Review

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Quantifying the Seasonal Crop Water Requirements of Mature Full-bearing Japanese Plum Orchards: A Review

Nonofo Motsei [1,*], Nebojša Jovanović [1,*], Timothy Dube [1], Munashe Mashabatu [1], Ubaidullah Mathews [1] and Yolanda Nqumkana [1]

[1] Department of Earth Science, University of the Western Cape, Bellville, 7535, South Africa
* Correspondence: 3852083@myuwc.ac.za (N.M.); njovanovic@uwc.ac.za (N.J.); Tel: +27 21 9592686 (N.J.)

Abstract: Japanese plums form part of a multi-billion rand deciduous fruit industry in South Africa. Despite this, there is a paucity of knowledge on the seasonal water requirements of plum orchards. In a time of changing climatic conditions and diminishing water resources, this gap in literature poses an imminent threat to the long-term sustainability and global competitiveness of the South African plum industry. Therefore, this paper aimed to provide a review of the available literature on the crop water requirements of full-bearing well-irrigated Japanese plum orchards for improved agricultural water management. Full-year water requirements for well-watered full-bearing Japanese orchards ranged between 921 and 1 211 mm a^{-1} with a mean value of 1 084 ±140 mm a^{-1}. Canopy growth and pruning appeared to be the most common causes of differences in water requirement estimates. Growing season length also plays a role with late-season maturing orchards having higher water requirements than their early and mid-maturing counterparts. The knowledge review provided benchmark figures for the annual water requirements of Japanese plums. However further research is required to determine the water requirement of plums from planting to full-bearing age and the response of plum trees to water stress, in a South African context.

Keywords: agricultural water management; crop water requirements; evapotranspiration; Japanese plums

1. Introduction

The South African deciduous fruit industry was valued at R 15.67 billion during the 2020/21 crop year with plums accounting for roughly 10.7% of the total gross production value (3rd behind apples and pears) [1]. Globally, South Africa is the 6th largest exporter of fresh plums and 2nd in the Southern Hemisphere behind Chile. Plum production in the country has been steadily growing since 2006 reaching a peak figure of 101 969 metric tons in 2021 [1]. Dzikiti et al. [2] attributed the increased production volumes of deciduous fruits in recent years to the use of improved plant material (e.g., scion-rootstock combinations) and orchard management practices (e.g., increased orchard densities and better cultivar selection). Intensive, high yielding plum orchards (>30 tons ha^{-1}) are becoming a common occurrence in the South African agricultural landscape. Norchitz and Noar [3] noted that increased crop yields were associated with higher crop water requirements. Plums along with other high value fruit crops are grown under irrigation. As such the availability of water is crucial for the sustainability and growth of the South African fruit industry.

There is a relative paucity of knowledge on the seasonal water requirements of plums. In a time of changing climatic conditions (characterized by increased drought frequency and rainfall variability) and diminishing water resources this gap in literature poses an imminent threat to the long-term sustainability and global competitiveness of the South African plum industry. The agricultural sector is the largest consumer of water in the country, with irrigated agriculture accounting for 62% of total consumption [4]. Pavel et al. [5] emphasized that the goal of modern-day agriculture is to utilize less water for irrigation (improve efficiency) without decreasing fruit yield and quality. These sentiments have become more prevalent in recent years where increased competition from municipal and commercial sectors has intensified the stress put on the agricultural sector to increase its water use efficiency. It is therefore imperative to equip water managers, policy makers and farmers with a set of tools for accurately quantifying the unstressed crop water requirements of full bearing (3 - 6 years) high-yielding plum orchards. This would assist in the allocation and licensing of water resources as well as promoting improved water use efficiency within the agricultural space through the development of water saving strategies. From a farmer's perspective, such information would provide a framework for the development of accurate irrigation scheduling programs and the determination of orchard water budgets. Stevens [6] revealed that less than 20% of South African farmers use science-based approaches for irrigation scheduling with the majority implementing a knowledge-based approach which often leads to over-irrigation and increased non-beneficial orchard water use. With science-based irrigation scheduling approaches, farmers typically estimate crop water requirements (and thus the required irrigation volume) using meteorological methods and crop coefficients [7,8]. Previous studies have successfully used crop coefficients (Kc) for crop water use estimation in South African fruit orchards [9–14]. However these Kc values often require parametrization for site-specific conditions which largely limits their transferability to other sites with differing conditions.

