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Assessment of crop evapotranspiration and deep percolation in a commercial irrigated citrus orchard under semi-arid climate: Combined Eddy-Covariance measurement and soil water balance-based approach

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A R T I C L E I N F O

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A B S T R A C T

An accurate estimate of crop coefficient (K_c) values at different development stages (K_{cini}, K_{cmid}, and K_{cend}) is crucial for assessing crop water requirements in semi-arid regions. The objectives of this study were first to quantify the reference evapotranspiration (ET_o) and to calculate the actual evapotranspiration (ET_a) over citrus in a semi-arid climate under drip irrigation. For this purpose, a site of a citrus orchard in Souss-Massa, planted with the *Esbal* variety of clementine, was equipped with an Eddy-Covariance (EC) system, and sensors to measure radiation, soil heat flux, and micrometeorological forcing data, during 2020 and 2021 seasons. Also, the soil moisture content at various soil depths in the root zone near the EC tower was monitored. The energy balance closure (EBC) approach was adopted for flux assessment to ensure a quality check for the EC measurements. The obtained EBCs were about 82% and 79% for the daily measurements in 2020 and 2021, respectively, which can be considered acceptable considering the nature of the citrus orchard (relatively tall and sparse). Second, the study aimed to estimate actual $K_{c\ act}$ values for citrus under the same irrigation strategy. The derived values were compared to different recommended K_c values in the literature. In the third stage, this work aimed to offer an alternative plan to sustainable irrigation management by elaborating an irrigation schedule for citrus crops in the region using the FAO-56 simple approach to avoid water stress and deep percolation (i.e., $K_s = 1$ and DP = 0). Eventually, an irrigation schedule was drawn following the crop's phenological stages. The seasonal mean citrus evapotranspiration (ET_a) values are 1.68, 3.02, and 1.86 mm/day for the initial, mid, and end-season. The seasonal actual $K_{c\ act}$ values were 0.64, 0.58, and 0.64 for K_{cini}, K_{cmid}, and K_{cend}, respectively. Additionally, the application of the water balance equation revealed that a large quantity of water is lost through deep percolation (52% of total water supplied). The study focuses on Citrus trees being a strategic crop with important socio-economic values in the Souss-Massa region. Thus, the results should support both scientists and farmers in planning and strategy development.

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1. Introduction

The citrus industry is an important market segment within the global fresh produce trade. In the Mediterranean region, citrus production is oriented toward fresh consumption, and only 10% is used in processing (FAO, 2017). The total Mediterranean citrus production reaches 20 million tons, and Morocco is among the largest producing countries, along with Spain and Portugal (Chen et al., 2019). Indeed, Moroccan annual production is estimated to rise by more than one-third, thus reaching 2.3 million tons (USDA Argentina, 2020). The country's rank is highly attributable to the increased planted area, as new orchards come into full production potential, plus its favorable meteorological conditions during the flowering season and fruit ripening. Regarding the Souss-Massa region, Citrus orchards cover an area of 40,000 ha, which is 31% of the surface devoted to citrus crops nationally (MAMPDREF, 2020). This area makes up about 82% of the land used for irrigated crops.

Generally speaking, irrigation is the foremost consumer of water in Morocco, with more than 85% of the water mobilized (Samih, 2020), although it only concerns 13% of the Utilized Agricultural Land. The water mobilized is responsible for 14% of the Gross Domestic Product. Hence, irrigation is mandatory to avoid water stress and ensure suitable conditions for growth, development, and yield. The familiar technique adopted for water supply in the region is drip irrigation. Its key advantages are greater fertilizer efficiency, contribution to environmental preservation, and higher water use efficiency (Bouchaou et al., 2017). Yet, water resources are still subject to decrease, negatively impacting crop yields (Brouziyne et al., 2018). This water scarcity puts Morocco as a hot spot of climate change, according to the Intergovernmental Panel on Climate Change. The situation in Souss-Massa is not different than the rest of the country: climate variability drastically affects water resources in this region (Seif-Ennasr et al., 2016). It can be easily deduced from the increase in drought length, the rise in temperature values, and the reduction in rainfall (Seif-Ennasr et al., 2016), harming agriculture in semi-arid regions (Todorović, 2019a).

The reduction in precipitation quantities induced the necessity to supplement rainfall with irrigation reasonably by controlling the balance between demand and supply. In other words, water needs to be optimized according to the real needs of the crop at any given moment of its development (Hssaisoune et al., 2020). The latter requires a good characterization of evapotranspiration (ET), which is considered the key to sustainable irrigation management. The ET process is specific to each location and plant growth dynamics due to its dependence on the weather, crop type, crop variety, and soil properties, among other crop features (Anapalli et al., 2018; Todorović, 2019b). From the energetic point of view, ET is defined as the energy mobilized to transport water from the plant leaves and soil to the atmosphere as a vapor. It is referred to as the latent heat flux and measured as an energy flux density (Rana and Katerji, 2000).

There are several methods for measuring actual evapotranspiration. It depends on time scales and the objectives to fulfill. The variety of options requires a classification according to the concept followed by each one: hydrology, micrometeorology, and plant physiology. Soil water balance and weighing lysimeters follow a hydrological approach (Holmes, 1984). Tilahun and John (2012) estimated evapotranspiration as an independent output of the soil water balance equation over a field crop grown in Australia's semi-arid environment. The energy balance/Bowen ratio, the aerodynamic method, and the Eddy-Covariance (EC) adopt a micrometeorological line (Rose and Sharma, 1984). Finally, the sap flow, isotope methods, and chambers system are based on plant physiology concepts (Rana and Katerji, 2000). The methods based on the later concept are usually hard to scale up. The energy balance/Bowen ratio method is not very expensive. Yet, it is necessary to use distinctive psychrometry and keep the bulbs wet and clean for a minimum accuracy, plus the aerodynamic measurement is not suitable for tall crops (Rana and Katerji, 2000). Malek and Bingham (1993) compared calculating evapotranspiration using the Bowen ratio-energy balance and the water balance. During the experimental period, the evapotranspiration determined by the water balance approach was 98% of that obtained by the Bowen ratio-energy balance method. Simple weighing lysimeters for determining crop coefficients and evapotranspiration for cotton showed that it is a hard-to-maintain tool (Fisher, 2012). Knowing this, the EC remains a cutting-edge science-based method for mass, energy, and momentum transfer quantification in the soil-plant-atmosphere continuum (Mauder et al., 2007). This method was widely exploited, particularly within the framework of the SUDMED Program (Chehbouni et al., 2008) to measure ET (Ezzahar et al., 2009) and thus estimate crop coefficients (Er-Raki et al., 2008, 2009, 2012) over olive and citrus orchards in Tensift basin, which is more or less similar in terms of climate (semi-arid) to the Souss-Massa.

The methods for ET estimation are either based on analytical modeling or empirical ones. In a global context, certain studies estimated ET and crop coefficients of citrus trees, in semi-arid climatic conditions, by different means. For instance, some studies focused on field measurements of the soil and plant water status (Rallo et al., 2017). Other studies covered either the analysis of stomatal conductance and leaf water potential (Jamshidi et al., 2020) or the assessment of the reliability of the ArcDualKc model based on the FAO-56 dual crop coefficient (Longo-Minnolo et al., 2020). More recently, Jafari et al. (2021) measured stem water potential (Ψ_{stem}), net photosynthesis (A_n), and stomatal conductance (g_s), highlighting this way soil moisture variability and crop physiological response. This study follows an ET operational model estimating water consumption as a fraction of reference evapotranspiration to simplify the operating strategy for agricultural usage.

Additionally, accurate quantification of deep percolation contributes highly to sustainable water resources management. Due to the difficulty of obtaining direct observations of deep percolation, it is frequently computed as a residual of the water balance. In the Moroccan context, deep percolation has been quantified following the soil water balance approach based on the principle of conservation of mass in the effective rooting depth, detailed in Section 2.6 (Nassah et al., 2018, 2017) or by mixing remote sensing data and SAMIR (Satellite Monitoring of Irrigation) tool (Nassah et al., 2022). Deep percolation is the unknown variable in the water balance approach. The known variables include irrigation, change in soil water content, and evapotranspiration.

