landsat (30 m)	Monthly, seasonal	Western Cape (Field)	Irrigated land	Monthly and seasonal ET estimates yielded R^2 values of 0.75 and 0.78 when compared to water meter recordings.
van der Laan et al. (2019)	SEBAL	DMC (30 m), VIIRS (375 m)	Weekly, seasonal	Northern Cape (Field)	Maize	SEBAL overestimated ET for most of the season, but showed good correlation with ground-based EC measurements (R^2 = 0.81)
Singels et al. (2018b)	SEBAL	DMC (30 m), MODIS (250 m)	Weekly, seasonal	Mpumalanga (Regional)	Sugarcane	SEBAL ET estimates were on average 5.1 mm week^{-1} higher than field measurements from the SR approach (~24% bias). R^2 = 0.67.
Gokool et al. (2016)	SEBS	MODIS (1 km)	Daily	Mpumalanga (Field)	Sugarcane	SEBS overestimated ET by 47% compared to measurements from the SR approach (R^2 = 0.33 and RMSE = 2.19 mm d^{-1})
Jarmain et al. (2014)	SEBAL	DMC (30 m), MODIS (1 km)	Weekly, seasonal	Northern Cape, Mpumalanga (Field)	Maize and sugarcane	SEBAL ET was validated against field measurements from an EC system in maize and SR in sugarcane fields yielding R^2 values of 0.81 and 0.72 - 0.78 respectively.

Author	Model	Sensor (spatial resolution	Temporal resolution	Region (Scale)	Crop type	Reported accuracies
Gibson (2013)	SEBS	MODIS (250 m)	Instantaneous, daily	Western Cape (Field)	Apple	Daily SEBS ET exceeded EC-based field measurements by 12 – 40% due to a high EF estimate (close or equal to 1) and a proportionally low H estimate. Rn and G estimates were in good agreement with field measurements ($R^2 > 0.6$) whilst H estimates showed poor correlation ($R^2 < 0.1$).
Jarmain et al. (2009)	SEBAL and SEBS	Landsat 5 (30 m)	Instantaneous, daily, monthly	KwaZulu-Natal (Field)	Acacia compartment	Instantaneous Rn estimates compared well with in-situ LAS measurements (within 7 -11%) while the accuracy of G and H estimates were more variable (within 82% and 3 - 65% respectively). SEBAL generally underestimated daily ET by 15% (summer) - 80% (winter), whereas SEBS ET exceeded measured values by 9%. SEBAL, on average, underestimated monthly ET measurements by 44%.

DMC is Disaster Monitoring Constellation, VIIRS is Visible Infrared Imaging Radiometer Suite, EC is Eddy covariance, SR is surface renewal, LAS is Large Aperture Scintillometer, EF is evaporative fraction, Rn is the net radiation, G is the soil heat flux, H is the sensible heat flux.

5.9.2 Seasonal water use of mature full-bearing Japanese plum orchards

Weekly ET estimates (aggregated to a monthly and seasonal time step) for the selected study orchards were extracted from the FruitLook portal from 2018 – 2022. The seasonality of water use in all four orchards (average over 5 seasons) is depicted in Figure 5.22. Water use followed the trend of ETo, where peak water consumption, which ranged between 171 and 185 mm month^{-1}, occurred during the summer months (December to February). This coincides with the third phenological stage of the stone fruit growth cycle, where rapid fruit growth occurs and fruit cells begin to fill with water and sugar (Torrecillas et al., 2018). High atmospheric demand and minimal rainfall during this crucial phenological stage highlight the importance of irrigation in meeting the water requirements of these orchards. Periods of low water use were observed during the winter months (June – August). During this period, minimal transpiration occurs as the trees begin to shed their leaves (resulting in reduced photosynthesis) and enter a period of dormancy. Seasonal water use estimates varied between 824 (Fortune L17) and 1144 mm a^{-1} (African Delight 47), while mean seasonal water use over the 5 seasons varied between 893 and 1046 mm a^{-1} in the same orchards (Table 5.9). The Fortune orchard in Wellington (block 82) was uprooted after harvest during the 2021/22 season. Therefore, water use estimates after the harvest date were omitted (data were collected from 1 August 2021 to 28 February 2022), which explains the low seasonal water use figure of 585 mm during the 2021/22 season (Figure 5.23).

Two trends were observed from the seasonal water use data. Firstly, the late-maturing African Delight orchards in both regions consumed more water (3% - 14%) than the mid-maturing Fortune orchards. This could be attributed to African Delight having a longer growing season than Fortune and being irrigated at a higher rate for longer. The Japanese plum growing season (from bud-break to harvest) typically starts from the 2nd week of September and ends during the 4th week of February to the 2nd week of March (week 8 – 10) for the late-maturing African Delight and during the 1st to the 2nd week of January (week 1 – 2) for the mid-maturing Fortune cultivar. This means that the crop canopy in late-maturing varieties is maintained for an extended period, allowing trees to transpire for longer and thus consume more water. This can be seen in Figure 5.23, where higher water use estimates were observed in the African Delight orchards during the latter half of the season (March – July). Similar findings were reported in a series of studies originating from Spain, where a Japanese plum orchard planted to an early-maturing cultivar (Red Beaut) (Samperio et al., 2015b) consumed less water than late-maturing Angeleno orchards (Samperio et al., 2015a; Monino et al., 2020), despite being cultivated under similar growing and climatic conditions.

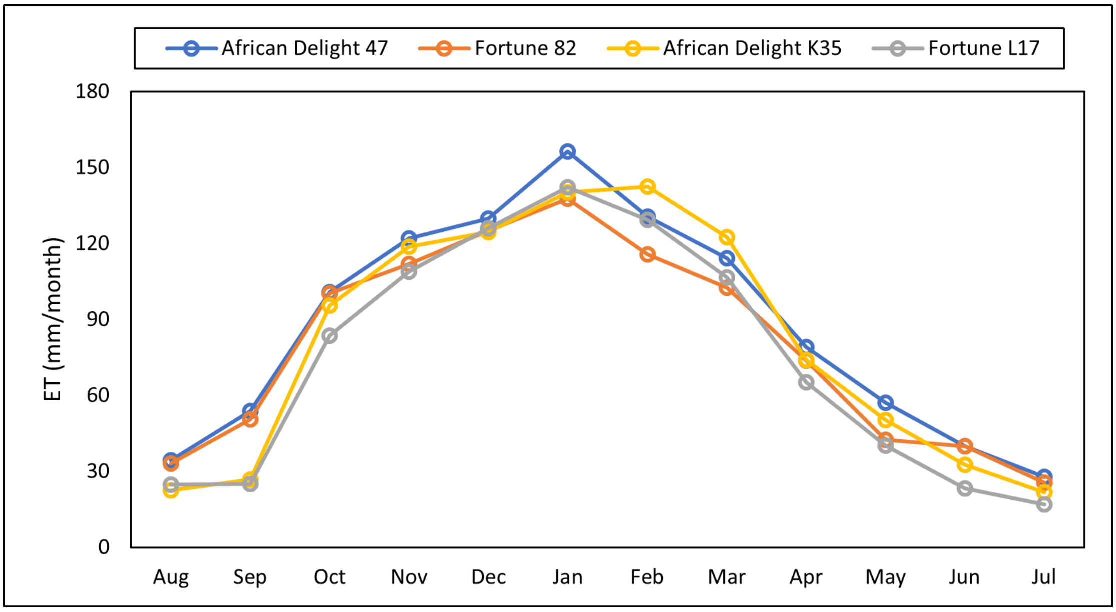


Figure 5.22 *Seasonality of water use in selected Japanese plum orchards in Wellington (African Delight 47 and Fortune 82) and Robertson (African Delight K35 and Fortune L17) averaged over 5 seasons (2018/19 – 2022/23).*

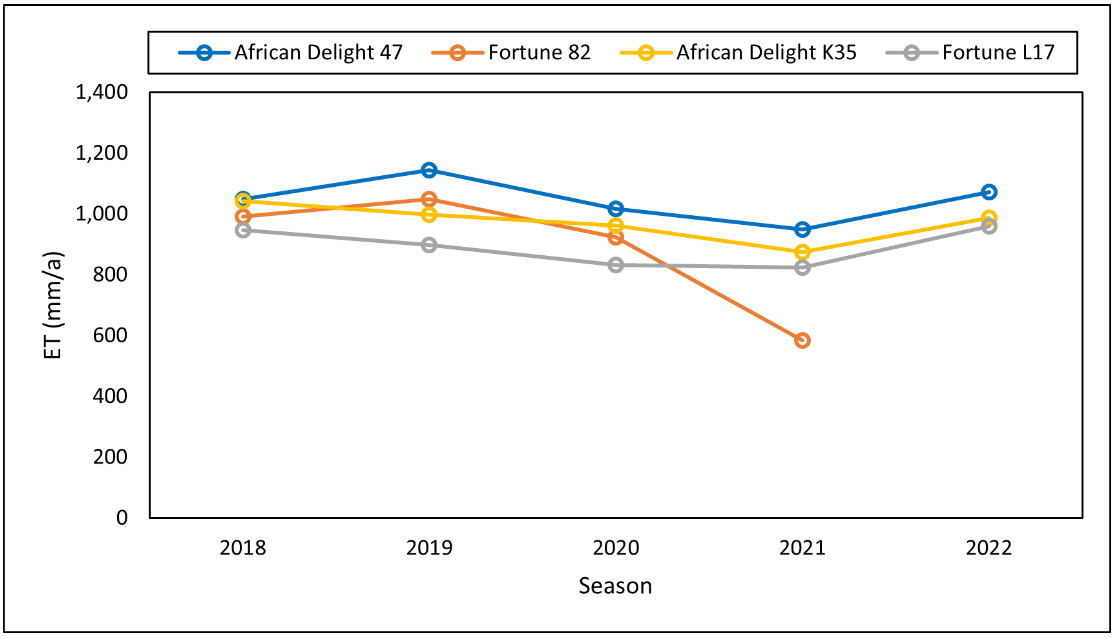


Figure 5.23 *Seasonal water use of selected Japanese plum orchards in Wellington (African Delight 47 and Fortune 82) and Robertson (African Delight K35 and Fortune L17).*

Table 5.9 Statistical summary of FruitLook-derived seasonal water use estimates of selected Japanese plum orchards in Wellington and Robertson (Fortune 82 water use estimate during the 2021/22 season was omitted due to an incomplete seasonal water use).

Statistics	Wellington		Robertson	
	African Delight 47	Fortune 82	African Delight K35	Fortune L17
Average	1046	988	972	893
Maximum	1144	1049	1042	960
Minimum	949	925	875	824
StDev	72	62	62	63
CV	7%	6%	6%	7%

Secondly, orchards in Wellington displayed higher water use estimates with an average seasonal water use of 1017 mm a^{-1} compared to 971 mm a^{-1} in Robertson. These differences in water use are likely due to higher atmospheric demand in Wellington (1360 mm a^{-1}) compared to Robertson (1275 mm a^{-1}), especially during the summer months (December – February) where, on average, ETo was 19 – 27% higher in Wellington. Additionally, orchards in Wellington had a higher planting density of ~2857 trees ha^{-1} compared to 1908 and 2222 trees ha^{-1} in the African Delight and Fortune orchards in Robertson. A higher planting density (smaller spacing across rows and between trees) often translates to a larger/denser crop canopy which has been noted to be a primary factor influencing water use (Doko, 2017; Mobe et al., 2021). Therefore, we hypothesized higher LAI values in the Wellington orchards. FruitLook-derived LAI estimates showed a contrasting pattern where higher mean seasonal LAI estimates of 2.0 and 2.8 were recorded for the Fortune and African Delight orchards in Robertson compared to 1.9 and 2.4 in Wellington. FruitLook appeared to overestimate LAI during periods of full-canopy cover, calculating a maximum LAI estimate of 6.6. The overestimation could be due to the contribution of the cover crop to whole orchard LAI estimation or due to a processing error from the FruitLook team. Despite this, mean seasonal LAI estimates corresponded with mid-stage LAI measurements of 2.1 – 3.2 (obtained using a Li-COR LAI-2200C plant canopy analyzer) reported by Jovanovic et al. (2023) for mature Fortune and African Delight orchards in Wellington and Robertson. Dzikiti and Schachtschneider (2015) reported a comparably lower seasonal measurement of 1.1 for a drip-irrigated African Delight orchard in Robertson. LAI reflects the canopy architecture of an orchard (canopy height, size and density) which is dependent on the training system, tree spacing and pruning regime. The relationship between these factors is expected to differ from one orchard to another due to differing management practices. There is, therefore, a need to validate satellite-based LAI estimates against ground-based measurements as well as determine the contribution of cover crop to whole orchard LAI estimates. The influence of different irrigation systems, namely drip and micro-sprinkler systems, on orchard water use is addressed in Section 5.10.

5.9.3 Influence of meteorological factors on water use

In this section, the influence of meteorological factors on FruitLook water use estimates was evaluated. The orchards responded differently to the variable climatic conditions in both regions. Quantitative information on these relationships is vital to understanding the orchard water use dynamics and for accurate irrigation scheduling, particularly during periods of high atmospheric demand. Table 5.10 illustrates the correlations (R^2) between monthly orchard water use and meteorological factors averaged over 5 seasons. On average, the primary meteorological drivers of water use in the Wellington orchards were ETo (R^2 = 0.84), solar irradiance (R^2 = 0.79) and average temperature (R^2 = 0.79). Whereas, in Robertson, average temperature was the primary driver (R^2 = 0.84) followed by ETo (R^2 = 0.70). Both rainfall and relative humidity displayed a negative relationship to water use, with a stronger correlation in the Wellington orchards (R^2 = 0.44 and 0.64) compared to Robertson (R^2 = 0.17 and 0.46). There was a substantial variation in the relationship between water use and wind speed, with wind speed only accounting for 12% of the variation in the Robertson orchards (negative correlation) compared to 70% in the Wellington orchards (positive correlation).

