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Modelling Soil Water Redistribution in Irrigated Japanese Plum (*Prunus salicina*) Orchards in the Western Cape (South Africa)

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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.

Keywords: African Delight; crop water productivity; crop water requirements; crop coefficients; Fortune; HYDRUS-2D

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1. Introduction

South Africa is a major exporter of stone and pome fruits. Amongst them, the Japanese plum (*Prunus salicina*) fruit industry is well-established and primarily aimed at supplying plums to the export market. Plums in South Africa are cultivated on 5319 ha, and the plum industry employs 5904 laborers and 23,616 dependents [1]. South African peak production was achieved in 2016 (87,746 metric tons), whilst exports were slightly declining in the last 6 years. The Western Cape is the dominant producing area, with the most represented cultivars in 2019 being Angeleno/Sumplumsix, Laetitia, Fortune, Ruby Sun and African Delight [1]. As with other commercial fruit types in South Africa, plum production is totally reliant on irrigation. Therefore, the availability of adequate water is critical for sustainable production [2]. Given the increased frequency of droughts in regions such as the Western Cape and the competition for water use amongst different economic sectors, it is imperative that the fruit industry be provided with tools and information on maximum water use that would inform water use licensing and allocations. 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.

Several methods and strategies for crop water requirements and irrigation scheduling are known from previous research. Jovanovic et al. stressed the importance of an integrated approach for measurement of atmospheric, plant and soil variables in order to accurately interpret plant–water relations [3]. Much of the past research focused on the determination of crop water requirements based on atmospheric measurements and crop coefficients [4,5].

However, little experimental work was conducted in South Africa on crop coefficients of plums and their disparities dependent on cultivar, growth stage, climatic conditions and irrigation methods. Such crop coefficients can be directly used to inform real-time irrigation scheduling and to develop robust orchard soil water balance models that distinguish between plant transpiration and soil evaporation. The application of such water balance models could then be extended to other growing regions and for planning purposes.

In day-to-day irrigation management, the aim of the farmers is to replenish the soil water depleted in the root zone through evapotranspiration. Traditionally, soil water balance models conceptualize soil layers as "reservoir tanks" sized depending on soil water retention properties. The soil water balance is described with the well-known equation:

$$\Delta S = (P + I + U) - (R + D + ET + E_c) - \Delta V \quad (1)$$

where P is precipitation, I is irrigation and U is capillary rise (gains to the soil); R is overland flow or run-off, D is deep percolation, ET is evapotranspiration and E_c is evaporation from the wet canopy (losses from the soil); the term ΔV represents the change in water stored in vegetation, and it is generally negligible. Solving the equation for soil water storage (ΔS) provides the required information on when and how much to irrigate. The equation is steady-state, with all units being volume per unit area for a given time interval. Infiltrating rainfall and irrigation water refill the top soil layer to field capacity (FC). Any excess water is redistributed to the next soil layer, and so on. Excess water refilling the bottom soil layer contributes to drainage (deep percolation), and it is lost to the plants. This simplistic one-dimensional representation of reality is, therefore, referred to as the "cascading" or "tipping-bucket" model. It is intuitive and relatively undemanding in terms of input data required. However, the main shortfall is that water movement in the soil is not replicated based on physical grounds. As such, one-dimensional cascading soil water balance models are not able to move soil water upwards (capillary rise) and side-wards (horizontally), and they do not allow variations in allowable soil water depletion level depending on the atmospheric evaporative demand [6].

A more realistic representation of water movement in the soil is given by physically based models that redistribute water according to gradients in water potential energy. These models make use of the mass balance continuity equation for unsaturated water flow described by Richards [7]. The equation can be solved iteratively with a finite-difference solution, where the soil profile is subdivided into a grid of nodes and water is redistributed between adjacent nodes in all directions based on soil water potential gradients and hydraulic conductivities [7]. These transient types of models have been discussed in [3,8]. However, besides the sound physical approach, finite-difference models are data-intensive, and they also bear inherent inaccuracies due to simplified assumptions. Soil properties are usually heterogeneous, which limits the practical ability to populate these models with accurate input data. In addition, bulk soil properties are usually used as inputs that do not describe the micro-scale intricacies of soil conduits, especially in well texturally sorted soils that may have solid particles and micro-pores of different sizes and distribution.

In the irrigation practice, it is not uncommon that farmers tend to over-irrigate based on their visual experience of the water status of their crops. There are a couple of known reasons for intentional over-irrigation. Firstly, farmers tend to over-irrigate as "assurance" to reduce the risk to crop loss, particularly in semi-arid and arid areas prone to drought. It was demonstrated that the practice of deficit irrigation is beneficial in areas of water shortage to increase crop water productivity; however, this increases the risk of yield reduction [9]. Secondly, the practice of over-irrigation is justified when poor irrigation water quality is used, and an additional volume of water is added to crop water requirements in order to leach salts, thereby preventing salinity build-up in the root zone [10]. In this study, we argue that there may be some additional physical reasons for farmers tending to over-irrigate their crops, beyond the scientists' traditionally simplified understanding and representation of the soil water balance. The hypothesis is that water movement continues to occur in the soil profile even at soil water contents below field capacity, especially in soils with heterogeneous pore sizes and at times of the year when the soil below the root-zone has dried out. To demonstrate this, we used experimental data from high-density Japanese plum (*Prunus salicina* Lindl.) orchards in the Western Cape (South Africa) and modelling with HYDRUS-2D [11]. Due to the paucity of data on plum water requirements in the study region, the overarching aim was to determine seasonal plum water requirements for the purpose of securing correct and reliable water allocations to plum producers. The specific objective was to quantify the soil water balance in the intensively irrigated plum orchards with the physically based HYDRUS-2D model and to test the hypothesis that soil water redistribution and water losses to drainage may occur at levels below FC, thereby elucidating the tendency of some farmers to over-irrigate.