The objectives of the current paper are: i) to compare the calculated daily crop coefficient, for the experimental period, to the different values given in the literature, ii) to assess the irrigation protocol followed by the farmer in a citrus orchard drip-irrigated under semi-arid climatic conditions, and iii) to optimize the irrigation water schedule according to crop phenological stages. The daily crop coefficient values were computed following the FAO-56 single crop coefficient approach. Meanwhile, irrigation assessment is achieved through an evaluation of deep percolation (DP) according to actual evapotranspiration (ET_a) based on the water balance approach. For recommending the appropriate irrigation schedule, two conditions were set; controlling the water stress coefficient ($K_s = 1$) and avoiding deep percolation ($DP = 0$). Irrigation scheduling attempts to maximize the economic benefits of agricultural output while minimizing environmental consequences and respecting the provision of ecosystem services by the maximization of water use, nutrients, and energy (Todorović, 2019c). The soil–water-balance method is currently the most widely utilized irrigation scheduling method. Several factors control irrigation scheduling, for instance, the crop, soil texture, ET_o, and other operational factors like the availability of water as well as the delivery and farm system's flexibility. A correct irrigation protocol can positively impact the farm's financial budget and eventually yield, especially in arid areas where water is a limited resource and rainfall events are rare.

All in all, the novelty of the study presented herein is to elaborate an irrigation schedule for citrus crops tailored to the Souss-Massa region, based on the combined use of Eddy-Covariance measurement and soil water balance-based approach. The research is significant because it is, to our best knowledge, the first protocol taking into consideration the specific climate conditions of the Souss-Massa zone. Besides, citrus is of high economic value among farmers, so the offered protocol will bring added value to this agricultural activity. Consequently, this study could be advantageous for farmers and decision-makers in the region as a guideline to appropriately design their irrigation strategy. However, it does not mean that the research results are exclusive and limited to Souss-Massa. It is a contribution to knowledge in all semi-arid conditions.

2. Materials and methods

2.1. Experimental site

This study was carried out in a commercial citrus orchard in Sebt El Guerdane town (latitudes: 30° 21′ 28.46″ N, longitudes: 8° 58′ 56.27″ W, elevation: 207 m) in the Souss-Massa region, Morocco (Fig. 1). It is an area falling into a semi-arid Mediterranean climate influenced by the ocean and the Sahara. This climate is characterized by low and irregular rainfall in space and time. Specifically, the precipitations vary between 70 and 350 mm/year, with an average of 200 mm/year (Bouchaou et al., 2011). As a result, a significant water deficit is observed in surface water and aquifer. Soil analysis revealed that the plot soil is loamy sand with 80% sand, 10% loam, and 10% clay. The field was planted with 12-year-s-old clementine trees (*Esbal* variety) grafted on *Citrus Macrophylla* rootstock. The planting density of the trees was 1000 trees/ha. The site is daily long watered by a drip irrigation system with a water amount reaching sometimes 15 mm/day, depending on the climatic conditions.

2.2. Meteorological measurements and energy balance closure of eddy covariance evaporation measurements

In the center of the site, a 7 m-tall tower was installed for the Eddy-Covariance and micrometeorological measurements on September the 27th, 2019, by the Laboratory of Applied Geology and Geo-Environment (LAGAGE) of Ibn Zohr University in collaboration with the International Laboratory LMI-TREMA (https://www.lmi-trema.ma/). It was placed in the center of the field (Fig. 1). The EC system set at a high of 6.3 m taking into consideration adequate instrument elevation above the canopy to increase eddy size to meet the sensor route length and decrease roughness sublayer distortions (Allen et al., 2011). It consisted of a 3D sonic anemometer (CSAT3, Campbell Scientific Ltd.) that measured fluctuations in wind velocity components and temperature, and a Krypton hygrometer (KH20, Campbell Scientific Ltd.) measuring the concentration of water vapor. Raw data were sampled at a rate of 20 Hz and half-hourly fluxes of sensible heat (H_{SONIC}) and latent heat (*LE*) were later calculated off-line, using the EC processing software "Ecpack," after performing several corrections including (1) planar fit corrections (Wilczak et al., 2001); (2) correcting the sonic temperature for the presence of humidity (Schotanus et al., 1983); (3) frequency response corrections for slow apparatus and path length integration (Moore, 1986); (4) the inclusion of the mean vertical velocity according to Webb et al., (1980); and (5) oxygen correction for the Krypton hygrometer, which is sensitive to O2 (van Dijk et al., 2003). The processing of the EC data was done by the EC-pack software, including all necessary corrections. This processing has been adapted in all experiments of SUDMED and LMI (Chehbouni et al., 2008). Over the same tower, a CNR4 radiometer (Kipp & Zonen) which measures the four components of the net radiation (incoming and outgoing shortwave and longwave) was placed at 5.13 m above the ground soil. Additionally, the air temperature and relative humidity were measured with the CS215 probe (Campbell Scientific Ltd.) installed at 2.11 m above the ground, and the precipitation was collected by a rain gauge. For the soil measurements, the soil heat was measured using the sensor for heat flux measurement in the ground (HFP01 model, Hukseflux). The sensors are distributed as the following: 2 at 5 cm depth from both sides of the tree and one at bare soil. Concerning the volumetric water content, six Time Domain Reflectometry sensors (CS655 model, Campbell Scientific Ltd.) were installed at 5, 20, 30, 60, and 80 cm depth. Two CS655 sensors were installed at 5 cm depth on both sides of the tree. Due to localized geographical differences in irrigation (or precipitation) additions, the soil is wetted differently (Allen et al., 2011). Thus, TDRs were positioned between the rows at 2.5 m from the tree trunk. These monitor soil volumetric-water content, bulk electrical conductivity, and temperature. All the measurements were recorded using a CR3000 Micro datalogger (Campbell Scientific Ltd.).

The evapotranspiration quantification through an *EC* system requires

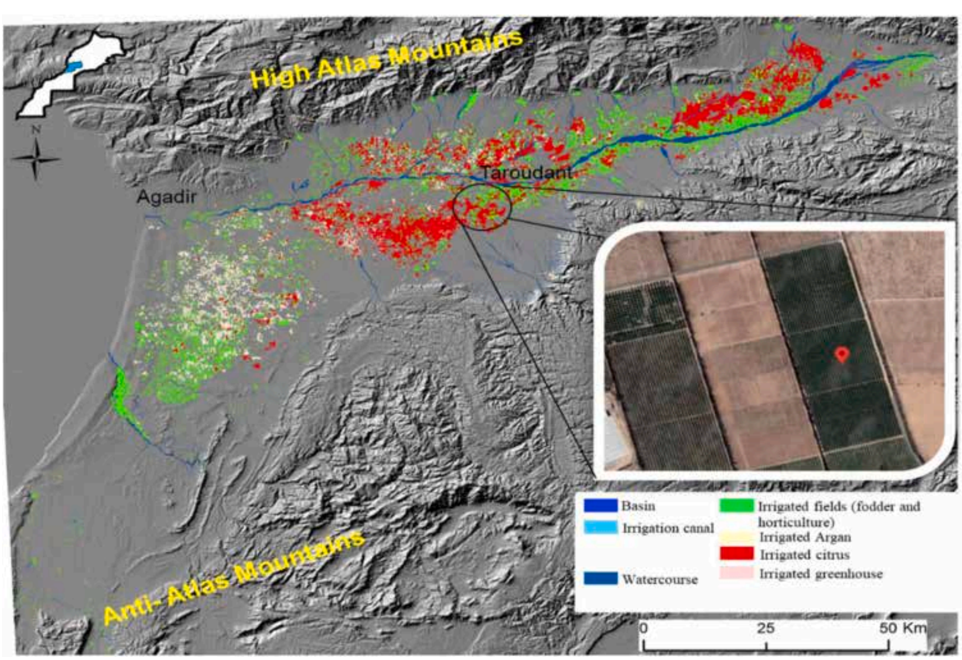

Fig. 1. Land cover map in Souss-Massa Basin and the experimental site location. The red pointer represents the exact location of the Eddy-Covariance station (ABHSM, 2015, modified).

a substantial number of calculations. Thence, it is fundamental to assess the performance of flux measurements by checking the Energy Balance Closure (*EBC*) approach, which is based on the principle of conservation of energy. For that purpose, the sum of the latent (*LE*) and sensible (H_{SONIC}) heat fluxes derived from the *EC* system is balanced by the available energy (net radiation (R_n) minus soil heat flux (*G*)). Both H_{SONIC} and *LE* data were eliminated when the precipitations occurred, and only R_n data between 9:00 a.m and 5:00 p.m were kept, which correspond to the available energy of soil-crop surface (R_n - *G*) being positive.