Table 5.10 Average annual correlation (R^2) between seasonal FruitLook ET estimates and meteorological factors over 5 seasons (2018/19 – 2022/23).

Region	Orchard	Rain	ETo	Average temperature	Average relative humidity	Solar irradiance	Wind speed
Wellington	African Delight 47	0.41	0.82	0.83	0.73	0.76	0.61
	Fortune 82	0.47	0.86	0.75	0.55	0.82	0.79
Average		**0.44**	**0.84**	**0.79**	**0.64**	**0.79**	**0.70**
Robertson	African Delight K35	0.16	0.66	0.83	0.44	0.60	0.13
	Fortune L17	0.18	0.74	0.85	0.49	0.67	0.11
Average		**0.17**	**0.70**	**0.84**	**0.46**	**0.64**	**0.12**

5.9.4 Conclusions

The seasonal water use of full-bearing, high-yielding Japanese plum orchards varied between 824 and 1144 mm a^{-1} depending on the length of the growing season (mid or late-maturing cultivar), prevailing climatic conditions (atmospheric demand) and orchard management practices (plant spacing and canopy size). These estimates were in line with plum water requirements reported in the literature. Such information is vital to farmers, water managers and the relevant stakeholders for accurate irrigation scheduling and farm water allocations. The FruitLook model accurately estimated ET, accounting for 92% (R^2 = 0.92) of the observed variation for a full year of field measurements, covering both periods of low water use and partial canopy cover (winter months) and periods of peak water use and full canopy cover (summer months).

5.10 Water consumption of plums under micro-jets and drip-irrigation

5.10.1 Statistical analysis

The normality of distribution of water consumption data obtained with FruitLook for micro-jets and drip-irrigated orchards was first tested. The results of the Shapiro-Wilk, f and t tests are presented in Table 5.11. A colour matrix was used to indicate whether the null hypothesis was accepted or rejected, where the p-values highlighted in yellow are above the 0.05 significance threshold (null hypothesis was accepted) and the values in red are below the threshold (alternate hypothesis was accepted). In the case of the Shapiro-Wilk test, all p-values were above the significance threshold, which suggests that the datasets are normally distributed. The f-test p-values follow a similar trend ($p > 0.05$; equal variances between datasets), except for the 2021 result where $p = 0.02$. In this case an unequal variance t-test was conducted. All but one (2021) of the t-test p-values were below the significance threshold ($p < 0.05$). This infers that there is a statistically significant difference between the estimated water use of selected micro-sprinkler and drip-irrigated plum orchards during the 2018, 2019, 2020 and 2022 seasons. The p-value for the 2021 season ($p = 0.44$) exceeded the significance threshold, suggesting that the observed differences in water use were not statistically significant. The deviation of t-test p-values from the significance threshold is shown in Figure 5.24. The degree of deviation gives information on the strength of evidence for/against the null hypothesis. A larger deviation towards smaller p-values ($p < 0.05$) suggests stronger evidence and greater confidence in rejecting the null hypothesis. Conversely, a larger deviation towards larger p-values ($p > 0.05$) suggests weaker evidence and less confidence in rejecting the null hypothesis.

Table 5.11 Statistical analysis results (p-values) for the normality, f and t tests; where the p values highlighted in orange are > 0.05 (H_o) and the values in red are < 0.05 (H_a).

Season	Shapiro-Wilk test		f-test	t-test
	Micro-irrigation	Drip irrigation		
2018	0.06	0.74	0.77	0.03
2019	0.07	0.43	0.79	3.23×10^{-12}
2020	0.24	0.18	0.96	1.02×10^{-5}
2021	0.66	0.21	0.02	0.44
2022	0.08	0.06	0.06	7.63×10^{-4}

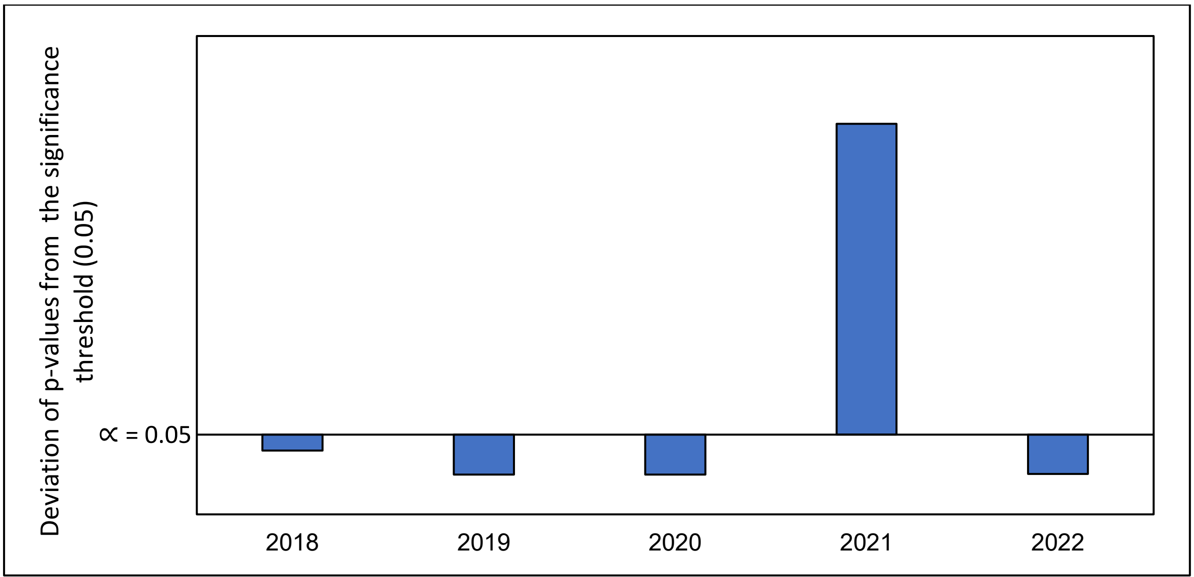


Figure 5.24 *Deviation of t-test p-values from the significance threshold (0.05)*

5.10.2 Water use of micro-sprinkler and drip-irrigated plum orchards (2022/23 season)

FruitLook-derived estimates were used to compare the water use and water deficit of full-bearing Japanese plum orchards under micro-sprinkler (Wellington) and drip (Robertson) irrigation methods from 1 August 2022 to 31 July 2023. Weekly estimates were aggregated to an annual time step and compared at a regional level. In this comparison, micro-sprinkler irrigated orchards at Mon Don farm in Robertson (13 orchards) and drip-irrigated orchards at Abendruhe farm (3 orchards) in Wellington were omitted. Figure 5.25 shows a histogram of the water use (ET) estimates, depicting a normal distribution with a high frequency of the observations occurring between 1000 and 1099 mm for micro-sprinkler irrigated orchards (44% of observations) and 950 and 1049 mm for drip-irrigated orchards (56% of observations). Micro-sprinkler irrigated orchards consumed significantly more water than drip-irrigated orchards ($p < 0.01$), with mean water use estimates of 1019 and 961 mm a^{-1} respectively (a 6% difference). The mean and median water use estimates for orchards under both irrigation methods were similar (<2% difference).

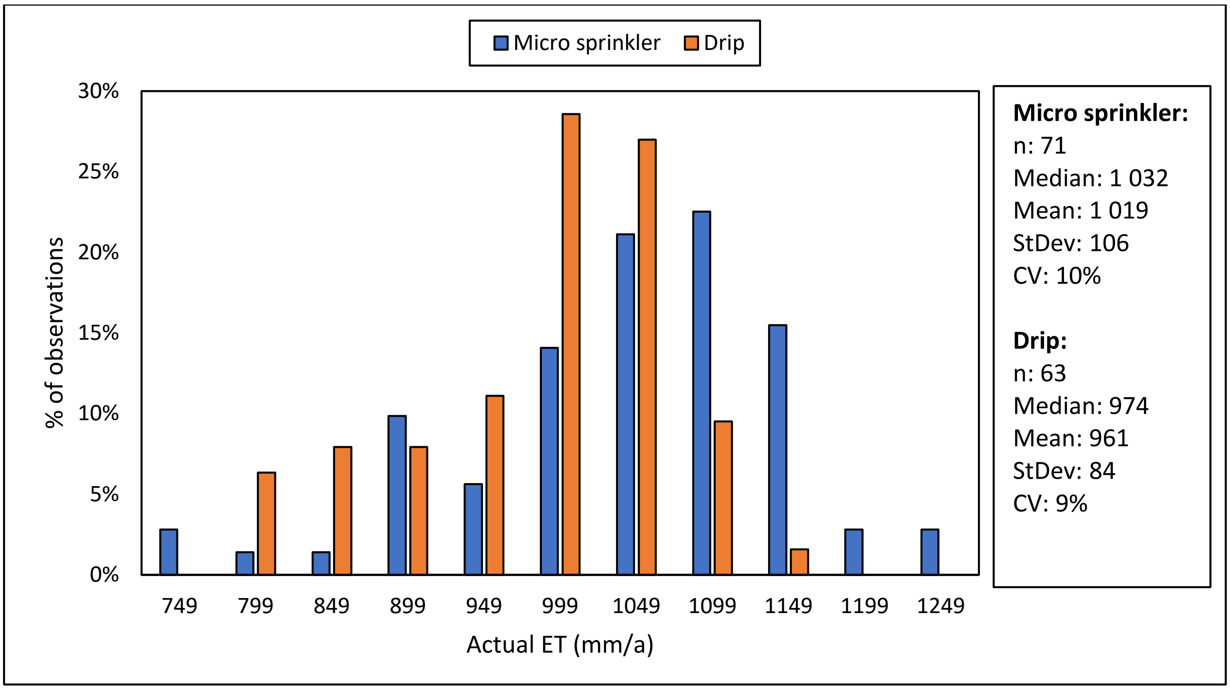


Figure 5.25 *Histogram of estimated water use of micro-sprinkler and drip-irrigated orchards in two production regions of the Western Cape.*

Figure 5.26 shows a histogram of water deficit estimates. Mean water deficit estimates were relatively low, ranging from 0 to 32 mm in micro-sprinkler irrigated orchards and between 2 to 47 mm in drip-irrigated orchards. The highest frequency of observations was between 0 and 13 mm (96% and 56% of observations for micro-sprinkler and drip-irrigated orchards). Thereafter a decreasing trend with an increasing value increment was observed. The relatively low ET deficit estimates suggest that most orchards experienced minimal water stress and as such were optimally irrigated. However, deficit estimates were substantially higher in drip-irrigated orchards (by 178%), indicating greater water stress compared to micro-sprinkler irrigated orchards.

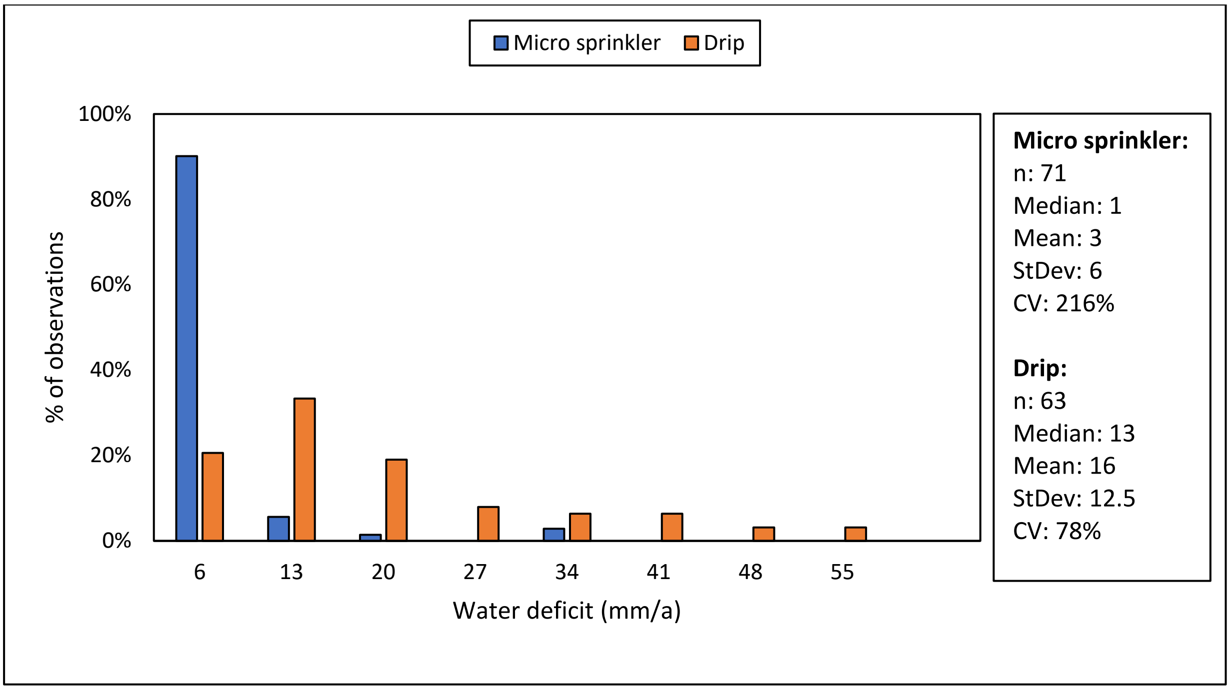


Figure 5.26 *Histogram of estimated water deficit under micro-sprinkler and drip-irrigated orchards in two production regions of the Western Cape.*

The same comparison was conducted at farm scale using estimates from the Mon Don (Robertson) and Abendruhe (Wellington) farms (Table 5.12). Orchards at these farms were irrigated using both micro-sprinkler and drip-irrigation methods. It was understood that farm scale results, due to a smaller sample size, are likely to be less representative of regional water use dynamics, as the influence of orchard management practices and site-specific conditions are expected to be more prevalent. Nonetheless, these estimates could provide valuable insights into orchard water use dynamics under similar growing conditions. Akin to the regional comparison, micro-sprinkler irrigated orchards consumed more water than their drip-irrigated counterparts with 0.7% and 3% higher consumption at the Mon Don and Abendruhe farms respectively. The water deficit estimates at Mon Don were comparable to regional estimates (30% higher under drip irrigation) although the order of magnitude of the difference was smaller. The opposite was observed at Abendruhe, where micro-sprinkler-irrigated orchards experienced greater water stress than those under drip irrigation. Water deficit estimates were highly variable, more so at regional scale where the coefficient of variation (CV) was 78 and 216% for drip and micro-sprinkler irrigated orchards respectively. Lower CV values (<60%) were observed at farm scale.