The advent of Earth Observation (EO) and remote sensing (RS) technologies provides an alternative avenue for evapotranspiration (ET) estimation. The capabilities of various RS-based ET models e.g., SEBAL, SEBS, METRIC and ETLook, in a South African context, have been evaluated across different land cover types and climate regions [15–20]. Estimated ET and other surface fluxes (net radiation, sensible and soil heat fluxes) were validated against ground-based flux measurements. A consensus from literature is that the use of RS-based ET models holds great potential for monitoring crop water requirements across various spatial (field, regional or national scale) and temporal (weekly, monthly, or seasonal) scales, due to its robust nature. This paper aims to provide a review of the available literature on the crop water requirements of full-bearing well-irrigated Japanese plum orchards for improved agricultural water management. A focus was put on the use of RS-based methods for crop water requirement estimation.

2. Evapotranspiration in orchards

Evapotranspiration (ET) is a combination of two processes, namely evaporation (E) and transpiration (T). Evaporation is defined as the loss of water from soil surfaces and water bodies to the atmosphere, whereas transpiration refers to the loss of water from plants (through their stomatal openings) and cover crops between tree rows to the atmosphere [21]. These processes occur simultaneously, making it difficult to differentiate between the two. Approximately 98% of water absorbed by a plant (through its roots, up the stem and to the leaves) is lost to the atmosphere through evapotranspiration (ET) [14]. This is referred to as crop ET or water consumption whereas the amount of water required to supplement this loss i.e., water required for optimal crop growth, is referred to as the crop water requirement. Ideally, these values are equivalent to each other and unless a clear distinction is made between the two, are often used interchangeably under sound irrigation management practices. In an orchard setting water is primarily lost through ET, with other avenues including surface runoff and the deep drainage of subsurface water below the crop root zone [22]. These processes are illustrated in Figure 1. The rate of ET is determined by the collective influence of meteorological factors, crop characteristics and orchard management practices.

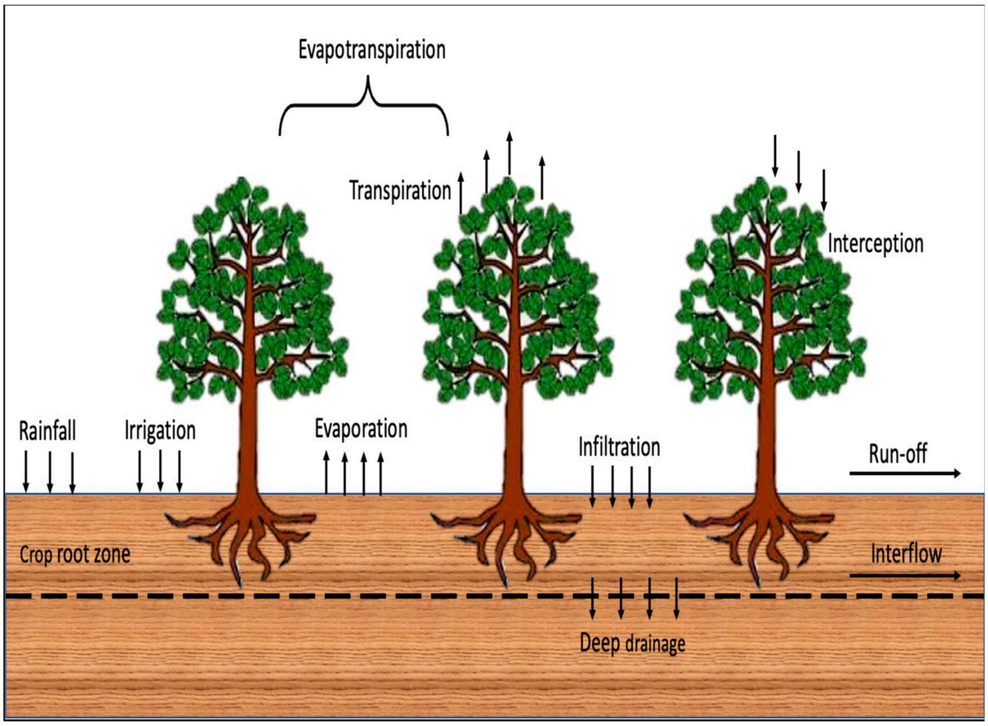

Figure 1. Illustration of water balance in an orchard setting.