Fig. 2 displays the plot of R_n-*G* against H_{SONIC}–*LE* for both the 2020 and 2021 seasons using daily values (Fig. 2a and Fig. 2b). *G* is calculated as the average of the two measurements taken at 5 cm. For daily measurements, the obtained results showed an 82% closure for 2020 and 79% for 2021, when the regression line is forced through the origin. Therefore, the obtained *EBC* here can be considered good, especially if one bears in mind the complexities of the study sites (tall and sparse canopy). The error obtained in the EBC is acceptable with reference to the literature. Therefore, it is not necessary to apply the methodology of Twine et al. (2000) and correct LE. The application of the method in this case (where the error is acceptable in our conditions which are complex, tall & sparse) can generate an error in the estimation of LE, especially with the use of G values, which is difficult to measure in a sparse cover. Consequently, the *LE* measured by the EC can satisfactorily be used afterward in this work. The different *EBCs* from the literature show a variance ranging from 70% to 100% closure (Anapalli et al., 2020; Er-Raki et al., 2009, 2008; Gao et al., 2017; Liu et al., 2017; Machakaire et al., 2021). Precisely for citrus orchards, closures of about 86% were reached both in the Moroccan context (Er-Raki et al., 2009) and worldwide (Peddinti and Kambhammettu, 2019).

In what follow, the values of the latent heat flux (*LE*) are converted from (W/m^2) to (mm/day), which is more understandable by the decision-makers as the actual evapotranspiration (ET_a). The obtained values of ET_a computed by the EC system were then compared to the standard crop evapotranspiration (ET_c). Estimating ET_c was through the FAO-56 simple approach (Allen et al., 1998), being the product of the suggested crop coefficient by Rana et al. (2005) and ET_o. Using the EC technique with soil water balance (FAO56), Rana et al. (2005) published K_c values of 0.80, 1.20, and 0.80 for K_{cini}, K_{cmid}, and K_{cend}, respectively, for irrigated citrus under Mediterranean conditions.

Later, the Nash–Sutcliffe model efficiency coefficient (*NSE*) was used to assess the predictive skill of the FAO-56 model and evaluate the extent of agreement or disagreement between the observed and computed data as follows (Nash and Sutcliffe, 1970):

$$NSE = 1 - \frac{\sum_{t=1}^{T}\left(ET_a^t - ET_c^t\right)^2}{\sum_{t=1}^{T}\left(ET_a^t - \overline{ET_a}\right)^2} \quad (1)$$

where $\overline{ET_a}$is the annual mean observed crop evapotranspiration, and ET_a, ET_c are observed and modeled daily crop evapotranspiration values.

An efficiency less than zero calls for a re-scale of the *NSE*, using the following equation (Eq. 2) of Normalized Nash–Sutcliffe Efficiency (*NNSE*) (Nossent and Bauwens, 2012):

$$NNSE = \frac{1}{2 - NSE} \quad (2)$$

The convenient rescaling eliminates the problem of the *NSE* lower limit of $-\infty$ and re-scales the *NSE* to lie solely within the range of [0,1].

2.3. Reference evapotranspiration

Daily averaged values of climatic data were calculated from half-hourly collected measurements to compute the daily reference evapotranspiration (ET_o) (mm/day), according to the FAO-56 Penman–Monteith equation (Allen et al., 1998):

$$ET_o = \frac{0.408\Delta(Rn - G) + \frac{900\gamma}{T + 273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (3)$$

Where *Rn* is the net radiation ($MJ\bullet m^{-2}\bullet day^{-1}$), *G* is the soil heat flux ($MJ\bullet m^{-2}\bullet day^{-1}$), *T* is the mean daily air temperature at 2 m height (°C), U_2 is the wind velocity at 2 m height (m/s), γ is the psychrometric constant (kPa/°C), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), and Δ is the slope vapor pressure curve (kPa/°C) at dew point temperature. All the standardized equations for calculating the parameters in Eq. (3) can be all found in Allen et al.

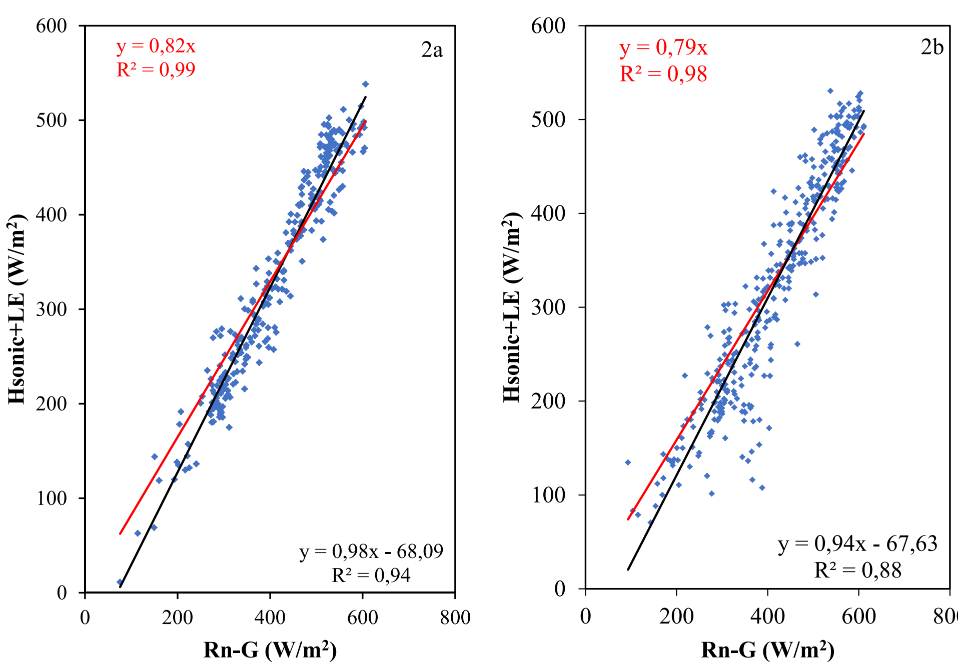

Fig. 2. Assessment of energy balance closure performed at the flux tower location considering daytime flux measurements at daily levels during 2020 (3a) and 2021 (3b). The black line is the regression line, and the red line is the regression line when forced through the origin.

(1998).

In order to evaluate the degree of dryness of the climate in Souss-Massa, we analyzed aridity impacts on ET_o, by utilizing the aridity index (*AI*). This indicator is calculated as the ratio of precipitation (*P*) to reference evapotranspiration (ET_o) using Eq. (4):

$$AI = \frac{P}{ET_o} \tag{4}$$

2.4. Soil water balance and water stress coefficient

One main feature to consider for irrigation management is to reduce water loss by deep percolation (*DP*). In the following experiment, *DP* losses have been quantified over the drip-irrigated citrus orchard using daily water balance for the root zone during 2020 and 2021. The *DP* values were derived from the simple water balance equation of the FAO-56 paper (Allen et al., 1998) by expressing the soil water content as the root zone depletion (*Dr*) as follows:

$$DP_i = (P - RO)_i + I_i + CR_i - ET_a - Dr_{i-1} \tag{5}$$

$$Dr_i = Dr_{i-1} - (P - RO)_i - I_i - CR_i + ET_{a,i} + DP_i \tag{6}$$

$$Dr_{i-1} = 1000 \times (\theta_{FC} - \theta_{i-1}) \times Zr \tag{7}$$

where i is the day number, *Dr* is the root zone depletion, *P* is the precipitation, *RO* is the runoff from the soil surface, *I* is irrigation and CR is the capillary rise from the water table, θ_{FC} is the volumetric soil water content at field capacity, *Zr* is the root zone depth. All these terms are in mm. The average value of 0.15 m^3/m^3 was selected from table 19 in the FAO-56 for θ_{FC} since it is a loamy sand soil and θ is the volumetric soil water content (m^3/m^3) over 60 cm depth of the soil layer.

In the specific study, the *RO* is neglected in the water balance equation for several reasons: the orchard is located on the Souss plain (no slope), the precipitations are generally low, and the applied irrigation method (drip). Likewise, *CR* was zero as the water table is deep on average, 50 m below the soil surface (Hssaisoune et al., 2016).