2. Materials and Methods

2.1. Experimental Set-Up

Experimental data were collected during the season 2021/22 in four Japanese plum orchards at Smuts Bros farm near Robertson (33°48′ S; 19°53′ E; altitude: 187 masl) and Sandrivier near Wellington (33°38′ S; 18°59′ E; altitude: 126 masl) in the Western Cape (South Africa) (Figure 1). The regions of Robertson and Wellington represent the two major plum production areas in the Western Cape. Climatic conditions of the two farms are Mediterranean (winter rainfall) with some marked differences. Robertson receives between 175 and 300 mm a^{-1} of rainfall [12]; Wellington has a long-term average rainfall of around 450 mm a^{-1}. Summer temperatures are higher, and winter temperatures are often cooler in Robertson than in Wellington, as Robertson is located in the interior shielded from cooling oceanic breezes, while Wellington is exposed seawards. Weather data for Robertson were collected from weather station No. 30049 (Lat: −33.8284; Long: 19.88534; Alt: 156 m) and those for Wellington from the Landau weather station No. 31016 (Lat: −33.5778; Long: 18.96795; Alt: 126 m) (Agricultural Research Council) (Figure 1). Weather data for the study period (from September 2021 to March 2022) are displayed in Figure 2.

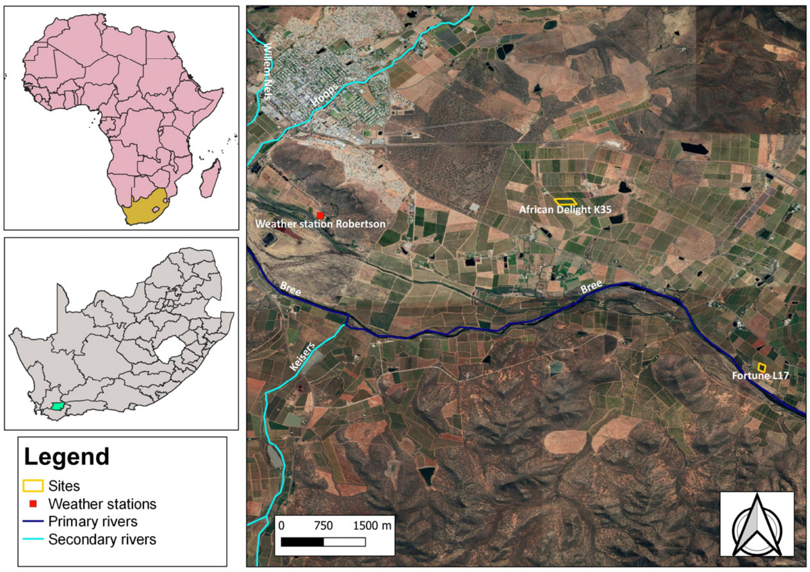


Figure 1. *Cont.*

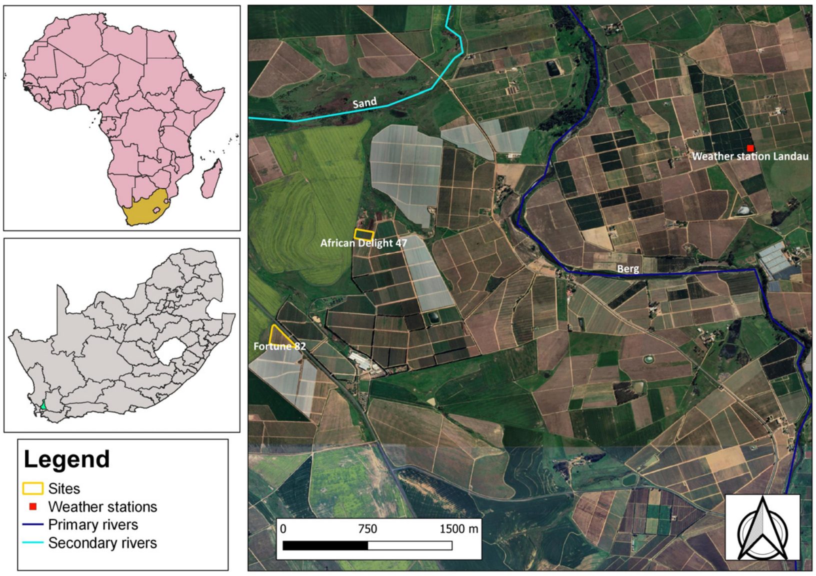


Figure 1. Location of the experimental orchards and associated weather stations on Google Earth maps: Smuts Bros farm near Robertson (**top**) and Sandrivier farm near Wellington (**bottom**).