2.1. Meteorological factors

The primary meteorological factors influencing ET are solar irradiance, relative humidity, air temperature and wind speed. The energy required to convert liquid water to vapour is provided by the incident solar radiation (and to lesser degree, the ambient temperature of the surrounding air) whilst the rate is determined by the atmospheric demand for vapour also referred to as the reference evapotranspiration (ETo) [21]. The influence of solar radiation on the ET rate is a function of the available radiation (which varies depending on the region, time of day, season, cloud conditions etc.) and the fraction of incident radiation intercepted by the crop canopy. Stomata (mouth-like pores found in the epidermis of leaves and stems) regulate gas exchanges between the plant and the atmosphere [23]. The stomata open and close in response to a light stimulus (in this case solar radiation), and as such they are typically open during the day and closed at night. They facilitate the diffusion of carbon dioxide (CO_2) from the atmosphere into the leaf and the movement of water from the leaf into the atmosphere (transpiration) [24]. Jones et al. [25] highlighted the strong correlation between solar radiation and observed transpiration rates given that water availability is not a limiting factor. The water holding capacity of air changes with temperature, where warmer air has a higher holding capacity than colder, denser air. Therefore, on warm, dry, sunny days the atmospheric demand for water vapour would be higher than on cold, humid, and cloudy days.

The influence of wind speed on ET rate can vary depending on the prevailing conditions. Generally, wind and air turbulence function to transfer water vapour from the evaporative surface into the overlying air. If the air at the evaporative surface is not replaced by drier air, the driving force for evaporation decreases due to the overlying air becoming saturated. The rate of ET increases with wind speed to a point where solar radiation or water availability becomes a limiting factor. At that point, a further increase in the wind speed will not increase the rate of evaporation. Relative humidity (RH) and vapour pressure deficit (VPD) give an indication of the amount of water vapour in the atmosphere. RH has a negative relationship with ET where, increasing RH values results in decreased ET over land surfaces. VPD, defined as the difference between the amount of moisture in the air and how much moisture the air can hold, has a positive correlation to transpiration [22]

2.2. Crop characteristics

A combination of factors, which vary from crop to crop, influence the water usage within an orchard. These include the type and variety of crop, crop height, canopy structure and density as well as the leaf area [21]. As such, different types of crops and potentially different cultivars will consume varying amounts of water under the same set of climatic conditions. Each crop type follows a set of phenological growth stages throughout the season with each growth stage differing in terms of water consumption. In the case of deciduous fruit trees, which are characterized by the seasonal growing and shedding of their leaves, orchard water use is typically lowest during the early and latter stages of the season with peak water use being achieved mid-way through the season. Canopy size (aggregate area of vegetative growth) and canopy structure (spatial arrangement of a plant canopy) are regarded as the most important factors influencing orchard water use throughout a season and the life span of the orchard [25]. The leaf area index (LAI) is commonly used as tool for better understanding and comparing the canopies of different trees. Dzikiti et al. [2] investigated the influence of canopy cover and crop load on the seasonal water use of mature, full-bearing and young non-bearing orchards in two major apple production regions in the Western Cape (South Africa). The study concluded that canopy cover, as opposed to crop load, was the main driver of orchard water use in mature full-bearing orchards. Similarly, Intrigliolo and Castel [26] reported no statistical significance between different crop loads (medium and low) and irrigation requirement in a 7-year-old Japanese plum orchard planted to cv. Black Gold.

The movement of water from the soil, through the plant and into the atmosphere (Soil-Plant-Atmosphere Continuum) is regulated by resistive forces within the plant. These include resistance at the soil-root interface, the root endodermic resistance, xylem resistance and the leaf hydraulic resistance at the leaf-atmosphere interface [27]. The collective influence of these resistive forces together with the stomatal conductance regulate the photosynthetic rate of a plant and consequently transpiration [28].

2.3. Management characteristics

The management practices employed in an orchard have a large influence on the water use. These include but are not limited to the use of netting or windbreakers, the chosen irrigation system (i.e., drip or microjet irrigation) the presence or absence of crop cover as well as its variety and the chosen planting system. The contribution of cover crops to total ET, particularly in apple orchards, has been well documented in the Western Cape. Ntshidi et al. [29] found that orchard floor evaporation (crop cover + soil evaporation) accounted for as much as 80% of the measured ET in young apple orchards with a dense cover crop. This value was significantly lower in mature orchards (fractional canopy cover >55%) where orchard floor evaporation contributed less than 30% of the measured ET. Dzikiti et al. [2] obtained similar results, where floor evaporation accounted for 18 – 36% of total ET in mature full-bearing orchards and over 60% in young non-bearing orchards. Both studies concluded that orchard water use could be reduced by decreasing floor evaporation rates. The planting system, which includes the tree planting arrangement, row orientation and the selected training system, along with pruning and thinning practices influence orchard ET by controlling the amount the solar radiation that can intercepted by the canopy [30]. Since photosynthesis is partly limited by light availability, modern day training systems and pruning techniques aim to enhance light penetration through the canopy, maximizing photosynthesis and fruit production. Chootummatat et al. [31] investigated the effect of different training systems (Lincoln, Vase, Palmette and Tatura trellis systems) on the water use of a plum orchard planted to cv. Laroba and Santa Rosa. The differences in water use ranged between 9 – 18% depending on the chosen irrigation regime (40% or 110% class A pan evaporation rate) with trees trained on the Vase and Tautra trellis using more water at 40% and 110% irrigation respectively. It is recommended that tree rows be orientated in a north-south direction (perpendicular to the sun’s orbit path) to maximize light interception and minimize the amount of shade created by each tree [9]. However, additional factors namely local climate, the slope of the land, prevailing wind direction and specific tree and fruit requirements largely influence the exact orientation of orchards within a given region.