The volumetric water content was measured by the Time Domain Reflectometry sensor (CS650) according to the equation of Topp et al. (1980). The equation converts permittivity to volumetric water content as follows:

$$\theta_i = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} K_a - 5.5 \times 10^{-4} K_a^2 + 4.3 \times 10^{-6} K_a^3 \tag{8}$$

This equation shows the relation between dielectric constant (K_a) and volumetric water content (θ). It does not require any specific soil calibration for the probes' readings since (1) the soil organic matter content is 0.77% (way lower than 5%), (2) the clay content is 10% (lower than 20%), (3) the soil porosity of sand generally varies between 0.43 and 0.36 which is not greater than 0.5, and (4) the soil is not derived from a volcanic parent material. Thus, the measurements are accurate and can be used for *DP* evaluation.

The effect of soil water stress on crop evapotranspiration was observed by the water stress coefficient (K_s). It is a dimensionless factor–- ranging between 0 and 1, depending on available soil and root zone water. The latter was quantified following the FAO-56 paper approach (Allen et al., 1998):

$$K_s = 1 \quad for \quad Dr < RAW$$

$$K_s = \frac{TAW - Dr}{TAW - RAW} = \frac{TAW - Dr}{(1-\rho) \quad TAW} \quad for \quad Dr > RAW \tag{9}$$

where *TAW* is the total available water defined as the difference between water content at field capacity θ_{FC} and wilting point θ_{WP} (m^3/m^3), *Dr* is the root zone depletion (m^3/m^3), RAW is the readily available soil water (m^3/m^3), and ρ is the depletion fraction. The equations to compute these different parameters are detailed below:

$$TAW = 1000 \times (\theta_{FC} - \theta_{WP}) \times Zr \tag{10}$$

$$RAW = \rho \times TAW \tag{11}$$

where the value of 0.06 m^3/m^3 for θ_{WP} was selected for a loamy sand soil and the value of 0.5 for the depletion fraction p was adopted for 70% canopy coverage of Citrus according to table 22 of FAO-56 (Allen et al., 1998).

2.5. Crop coefficient deriving

Ultimately, the previous computing allows calculating daily actual crop coefficient ($K_{c\ act}$) values, which are the *sine qua non* for irrigation water management. The daily stress coefficient (K_s) representing the water stress coefficient couldn't be assumed to equal unity even if the plot is drip-irrigated all year long and the trees in the experiment are supplied with irrigation water daily. Therefore, K_s was derived from FAO 56 model. The actual $K_{c\ act}$ values were computed as the ratio of ET_a measured by the EC system to the ET_o, following the single crop coefficient (Allen et al., 1998):

$$K_{c \quad act} = \frac{ET_a}{ET_o} \tag{12}$$

2.6. Irrigation management assessment

The irrigation assessment is done by comparing the amount of total water supplied through irrigation to the total deep percolation. The water from precipitation is negligible when compared to the amount from irrigation. The ratio comparing the deep percolation and irrigation amounts (I) is called relative deep percolation (DP_R) (Nassah et al., 2018) and is defined as:

$$DP_R = \frac{DP}{I} \times 100 \tag{13}$$

Another valuable percentage to assess the irrigation strategy is the depleted fraction (*DF*). It is a ratio of ET_a over the total supplied water through irrigation (*I*) and precipitation (*P*) (Bos, 2004), which represents the part of the water supply consumed by the actual evapotranspiration (Eq. 14).

$$DF = \frac{ET_a}{I + P} \tag{14}$$

The more DP_R values tend towards zero and *DF* ratio approaches 1, the successful is the irrigation strategy.

2.7. Irrigation scheduling

As previously mentioned, one of the objectives of the current paper is to schedule irrigation effectively. 'The designed protocol is based on the needs of the different phenological stages in terms of water requirements and follows the FAO-56 approach. The essential growing stages for the citrus crop are dormancy, flowering, fruit set, fruit growth, slowdown of fruit growth and maturation, and finally, the harvest (Bouazzama et al., 2008).

Irrigation requirements were assumed to be the root zone depletion (*Dr*) if the latter exceeds the allowable depletion (*Da*). *Dr* values are calculated according to Eq. 6 with an initial value assumed to be the amount of rainfall subtracted from the sum of initial depletion (Dr_i) and $ET_{a,initial}$. Dr_i is the water that has been depleted from the root zone at the beginning of calculations set as 54 mm equaling the total available water (*TAW*) for the soil texture.

Da values varied according to the management allowable depletion (MAD) of the different growing stages and were computed as follows:

$$Da = MAD \times TAW \tag{15}$$

MAD is the maximum amount from *TAW* allowed to be depleted from the soil profile for root water usage before the next irrigation. It can be less than or equal to RAW in optimal or full irrigation and maximum production or larger than RAW in deficit irrigation and yield reduction strategy (Todorović, 2019c). Its value changes from one phenological stage to another (Table 1).

3. Results

3.1. Site climate and reference evapotranspiration

The long-term average meteorological variables (maximum temperature, minimum temperature, and solar radiation) of two crop seasons (2020 and 2021) are given in Fig. 3. The measured data reveal that the temperatures were, to some extent, cool in the first two months of the year, corresponding to the dormancy of the crop. Gradually, the temperatures increase, reaching the peaks during the fruit development phenological stage. Also, fruit ripening occurs when the temperatures are relatively high. In both years, the pattern of average maximum and minimum temperature was similar. The average maximum temperature of the site varied from 15 °C in February 2021–48 °C in August 2021. The minimum temperature ranged from 2 °C in January 2020–32 °C in August 2020. The solar radiation values (*Rs*) are high and follow the same pattern as temperature measurements. The computed values ranged from 55 (W/m^2) in December 2020–354 (W/m^2) in June 2020. Yet, Fig. 3 shows some sudden dips in radiation. It could be explained by the cloudy conditions. Both meteorological parameters slowly decrease as summer ends.

The computed reference evapotranspiration (ET_o) values for the study period (2020 and 2021) are shown in Fig. 4. These values were calculated according to Eq. (3). The observed seasonal variations within the citrus orchard during the growing seasons are typical of a semi-arid climate. The accumulated ET_o value reaches 1535 mm in 2020 and 1335 mm in 2021, reflecting the high climatic demand. The obtained difference between the two years (about 200 mm) is strongly related to accumulated Rs values, higher in 2020, as depicted in Fig. 4. The highest value was observed at the latest of August 2020, reaching 7.9 mm/day, and the lowest value equaling 1 mm/day, occurred in December 2020. Generally, ET_o is higher than 5 mm/day from May till the end of mid-September for both seasons. With these significant values of ET_o and extremely low rainfall, the AI resulted in a value of 0.04 and 0.12 in 2020 and 2021, respectively. According to Middleton et al. (1997), we are falling under a hyperarid to arid area as the *AI* is lower than 0.05 in 2020 and lower than 0.2 in 2021.

3.2. Actual evapotranspiration

The actual evapotranspiration (ET_a) is the value required to derive the crop coefficients. As mentioned in the methodology, ET_a values (Fig. 4) were computed from the latent heat flux values (*LE*) measured by the Eddy-Covariance system. The accumulated ET_a values were 938 mm in 2020 and 795 mm in 2021. The difference of 143 mm between the two consecutive years is the result of the difference in meteorological parameter values. In contrast to 2020, the farmer irrigated extensively during the wet winter of 2021. More, R_s values were lower in 2021, and consequently, ET_o dropped compared to 2020. The highest values of actual evapotranspiration (4–5 mm/day) occur in July and August, which happens to be the period of fruit growth and enlargement. Pertain to the lowest values (around 1 mm/day), they are observed in December. It is supposed to be the dormancy of the crop that starts in December and lasts until early March. Altogether, we have an average amount of 839 mm/year to be supplied to the crop. The considerable rainfall deficit indicates the necessity to irrigate citrus crops in the region.