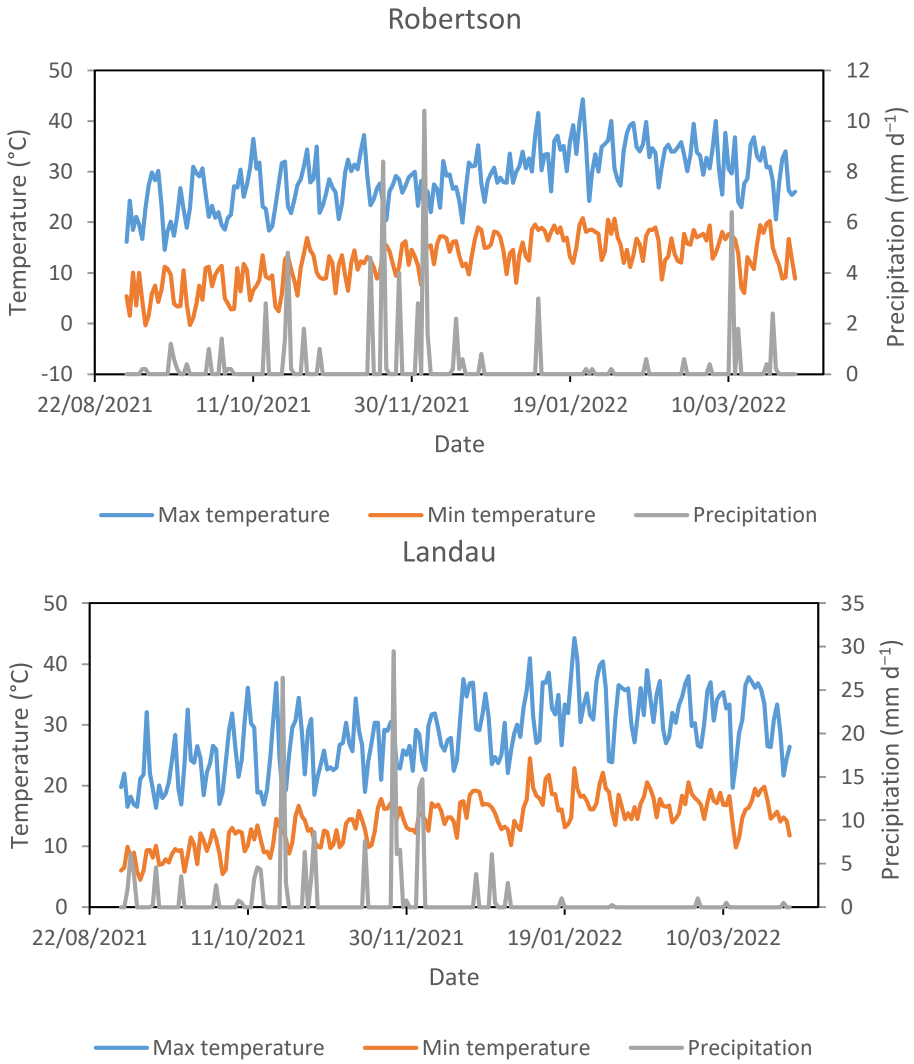


Figure 2. Weather data for Robertson (**top**) and Landau, Wellington (**bottom**) during the period of study from September 2021 to March 2022.

Two full-bearing orchards with high-yielding cultivars were considered at each farm, namely a late-maturing African Delight and a mid-maturing Fortune (Figure 1). Full-bearing and high-yielding cultivars were specifically selected to determine maximum water requirements to be allocated to farms, whilst the choice of the plum cultivars was informed by the deciduous fruit growers' association. Tree spacing in the orchards at Smuts Bros farm was 4 m × 1.5 m, with trees pruned at 3 m height on a Palmette pruning system to maximize radiation interception and facilitate harvesting. The soil is predominantly loam (Table 1). The orchards were irrigated with dripper lines. The water source was the Breede River (Figure 1). Tree spacing at Sandrivier was 3 $\frac{1}{2}$ m × 1.0 m, and tree height about 2.8 m on Palmette trellises. Trees were planted in a zig-zag layout along ridges constructed to favor root development and reduce competition between plants. The soil is sandy to loam (Table 1). The orchards were irrigated with micro-jets; the water source was the Berg River (Figure 1). Soil physical and hydraulic properties are summarized in Table 1 for all orchards.

Table 1. Soil physical and hydraulic properties.

Soil Physical and Hydraulic Properties	Robertson		Wellington	
	African Delight	Fortune	African Delight	Fortune
Texture [1]	Loam	Loam	Sandy	Loam
Bulk density (g cm^{-3}) [2]	1.20	1.42	1.33	1.41
Soil water content at saturation [3]	0.41	0.40	0.38	0.36
Soil water content at field capacity [4]	0.16	0.25	0.20	0.20
Soil water content at permanent wilting point [4]	0.06	0.08	0.07	0.07
Residual soil water content [3]	0.03	0.04	0.04	0.04
Saturated hydraulic conductivity (m d^{-1}) [3]	0.20	0.17	0.43	0.31

[1] Determined by soil analyses. [2] Determined with Kopecki cylinders. [3] Estimated with the neural network function in HYDRUS-2D [11]. [4] Estimated by HYDRUS-2D model calibration against observed data.

Data collection, processing and modelling are described below using the African Delight orchard at Smuts Bros (Robertson) as an example. The same methodology was applied to the other three orchards. The African Delight orchard in Robertson was a 3.8 ha high-density, full-bearing, 7-year-old orchard characterized by a well-drained loamy soil with a shallow conglomerate layer. Volumetric soil water content at FC was estimated to be 0.17 m m^{-1} given the large percentage of stones (Table 1). The trees were grafted on Mariana rootstock with a cover grass between rows. Irrigations were performed with two dripper lines per row, with drippers spaced 0.5 m apart and discharge rates of 2.3 L h^{-1}. The wetted bulb was approximately 1.0 m on both sides of the row, which was the estimated width of the bulk root system confirmed through field observations. The depth of the bulk root system was about 0.8 m. Irrigations were scheduled based on soil probes and an Irricon logging system [13].