3. Water requirement of plum orchards

The water requirements of an orchard vary throughout a season, depending on the phenological growth stage, and throughout the orchard's life span depending on its age and canopy cover [22]. Stone fruits are characterized by four phenological growth stages. The first of which is stage I: the first rapid fruit growth, followed by stage II: pit hardening then stage III: the second rapid growth and lastly stage IV: post-harvest [32]. Vegetative growth (growth of leaves, stems and roots) mainly occurs during stages I and II, when plant vigour can be manipulated to control fruit size and quality. Fruit growth occurs exponentially during the first stage (stage I) which typically lasts 30 days or less. The exponential growth is succeeded by a lag growth phase during which the pit (stone) hardens, and embryo development occurs (stage II). Stage III is characterized by a second period of rapid fruit growth where the fruit can double in size (up to 40-60%) [32,33]. By the end of stage III, the fruit is mature and ready to be harvested.

The duration and susceptibility to water stress of each phase differs in different stone fruit varieties (i.e., plums, peaches, apricots and nectarines) and cultivars, with early-season plum cultivars typically experiencing a shorter stage II growth phase [34]. In early-season cultivars fruit growth will continue into the pit hardening phase (stage II), albeit at a slower rate, making it difficult to distinguish between the two stages [34]. In late season cultivars the duration of the pit hardening phase is longer and the degree of fruit growth during this stage is minimal. Generally peak water consumption is experienced during stage III when the second rapid fruit growth occurs, and fruit cells begin to fill with water and sugar. After harvest, tree transpiration rates gradually begin to decline resulting from reduced photosynthesis rates, associated with the onset of leaf senescence, and a reduction in leaf area as the tree enters a winter dormancy period. Trees are more susceptible to water stress during stage I and III, and as such accurate irrigation scheduling is crucial to achieve an economically viable yield.

Limited information is available on the seasonal water requirements of plum orchards, both locally and on an international scale. In their 2010 report on plum production guidelines, the South African Department of Agriculture, Forestry and Fisheries (DAFF) proposed a set of water use estimates for full-bearing plum orchards (Table 1). These however only serve as a reference guideline, as site specific conditions such as the soil texture and depth, climatic conditions, the chosen irrigation system etc., must be taken into consideration when developing an irrigation schedule. The water use estimates were based on evaporation rates measured from a class-A evaporation pan.

Table 1. Estimated water requirement of full-bearing Japanese plum orchards [33].

Month	**Water requirement (mm month^{-1})**
August	32.2
September	41.5
October	84
November	126
December	182.1
January	193.8
February	162.7
March	118.5
April	32.2
May	21.7
June	16.5
July	17
Total	**1 019**

Plum evapotranspiration data estimated/measured in literature are summarized in Table 2. Jovanovic et al. [8] estimated the water requirements of four full-bearing Japanese plum orchards (cv. African Delight and Fortune) in two prominent production regions of the Western Cape (Robertson and Wellington) using the HYDRUS 2D model. The late maturing African Delight orchards in both regions displayed higher water usage figures of 858 and 864 mm in Wellington and Robertson respectively compared to 534 and 641 mm for the mid maturing Fortune orchards. The differences in water use were attributed to the longer growing season of African Delight (September – March) compared to Fortune (September – January). It is a common practice amongst farmers in the Western Cape to continue irrigating plums after harvest (until the end of summer), although at reduced rates, to avoid damage or death of trees due to drought and water stress, and to prevent carry-over effects to the next season. Annual plum water requirements may therefore be higher than the water requirements estimated for the growth season by Jovanovic et al. [8].

Dzikiti and Schachtschneider [35] investigated the seasonal water requirements of a late-season Japanese plum cultivar, cv African Delight, planted on a 3 ha plot at Sonskyn farm in Robertson, South Africa. The trees were grafted to a GF-677 rootstock with a tree spacing of about 5 m between rows and 1.5 m within the rows. The orchard was trained on a V-Haag trellis system with dual rows orientated in an east-west direction. The trees were irrigated via a drip irrigation system with a discharge rate of 2 L h^{-1}. The water usage of individual trees was measured using a heat pulse velocity sap flow system from late spring (October 2013) to winter of the following year (2014). The actual ET for the entire orchard, measured using an eddy covariance (EC) system, was 921 mm with an approximate irrigation figure of 1 006 mm.