The measured ET_a was compared to the estimated ET_c by the FAO-56 single crop coefficient approach as the product of K_c (Rana et al., 2005) and ET_o. The linear regression analyses in Fig. (5) reveal that the model overestimates actual crop evapotranspiration. This weak estimation might be due to the high single K_c values suggested in Rana et al. (2005). The K_{cmid} high value might be due to phenological reasons. The mid-season is an active period of growth known for its high stomatal conductance (Bethenod et al., 2000; Rana et al., 2005). Another reason could be high wind speed associated with high vapor pressure deficit. These conditions result in above-average values of evapotranspiration (Rana et al., 2005). The values might not be suitable for the local context of Souss-Massa since they are influenced by crop characteristics and agronomic practices. Consequently, appropriate K_c values are needed for accurate quantification of crop water requirements. Er-Raki et al. (2009) came to the same conclusion while studying citrus evapotranspiration in the Haouz region.

As mentioned in the methodology, an evaluation of the predictive skill of the FAO-56 model was done by using *NNSE*. The coefficient resulted in very low values of 0.13 and 0.08 for 2020 and 2021, respectively. These values mean that the model does not explain any part of the initial variance.

3.3. Deep percolation evaluation and K_s variation

DP evaluation was done by the soil water balance equation (Eq. 5). The annual amount of water percolating equals 633 mm in 2020 and 993 mm in 2021, which cannot be neglected in a semi-arid context suffering from water scarcity. In 2021, precipitation and the amount of water allocated to irrigation were higher than in 2020, which explains the difference in annual deep percolation values. From Fig. 6, the high percolation occurs on rainy days and when the irrigation events are frequent. This said, even with drip irrigation, there are still losses due to the non-rational use of the method. The maximum value of percolated water in 2020 was 20 mm in late November due to the sudden precipitations and low evapotranspiration. In 2021, the highest value of *DP* was 16.71 mm in late February when the supply reached 18.25 mm, from which 14.5 mm were from rainfall.

In Fig. 6, the zone above θ_{FC} represents the deep percolation and below θ_{WP} corresponds to the unavailable soil water zone of soil moisture. In between is the available soil water area. The figure draws the variation of soil water volumetric content from 60 to 80 cm depth over the 2020 and 2021 growing seasons. Generally, the soil moisture varies between the wilting point moisture and field capacity. In 2020, the recorded pic was due to the irrigation water leak in late March. Thus, the soil water moisture values are low even if the deep percolation values are high.

The K_s values were determined by the amount of water depleted in the soil root zone, which was linked to water supply, ET_a and deep percolation. Fig. 7 illustrates K_s values evolution in 2020 and 2021. The shows that K_s values vary from 0 to 1 according to Eq. (9). Computed K_s are extremely low at the beginning of every year since the irrigation water wasn't supplied daily. When irrigation events became more frequent, its value was all year long equal to unity. But it started dropping in Mid-December when the amount of water supplied was again reduced. However, the fall was huge from December 20th. Thus, K_s

Table 1
Management allowable depletion (MAD) of available water (RAW) for different stages (Adapted from Falivene et al., 2006).

Phenological Stage	Management Allowable Depletion (%)
Dormancy	35–40
Flowering	20
Fruit set	20
Fruit growth	15
Slowdown growth and maturation	25–30
Harvest	40

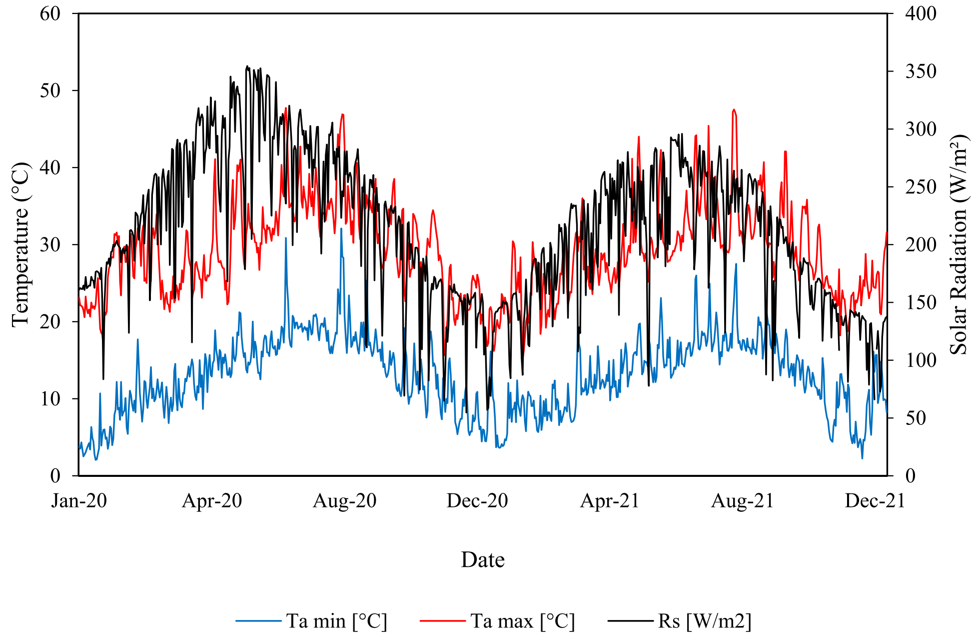

Fig. 3. Daily average meteorological conditions over the citrus experiment during 2020 and 2021 in the Elguerdane area (Souss-Massa basin).

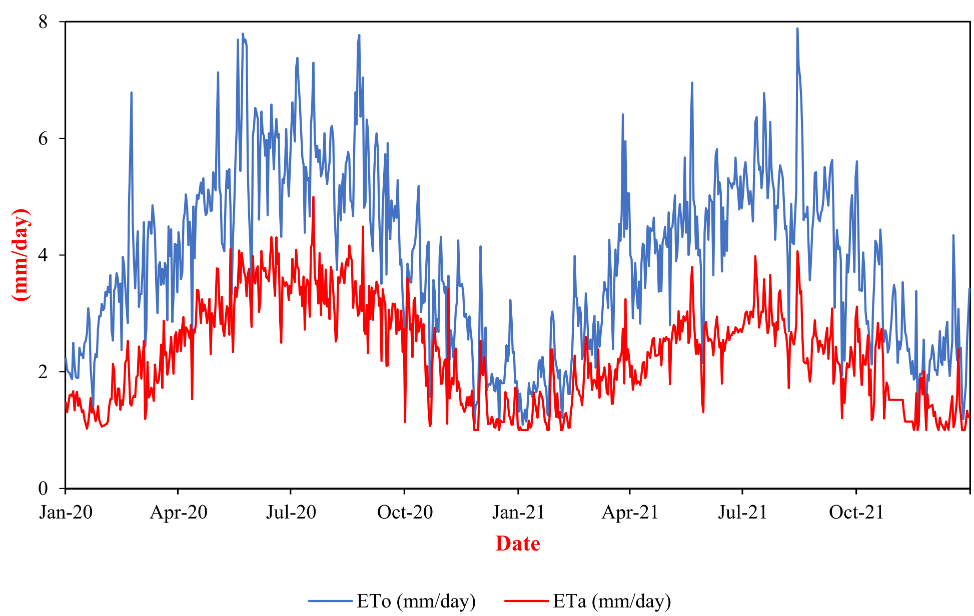

Fig. 4. Daily reference evapotranspiration ET_o (in blue) calculated following the FAO–Penman–Monteith equation during 2020 and 2021 and ET_a (in red) values computed from the latent heat flux measured by the EC system.

values are related to irrigation and rainfall by affecting root zone depletion directly related to the water stress coefficient.

3.4. Crop coefficients ($K_{c\ act}$) deriving

When deriving the crop coefficients, the previous data is taken into account as an intermediate calculation. The computed $K_{c\ act}$ coefficients are the main parameters allowing the determination of water requirements for the citrus crop in the Souss-Massa region. The curve in Fig. 8 displays the average values of $K_{c\ act}$ over 2020 and 2021 ($K_{c\ act}$ Experiment) compared to values reported in the FAO-56 paper (K_c FAO). Take heed of the fact that during the dormancy of the crop going from December to early March, farmers tend to irrigate less.

The computed $K_{c\ act}$ values for the citrus orchard at the three-growth stage (initial, mid, and late-season) are 0.64, 0.58, and 0.64, respectively. It should be noted that the crop is irrigated daily, which makes ET_c close to ET_a. After this adjustment, following the FAO-56 single approach gives close estimates of ET_c – equal to 800 mm/year, not far from the Eddy-Covariance values. The K_c values from the FAO-56 paper range from 0.65 to 0.70 for a clean cultivated and mature citrus orchard. These values are presented for canopy cover of 70%.