Four calibrated AquaCheck Basic II probes were installed to measure volumetric soil water content down to a depth of 0.8 m (0.1, 0.2, 0.3, 0.4, 0.6 and 0.8 m), two in the row and two mid-way between rows, and half-hourly data were collected regularly with an AquaCheck logger [14]. Canopy fractional interception of radiation (fc) and leaf area index (LAI) were measured with an LAI-2200C plant canopy analyzer [15].

2.2. HYDRUS-2D Modelling

The HYDRUS-2D/3D model [11] was used to simulate water transport in the 2D orchard system. There were a number of reasons for using HYDRUS in this specific study. Firstly, the model is fit to describe a two-dimensional water balance system with micro-irrigation, where a portion of the land is wetted (along tree hedgerows), and another portion is non-wetted (between tree rows). Secondly, the HYDRUS model uses Richards' equation [7], which gives a more physically based representation of soil water redistribution compared to traditional tipping bucket/cascading soil water balance models. It is, however, also more data-intensive. Thirdly, given the underlying physics of the 2D processes, it was deemed that the HYDRUS model would give realistic and accurate results of the field water balance, in particular the volume of water that passes the root system and ends up recharging groundwater due to over-irrigation.

In order to parametrize the HYDRUS model for the African Delight orchard in Robertson, a model domain geometry was constructed in HYDRUS-2D. The model domain had a rectangular shape to represent a row cross-section of the orchard (Figure 3). The dimensions of the cross-section were 4 m (tree row width) × 1 m (soil depth). The grid mesh was generated automatically and is visible with blue lines in Figure 3. The simulated processes were water flow and root water uptake at a time interval of 1 day with daily outputs (from 1 September 2021, beginning of irrigation season, to 9 March 2022, end of harvest). Default iteration criteria were used.

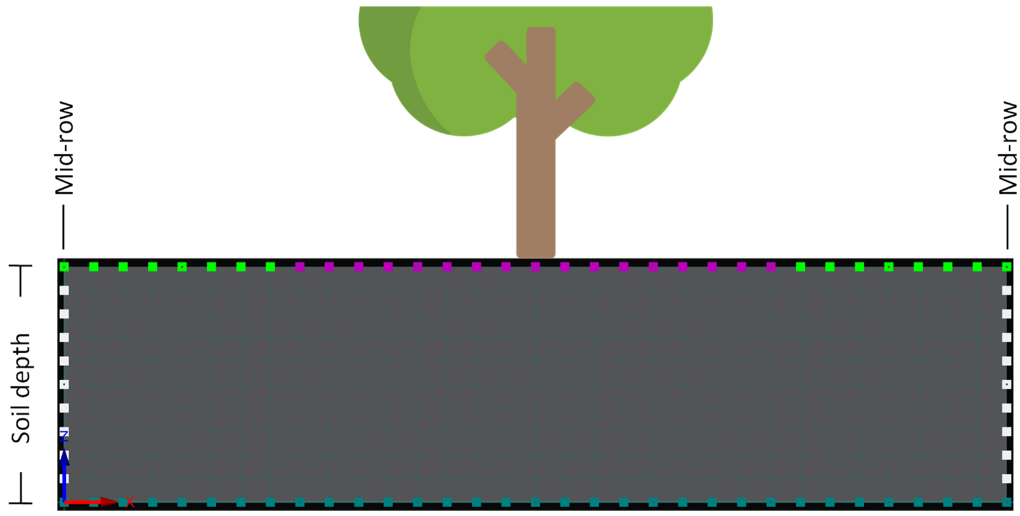


Figure 3. Print screen of HYDRUS-2D representing the model domain geometry, grid mesh (thin blue lines) and boundary conditions. The rectangular cross-section of the African Delight orchard in Robertson has dimensions 4 m (tree row width) × 1 m (soil depth). Boundary conditions at boundary nodes are represented with squares in different colors: light green—atmospheric boundary conditions; purple—surface drip with dynamic wetting; white—no flux boundary; dark green—free drainage boundary.

Time-variable conditions on the domain boundaries were specified according to Figure 3. The boundary nodes in light green represented the atmospheric boundary conditions. This is a time-variable boundary condition that requires daily precipitation data obtained from the weather station. Reference evapotranspiration ETo [4] calculated from weather data was partitioned into an evaporation and transpiration component using canopy cover fc measured with the LAI-2200C plant canopy analyzer. Potential transpiration was multiplied by a basal crop coefficient (Kcb) specific to this orchard based on the procedure described in [16].

The Allen and Pereira method [16] was used to determine Kcb as a function of canopy cover or LAI. For tree crops having grass or other ground cover, Kcb is calculated as follows:

$$K_{cb} = K_{cbcover} + K_d \left(\max \left[K_{cbfull} - K_{cbcover}, \frac{K_{cbfull} - K_{cbcover}}{2} \right] \right)$$

$K_{cb\ cover}$—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 in [16] for the initial stage of fruits (apricots, peaches, pears, plums, pecans) with no killing frost.