Recently, Mhawej and Faour [36] utilized a Google Earth Engine (GEE) integrated surface energy balance model (SEBALI) to estimated ET rates over a 307 000 km^2 agricultural plain in California. Plums were one of 83 different crop types planted in the area. Model input parameters which included remotely sensed biophysical parameters and meteorological data were derived from Landsat 8 images and open source ERA5 reanalysis dataset respectively. The average annual ET rate for each crop type was estimated for 3 consecutive years (2017-2019). The average ET for plums was estimated to be 994 mm a^{-1} with a standard deviation of 188 mm a^{-1} whilst the cumulative water consumption between 2017 and 2019 was estimated to be 4.1 km^3 (accounting for 0.65% of total water use across the study area during that period). The remotely sensed estimates were validated using a network of eddy covariance (EC) flux towers yielding coefficient of determination (R^2), Root Mean Square Error (RMSE) and average marginal effect (AME) values of 0.82, 11.53 mm $month^{-1}$ and 9.56 respectively.

Gavilan et al. [37] used a Landsat 8 and Sentinel 2 derived NDVI time series analysis to estimate the ET rates over a 70 km^2 stretch of land in the agriculturally prominent O'Higgins region in Chile. Plums accounted for 4.51 km^2 of the total area. Landsat 8 and Sentinel 2 images were atmospherically corrected using the Semi-Automatic Classification plugin integrated into the open-source QGIS software. The Sentinel 2 images were resampled from 10m to 30m using the linear interpolation method. NDVI maps were then created for each sensor. These maps were subsequently harmonized and used to estimate the actual and reference ET rates for each crop type for the agricultural season (from December 2017 to March 2018). Daily ET estimates for the plum orchards ranged between 3 – 5 mm day^{-1}. The actual and reference ET (ETo) for the season were estimated to be 331 and 525 mm respectively. Gavilan et al. [37] concluded that the plum orchards were under-irrigated with the actual ET significantly below the reference ET. Water stress in the latter stages of fruit development resulted in increased fruit quality (higher sugar concentration attributed to an earlier maturation date) and reduced fruit size. The remotely sensed estimates had a good agreement with ground-based ET values producing RMSE and BIAS values of 0.6 mm day^{-1} and -0.4 mm day^{-1} respectively.

Monino et al. [38] estimated the average annual water requirement (irrigation + effective rainfall) for a 9-year-old cv Angeleno orchard to range between 1 011 – 1 187 mm a^{-1} depending on the imposed regulated deficit irrigation (RDI) regime. The study was carried out over 3 seasons (2014 – 2016) on an experimental plot situated in Badajoz, Spain. The late-maturing cv Angeleno trees were budded to Mariana 2625 rootstock with a tree spacing of 6 m x 4 m. The orchard was trained on an open vase system with rows orientated in an east-west direction. A drip irrigation system was employed with one emitter per row at a discharge rate of 4 L h^{-1}.

In another study originating from Spain, Sampeiro et al. [39] estimated the average water requirement (irrigation + rainfall) of an early maturing Japanese plum cultivar cv Red Beaut, under 3 different regulated irrigation regimes over 5 seasons (2009 – 2013). The crop water requirement was estimated using the crop coefficient approach detailed in the FAO irrigation guidelines [21]. The imposed irrigation regimes included a control regime where trees were irrigated at the estimated crop water requirement along with two regulated deficit irrigation (RDI) regimes where trees were irrigated at 60 (RDI-60) and 30% (RDI-30) of the crop water requirement. RDI regimes were imposed during the post-harvest phenological phase of tree growth. The average water requirement was estimated to range between 835 – 1 159 mm a^{-1} with trees under the RDI-30 regime having the lowest water use and the trees under the control irrigation regime having the largest.

In a second study, Sampeiro et al. [40] estimated the average water requirement (irrigation + rainfall) of a 4-year-old cv Angeleno orchard in Badajoz, Spain to be between 963 – 1 211 mm a^{-1} depending on the irrigation regime. Both orchards in the respective studies [39,40] were budded to a Mariana 2624 rootstock with a tree spacing of 6 m x 4 m. Both orchards are 1 ha in size and irrigated via a drip irrigation system, with a discharge rate of 4 L ha^{-1}. Differences in the water requirement at each orchard could be attributed to differences in the imposed RDI regimes, pollinator species (cv Black Diamond and Ambra in Red Beaut; and cv Lady Ann and Fortune in Angeleno) or the inherent characteristics of each cultivar (length of growing season).