Table 5.12 Water use (ET) and water deficit estimates for micro-sprinkler and drip-irrigated orchards at the Mon Don (Robertson) and Abendruhe (Wellington) farms.

Parameters	Mon Don		Abendruhe	
	Micro sprinkler	Drip	Micro sprinkler	Drip
No. of orchards	13	7	5	3
ET median	990	982	908	879
ET mean	999	1001	917	877
Water deficit	5	14	10	5
StDev	60	71	83	44
CV	6%	7%	9%	5%

StDev: Standard deviation; CV: Coefficient of variation; ET and water deficit estimates are in mm a^{-1}

5.10.3 Seasonal water use of micro-sprinkler and drip-irrigated plum orchards (2018/19-2022/23 season)

The annual water use and water deficit of micro-sprinkler and drip-irrigated orchards from the 2018/19 to the 2022/23 season (5 seasons) were compared using the same methodological procedure described in the previous Section 5.10.2. Orchards younger than 3 years (deemed not to be full-bearing) and orchards where the planting year was not available (orchards selected based on visual observation) were omitted in seasons preceding the 2022/23 season (2018/19 to 2021/22). The latter were omitted because, without sound knowledge of the age of the orchard, it would not be possible to determine the bearing status of orchards in previous seasons accurately. Young, non-bearing trees have been recorded to use significantly less water than mature full-bearing trees (Dzikiti et al., 2018; Mobe et al., 2021), and therefore, their inclusion would add an element of uncertainty to the estimated water use values**.** Table 5.13 presents the number of orchards available for comparison in the respective seasons.

Seasonal mean ET and water deficit estimates are presented in Table 5.14 and Figure 5.27. There was minimal variation in annual water use estimates (2018 to 2022) with a CV value of around 10% for orchards under both irrigation methods. Estimates varied between 782 (2021) and 1077 (2019) mm a^{-1} for micro-sprinkler irrigated orchards and between 791 (2021) and 961 (2022) mm a^{-1} for drip-irrigated orchards. The low water use estimate for drip-irrigated orchards in 2021 was due to 2 months of missing data (August and September). Micro-sprinkler irrigated orchards consistently consumed more water than drip-irrigated orchards with long term water use figures of 968 and 897 mm a^{-1} respectively (9% difference). The largest differences in water use occurred during the 2019/20 and 2020/21 seasons with deviations of 18% and 14% ($p < 0.01$). Conversely, higher water deficit estimates were observed in drip-irrigated orchards (on average 38% higher), with the 2021/22 season being the only exception potentially due to the period of missing data at the beginning of the season. There was a negative correlation between the percentage differences and the obtained p-values, where a larger difference correlated to a smaller p-value (Figure 5.28). This is because larger differences are more likely to be statistically significant than smaller differences.

Table 5.13 Number of orchards under micro-jet and drip irrigation system from the 2018/19 to 2022/23 season.

Season	Micro-sprinkler	Drip	Total
2022/23	71	63	**135**
2021/22	47	35	**82**
2020/21	29	41	**70**
2019/20	24	40	**64**
2018/19	19	31	**50**

Table 5.14 Seasonal mean water use (ET) estimates of micro-sprinkler and drip-irrigated orchards at regional scale. The highlighted row (2021) had 2 months of missing data (August and September).

Season	Micro	Drip	Difference (%)
2018	1019	948	7%
2019	1077	886	18%
2020	944	810	14%
2021	782	791	1%
2022	1019	961	6%
Average	**968**	**879**	**9%**
StDev	**114**	**78**	
CV	**12%**	**9%**	

StDev: Standard deviation; CV: Coefficient of variation

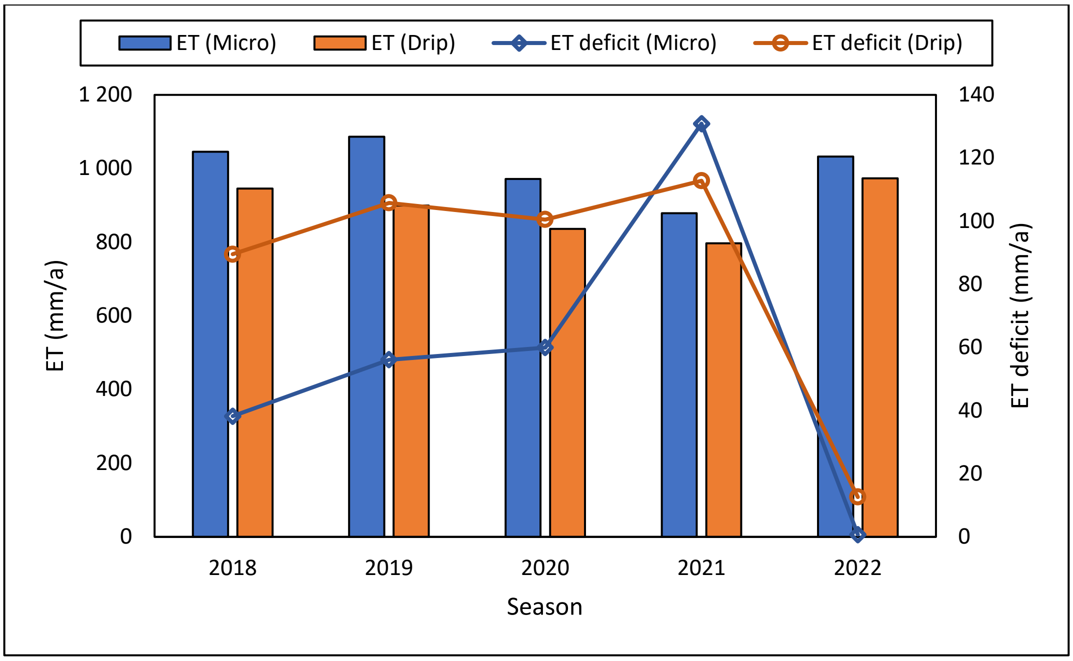


Figure 5.27 *Seasonal median ET and ET deficit estimates for micro-sprinkler and drip-irrigated orchards in Wellington and Robertson.*

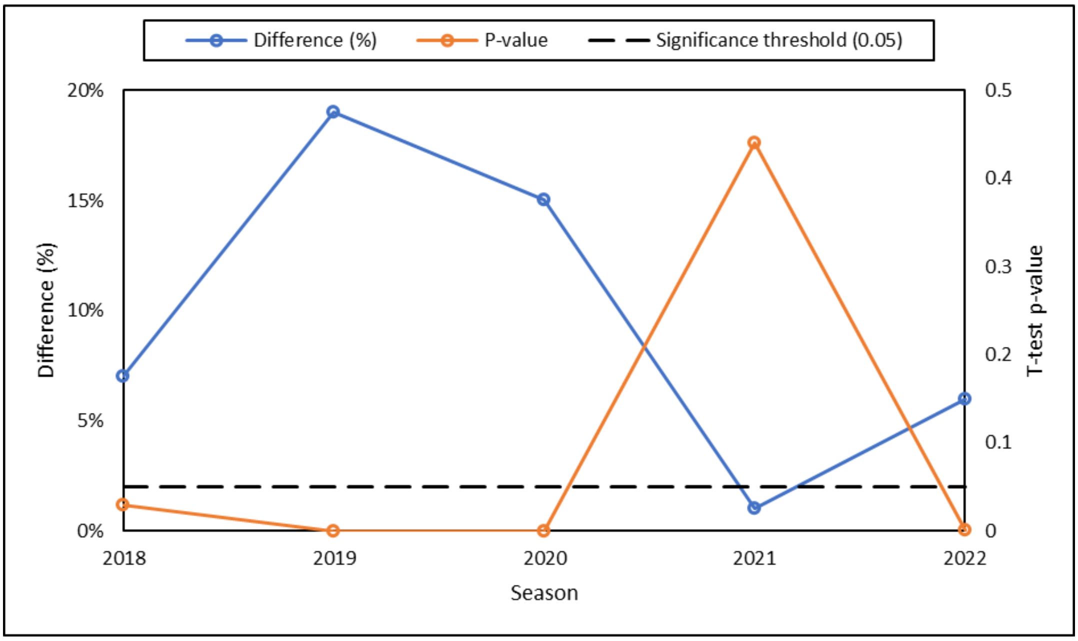


Figure 5.28 *Relationship between the percentage difference and t-test p-value*

Contrasting findings were observed at the Mon Don (Robertson) farm, as drip-irrigated orchards consumed on average 3% more water than micro-sprinkler irrigated orchards, with a peak deviation of 11% occurring during the 2020/21 season (Table 5.15). Average water use estimates from 2018/19 to the 2022/23 season for micro-sprinkler and drip-irrigated orchards were 928 and 959 mm a^{-1}, with a CV of 12% and 11% respectively. Water use of drip-irrigated orchards was higher at Mon Don (959 mm a^{-1}) compared to regional estimates (879 mm a^{-1}). This is likely a result of the larger sample size at regional scale, which encompasses orchards under variable growing conditions and thus a wider range of water use estimates, more so on the lower end of the spectrum. Additionally, water deficit estimates were marginally higher in drip-irrigated orchards with an average difference of 1% (Figure 5.29). An inverse relationship between water use and water deficit can be seen where maximum water deficit estimates coincide with minimum water use estimates in both micro-sprinkler and drip-irrigated orchards. This is most evident during the 2021/22 and 2022/23 seasons at both regional and farm (Mon Don) scale, where maximum water deficit in 2021/22 coincided with reduced water use, followed by a sharp decline in the following season (2022/23) coupled with an increase in water use. Six of the eight orchards at the Abendruhe farm were omitted in the seasons preceding the 2022/23 season according to the omission criterion. Therefore, a long-term farm scale water use comparison in Wellington was not possible.

Table 5.15 Summary of seasonal average water use (ET) estimates under micro-sprinkler and drip irrigation systems at Mon Don farm (Robertson).