The K_d coefficient can be calculated as follows [16]:

$$K_d = 1 - e^{(-0.7LAI)}$$

LAI and fc were measured with the LAI-2200 plant canopy analyzer, and they were found to be quite stable during the season 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 [16]:

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

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, whilst u_2 and RH_{min} were obtained from the weather stations. The adjustment F_r can be calculated as follows [16]:

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

Δ—Slope of the saturation vapor 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 vapor pressure–air temperature curve can be calculated with the following equation:

$$\Delta = \frac{4098\left[0.6108\exp\left(\frac{17.27T}{T+237.7}\right)\right]}{(T + 237.3)^2}$$

where T 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.

The purple boundary nodes in Figure 3 represent a special time-variable boundary condition, namely surface drip with dynamic wetting, and they were used to simulate surface drip (or micro-jet) wetting of the surface [11]. Irrigation volumes were obtained from the farm, and the surface area associated with transpiration was set to be 2 m. The boundary nodes in white on the vertical faces of the domain represented no flux boundaries, assuming that no horizontal fluxes occur in the soil (Figure 3). The bottom boundary was a free drainage boundary (dark green boundary nodes) across which water percolation beyond the root zone was calculated (Figure 3).

The Van Genuchten–Mualem soil hydraulic model was used to characterize unsaturated hydraulic conductivity vs. pressure head. Soil hydraulic parameters were calculated with a neural network prediction incorporated in HYDRUS, based on volumetric soil water content at field capacity (0.17) and permanent wilting point (0.06) estimated with the gravimetric method, texture of the loamy soil and bulk density (1.2 g cm^3). Initial conditions were set with soil water content at FC, as simulations started on 1 September 2021 at the end of the rainy season. Root distribution in the orchard was set to decrease linearly down to a depth of 0.8 m, based on discussions held with farm managers on the soil volume explored by tree roots. The root water uptake model of Feddes et al. was selected for the simulations with no solute stress [17]. Root water uptake parameters of the Feddes model for deciduous fruits were selected from the database incorporated in HYDRUS.

Observation nodes in HYDRUS-2D were set to correspond to the sensor positions of the AquaCheck probes. The model was calibrated by comparison between the soil water contents measured with AquaCheck probes and those simulated with HYDRUS-2D for each soil depth. Input parameters of HYDRUS-2D, in particular soil hydraulic properties and root distribution patterns, were changed until the best fit was obtained between observed and simulated data. The statistical measure was the mean absolute error (MAE), and the calculations were performed in Excel.

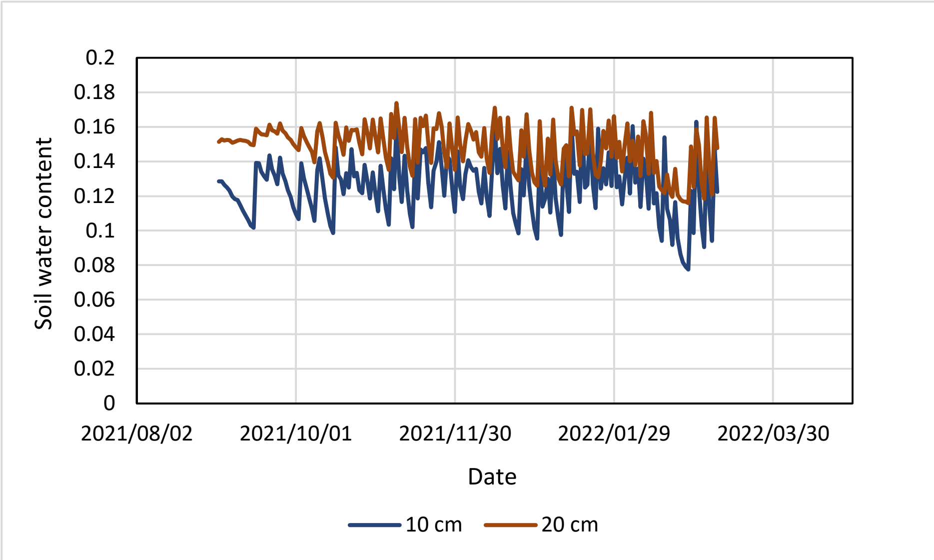
3. Results

3.1. Case Study of African Delight in Robertson

HYDRUS-2D simulations for the African Delight orchard in Robertson were run for the period from 1 September 2021 (beginning of the vegetative season) until 9 March 2022 (completion of harvest, coinciding with a marked reduction in irrigation rate and frequency). Initial Kcb at the beginning of the season (1 September 2021) was calculated from K_d and LAI measurements (LAI = 1.63) [16]. The value of LAI was increased linearly until day 45 of the season (15 October 2021), 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 (0.78) and average LAI (2.08) measured with the LAI-2200C plant canopy analyzer. Values of fc and LAI did not change much during the full cover period because the trees were pruned to reduce vegetative growth and facilitate harvesting. The canopy density coefficient K_d was calculated to be 0.77 at full cover, and a standard value of mean leaf resistance was assumed to be 100 s m^{-1} [16]. The average Kcb at full cover was calculated to be 1.11, which is very close to the values estimated in [16,18].

The model was calibrated via comparison between simulated soil water content and those observed with AquaCheck probes. Figure 4 represents simulated and observed values at two soil depths within the tree row, where most of the soil water flux dynamics are expected to occur. Simulated data reflected the general trends and peaks of measured data with an MAE of 0.028 m m^{-1}. It is interesting to note the fluctuations in soil water content data from the onset of the irrigation season. The decreasing trends in soil water content were also consistent in the beginning of the season and during short periods when irrigations did not take place.