Intrigliolo and Castel [26] used an adjusted Kc for canopy size to estimate crop water requirements of a 7-year-old Japanese plum cv. Black Gold in Valencia, Spain for 3 seasons (2004 – 2006). The seasonal water requirement, calculated as the sum of irrigation and effective rainfall from April to October, was between 432 – 525 mm, depending on the irrigation water treatment and crop load. Iancu [41] measured the evapotranspiration rate of plum trees (cv Vinete Romanesti) using a non-weighing percolation lysimeter in Pitesti-Maracineni, Romania. The experiment was conducted over 19 years (1971 – 1989) in three lysimeters with dimensions 4m x 3m x 1.5m. These lysimeters were placed in the middle of a 6 ha plot containing trees of the same cultivar. In addition to that, three smaller lysimeter (1m x 1m x 1.5m) were used to measure the evaporation rate at the soil surface. The crop ET (Apr - Oct) was measured to be 622 mm, with daily values ranging from 1.69 mm day-1 in April and 4.24 mm day-1 in July.

Table 2. Summary of annual and seasonal plum water use estimates from literature.

Cultivar	Age	Water use (mm a^{-1})	Water use (mm growing $season^{-1}$)	Method	Location	Author
African Delight Fortune			858-864 (Sep-Mar) 534-641 (Sep-Jan)	HYDRUS 2D	South Africa	[8]
		994		SEBALI	United States	[36]
Angeleno	9	1 011-1187		SWB	Spain	[38]
			331 (Dec-Mar)	NDVI time series	Chile	[37]
African Delight	5	921		EC	South Africa	[35]
Red Beaut	4	835-1 159		Kc	Spain	[39]
Angeleno	4	962-1 211		Kc	Spain	[40]
Black Gold	7		432-525 (Apr-Oct)	Kc	Spain	[26]
Vinete Romanesti			622 (Apr-Oct)	Lysimeter	Romania	[41]

SWB: Soil water balance, EC: Eddy covariance system, Kc: Crop coefficient approach.

4. Methods for estimating orchard ET

Over the years, various ET estimation methods have been developed and validated over a diverse range of land cover types (i.e., grasslands, agricultural land and forests). ET can either be measured directly using instrumentation or derived empirically based on its relationship with other atmospheric and ground-based parameters [24]. The methods include meteorological methods (e.g., Penman-Monteith, Blaney Criddle, Priestley Taylor, Thronthwaite), micro-meteorological methods (e.g., Bowen ratio, eddy covariance, scintillometery, eco-physiological techniques (e.g., sap flow, isotope method, Iysimeter) and more recently remote sensing-based methods [42]. In many studies, method selection is often motivated by data availability, the aim and proposed spatial and temporal scale of the study, the required accuracy as well as the associated costs of the study (available funds).

The main difference between these methods is their spatial footprint (the spatial scale at which they can accurately estimate ET). Eco-physiological methods, specifically the sap flow method, were developed to provide plant scale estimates of ET whereas meteorological and micro-meteorological methods can measure ET for a homogeneous surface (i.e., an orchard) at a local scale. These methods provide point estimations of ET which, given the homogenous nature of the site, are considered to be representative of the whole study area. A major drawback of these methodologies, apart from scintillometry, is their inability to measure the spatial variability of ET fluxes over an area of interest. For the application of meteorological and micro-meteorological methodologies in heterogeneous landscapes a network of stations is required. However, there are several challenges associated with this network which include the cost associated with the establishment, operation, and maintenance of the stations along with the costs of employing a team of experienced technicians needed to operate said stations. Another challenge relates to the interpolation of point ET estimates. Lott and Hunt [43] noted that interpolation introduces errors in the estimation of ET particularly in mountainous areas (where meteorological conditions vary over short distances) as well as areas where stations are unevenly distributed, which is often the case. Remote sensing-based models have been proposed as alternatives to traditional methods as they can measure the spatial variation of ET across an area with relatively high accuracy [16,44]. Shoko [42] echoed the importance of accurately estimating the amount and spatio-temporal variability of ET for improved water resource management and monitoring, particularly in water scarce environments.