Year	Micro	Drip	Difference
2018	1085	1085	0%
2019	929	996	7%
2020	820	919	11%
2021	818	812	1%
2022	990	982	1%
Average	**928**	**959**	**3%**
StDev	**114**	**101**	
CV	**12%**	**11%**	

StDev: Standard deviation; CV: Coefficient of variation

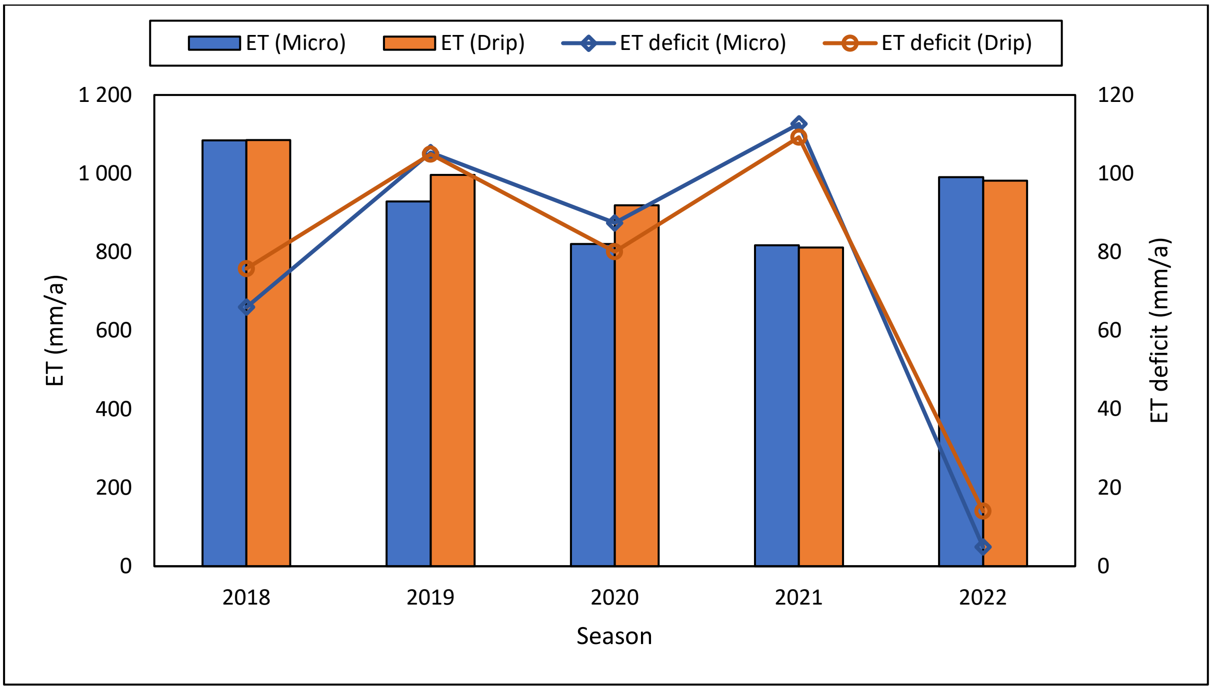


Figure 5.29 *Average water use (ET) and ET deficit estimates of micro-sprinkler and drip-irrigated orchards at Mon Don farm (Robertson).*

5.10.4 Discussion

The study produced contrasting findings on water use and water deficit at regional and farm scale over the study period. At a regional scale, micro-sprinkler irrigated orchards consumed significantly more water (up to 18%), whilst ET deficit estimates were 38% higher in drip-irrigated orchards. At the Mon Don farm, water use was higher in drip-irrigated orchards, whilst the difference in ET deficit estimates was marginal (1% difference). Conversely, micro-sprinkler irrigated orchards at the Abendruhe farm exhibited a greater water deficit than drip-irrigated orchards despite having higher water consumption. Results at regional scale are in line with findings by Ntshidi et al. (2023) and Teixeira et al. (2021), where drip-irrigated apple and lemon orchards used less water, but experienced greater water deficit stress compared to micro-sprinkler irrigated orchards. Given the larger sample size (n = 135 in the 2022/23 season), the regional scale comparison provided a more representative depiction of orchard water use dynamics under both irrigation methods in each area.

However, contradictory results on the farm scale suggest that site-specific conditions largely impact the performance of drip and micro-sprinkler irrigation methods at orchard scale. These include irrigation system design, irrigation scheduling, orchard management practices, soil texture etc. The impact of a chosen irrigation method (drip or micro-sprinkler) on tree water status and subsequently water deficit is likely to differ from one orchard to another (even on the same farm) due to the influence of these factors. This assumption is corroborated by contrasting results observed in literature. For example, Lebese et al. (2010), Fallahi et al. (2017), and Li et al. (2021), reported increased yield and fruit quality in drip-irrigated fruit orchards with no indication of significant water deficit stress in contrast to findings by Teixeira et al. (2021) and Ntshidi et al. (2023). A commonality in these studies is that the tree water status was largely affected by water availability in the soil profile for root uptake. Water movement through the soil profile differs under drip and micro-sprinkler irrigation, which ultimately affects the root distribution and soil water availability (Li et al., 2019). Irrigation in drip systems is more localized, promoting a smaller, narrow and deep wetting pattern whereas the larger application radius in micro-sprinkler systems promotes a laterally wider pattern. Vercrumbre et al. (2003) modelled the root distribution of a plum rootstock (Damas 1869) grafted to a peach scion in silty clay loam soil. They found that the plum root system exhibited a shallow and horizontal growth pattern from the tree trunk. Ntshidi et al. (2023) noted a similar feature in apple orchards in the Western Cape. Water deficit occurs when the wetted soil area does not sufficiently enclose the root system to meet the plant water demand. Therefore, it can be argued that the wetting pattern under micro-sprinkler irrigation facilitates greater water availability for root uptake, thus promoting better tree water status.

Using a modified soil-plant-atmosphere continuum model, Garcia-Tejera et al. (2017) assessed the influence of wetted area size on the transpiration rate of a drip-irrigated olive orchard. Despite optimal irrigation scheduling, they concluded that the smaller wetted area under drip irrigation limited maximum tree transpiration. Espadafor et al. (2018) and Roble et al. (2023) reported similar findings where an increase in the wetted area culminated in increased transpiration rates and improved tree water status compared to trees with a smaller wetted area. While increasing the size of the wetted area either by converting from drip to micro-sprinkler methods (Espadafor et al., 2018; Ntshidi et al., 2023) or adding more driplines and emitters per tree (Roble et al., 2023) improved tree water status, orchard yield and fruit quality, it should also be noted that a larger wetted area is associated with increased orchard floor evaporation (Dzikiti et al., 2018; Ntshidi et al., 2021; Campos et al., 2021; 2022; Darouich et al., 2022). Therefore, designing and implementing precision irrigation systems requires a detailed understanding of tree physiological responses to irrigation to minimize water consumption while maximizing productivity.

5.10.5 Conclusions

This study has provided a comparison between the water-saving potential of drip irrigation and micro-sprinkler irrigation. However, the potential limitations of drip systems were highlighted, and emphasis was put on the need for adequate design and implementation of precision irrigation technologies to maximize water use efficiency without negatively impacting yield and fruit quality. Additionally, it was noted that orchard responses to a specific irrigation method were inconclusive and variable at the farm scale, indicating the influence of site-specific conditions on irrigation system performance. Therefore, a blanket approach cannot be used when selecting an irrigation method and design. Instead, a case-by-case approach is advised, which takes into account the root distribution, soil texture and planting density, among other factors.

6. SYNTHESIS AND DISCUSSION OF RESULTS

This Chapter of the report summarizes the crop water requirements (plum water consumption assuming optimal soil water supply) recorded in this project with different methods, the crop coefficients, crop yield (biophysical) and economic water productivities. The methods used to determine consumptive water use of plums (evapotranspiration) were the following:

- Soil water balance with the HYDRUS 2D at five orchards in the Western Cape production region (Robertson and Wellington), including information from the dedicated study conducted by Mathews et al. (2024).
- Actual evapotranspirative flux measurements with the eddy covariance system in the African Delight orchards at Robertson.
- Actual evapotranspiration derived from satellite remote sensing with FruitLook:
    - Five orchards in the experiments at Robertson and Wellington.
    - Average and median evapotranspiration from 11 farms (135 orchards) in the Western Cape production region extracted from the study of the comparison between micro-jets and drip irrigation over five years (2018-2023).

The assumption was that all orchards operate under irrigation and they were not short of water or subjected to other environmental stresses. The evapotranspiration of these orchards was therefore assumed to represent crop water requirements. In reality, mild water stress may have occasionally occurred in periods between irrigations, as indicated by stem water potential measurements during February-April 2023 (Figures 5.9-5.12).

Table 6.1 summarizes crop yields and crop water requirements estimated with different methods. Crop (biophysical) water productivity (CWP) was calculated as the ratio of crop yields (obtained for each experimental orchard from the farms) and crop water requirements calculated with HYDRUS 2D. Gross income for each experimental orchard in Wellington was obtained from the farm manager for each season. In Robertson, the gross income of the experimental orchards was an estimated range based on data from previous years as sales are calculated in bulk for the farm. Economic water productivity (EWP) was calculated as the ratio of gross income and crop water requirements.

Table 6.1 Summary of crop yields, crop water requirements estimated with different methods, crop (biophysical) water productivity (CWP), estimated income and economic water productivity (EWP) of Japanese plum in the Western Cape production region.

Location	Orchard	Period	Yield (t ha^{-1})	Crop water requirements (mm)				CWP* (kg m^{-3})	Income (ZAR ha^{-1})	EWP** (ZAR m^{-3})
				HYDRUS 2D	HYDRUS 2D (Mathews, 2024)	Eddy covariance	FruitLook			
Wellington	African Delight	01/09/2021-08/03/2022	36.0	780	980	-	644	4.62	228,669	29.3
		01/09/2021-31/08/2022		1123	1265	-	948	3.21		20.4
		01/09/2022-08/03/2023	32.0	691	980	-	762	4.63	495,092	71.7
		01/09/2022-31/08/2023		958	1310	-	1067	3.34		51.7
		01/09/2023-08/03/2024	34.8	845	-	-	708	4.12	-	-
		01/09/2023-31/08/2024		1170	-	-	944	2.97		
	Fortune	01/09/2021-09/01/2022	37.9	488	524	-	373	7.77	316,628	64.9
	Ruby Sun	01/09/2022-08/03/2023	28.4	790	-	-	854	3.59	439,117	55.6
		01/09/2022-31/08/2023		1094	-	-	1144	2.60		40.1
		01/09/2023-08/03/2024	33.0	854	-	-	814	3.86	-	-
		01/09/2023-31/08/2024		1149	-	-	1076	2.87		
Robertson	African Delight	01/09/2021-08/03/2022	51.0	910	1018	-	609	5.60	190,000-200,000	20.9-22.0
		01/09/2021-31/08/2022		1267	1307	-	894	4.03		15.0-15.8
		01/09/2022-08/03/2023	52.0	834	1030	-	712	6.24	190,000-200,000	22.8-24.0
		01/09/2022-31/08/2023		1154	1287	-	992	4.51		16.5-17.3
		01/09/2023-08/03/2024	20.0	816	-	782	740	2.45	-	-
		01/09/2023-31/08/2024		1076	-	1026	1023	1.86		
	Fortune	01/09/2021-08/03/2022	39.8	921	1017	-	586	4.32	190,000-200,000	20.6-21.7
		01/09/2021-31/08/2022		1285	1311	-	837	3.10		14.8-15.6
		01/09/2022-08/03/2023	42.0	915	1038	-	670	4.59	190,000-200,000	20.8-21.9
		01/09/2022-31/08/2023		1267	1414	-	931	3.31		15.0-15.8
		01/09/2023-08/03/2024	33.0	894	-	-	693	3.69	-	-
		01/09/2023-31/08/2024		1190	-	-	948	2.77		
Western Cape	71 orchards (micro-sprinkler irrigation)	2018-2023	-	-	-	-	968 (782-1077)	-	-	-
	63 orchards (drip irrigation)	2018-2023	-	-	-	-	879 (791-961)	-	-	-

*CWP – ratio of crop yield and water requirements; **EWP – Ratio of income and crop water requirements.

6.1 Comparison of plum water consumption estimated with different methods

It is evident from Table 6.1 that the seasonal values of evapotranspiration modelled with HYDRUS 2D and FruitLook were very close to the evapotranspiration measured with eddy covariance (reference method). HYDRUS 2D slightly over-estimated (816 mm), whilst FruitLook slightly under-estimated (740 mm) seasonal evapotranspiration measured with eddy covariance (782 mm). These data refer to the last season of monitoring (from 1 September 2023 to 8 March 2024) in the African Delight orchard at Robertson. For the full year, seasonal evapotranspiration measured with eddy covariance was 1026 mm as compared to 1023 mm (FruitLook) and 1076 mm (HYDRUS 2D). This result gave confidence that both models can provide realistic estimation of seasonal evapotranspiration and crop water requirements for other orchards.

The following ranges of plum water requirements were calculated with HYDRUS 2D for the different cultivars and regions (Table 6.1):

- Wellington
    - African Delight
        - 691-845 mm for the main irrigation season
        - 958-1170 mm for the full year
    - Fortune
        - 488 mm for the main irrigation season
    - Ruby Sun
        - 559-578 mm for the main irrigation season
        - 1094-1149 mm for the full year
- Robertson
    - African Delight
        - 816-910 mm for the main irrigation season
        - 1076-1267 mm for the full year
    - Fortune
        - 894-921 mm for the main irrigation season
        - 1190-1285 mm for the full year

It is evident from these data that crop water requirements were higher for African Delight and Fortune in Robertson compared to Wellington because of the different climatic areas. Farmers practice irrigation after harvesting to keep trees healthy and this substantially increases crop water requirements for the full year compared to the main irrigation season. Differences were recorded between years with season 2022/23 (rainfall above average) requiring substantially less water than season 2021/22 (rainfall below average). Cultivar Fortune in Wellington showed the least crop water requirement (488 mm), however this value represents evapotranspiration from 1 September 2021 to 9 January 2022, after which irrigations were stopped and the orchard was uprooted. A Ruby Sun orchard was monitored thereafter and it displayed high water requirements. However, AquaCheck probes for soil water content monitoring were not installed in the Ruby Sun orchard to check the soil water balance. The highest crop water requirements were calculated for cultivar Fortune in Robertson, irrigated with three dripper lines to make sure the full profile of the loamy-clayey soil was wetted during the season. Cultivar African Delight in Robertson had also high crop water requirements, however this cultivar produced the highest yields, except in the last season when poor fruit set occurred. HYDRUS 2D simulations generated independently by Mathews (2024) produced consistently higher crop water requirements, possibly due to adjustments to soil hydraulic properties.

Crop water requirements calculated with FruitLook were consistently lower than those calculated with HYDRUS 2D, ranging from 837 mm (Robertson, Fortune in 2021/22) to 1144 mm (Wellington, Ruby Sun in 2022/23) for the full year. Some weekly records in FruitLook are occasionally missing and this could be one of the reasons for the under-estimation. Exceptions were the crop water requirements of Ruby Sun in 2022/23, when FruitLook calculated substantially higher evapotranspiration than HYDRUS 2D. The Ruby Sun orchard is planted on a moderately steep slope and pruned regularly to a height taller than the other orchards. An exception when FruitLook over-estimated evapotranspiration compared to HYDRUS 2D was also the African Delight orchard in Wellington during the 2022/23 season with above average rainfall (Table 5.6).