The soil water balance components are summarized in Table 2. Reference evapotranspiration and rainfall were calculated/measured from the weather station data. Irrigation data were obtained from the farm and used as inputs into the model. Soil evaporation, actual root water uptake (plant transpiration) and free drainage were calculated with the HYDRUS-2D model. The crop water requirement of the well-irrigated orchard was calculated as the sum of root water uptake and evaporation directly from the soil. It is evident from Figure 4 and Table 2 that the orchard was over-irrigated, especially during the mid-stage of the growing season. The specific reason for the over-irrigation was the unevenness of orchard pollination, where trees were better pollinated and produced more fruits at the edges of the 3.8 ha field, and this section of the field was, therefore, used to schedule irrigations. A weaker pollination of the trees occurred in the middle of the field, where the AquaCheck probes were installed for monitoring soil water content.



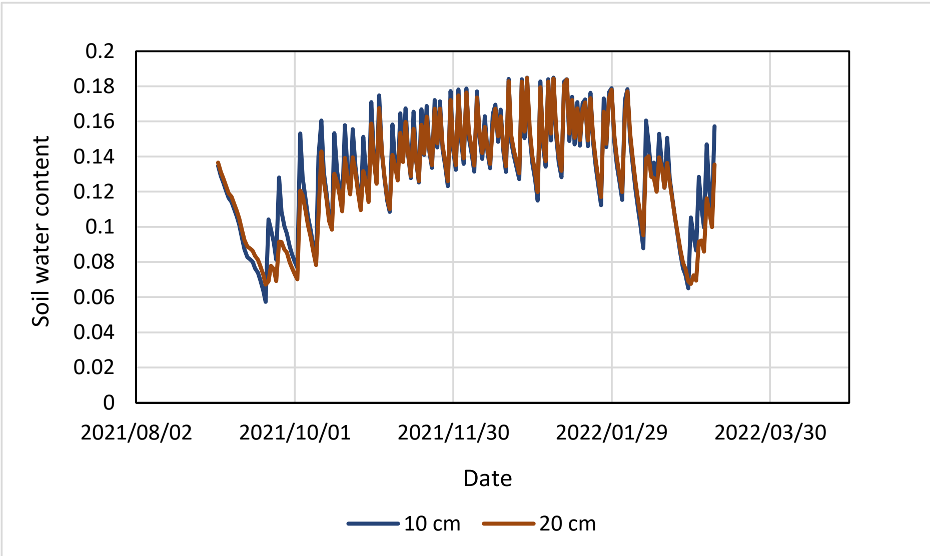


Figure 4. HYDRUS-2D simulations of daily volumetric soil water content (**top** graph) and AquaCheck probe measurements (**bottom** graph) in the African Delight plum orchard in Robertson. Data refer to simulations/measurements at two soil depths within the tree row.

Table 2. Seasonal reference evapotranspiration, water balance components (rainfall, irrigation, soil evaporation, actual root water uptake and free drainage) and crop water requirements for the plum orchard.

Simulation	Field Measurements (Season 2021/22)	Hypothetical Scenario
Reference evapotranspiration (mm)	841	841
Rainfall (mm)	59	0
Irrigation (mm)	943	754
Soil evaporation (mm)	153	109
Actual root water uptake (mm)	711	706
Drainage (mm)	134	46
Crop water requirement (mm)	864	815

A hypothetical simulation with HYDRUS was then conducted to test whether free drainage may have occurred if less water was applied to the field. For this purpose, rainfall was omitted from the simulation, whilst irrigation was set at 80% of the real measurements. The results of the hypothetical scenario are shown in Table 2. It is evident that, compared to real measurements, root water uptake decreased slightly, and soil evaporation decreased substantially. Free drainage decreased substantially; however, some drainage occurred regardless of the irrigation volumes that maintained the soil water content below FC. This was due to weaker, but continued water redistribution in the soil at levels even below FC as well as the drying of the sub-soil that resulted in stronger water potential gradients.

3.2. Water Balance Summary of Four Orchards

The same methodological procedure described for the African Delight orchard in Robertson was used to calculate the water balance for the other three orchards. However, the season duration was different for each orchard, as reported in Table 3. The duration of the growing season coincided with the end of harvesting and a drastic reduction of irrigation volumes and frequency in each orchard. The growing season of the late-maturing cultivar African Delight was longer compared to that of the mid-maturing Fortune. Table 3 also summarizes the initial canopy cover fc and LAI, measured with the LAI-2200C plant canopy analyzer during dormancy, and the calculated initial Kcb. The average measured fc and LAI and the calculated Kcb at full canopy development (mid-stage) are also shown in Table 3. Crop heights, used in the calculation of Kcb values, are controlled on the farms for the purpose of managing canopy growth and facilitating harvesting.

Table 3. Summary of duration of growing seasons (length of HYDRUS simulations) and canopy characteristics (canopy cover fc, leaf area index LAI, basal crop coefficient Kcb and crop height) for four Japanese plum orchards.