Zhang et al. [45] described six approaches for estimating actual ET from remotely sensed data namely, Surface Energy Balance (SEB) based models, Penman-Monteith, Priestley-Taylor, Surface Temperature Vegetation Indices, Water Balance models and Empirical models. SEB based models were one of the easiest remote sensing (RS) based ET estimation models with leading-edge research from Kalma and Jupp [46] and Kustas [47]. These models estimate actual ET (also denoted as LE, the latent heat flux) as a residual term of the energy balance equation. SEB models can be categorized into single-source and dual-source models. Single-source models regard the Earth’s surface as a uniform (single) layer and do not distinguish between soil evaporation (E) and transpiration (T) when computing for ET over a land surface. Dual-source models, as the name suggests, account for the individual contributions of the soil and vegetation components to the total surface energy flux.

Single-source SEB based models primarily differ by how they calculate the sensible heat flux (H). The net radiation (Rn) and soil heat flux (Go) can be calculated indirectly from acquired satellite images or measured directly using ground-based net radiometers and soil heat plates respectively [42]. The sensible heat flux (H), on the other hand is typically derived based on differences between the dry and wet limits within the area of interest [48]. The wet and dry limits refer to selected pixels in the acquired satellite image which depict the two extreme surface flux conditions within the study area. The wet limit refers to a pixel where the surface is covered with water (e.g., a lake) or where the surface is well-irrigated (e.g., a well-irrigated orchard). At the wet limit, we assume high/maximum LE, minimum surface temperature and low to negligible H. Conversely, the dry limit refers to a pixel where the surface is dry with little to no water. Therefore, H and surface temperature are at their maximum and H is equated to the available energy (Rn – Go) [49]. At present, there is no universal consensus on which model is the best as each approach has a set of assumptions and associated advantages and limitations [45,50]. However, through a comprehensive review of literature, Mohan et al. [51] 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.

5. Discussion

The conceptualization of this review was motivated by the lack of knowledge on the crop water requirements of mature full-bearing Japanese plum orchards in South Africa despite the increasing yearly production figures. Literature originating from Spain [26,39,40], South Africa [8,35], the United States [36],Chile [37] and Romania [41] were reviewed. The orchards in these studies were planted to a variety of early (Black Gold and Red Beaut), mid (Fortune) and late-season (African Delight and Angeleno) maturing Japanese plum trees cultivated under differing growing conditions. All but one site, Romania, were situated in Mediterranean-type climates (according to the Koppen-Geiger classification system) which is characterized by dry hot summers and cold wet winters. Romania shares similar climatic characteristics with areas being classified as a humid subtropical/continental region. These conditions are conducive for plum growth as they meet the required cold temperatures (typically 2.5 and 12.5 °C) during the dormancy period and increase in temperature when spring approaches to stimulate flowering and vegetative growth [33]. However, there were marked differences in the average annual rainfall across these regions which ranged between ± 200 mm a^{-1} in Robertson and Valencia, and 756 mm a^{-1} in California.

Plum water requirements collated from literature ranged between 331- 1 211 mm (Table 2). A distinction was made between water requirements during the growing season and throughout the year. The growing season is defined as the period from bud-break (typically in early spring) to harvest. Full-year crop water requirements encompass the water requirements during the growing season along with supplementary requirements before the beginning of the growing season and post-harvest. Irrigation during these periods, although at reduced rates, is essential for maintaining tree health and minimizing alternate bearing. As such it should be considered when determining the total water requirement of an orchard as well as water allocation. Full-year water requirements ranged between 835 and 1 211 mm a^{-1} when considering figures from orchards under regulated deficit irrigation (RDI) regimes. When these were omitted i.e., only the control orchards (irrigated at 100% of crop water requirement) were considered, water use ranged between 921 and 1 211 mm a^{-1} with a mean value of 1 084 ± 140 mm a^{-1}. Water requirements during the growing season ranged between 331 and 864 mm. The low ET estimate reported by Gavilan et al. [37] (331 mm) was attributed to a water deficit during the season resulting from poor irrigation management in the area. The study also had a shorter growing season of 3 months (Dec - Mar) compared to 5 – 6 months in the other studies.

Canopy growth and pruning appeared to be the most common causes of differences in water requirement estimates. Growing season length also plays a role with late season maturing orchards having higher water requirements than their early and mid-maturing counterparts. Late-season maturing orchards have a longer growing season which means the trees retain their leaves for longer. This maintains the crop canopy for an extended period, which facilitates continual crop water usage in comparison with early and mid-season maturing orchards which experience leaf fall at an earlier stage. Additional causes of variation include differences in growing conditions (combination of climate and orchard management practices) and the chosen regulated deficit regime (where applicable).