3.5. Irrigation management and assessment

The irrigation strategy (Fig. 9) follows the standard recommendations encouraging irrigation during the fruit ripening (June to September) and maturity and lowering the irrigation quantities during the dormancy (December to early March) (El Hari et al., 2010). Good

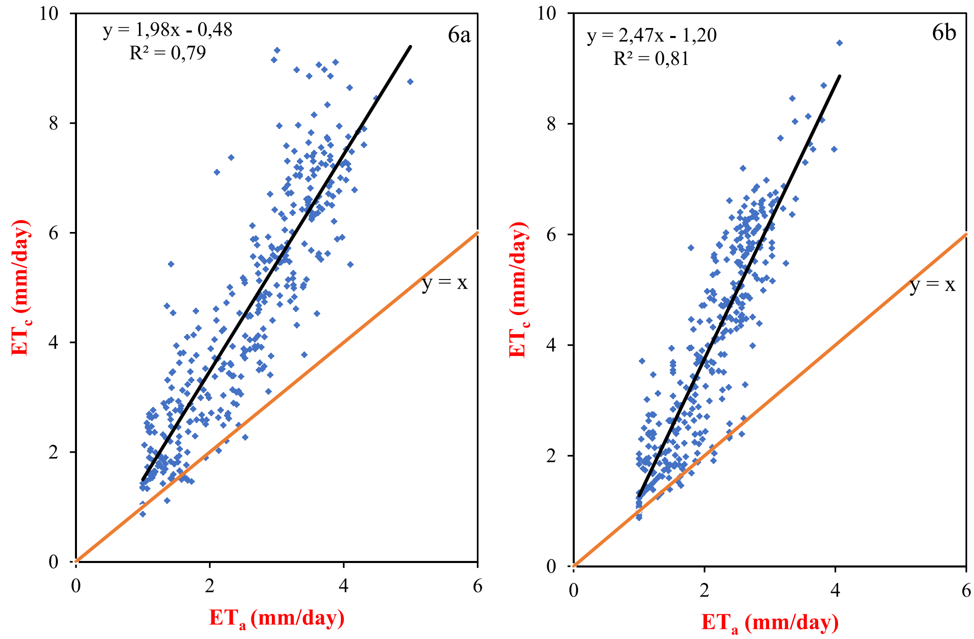

Fig. 5. ET_a measured by the Eddy-Covariance tower in 2020 (6a) and 2021 (6b) versus ET_c estimated by the single approach using the Kc values given in Rana et al. (2005).

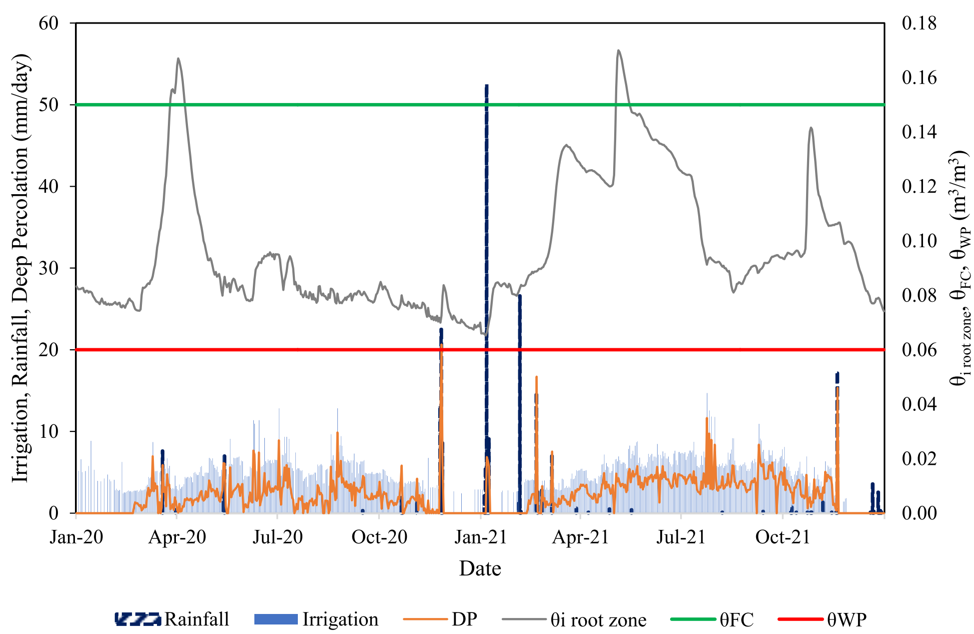

Fig. 6. The daily water supply from irrigation and rainfall, deep percolation, and soil water content at 60–80 cm depth framed by both the soil water content at field capacity and at wilting point in 2020 and 2021.

irrigation management is one of the interventions favoring fruit size in the fruit setting (April to May). It is essential to avoid water stress at this stage, especially when temperatures are high. The accumulated quantity of water given to the orchard reached 1501.6 mm in 2020 and 1613.7 mm in 2021. The irrigation amount for the treatments varied from 0.55 mm/day in mid-May to 12.84 mm/day in early July 2020 and reached 14.69 mm/day in July 2021. The days with too much water given are justified by the number of irrigation events per day. On the other side of the coin, rainfall events are low and irregular, with a total precipitation volume of 66.20 mm/year in 2020. They were limited to 11 events reaching 22.50 mm/day in its best scenario. In 2021, the total amount of precipitation was equal to 160.36 mm/year. Given the paucity of rainfall events and the lack of water when most needed, it is mandatory to irrigate. The critical periods when water deficit is detrimental to the yield are: (1) the flowering (March and April), (2) the fruit set (May to June), and (3) the fruit growth and ripening stage; with specific attention to the period from mid-July till mid-August (El-Otmani et al., 2020). The big picture is that irrigation is a consubstantial part of citrus cropping in the study area.

Soil water content is affected by the irrigation strategy and has an impact on plant health. As visualized in the figure, water volumetric content shows similar temporal trends at the different layers except that of the upper layer, which is more affected by the irrigation events. It shows much higher values and a completely different pattern. The rise in

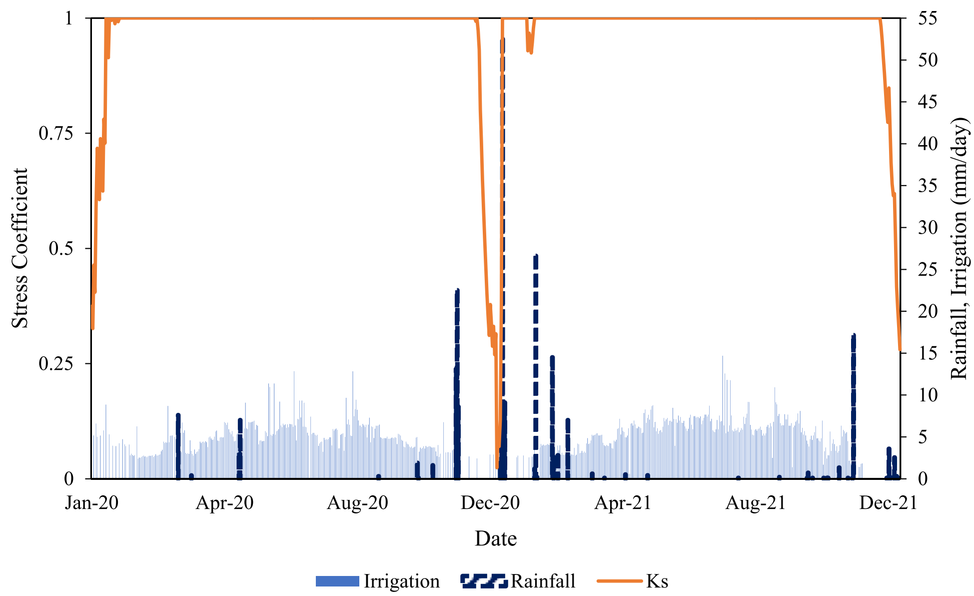

Fig. 7. The stress coefficient Ks calculated by the FAO-56 model.