There could be several reasons for FruitLook producing lower crop water requirements than HYDRUS 2D. According to the eddy covariance evapotranspiration in the African Delight orchard at Robertson used as validation reference (Figure 5.18), the under-estimation of FruitLook occurred mainly in the winter season. During the winter season, the temperate species used as cover crops are actively growing and providing lavish biomass that transpires. This transpiration flux was recorded by the eddy covariance flux tower. It is possible that the remote sensing method does not detect/calculate properly the contribution of cover crops to transpiration. The under-estimation of FruitLook during the summer period (Figure 5.18) is due to some eddy covariance data missing. FruitLook data for 134 micro-sprinkler and drip-irrigated orchards across the Western Cape were in the range of those recorded at the experimental orchards, spanning from 836 to 1086 mm a^{-1} (Table 6.1).

Crop water requirements in Table 6.1 were obtained with three different methods (eddy covariance, HYDRUS 2D and FruitLook). Although the results are comparable, they also call attention to some discrepancies. Therefore, the importance of ground-based data, in particular measurements of direct fluxes of evapotranspiration with eddy covariance, is hereby stressed to validate the results of soil water balance models and remote sensing-derived data. However, micrometeorological stations are research equipment that is expensive and complex to handle. A calibrated and parametrized soil water balance model is the second choice for the determination of crop water requirements. The use of such models can be extended to many farms, however obtaining input parameters requires intensive data collection. The third choice is remote sensing that permits to obtain data at large scale, however this is the most indirect method to determine crop water requirements and it necessitates validation. Each method therefore bears advantages and disadvantages, and it should be selected based on the specific questions that need to be answered.

Mashabatu et al. (2024) conducted a systematic review of internationally published literature on plum water requirements. Little detailed information was found in the literature on the seasonal water use of plums, not only in South Africa but globally. However, plum water requirements determined in the current project were generally in line with those found in published literature that ranged from 835 to 1211 mm a^{-1} for the full year (Dzikiti and Schachtschneider, 2015; Samperio et al., 2015a and b; Mhawej and Faour, 2020; Monino et al., 2020), and between 331 and 718 mm for the main irrigation season (Intrigliolo and Castel, 2010; Gavilan et al., 2019; Stachowski et al., 2021). The South African Department of Agriculture, Forestry and Fisheries (2010) recommended plum water requirements of 1019 mm a^{-1}. Intrigliolo and Castel (2010) estimated crop water requirements of Japanese plum cv. Black Gold in Spain to be between 409 and 558 mm from April to October, depending on the irrigation water treatment and crop load. Intrigliolo et al. (2014) also reported irrigation water requirements to be between 250 and 311 mm season^{-1} (from April to September) for cv Black Gold in Spain. Iancu (1997) measured evapotranspiration of plums using non-weighing lysimeters in Romania. The actual evapotranspiration was 622 mm for the period from April to October.

In the current project, Kc and Kcb crop coefficients were estimated according to the procedure reported by Allen and Pereira (2009) based on LAI, fc and Kd (Section 4.6 of methodology), and used in HYDRUS 2D to calculate the soil water balance. Calculated Kcb in the initial stage ranged between 0.84 (African Delight in Wellington) and 0.98 (African Delight in Robertson). In the mid-stage, average Kcb varied between 1.14 (Fortune in Robertson) and 1.20 (Ruby Sun in Wellington). The crop coefficient Kc was calculated for the African Delight orchard in Robertson as the ratio of evapotranspiration measured with eddy covariance and ETo (Table 5.7). Monthly Kc values ranged between 0.49 (July and August) and 1.20 (January). The September value of Kc (0.84) appears to be consistent with Kcb for the initial stage calculated with the Allen and Pereira (2009) method. In the period from June to August, farms stop irrigations of plums because rainfall in the Western Cape is sufficient to replenish the soil water profile up to field capacity.

The values Kc and Kcb calculated in this project are in line with those estimated by Allen and Pereira (2009; Table 3) and Rallo et al. (2021) for very high-density, full-bearing orchards. In other published research, crop coefficients of around 1 at mid-season were recommended for stone fruits by Steduto et al. (2012). Higher crop coefficients may occur in high-density orchards and when using cover crops according to Fereres and Goldhamer (1990). Naor et al. (2004) proposed an optimum Kc between 0.6 and 0.8 in the month prior to harvest, based on a multi-level irrigation and crop load experiment conducted on cv Black Amber. Intrigliolo et al. (2014) estimated Kc to be between 0.29 in March and 0.57 in June in 10-years old Japanese plum cv Black Gold cultivated in Spain (average seasonal Kc was 0.46). In South Africa, Dzikiti and Schachtschneider (2015) found the Kc coefficient to be between 0.9 and 1.0 for an African Delight plum orchard in Robertson during peak irrigation season. However, they also recommended further research to update crop coefficients for plums to increase the accuracy of irrigation scheduling thereby saving significant amounts of water and reducing water risk.

6.2 Crop and economic water productivity

Crop yield, gross income generated by the experimental orchards and evapotranspiration (crop water use) were used to calculate CWP and EWP. The results are summarized in Table 6.1.

By far the highest yields were obtained in the African Delight orchard in Robertson (51-52 t ha^{-1}), followed by Fortune in Robertson (39.8-42.0 t ha^{-1}) (Table 6.1). Exception was the final season of the experiment, when poor fruit set occurred in Robertson, possibly due to the extremely wet winter 2023, during which floods occurred. Crop yields were higher in Robertson than Wellington, where African Delight produced 32.0-36.0 t ha^{-1} and Fortune 37.9 t ha^{-1} (season 2021/22). Ruby Sun produced the lowest yields of 28.4-33.0 t ha^{-1}.

Crop water productivities of well-irrigated, healthy orchards were calculated as the ratio of yields and crop water use (Table 6.1; Figure 6.1). Considering evapotranspiration estimated with HYDRUS 2D for the full year, CWP were the highest for African Delight in Robertson (4.03-4.51 kg m^{-3}) because the crop yields were by far the highest of all orchards. This was followed by African Delight in Wellington (2.97-3.34 kg m^{-3}). It appears that, taking into account irrigations for the full year, African Delight uses water more efficiently than Fortune. Fortune CWP in Robertson was 3.10-3.31 kg m^{-3}, possibly lower because of large irrigation volumes applied with three irrigation drip lines. Fortune CWP in Wellington was 7.77 kg m^{-3} for season

2021/22, however evapotranspiration refers only to the main irrigation season (1 September 2021-9 January 2022). Ruby Sun had a comparable CWP (2.87-3.59 kg m^{-3}) to African Delight in Wellington because substantially less irrigation volumes were applied, however the yields were lower.

Values of CWP obtained in the current project are in line with the scarce information found in the literature. For example, Dzikiti and Schachtschneider (2015) reported a water productivity of 5.97 kg plums m^{-3} of water transpired in the Western Cape. Intrigliolo and Castel (2010) calculated CWP between 4.2 and 7.5 kg m^{-3} for Japanese plum cv Black Gold grown in Spain, whilst Monino et al. (2020) estimated CWP nine-year trees cv Angeleno to be between 5.6 and 13.38 kg m^{-3}, depending on irrigation treatments and crop yields.

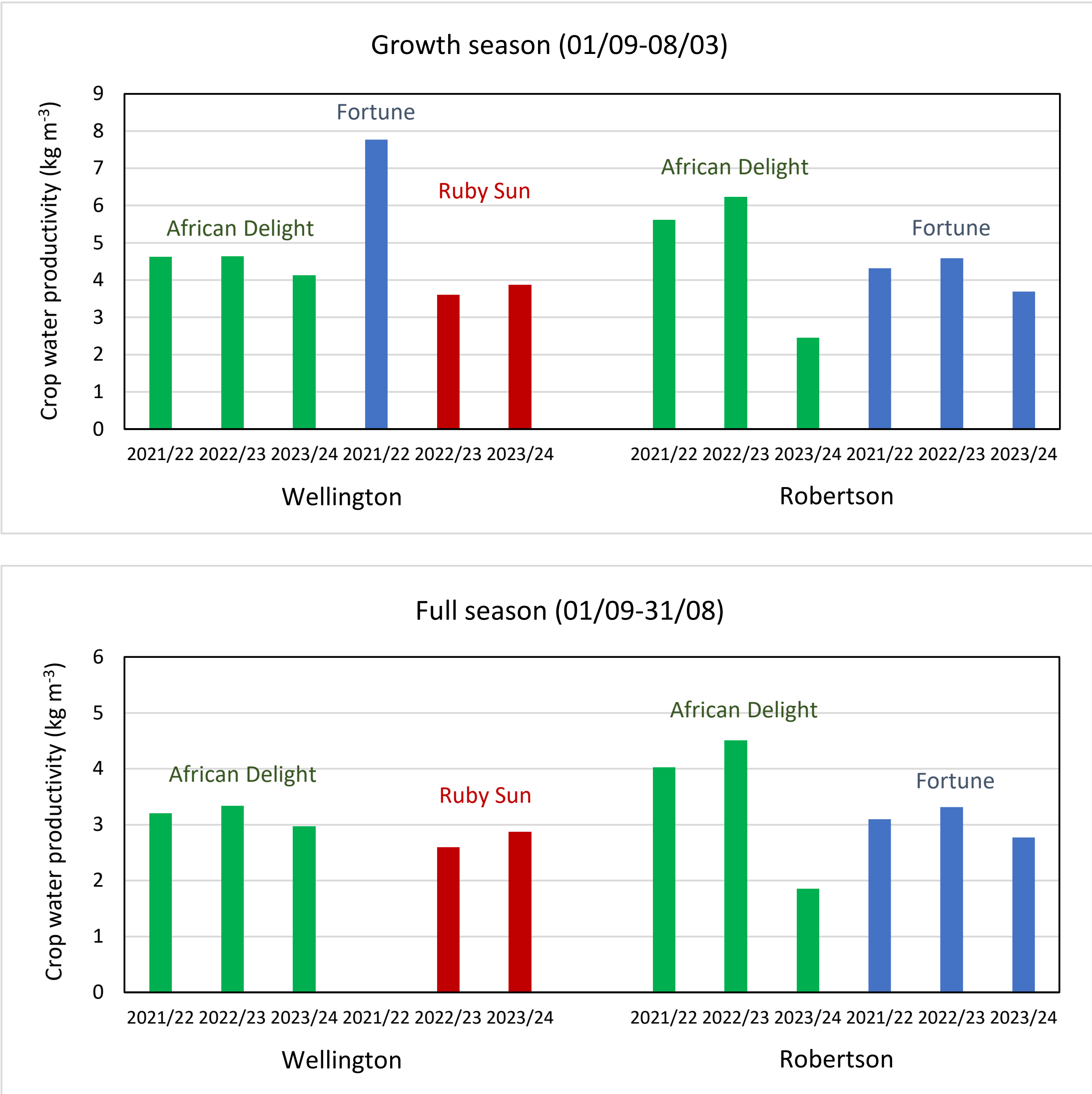
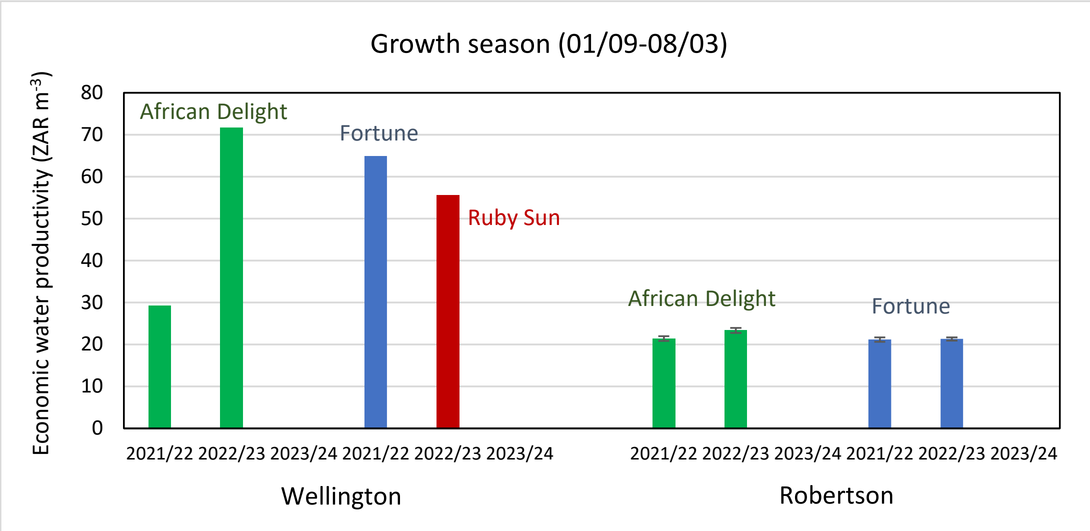


Figure 6.1 *Crop water productivities calculated as the ratio of crop yield and water requirements calculated with HYDRUS-2D for all cultivars grown in Wellington and Robertson during the growth season (01/09-08/03; top graph) and for the full season (01/09-31/08; bottom graph).*

Economic water productivity was calculated as the ratio of gross income and crop water use (Table 6.1; Figure 6.2). Income depends greatly on crop yield, fruit quality, cultivar, season and market prices. Income from individual orchards on large farms is difficult to obtain. This was available at Sandrivier in Wellington where the farm records crop yields and sales. At Smuts Bros in Robertson, sales are not recorded for each orchard and an estimated range of gross income was obtained from the farm based on historic information. It was impossible to obtain net income or profit for each orchard because the costs of production (fertilizers, chemical applications, labour etc.) are generally shared amongst many orchards. Income data were not available for the last season of experimentation (2023/24) at the time of compilation of this report.