Full-bearing plum orchards reported in studies by Sampeiro et al. [39,40] and Monino et al. [38] were cultivated under similar growing conditions (climate and management practices) in Badajoz, Spain. The trees in each orchard were budded to a Mariana 2624 rootstock and spaced at 6 m x 4 m (417 trees ha^{-1}). The orchards were irrigated via a drip irrigation system, with a discharge rate of 4 L ha^{-1}. Different RDI regimes were applied at each orchard, but the control plots were irrigated at 100% of the crop water requirement. The early maturing Red Beaut orchard had the lowest water requirement (1 159 mm a^{-1}) [39]. Monino et al. [38] and Sampeiro et al. [40] reported water requirements of 1 187 and 1 211 mm a^{-1} for late maturing Angeleno orchards. These orchards were well-watered and thus considered to be indictive of the maximum unstressed water requirement for mature full-bearing Japanese plum orchards in the region. In South Africa, Dzikiti and Schachtsheider [35] reported water use of 921 mm a^{-1} (1 006 mm total irrigation) for a well-water drip irrigated African Delight orchard in Robertson, Western Cape. This is ±30% lower than the figures reported for well-watered late maturing orchards in Spain despite having a higher plant density (2 667 trees ha^{-1}) and markedly drier climate. Jovanovic et al. [8] observed similar water use figures (864 mm), also in Robertson, for the same cultivar from September – March. These observations suggest better orchard management and water saving practices in South Africa compared to Spain. However further research on plum water requirements in South Africa, particularly of high-density orchards (>1 000 trees ha^{-1}) is required for a more comprehensive assessment.

Different methods were employed to estimate crop water requirements in the reviewed literature with crop coefficient [26,39,40] and remote sensing-based [36,37] approaches being the most utilized. The crop coefficient approach [21] is a tried and tested method which has been extensively employed to estimate the water requirement of various fruit trees both locally and internationally [13,14,52]. However, the method often requires parametrization for site-specific conditions which largely limits its transferability to other sites with differing growing conditions. Remote sensing-based approaches, particularly surface energy balance (SEB) models, provide an alternative avenue for crop ET estimation. SEB models compute crop ET and other surface energy fluxes (net radiation, sensible heat flux and soil heat flux) using remotely sensed data derived from acquired satellite images in combination with meteorological data. This removes the need for crop-specific information (e.g., crop height, crop type and cultivar, planting density, and phenological growth stage), making the models easily scalable to various spatial and temporal scales [53]. Quantitative data on the water requirements of plum orchards coupled with the provision of techniques for monitoring water use are essential for irrigation scheduling, irrigation system design and for water allocation purposes.

In recent years innovative strides have been made in the Western Cape agricultural scene with regard to the use of Earth Observation and remote sensing technologies for crop ET estimations. The largest feat achieved was the development of web-based platforms GrapeLook and FruitLook for the dissemination of weekly crop water use, growth and nitrogen status data for key crops (e.g., grapes, pome and stone fruits) to farmers, agricultural consultants, researchers and other relevant stakeholders within the Western Cape [15,54,55]. These datasets are derived using the SEBAL and ETLook models with input data from various satellites (Landsat 8, Sentinel 2, VIRS and MODIS) and widespread ground-based metrological stations. Roux et al. [56] highlighted the importance of crop information derived from these platforms for improved agricultural water management with the aim of increasing productions volumes while reducing water consumption. However, extensive validation of these model outputs especially crop ET is required to ensure the accuracy of crop parameters disseminated to end-users.

6. Conclusion

Full-year water requirements for well-watered full-bearing Japanese orchards ranged between 921 and 1 211 mm a^{-1} with a mean value of 1 084 ±140 mm a^{-1}. Canopy growth and pruning appeared to be the most common cause of differences in water requirement estimates. Growing season length also plays a role with late season maturing orchards having higher water requirements than their early and mid-maturing counterparts. Additional causes of variation include differences in growing conditions (combination of climate and orchard management practices) and the chosen regulated deficit regime (where applicable). Extensive research on the water saving potential of regulated deficit irrigation (RDI) was found, with a bulk of the work originating from Spain. Similar to South Africa, increasing water scarcity and climate change appear to be major challenges in Spanish agriculture. RDI regimes (particularly in stage II and post-harvest phenological growth stages) were demonstrated to reduce water use and improve fruit quality, whilst maintaining commercially acceptable crop yields. In the wake of a recent drought in the Western Cape, this methodology could assist in the development of a drought resiliency framework to protect the plum industry from the effects of climate change. However further research on the response of plums to water stress, in the context of South Africa, is required. Additionally, there is a need to quantify the water use of plum orchards from planting to full-bearing age for holistic long term water planning and sustainability of the industry. Lastly, extensive validation of remote sensed-based crop ET estimates against ground-based measurements is required to evaluate the performance of models. The continual validation and calibration of models aid in improving model accuracy.

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