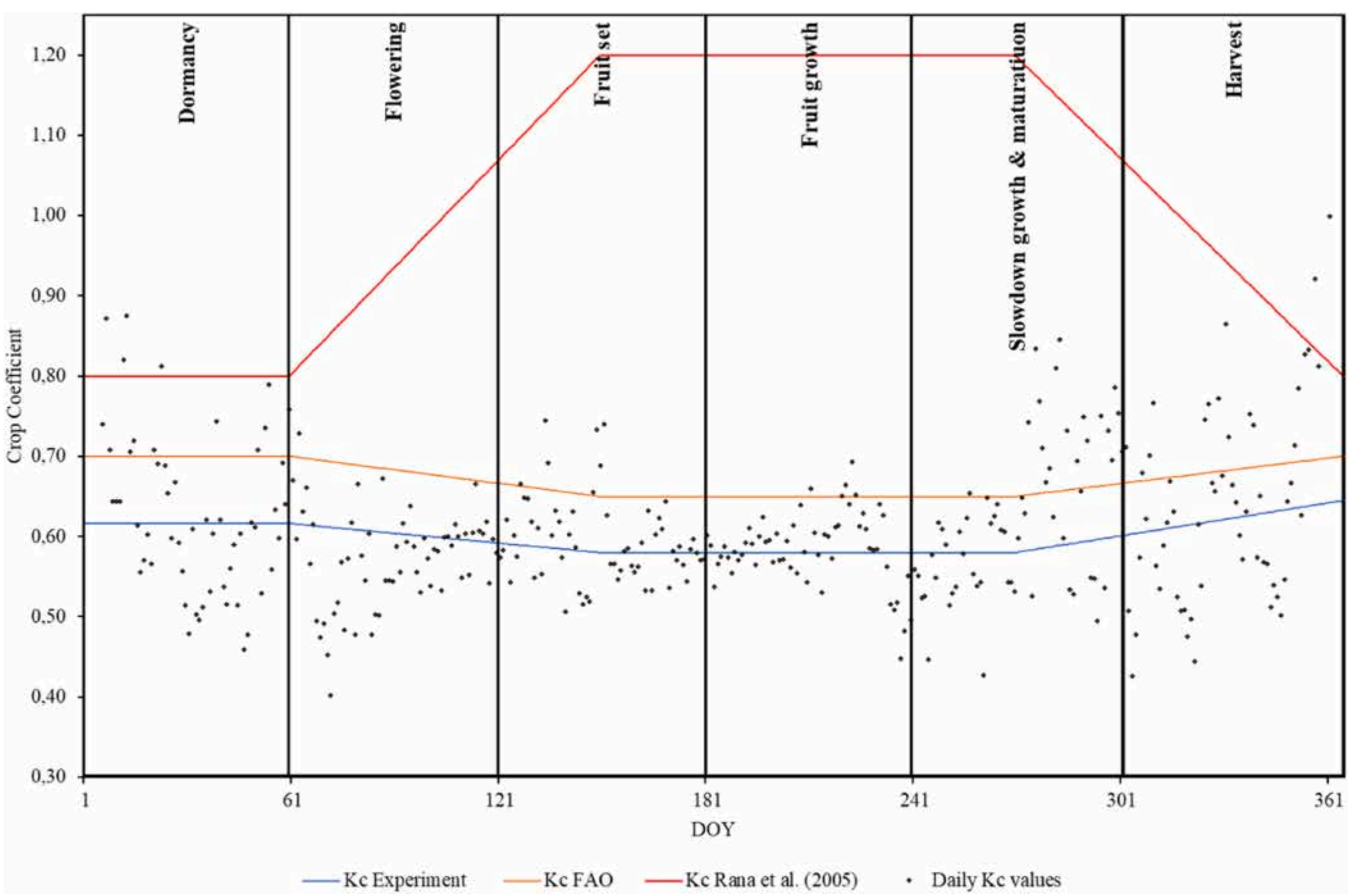

Fig. 8. Daily $K_{c\ act}$ values and derived stage average values for citrus crop compared to the values from FAO-56 paper and Rana et al. (2005).

volumetric moisture is proportional to the water dose, indicating the correct response of TDR sensors. The highest value in terms of soil water content in 2020 is observed in early April. This sudden peak could be an aftereffect of a water leak that occurred in late March.

The irrigation water supply was first compared to *DP* by DP_R percentage (Eq. 13). The sum of the deep percolation computed by the water balance equation is 633 mm in 2020 and 993 mm in 2021, with an average value of 2.22 mm/day. When compared to irrigation, it represents 42% in 2020 and 62% in 2021, an average of 52% of the allocated amount of irrigation. The high values might be the result of over-irrigation and soil texture, therefore inappropriate irrigation management. But by no means questions the high efficiency of the drip-

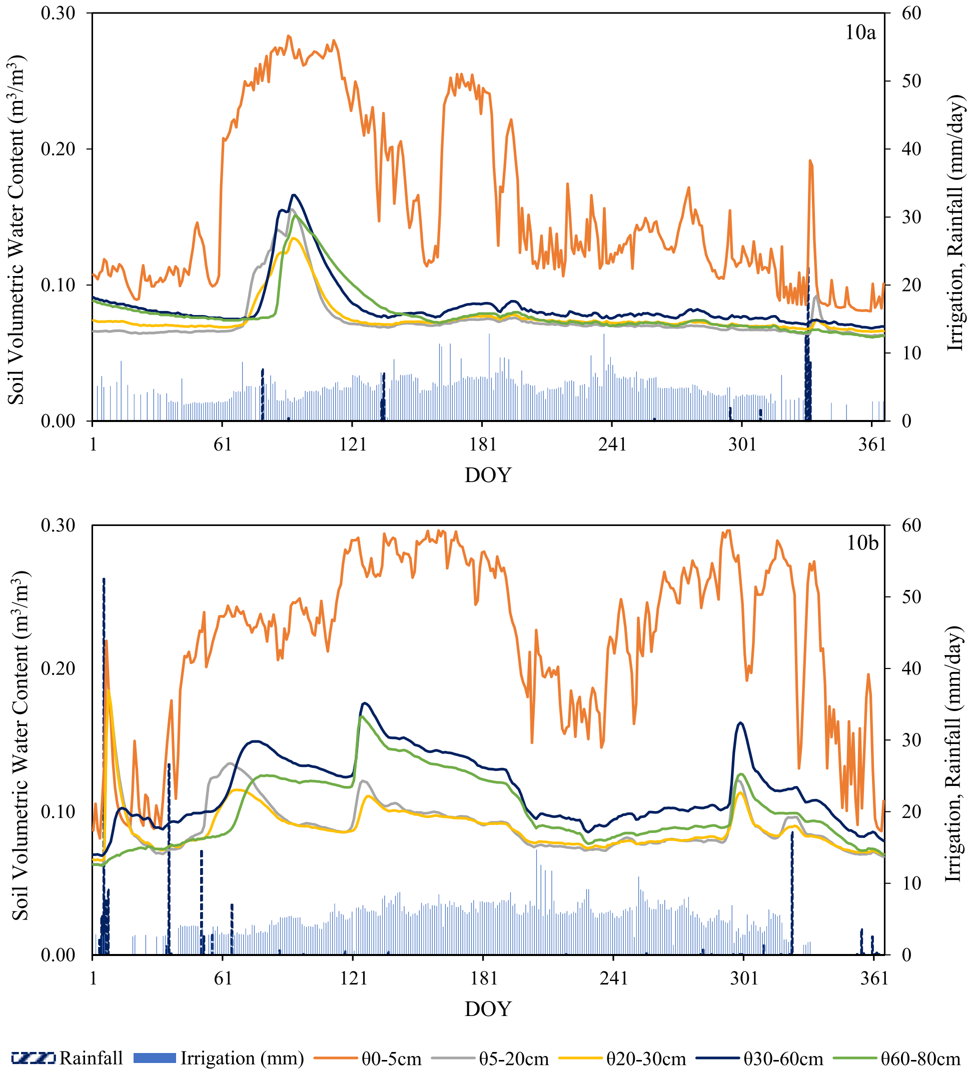

Fig. 9. Water supply from applied irrigation and rainfall for the plot of interest in 2020 (10a) and 2021 (10b) compared to soil volumetric water content in different horizons.

irrigation technique.