Considering crop water consumption for the entire year, it is evident from data in Table 6.1 and Figure 6.2 that African Delight in Wellington had a wide range of EWP from 20.4 ZAR m^{-3} in 2021/22 to 51.7 ZAR m^{-3} in 2022/23. The two early-maturing cultivars in Wellington were very viable with EWP at 64.9 ZAR m^{-3} for Fortune (evapotranspiration calculated until 9 January 2022) and 55.6 ZAR m^{-3} for Ruby Sun. Economic water productivities appeared to be driven mostly by the gross income, which varied widely possibly due to market prices. For example, gross income of African Delight in Wellington ranged from 228,669 ZAR ha^{-1} in 2021/22 to 495,092 ZAR ha^{-1} in 2022/23. Economic water productivity at Robertson was less compared to Wellington, in the ranges of 15.0-17.3 ZAR m^{-3} for African Delight and 14.8-15.8 ZAR m^{-3} for Fortune. These data, however, are based on estimated historic ranges of gross income. No information on EWP of plums was found in the literature for comparative purpose.

In summary, the current project quantified values of crop coefficients, evapotranspiration of well-irrigated, healthy plum orchards (representing crop water requirements), crop water and economic productivities with different methods. An analysis of plum water consumption in micro-sprinklers and drip-irrigated orchards across the Western Cape was also conducted with the use of remote sensing information (FruitLook). The figures measured/estimated in the current study were generally well within the range of those reported in the literature, which gives confidence that realistic and accurate values are provided that can be used in practice to allocate water to farms for irrigation of plums.



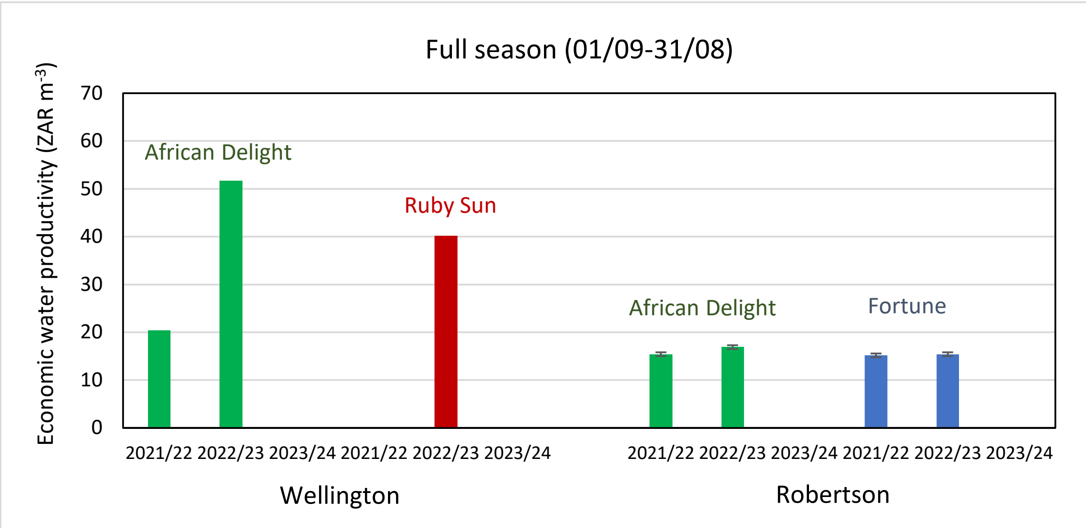


Figure 6.2 *Economic water productivities calculated as the ratio of income and water requirements calculated with HYDRUS-2D for all cultivars grown in Wellington and Robertson during the growth season (01/09-08/03; top graph) and for the full season (01/09-31/08; bottom graph).*

7. CONCLUSIONS

The main findings and conclusions from this three-year research projects are outlined in this Chapter primarily in response to the stipulated research questions and objectives of the project:

1. To determine the water use of high performing full-bearing Japanese plum orchards under micro- and drip-irrigation.
2. To relate the water use of high performing full-bearing Japanese plum orchards to physical and economical water productivity.
3. To determine crop coefficients (Kc) and basal crop coefficients (Kcb) of Japanese plums to serve in the calculation of crop water requirements and water allocations.
4. To develop models of orchard water use in order to extrapolate the research results to other production regions.

Main findings and conclusions were:

- Historical meteorological data (2011-2022) indicated the prevailing climatic conditions in the main plum production regions of the Western Cape, namely Robertson and Wellington. Robertson had a mean annual rainfall of 265 mm a^{-1} compared to 396 mm a^{-1} in Wellington. Average annual reference evapotranspiration (ETo) was 1360 mm a^{-1} in Wellington and 1275 mm a^{-1} in Robertson. There was a decline in rainfall from 2015/16 to the 2018/19 season coinciding with the drought in the Western Cape, with rainfall minima of 266 mm a^{-1} in Wellington (2017/18) and 125 mm a^{-1} in Robertson (2016/17). Over the same period, ETo measurements were 4% – 24% higher than the long-term averages. These data demonstrated the water supply risks that may occur in the Western Cape due to climatic changes and increased frequency of extreme droughts. Weather conditions are the main drivers of crop water requirements.
- During the course of the project, season 2021/22 was drier and wetter than season 2022/23. Reference evapotranspiration ranged 1129-1196 mm a^{-1} in Wellington and 1188-1214 mm a^{-1} in Robertson. In 2021/22, rainfall was 462 mm a^{-1} in Wellington and 184 mm a^{-1} in Robertson. Season 2022/23 was particularly wet causing floods in the Western Cape, with 665 mm a^{-1} in Wellington and 518 mm $^{-1}$ in Robertson.
- Plum water requirements were estimated with HYDRUS 2D, eddy covariance and satellite remote sensing applications at five orchards from 2021/22 to 2023/24. Evapotranspiration (crop water requirements) estimated from 1 September 2023 to 31 August 2024 in the African Delight orchard in Robertson were:
    - 1076 mm modelled with HYDRUS 2D
    - 1023 mm with FruitLook

    - 1026 mm measured with eddy covariance

  These figures gave confidence that both HYDRUS 2D and FruitLook gave reliable estimates of evapotranspiration compared to the reference method (eddy covariance).
- Plum water requirements calculated with HYDRUS 2D were:
    - Wellington
        - African Delight
            - 691-845 mm for the main irrigation season
            - 958-1170 mm for the full year
        - Fortune
            - 488 mm for the main irrigation season (2021/22)
        - Ruby Sun
            - 790-854 mm for the main irrigation season
            - 1094-1149 mm for the full year
    - Robertson
        - African Delight
            - 816-910 mm for the main irrigation season
            - 1076-1267 mm for the full year
        - Fortune
            - 894-921 mm for the main irrigation season
            - 1190-1285 mm for the full year
- Plum farmers practice irrigation after harvesting to keep trees healthy and this substantially increases crop water requirements for the full year compared to the main irrigation season.
- As a result of annual rainfall, more irrigation was applied in season 2021/22 compared to 2022/23, and irrigation volumes were higher in Robertson than in Wellington. The highest annual irrigation was delivered to the African Delight orchard in Robertson in season 2021/22 (1152 mm a^{-1}). This orchard is particularly difficult to manage due to the stony soil, but it produced by far the highest crops yields. The early-maturing cultivar Ruby Sun generally received the least irrigation, however it also produced the lowest yield.
- Drainage volumes calculated with HYDRUS 2D depended on irrigation management and rainfall distribution. The highest drainage (bottom boundary flux) was in the African Delight orchard in Robertson (73-148 mm a^{-1}). This orchard appeared to be slightly over-irrigated, however it excelled in terms of crop yields. Higher drainage was calculated for all orchards in years 2022/23 and 2023/24 due to high rainfall.

- Plum water requirements were higher for African Delight and Fortune in Robertson compared to Wellington because of the different climatic areas (warmer summers and drier winters in Robertson).
- Differences in plum water requirements were recorded between years with season 2022/23 (rainfall above average) requiring substantially less water than season 2021/22 (rainfall below average).
- The highest crop water requirements were calculated for cultivar Fortune in Robertson, irrigated with three dripper lines to make sure the full profile of the loamy-clayey soil was wetted during the season.
- Cultivar African Delight in Robertson also displayed high crop water requirements, however this cultivar produced the highest yields, except in the last season when poor fruit set occurred.
- Plum water requirements calculated with FruitLook were generally lower than those calculated with HYDRUS 2D, ranging from 837 mm (Robertson, Fortune in 2021/22) to 1144 mm (Wellington, Ruby Sun in 2022/23) for the full year. Exception was the Ruby Sun orchard planted on a moderately steep slope and pruned regularly to a height taller than the other orchards. Some weekly records in FruitLook were occasionally missing.
- Evapotranspiration estimated with FruitLook for 134 micro-sprinkler and drip-irrigated orchards across the Western Cape were in the range of those recorded at the experimental orchards, spanning from 810 to 1077 mm a^{-1}.
- The crop coefficient Kc calculated for the African Delight orchard in Robertson as the ratio of evapotranspiration measured with eddy covariance and ETo ranged between 0.49 (July and August) and 1.20 (January).
- Basal crop coefficients Kcb were estimated according to the procedure reported by Allen and Pereira (2009). Kcb in the initial stage ranged between 0.84 (African Delight in Wellington) and 0.98 (African Delight and Fortune in Robertson). In the mid-stage, average Kcb varied between 1.14 (Fortune in Robertson) and 1.20 (Ruby Sun in Wellington).
- Crop yields were generally in the range of the expected values for full-bearing high-density orchards. By far the highest yields were obtained in the African Delight orchard in Robertson (51.0-52.0 t ha^{-1}), followed by Fortune in Robertson (39.8-42.0 t ha^{-1}). Exception was the final season of the experiment, when poor fruit set occurred. Crop yields were higher in Robertson than Wellington, where African Delight produced 32.0-36.0 t ha^{-1} and Fortune 37.9 t ha^{-1} (season 2021/22). Ruby Sun produced the lowest yields of 28.4-33.0 t ha^{-1}.

- Crop water productivities for the full year were the highest for African Delight in Robertson (4.03-4.51 kg m^{-3}) because the crop yields were by far the highest of all orchards. This was followed by African Delight in Wellington (2.97-3.34 kg m^{-3}).
- African Delight (4.03-4.51 kg m^{-3}) used water more efficiently than Fortune (3.10-3.31 kg m^{-3}) in Robertson, possibly because of large irrigation volumes applied with three irrigation drip lines in the latter orchard.
- Ruby Sun had a comparable CWP (2.87-3.59 kg m^{-3}) to African Delight in Wellington (2.97-3.34 kg m^{-3}) because less irrigation volumes were applied, however the yields were lower.
- Plum water requirements, crop coefficients and water productivities were in the range of those reported in the literature for very high-density, full-bearing orchards.
- Economic water productivity depended greatly on crop yield, fruit quality, cultivar, season and market prices. Early-maturing cultivars (Fortune and Ruby Sun) in Wellington were economically comparable to the late-maturing African Delight.
- Economic water productivity at Robertson appeared to be less compared to Wellington, however EWP were estimated based on historic averages of income.
- The in-field effects of irrigations and rainfall were visible in the soil water content fluctuations recorded with AquaCheck probes, particularly in the upper soil layers. Peaks in in-row soil water content were usually stable around a value corresponding to field capacity, which is testimonial that scheduled irrigations were generally appropriate. A remarkable difference in soil water content was observed between the in-row and mid-row probes (wetted and non-wetted areas), the latter exhibiting a drying cycle during the summer season. Differences in soil water content at different depths were also recorded, indicating the layering nature of the soils and vertical variability in soil hydraulic properties.
- The highest actual root water uptake calculated with HYDRUS 2D occurred in the African Delight (822-1018 mm a^{-1}) in Robertson and the Ruby Sun in Wellington (930-991 mm a^{-1}). The latter had the highest LAI of all orchards.
- Soil evaporation measured with micro-lysimeters varied across the row depending on the row orientation, time of the day and shading, pruning practices, irrigation method and duration of irrigation events. Wellington had a higher evaporation rate in the tree rows, whereas Robertson showed a flatter evaporation line across the row.
- Annual soil evaporation calculated with HYDRUS 2D for African Delight orchards in Robertson and Wellington was comparable, ranging between 249 and 264 mm a^{-1}. Soil evaporation in the Ruby Sun cultivar was the lowest (158-164 mm a^{-1}), whilst the

highest was calculated for cultivar Fortune in Robertson (310-339 mm a^{-1}). Simulated daily soil evaporation data were within range of those measured with micro-lysimeters.