Location and Orchard		Robertson		Wellington	
		African Delight	**Fortune**	**African Delight**	**Fortune**
Season duration		1 September 2012–9 March 2022	1 September 2021–19 January 2022	1 September 2021–31 March 2022	1 September 2021–9 January 2022
Initial stage	fc	0.68	0.62	0.61	0.62
	LAI	1.63	1.5	1.28	1.5
	Kcb	0.98	0.97	1.01	1.01
Mid-stage	fc	0.78	0.8	0.81	0.89
	LAI	2.08	2.25	2.55	3.19
	Kcb	1.11	1.12	1.15	1.18
Crop height (m)		3	3	2.8	3.5

Table 4 represents the components of the water balance calculated with the calibrated HYDRUS-2D model. Cumulative reference evapotranspiration and rainfall were calculated for the duration of the growing season. The values were, therefore, higher for crops with a longer growing season. The difference in total rainfall between Robertson and Wellington was noticeable (Table 4). Irrigation volumes depended primarily on the duration of the growing season and the occurrence of rainfall. The common practice on the farms is to increase irrigation volumes from the beginning of the growing season in September up to rates and frequency that support full development until harvest, and then to decrease volumes and frequency for controlling canopy growth and carry-over effects to the next season. Seasonal irrigation was the highest in the African Delight orchard in Robertson (943 mm); this orchard was also the most successful in terms of yield (51 t ha^{-1}). However, this led to intentional over-irrigation due to heterogenous pollination of the orchard. As a result, drainage (deep percolation) was also the highest in this orchard. It should also be noted that irrigations in the African Delight orchard in Robertson are difficult to manage because of the high percentage of stones and conglomerates in the soil that reduce the effective soil water retention capacity (FC is lower than in other orchards, Table 1).

Table 4. Growing season reference evapotranspiration, water balance components (rainfall, irrigation, soil evaporation, actual root water uptake and free drainage), crop water requirements, yield and biophysical crop water productivity for four plum orchards.

Location and Orchard	Robertson		Wellington	
	African Delight	Fortune	African Delight	Fortune
Reference evapotranspiration (mm)	841	590	876	514
Rainfall (mm)	59	57	180	176
Irrigation (mm)	943	512	714	401
Soil evaporation (mm)	153	122	144	66
Actual root water uptake (mm)	711	519	720	458
Drainage (mm)	134	22	16	17
Crop water requirement (mm)	864	641	858	524
Yield (t ha^{-1})	51	39.8	38	38
Biophysical crop water productivity (kg m^{-3})	5.9	6.2	4.4	7.3

Comparatively, soil evaporation was slightly higher, and transpiration (actual root water uptake) was slightly lower for African Delight in Robertson compared to the same cultivar in Wellington (Table 4). This was mainly due to the difference in growing season (Table 3) and planting density. The 4 m spacing between rows in Robertson, compared to 3.5 m spacing in Wellington, allowed for less canopy cover, resulting in more light penetration between the rows and soil evaporation. Irrigations in the African Delight orchard in Wellington were estimated on a weekly basis, due to the absence of the farm manager during the course of the season. However, the total seasonal volumes were recorded. For cultivar Fortune, the harvesting season occurred later in Robertson compared to Wellington. As a result, the Fortune orchard in Robertson was irrigated for longer; therefore, higher soil evaporation and transpiration were calculated.

Seasonal crop water requirements, determined as the sum of soil evaporation and actual root water uptake calculated with HYDRUS-2D, ranged between 524 mm for cultivar Fortune in Wellington and 864 mm for African Delight in Robertson (Table 4). These are the recommended water allocations for these cultivars in these two production regions. By far the highest crop yield was obtained for the African Delight orchard in Robertson (51 t ha^{-1}, with 43 t ha^{-1} of fruit of sufficiently good quality for packing). The yields in the remaining orchards were similar to each other. Biophysical water productivity, calculated as the ratio of yield to evapotranspiration (sum of soil evaporation and root water uptake), ranged between 4.4 kg m^{-3} for African Delight in Wellington and 7.3 kg m^{-3} for Fortune in Wellington.

4. Discussion

The HYDRUS-2D model coupled with the two-step crop coefficient approach of the FAO56 [4] was adopted to calculate the soil water balance and crop water requirements in four irrigated plum orchards in the Western Cape. Crop coefficients (Kc) and basal crop coefficients (Kcb) provided in [4] and revised in [5] 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 (e.g., cultivar, irrigation method and management, row spacing, canopy density, cover crops, etc.). This was corroborated in a modelling study with the CropSyst model on plum cultivars Angeleno and Red Beaut with different pruning over 3 years (2010–2012) [19]. The main conclusion was that different Kc at full canopy were required in order to accurately simulate evapotranspiration, depending on canopy sizes and different tree vigor exhibited by the two cultivars [19]. According to Fereres and Goldhamer, higher crop coefficients may occur in high-density orchards and when using cover crops [20]. Allen and Pereira [16] proposed a methodology to adjust crop coefficients based on LAI, fc and r_l. In the current study, the methodology of Allen and Pereira [16] was used to adjust crop coefficients for full-bearing cultivars African Delight and Fortune in the

Western Cape. The results of crop coefficients, evapotranspiration (crop water requirements) and plum water productivity were compared to internationally available data.

The initial Kcb (0.98–1.01) and the mid-stage Kcb at full canopy cover (1.11–1.18) obtained in the current study (Table 3) are consistent with values reported in the literature for high-density orchards [16,18]. In other published research, crop coefficients (Kc) of around 1 at mid-season were recommended for stone fruits [21]. Naor et al. 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 [22]. Intrigliolo et al. estimated Kc to be between 0.29 in March and 0.57 in June in 10-year-old Japanese plum cv Black Gold cultivated in Spain (average seasonal Kc was 0.46) [23]. In South Africa, Dzikiti and Schachtschneider found the Kc coefficient to be between 0.9 and 1.0 for an African Delight plum orchard in Robertson during peak irrigation season [24].