- The average LAI in the initial stage varied between 0.55 (African Delight in Wellington) and 1.22 (Ruby Sun in Wellington). The average LAI in the mid-stage ranged between 2.35 (Fortune in Robertson) and 3.37 (Ruby Sun in Wellington).
- The canopy cover fc in the initial stage varied between 0.34 and 0.59 (Ruby Sun in Wellington), whilst in the mid-stage it was between 0.82 (Fortune in Robertson) and 0.91 (Ruby Sun in Wellington).
- LAI and fc did not vary much during the growing season as the vegetation growth was controlled by pruning.
- Canopy density (Kd) in the initial stage ranged between 0.32 (African Delight in Wellington) and 0.57 (Ruby Sun in Wellington). In the mid-stage, the lowest Kd of 0.83 was measured in Fortune at Robertson, whilst Ruby Sun in Wellington appeared to have the densest canopy (Kd = 0.91).
- Saturas sensors for logging stem water potential responded well to rainfall or irrigation water applied as well as to periods of no water inputs, demonstrating the potential for use in irrigation scheduling. However, data were available only from February to July 2023, after which the service provision was discontinued.
- HYDRUS 2D generally simulated well the general trends of soil wetness, seasonal evapotranspiration and the full profile soil water content. However, it was less successful in capturing the details of soil water dynamics in individual layers, possibly due to variabilities in soil properties and the inconsistency between the daily time step and the timing of irrigations.
- Surface energy balance data collected with eddy covariance demonstrated that the latent heat flux was the main consumer of net radiation in the African Delight orchard in Robertson, followed by H and lastly G. These fluxes accounted for 83.5, 15.7 and 0.8% of Rn respectively, for the period of measurement. The average Bowen ratio was 0.23, which supports the assumption that the orchard did not suffer from water or other environmental stresses.
- Remote sensing estimates of ET were in good agreement with eddy covariance, with FruitLook ET showing a better correlation than SEBS. On average, eddy covariance ET was under-estimated by both remote sensing methods, especially during periods of low water use in winter.
- The comparison between plum orchard water consumption under micro-jets and drip-irrigation with FruitLook over five seasons (135 orchards on 11 farms) indicated that micro-jets use on average 9% more water (968 mm a^{-1}) than drippers (879 mm a^{-1}).

However, they experience less ET deficit as manifestation of water stress. Nevertheless, instances were recorded where drip-irrigation used more water than micro-jets on the same farm. This suggests that site-specific conditions largely impact the performance of drip and micro-sprinkler irrigation systems at orchard scale.

In summary, the current project achieved the set objectives of quantifying crop coefficients, evapotranspiration of well-irrigated, healthy plum orchards (representing crop water requirements), crop water and economic productivities by using different methods. An analysis of plum water consumption in micro-sprinklers and drip-irrigated orchards across the Western Cape was also conducted with the use of remote sensing information (FruitLook). The figures measured/estimated in the current study were generally well within the range of those reported in the literature, which gives confidence that realistic and accurate values are provided that can be used in practice to allocate water to farms for irrigation of plums.

8. RECOMMENDATIONS

The main aim of this project was to determine water use of high-performing Japanese plums (*Prunus salicina* Lindl.) in the major plum production regions of South Africa. For this purpose, well-managed, full-bearing plum orchards were selected in order to estimate evapotranspiration under optimal conditions (evapotranspiration can be equated to crop water requirements). The main recommendations emanating from this project are the following:

- In order to calculate water allocations for plum orchards, maximum yearly evapotranspiration estimated with HYDRUS 2D was reduced by the average annual rainfall in Wellington and Robertson. These values, representing irrigation water requirements, were recommended for annual plum water allocations (rounded off to the nearest hundred in m^3 ha^{-1}):
    - Wellington
        - African Delight: 7,800 m^3 ha^{-1} (780 mm)
        - Ruby Sun: 7,500 m^3 ha^{-1} (750 mm)
    - Robertson
        - African Delight: 10,000 m^3 ha^{-1} (1000 mm)
        - Fortune: 10,200 m^3 ha^{-1} (1020 mm)

  These water allocations would have to be increased during years of below-average rainfall and because winter rainfall replenishes the soil profile, but not all of it is available during peak water demand.
- The economic water productivity (EWP) may be considered a more influential factor in orchard irrigation management than biophysical water productivity. In view of water scarcity and the increasing incidence of extreme droughts in the Western Cape, it would be worthwhile conducting research on deficit irrigation in order to investigate how water consumption can be reduced without affecting yield quantity, and perhaps improve yield quality. Based on international literature, deficit irrigation could target particularly the less sensitive stage to water stress, such as stage II (pit hardening) and post-harvest. The purpose would be to determine the minimum plum water requirements that would ensure an acceptable economic yield. Before this technique can be implemented, however, quantitative information on the physiological response of plum trees to imposed water stress conditions is required. This information is crucial for determining the ideal stem water potential thresholds under local climate conditions (values of around -1.5 MPa reported in literature).
- Data on individual orchard income and profit were difficult to obtain in order to calculate EWP. In particular, net income or profit is difficult to obtain because it depends on fruit quality, market prices and the costs of production (fertilizers, chemical applications,

labour etc.) are generally shared amongst many orchards. However, EWP is an important indicator in the management of water resources and farming, and farms should be encouraged to track and break down these data.

- The practice of irrigating with three dripper lines is applied to ensure sufficient discharge rates especially in deeper alluvial soil and to refill the sub-soil that may have dried out during the dry season. However, this practice results in more water use and it should be avoided whenever possible.
- Soil evaporation data measured with micro-lysimeters suggested that cultivation in ridges, although beneficial in terms of increasing the soil volume explored by roots, may increase non-beneficial losses of water through evaporation directly from the soil due to exposure of ridge slopes to solar energy. In the measurement of soil evaporation, micro-lysimeters should be tightly sealed at the bottom to prevent water seepage through the bottom cap.
- Canopy size is an important driver of water use in plum orchards. LAI reflects the canopy architecture of an orchard (canopy height, size and density) which is dependent on the training system, tree spacing and pruning regime. The relationship between these factors is expected to differ from one orchard to another due to differing management practices. The practice of pruning to control vegetative growth is beneficial to reduce water consumption while maintaining high crop yields.
- A parametrized HYDRUS 2D model proved to be useful to run simulations of the soil water balance for different orchards and under different conditions. It could be applied to other orchards in the area.
- Despite the promising results, the continual validation of remote sensing-based ET estimates and model calibration is required to improve model accuracy and operational capabilities as more high-resolution (spatial and temporal) open-source satellite images become available.
- The use of FruitLook in this study was non-exhaustive due to the lack of ground-based measurements to validate the estimates. Therefore, seasonal yield (biomass production) and water use efficiency estimates were not assessed. Although this was not within the scope of the study, quantitative information on these parameters is crucial for the identification and monitoring of highly productive regions/cultivars and conversely the identification of regions with sub-optimal yield and water use efficiency.
- FruitLook under-estimated evapotranspiration mainly in the winter season, when cover crops are actively growing and providing lavish biomass that transpires. It is possible that the remote sensing method does not detect/calculate properly the contribution of cover crops to transpiration and this could be addressed to improve FruitLook outputs.

- The spatial resolution of satellite-derived ET data is fundamental as the edges of the field often result in pixel mixing, where pixels at the edge of the field contain other land cover types (i.e. bare soil between orchards, different crop types), which decrease or increase the overall ET for the pixel. Within-field spatial variability was captured adequately by FruitLook.
- FruitLook estimated LAI generally well. However, there were instances when it appeared that FruitLook over-estimated LAI during periods of full-canopy cover, with unrealistic LAI values up to 6.6. The over-estimation could be due to the contribution of the cover crop to whole orchard LAI estimation or due to a processing error from the FruitLook team. There is therefore a need to validate satellite-based LAI estimates against ground-based measurements as well as to determine the contribution of cover crop to whole orchard LAI estimates.
- The potential of using sensors for logging stem water potential as water stress indicator for irrigation scheduling should be investigated. Two working systems could be sourced on the market: i) sensors that work on the principle of gas exchange through a semi-permeable membrane and measurement of osmotic potential at equilibrium; and ii) sensors that measure water potential with a pressure transducer. The reliability of these sensors should be checked against manual measurements of stem water potential with a Scholander pressure chamber (Scholander, et al. 1962).
- The research demonstrated the potential of using eddy covariance as reference method for evapotranspiration, despite the high cost and complexity of the equipment. At least a full season of data collection is recommended in order to cover a full hydrological year, both periods of low water use and partial canopy cover (winter months) and periods of peak water use and full canopy cover (summer months). This would generate very valuable data to answer other research questions and to comprehensively assess other modelling approaches that are more transferable.
- Although research data showed that micro-jets use on average 9% more water than drip irrigation, a blanket approach cannot be used when selecting an irrigation method, but rather a case-by-case approach is advised which takes into account the root distribution, soil texture and planting density among other factors. The choice of the irrigation method also depends on the design, irrigation scheduling, farm operations, orchard management practices etc. It should be based on a detailed understanding of tree physiological responses to these irrigation methods to minimize water consumption while maximizing productivity.
- This research demonstrated the water-saving potential of drip-irrigation compared to micro-sprinkler irrigation, whilst highlighting the potential pitfalls of both methods.

Micro-sprinkler systems use more water, however the shallow and wide wetting pattern is more conducive for optimal tree water status (meeting the plant's water demand by adequately wetting the root zone) compared to the narrow and deep wetting pattern observed under drip irrigation systems, which leaves the trees more prone to water stress. This has resulted in numerous farmers converting from drip to micro-sprinkler systems. It is clear that farmers would rather use more water (using micro-sprinklers) to ensure a desirable yield of good quality as opposed to reducing water consumption and run the risk of imposing a water deficit which can negatively impact yield and economic returns. Therefore, the solution lies with the design and implementation of precision irrigation technologies which strike a balance between reducing water consumption (maximizing water use efficiency) and maintaining fruit yield and quality.

- There is an increasing trend of orchards grown under agricultural nets both locally and internationally. This is due to the numerous benefits provided by netting, e.g. protection against adverse weather conditions, sunburn of fruits, pests and birds, reduced water use (improved water use efficiency), increased yield and an earlier harvest. There is therefore a need to develop new methodologies for crop growth and water use monitoring under agricultural nets. Netting presents a challenge to remote sensing-based crop monitoring approaches as it influences the spectral reflectance of land cover types which impacts the computation of land surface biophysical parameters (i.e. NDVI, LAI, albedo, emissivity and surface temperature), which in turn impact the accuracy of estimated surface energy fluxes (most importantly ET). A detailed understanding of the spectral response of commonly used agricultural nets is required, which can be used to calibrate land cover classification techniques.
- The current study aimed to quantify the seasonal water use of full-bearing Japanese plum orchards. However, although at a reduced rate, young non-bearing orchards also consume a substantial amount of water. Therefore, for holistic water management and long-term planning purposes, quantitative knowledge on the water use of Japanese plum trees from planting to full-bearing age is vital.
- Overall, the findings of this project, in conjunction with those from literature, highlighted the contribution of multiple factors to orchard water use. These were characterized as meteorological factors (prevailing weather conditions, particularly during periods of peak water use), crop characteristics (crop type, cultivar selection and growing season length) and management practices (canopy size, crop height, tree spacing, training system, and pruning regime). Due to the complex relationship between these factors, the crop water requirement is expected to differ from orchard to orchard and from one

region to another. Therefore, this should be considered when developing an irrigation schedule to achieve optimal yield and fruit quality.

The findings and recommendations of this research were built into the “Guidelines for Irrigation of Japanese Plum” that is appended as a separate document to this report.

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APPENDIX A – WEATHER DATA

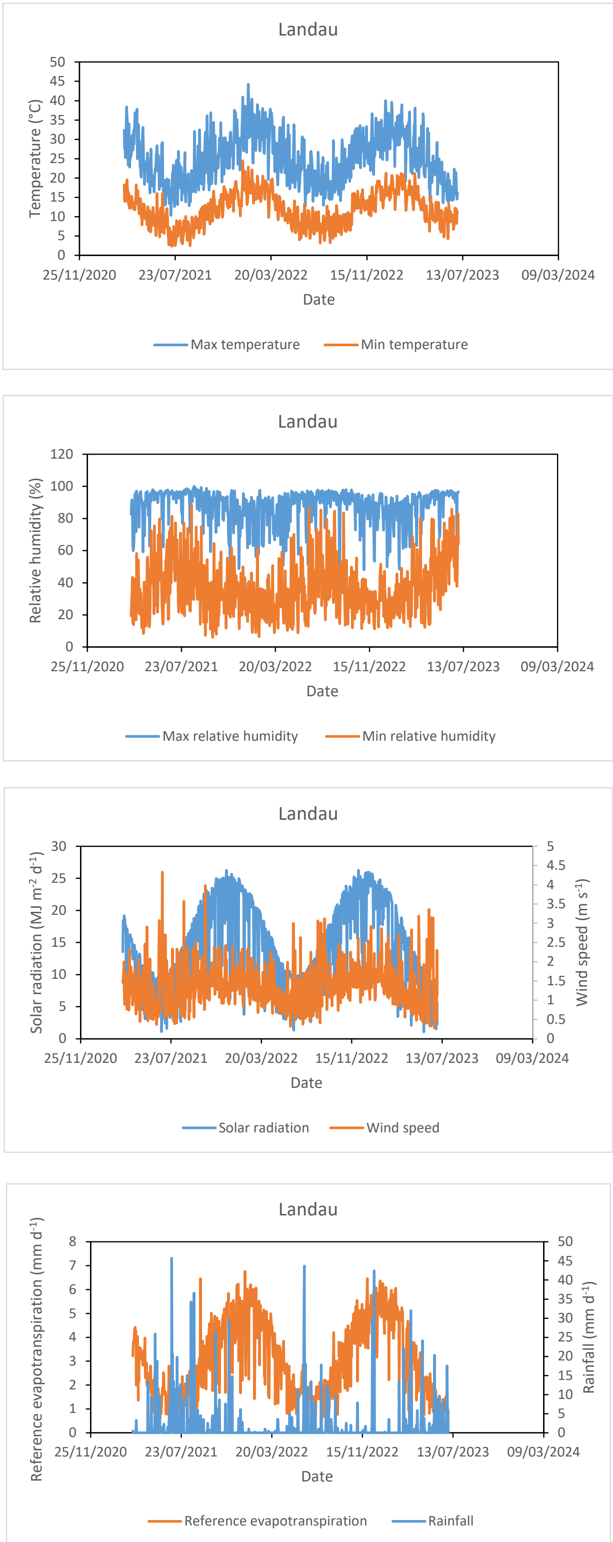

Figure A1 *Weather data collected at Wellington from weather station No. 31016 in Diemerskraal (Agricultural Research Council) during the course of the experiment: maximum and minimum temperature; maximum and minimum relative humidity; solar radiation and wind speed, reference evapotranspiration and rainfall.*