In the current study, seasonal evapotranspiration (crop water requirements) was calculated to be between 524 and 864 mm (Table 4). Dzikiti and Schachtschneider estimated total seasonal evapotranspiration of African Delight in Robertson to be 921 mm using eddy covariance measurements, with an estimated peak maximum transpiration of 20 L tree^{-1} d^{-1} (2.7 mm d^{-1} by accounting for the planting density) using heat pulse velocity sap flow measurements [24]. In work conducted on Japanese plums cv Angeleno in Spain, Samperio et al. estimated average water input over 5 years to be between 962 and 1211 mm a^{-1} (irrigation + rainfall) depending on well-irrigated and deficit irrigation treatments [25]. Samperio et al. 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 5-year experiment on cv Red Beaut [26]. Monino et al. estimated annual water input (irrigation + rainfall) to be between 895 and 1287 mm a^{-1} for cv Angeleno (9-year-old trees), depending on the deficit irrigation strategy, in an experiment conducted in Spain over 3 years [27]. Intrigliolo and Castel 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 [28]. 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. reported irrigation water requirements to be between 250 and 311 mm season^{-1} (from April to September) for cv Black Gold in Spain [23].

Iancu measured evapotranspiration of plums using non-weighing lysimeters in Romania [29]. 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. researched the effects of different trellis systems (Lincoln, Vase, Palmette and Tatura) on water use of 6-year-old plum trees (cv Laroda and Santa Rosa) in Western Australia [30]. 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 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 [31]. The USDA NASS Cropland Data [32] were used to identify crops at 30 m spatial resolution. Average plum evapotranspiration was estimated to be 994 ± 188 mm a^{-1}.

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 actual 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. In the current study, biophysical crop water productivities ranged from 4.4 kg m^{-3} to 7.3 kg m^{-3} (Table 3). Dzikiti and Schachtschneider reported a plum water productivity of 5.97 kg m^{-3} of water transpired [24]. Intrigliolo and Castel 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 [28]. Monino et al. estimated plum water productivity (9-year-old trees cv Angeleno) to be between 5.6 and 13.4 kg m^{-3} depending on the deficit irrigation strategy [27]. Values of crop coefficients, evapotranspiration and crop water productivities estimated in the current study were generally well within the range of those reported in the literature, which gives confidence that realistic values were simulated with HYDRUS-2D.

In the hypothetical scenario analysis (Table 2), the finite-difference HYDRUS-2D soil water balance model indicated that water losses out of the root zone may occur even at soil moisture values below FC as a result of soil water redistribution. These losses at field scale may be viewed as irrigation return flow into the water resource system, as this water could be re-used downstream. The practice of slight over-irrigation may be justified due to these water losses at field scale, besides representing an "assurance" means of controlling soil salinity. Torrecillas et al. drew attention to the variability of plum responses to water stress, especially in early maturing cultivars [33]. 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 be easily replenished with micro-irrigation systems. Paltineanu et al. demonstrated that soil physical properties are more variable in orchards compared to arable soils with homogeneous tillage, and less favorable to plants in the inter-row soil volume compared to intra-row, mainly due to mechanization traffic [34]. This should be considered in irrigation management, as soil physical properties determine the soil water retention capacity and ultimately root water uptake.

However, any beneficial effects of over-irrigation should be weighed against potentially negative effects that may manifest through leaching of nutrients/chemicals and economic losses. Nutrients, pesticides and other chemicals are some of the most expensive inputs in farming, and their loss bears economic costs to the farm. In addition, they impact the water resources and environment, which may imply remediation costs. The practice of deficit irrigation has been recently investigated, where reduced irrigation results in lower yields, but better quality fruit and higher profits [33]. Much research can be found in the literature on deficit irrigation strategies specifically targeted to non-critical phenological stages to reduce plum water use and improve fruit quality [25,27,35,36] and carry-over effects to subsequent seasons [23,26,27,37–41]. In these instances, the economic yield water productivity [42] may be considered a more influential factor in irrigation management than biophysical water productivity. It is clear that further research is required on finding a fine balance between irrigation management, scheduling and other practices to reduce water use and sustain profitable farming.

5. Conclusions

Seasonal plum water requirements calculated with the HYDRUS-2D model differed depending primarily on the duration of the growing season (mid- or late-season cultivar) and canopy cover (pruning to control vegetative growth). This information is invaluable to plum producers in order to plan irrigations and obtain correct water allocations. It appears that the methodology of Allen and Pereira [16] may be applicable to extrapolate crop coefficients to sites with different irrigation and crop management in order to calculate crop water requirements. The comparison of the soil water balance calculated with the physically based HYDRUS-2D model using real data and a hypothetical scenario of deficit irrigation demonstrated that water redistributes dynamically in the soil, and deep percolation of water beyond the root system continues even after the soil dries to levels below FC, although at much reduced rates. This amount of water is not always accounted for in simplified soil water balance models, and it needs to be considered in irrigation scheduling to replenish the water loss from the soil profile. It is essential that scientists collaborate closely with farmers to acquire on-the-ground information for improving the accuracy of irrigation scheduling, yields and profits, in combination with other farming practices.

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