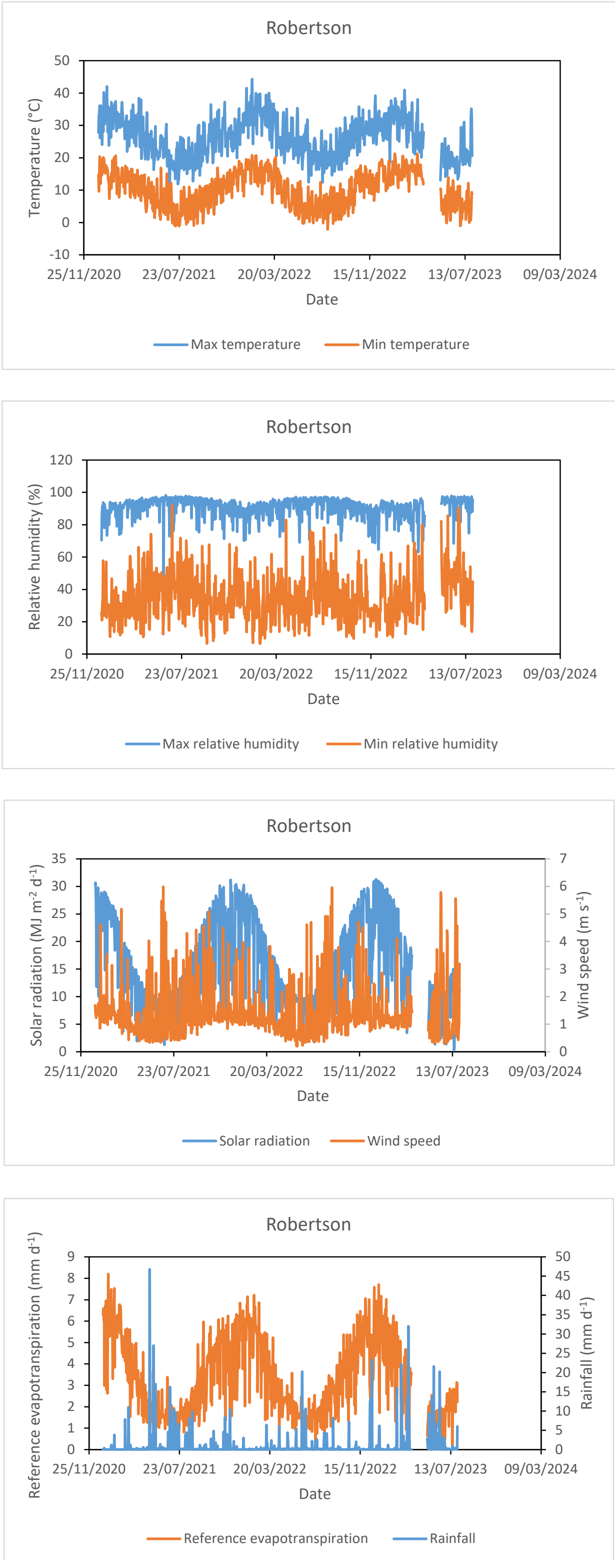

***Figure A2** Weather data collected from weather station No. 30049 at Robertson (Agricultural Research Council) during the course of the experiment: maximum and minimum temperature; maximum and minimum relative humidity; solar radiation and wind speed; reference evapotranspiration and rainfall.*

APPENDIX B – CAPACITY BUILDING

The research project produced students and degrees beyond the original proposal plan of 2 MSc students. The following students were funded and graduated from this project:

- Mr **Ubaid Mathews** completed the **Hons degree** in Environmental and Water Science, University of the Western Cape, on "*Quantifying water use of high-yielding, full-bearing Japanese plum trees*".
- Ms **Yolanda Nqumkana** completed the **Hons degree** in Environmental and Water Science, University of the Western Cape, on "*Measurement of leaf area index (LAI) and canopy cover in plum orchards in Western Cape, South Africa*".
- Ms **Linda Mavuso** completed the **Hons degree** in Environmental and Water Science, University of the Western Cape, on "*Calibration of AquaCheck soil water sensors in selected Western Cape soils of plum orchards: Robertson and Wellington*".
- Ms **Emily Gavor** completed the **Hons degree** in Environmental and Water Science, University of the Western Cape, on "*Soil moisture measurements in plum orchards in the Western Cape*".
- Mr **Ubaid Mathews MSc** in Environmental and Water Science, University of the Western Cape, on "*Quantification of consumptive water use of full-bearing, high-yielding Japanese Plum trees with the HYDRUS-2D model*" (thesis submitted and examined).
- Mr **Nonofo Motsei MSc** in Environmental and Water Science, University of the Western Cape, on "*Quantifying the consumptive water use of Japanese plum orchards in the Western Cape province using the SEBS and SEBAL models*" (thesis submitted and examined).
- Mr **Munashe Mashabatu PhD** at the University of the Western Cape on "*Determining evapotranspiration in a full-bearing Japanese orchard using an integration of eddy covariance, stem water potential, remote sensing, and soil water content measurements*" (in progress).
- Ms **Yolanda Nqumkana MSc** in Environmental and Water Science, University of the Western Cape, on "Validating Leaf Area Index (LAI) and canopy cover estimated from satellite imagery products with ground measurements in plum orchards, Western Cape" (in progress).

Three scientific papers were published during the course of the project at the time of compilation of the final report:

- MASHABATU M, MOTSEI N, JOVANOVIC N, DUBE T, MATHEWS U and NQUMKANA Y (2024) Assessing the seasonal water requirement of fully mature Japanese Plum orchards: A systematic review. *Applied Science* **14** 4097. https://doi.org/10.3390/app14104097

  Abstract: Japanese plums have relatively high water requirements, which depend on supplementing rainfall volumes with accurately quantified irrigation water. There is a lack of knowledge on the seasonal water requirements of plum orchards. This gap in the literature poses an imminent threat to the long-term sustainability of the South African plum industry, which is particularly plagued by climate change and diminishing water resources. The systematic literature review conducted in this study aimed to provide a foundation for supporting water management in irrigated Japanese plum [*Prunus salicina* Lindl.] orchards. Seventeen peer-reviewed articles obtained from the literature were analyzed. Approximately 66% of the cultivars were cultivated under different regulated deficit irrigation regimes for water-saving purposes and to increase fruit quality. This review of our knowledge provided benchmark figures on the annual water requirements of Japanese plums. The full-year plum crop water requirements obtained from the literature ranged between 921 and 1211 mm a^{-1}. Canopy growth, pruning and growing season length were the most common causes of differences in the water requirement estimates. Further research is required to measure the water requirement of plums from planting to full-bearing age and the response of plum trees to water stress, especially in the South African context.

- JOVANOVIC N, MOTSEI N, MASHABATU M and DUBE T (2023) Modelling Soil Water Redistribution in Irrigated Japanese Plum (Prunus salicina) Orchards in the Western Cape (South Africa). *Horticulturae* **9** 395. https://doi.org/10.3390/horticulturae9030395

  Abstract: Japanese plum (Prunus salicina) farming in the Western Cape (South Africa) is an important industry for the export market and job creation and is a large water user; however, adequate information on water requirements of this crop is not available in this semi-arid area. The objective of this study was to determine seasonal plum water requirements for the purpose of water use planning and allocation. The study made use of experimental data from four fully bearing, high-yielding plum orchards (cv African Delight and Fortune) in two major plum production regions (Robertson and Wellington). Crop water requirements and the soil water balance were modelled with the physically based HYDRUS-2D model. Seasonal crop water requirements were estimated to be between 524 mm (cv Fortune in Wellington) and 864 mm (cv African Delight in Robertson). Initial basal crop coefficients (Kcb) ranged between 0.98 and 1.01, whilst Kcb for the mid-stage averaged between 1.11 (cv African Delight in Robertson) and 1.18 (cv Fortune in Wellington). Modelling scenarios indicated that soil water redistribution beyond the root zone continues at reduced rates after the soil dries to levels below field capacity. Irrigation management needs to be balanced with other farming practices to reduce leaching and impacts on water resource quality, as well as with the economics of the farm.

- MASHABATU M, NTSHIDI Z, DZIKITI S, JOVANOVIC N, DUBE T and TAYLOR NJ (2023) Deriving crop coefficients for evergreen and deciduous fruit orchards in South Africa using the fraction of vegetation cover and tree height data. *Agricultural Water Management* **286** 108389. https://doi.org/10.1016/j.agwat.2023.108389

  Abstract: Inaccurate crop coefficients are major contributing sources of uncertainty that lead to inefficient use of limited available water resources. Understanding the need to improve water use efficiency in South Africa's fruit industry, this study evaluated the method of deriving crop coefficients developed by Allen and Pereira (2009) over a variety of irrigated fruit tree crops.

Detailed data of transpiration, evapotranspiration and weather variables measured using the heat ratio method, eddy covariance method and automatic weather stations, were collected from a water research funding body established by the South African government. This study adjusted the stomatal sensitivity function (Fr) in the model by replacing the ratio of the leaf resistance (r_l) to the standard leaf resistance of a reference crop (100 s m^{-1}) with r_l/α where α is a resistance parameter for the specific crop. The resistance parameter was solved accordingly for each fruit type. Respective unique α values were obtained as: macadamia nuts (200 s m^{-1}), citrus (50 s m^{-1}), peaches (20 s m^{-1}) and pecans (20 s m^{-1}). These unique values were used to simulate basal and single crop coefficients that produced satisfactory results when compared to the actual measured values. Overly, no unique standard α value exists for most tree crops although a value close to 20 s m^{-1} may give reasonable estimates for pome and stone fruit. Crop coefficients derived using locally measured data were standardised and tabulated in a format that facilitates their transferability between sites. However, there is still a need to acquire crop specific information to parameterize α and improve accuracies.

Four conference paper were presented:

- MASHABATU M and JOVANOVIC N (2024) Determining evapotranspiration of a fully mature Japanese plum (cv African Delight) orchard in a Mediterranean-type climate. *South African Hydrological Society, 2nd Hydrology Conference*, 2–4 October 2024, Cape Town, South Africa.
- MASHABATU M (2024) Estimating evapotranspiration of a fully mature African Delight orchard using the eddy covariance system. *16th Annual NRF-SAEON GSN Indibano*, September 2024, Port Elizabeth, South Africa.
- JOVANOVIC N, Invited Speaker (2023) Achieving Efficiency in Agricultural Water. *Western Cape Water Indaba & Innovation Showcase 22 – 23 March 2023*, Cape Town, South Africa.
- JOVANOVIC N, MASHABATU M, MATHEWS U and MOTSEI N (2023) Water use of high-performing full-bearing Japanese plum (Prunus salicina) in two major production regions of the Western Cape. *HortGro Stone Fruit Research Showcase, 7 June 2023, STIAS,* Stellenbosch, South Africa.

Two articles in popular magazines were published:

- Estimating Water Consumption in Japanese Plums (2024) *Fresh Quarterly* by HortGro, Issue 27, December 2024, pp. 26-27.
- Water Use in Japanese Plums (2020) *Fresh Quarterly* by HortGro, Issue 9, June 2020, pp. 11-12.

A separate guideline document entitled "*Guidelines for irrigation of Japanese plums*" was developed, targeting primarily farmers, and it is appended to this report. This includes an Excel Kcb calculator to calculate Kcb of specific orchards based on LAI and canopy cover. A database of photos of orchards with different LAI and canopy cover is also provided.

10.

APPENDIX C - DATABASE OF PICTURES OF PLUM ORCHARD AT DIFFERENT STAGE, LEAF AREA INDEX (LAI) AND CANOPY COVER (F_C)

Plum orchard with LAI ≈ 0 and f_c = 0.35 (mid-August)

Plum orchard with LAI = 2.42 and f_c = 0.78 (mid-October)

Plum orchard with LAI = 0.52 and f_c = 0.31 (beginning of September)

Plum orchard with LAI = 2.58 and f_c = 0.84 (beginning of December)

Plum orchard with LAI = 3.31 and f_c = 0.91 (beginning of December)

Plum orchard with LAI = 1.28 and f_c = 0.61 (mid-June)

Plum orchard with LAI = 1.93 and f_c = 0.71 (end of March – after harvest)