The second ratio used to assess the irrigation strategy is *DF*. It reflects the part of the supplied irrigation consumed by ET_a (Eq. 14). The average annual *DF* value was 0.62 in 2020 and 0.64 in 2021. In arid to semi-arid areas, *DF* for citrus equaling 0.6 is critical (Kharrou et al., 2013). *DF* per growth stage was calculated to dig deep within this low value. Flowering, fruit set, growth, and maturation are the phases that are characterized by a value lower than 0.6, corresponding to excessive irrigation. The phenological stages, characterized by low *DF* value, are flowering, fruit set and growth, and maturation. When *DF* ranges between 0.6 and 1.1, it reflects proper water use (Kharrou et al., 2013). Dormancy is the sole step in this scenario that falls within the parameters of wise water management. All the values mentioned earlier emphasize the need for proper irrigation water use.

In this caption (Fig. 10), the water inflow is compared to the climatic demand considering daytime values. The water amount or quantity to integrate equals 872 mm for the first year, given that rainfall in 2020 was 66,20 mm. The ET_a values obtained from the EC system based on the measured values reach the sum of 938 mm. Meanwhile, the farmer offers an amount of 1501 mm. The interesting fact is that 630 mm is subject to seepage. This simple equation is confirmed by the values obtained from the water balance equation in Fig. 10 (633 mm/day). In other words, 40% of the water supplied leaches into the soil, keeping the soil humidity and recharging the water table when the groundwater level is not deep, which is not the case for our study site. In 2021, the water amount to integrate was 614 mm, lower than the previous year because the annual rainfall was 160 mm. The accumulated ET_a value obtained from the EC system based on the measured values in the same year is 795 mm. The supplied water is higher than the previous year, reaching 1774 mm/year, from which 1614 mm are supplied by irrigation. Again, 979 mm are not used by the plant and thus percolate. An approximate value of 993 mm/day was evaluated by the water balance equation (Fig. 10).

3.6. Irrigation schedule

After evaluating the real water supply, the optimization of irrigation water scheduling, in time and quantity, was performed using the FAO-56 simple approach to avoid water stress and deep percolation (i.e., $K_S = 1$ and $DP = 0$ always). The accumulated recommended irrigation obtained is an average of 831 mm/year, which is only 51.5% of the average amount of water applied by the farmer. Fig. 11 shows the adequate amount of water irrigation for each phenological stage with the depleted fraction values. The new depleted values serve as an assessment for the irrigation protocol given. The values are equal to 1 in most keystone phenological stages, which is the adequate water use interval. The

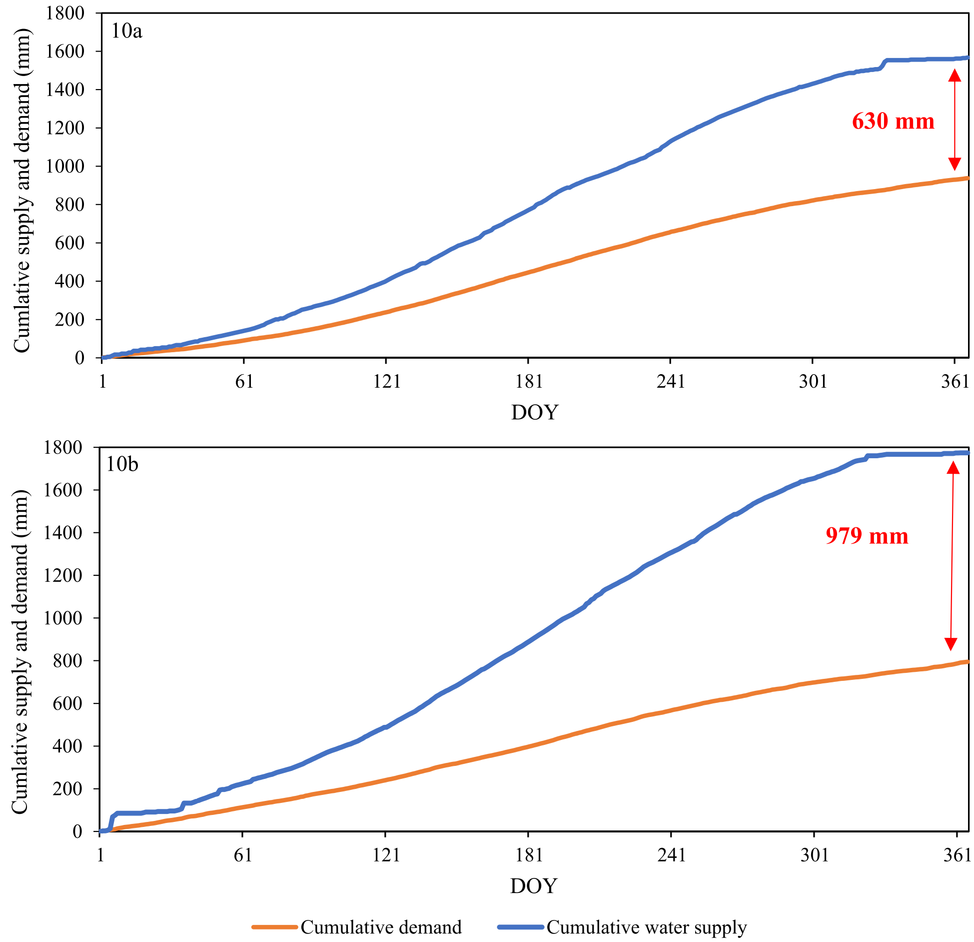

Fig. 10. Water inflow compared to the actual evapotranspiration in 2020 (11a) and 2021 (11b).

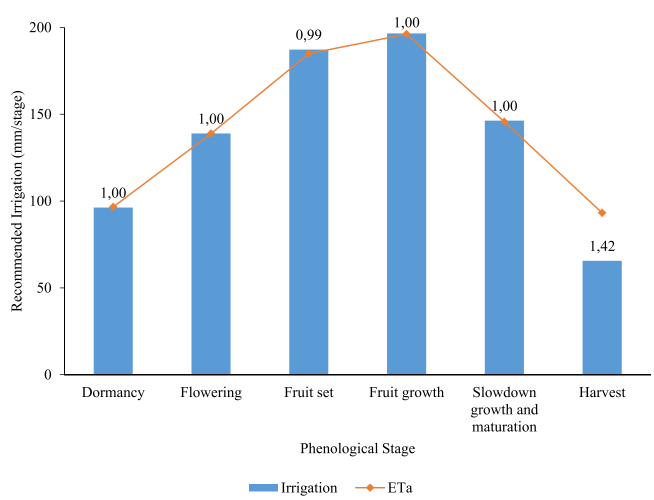

Fig. 11. Irrigation amount recommended for the different phenological stages with the corrected DF values. In orange, the average evapotranspiration values in different stages.

harvest is not a critical period requiring an abundant amount of water. The following strategy suggests applying 831 mm/year of irrigation water if we consider average precipitation equal to 113 mm/year. The water quantity is distributed as in Fig. 11 according to the different phenological stages. The flowering, fruit set, and growth phases must not be subject to any form of water stress. The fruit growth stage is the most demanding in terms of water, reaching almost 200 mm. It is justified by the cell division that ensures fruit size. To our best knowledge, it is the first time that an irrigation schedule has been done for citrus under Souss-Massa conditions.

4. Discussion

The assessment of crop evapotranspiration was done following the FAO-56 approach. Overall, the meteorological conditions are not strange in a region characterized by a semi-arid climate, which is dry and hot in summer and relatively cold in winter (El-Otmani et al., 2020). The issue of water scarcity in the area has been made worse by climate change and agricultural development (Marieme et al., 2017), which is confirmed by the low values of the aridity index. The different patterns of ET_o under semi-arid climates reported in the literature (Er-Raki et al., 2009, 2008; Jafari et al., 2021; Tabari et al., 2012) do not differ from the pattern of the experiment. However, ET_a values fall in the conventional range of 700–1300 (mm/year), with an average of 1000 (mm/year) (El-Otmani et al., 2020). The same range of values (765, 820, and 786 mm/year) was reported for citrus orchards in the Haouz region (Er-Raki et al., 2009, 2012; El Hari et al., 2010; Nassah et al., 2018). These values are slightly different since they characterize the same region: Tensift Al Haouz. It is a region with a typical Mediterranean climate known for its low and erratic rainfall, roughly 240 mm. The annual average rainfall was way lower than the average crop water requirement (Er-Raki et al., 2009).

Regarding the *DP* losses, they cannot be assessed by the variation in soil moisture content in the root zone in this case. The soil is loamy sand with 80% sand, making the particles coarse and the soil porosity larger.

These properties are faster infiltration and lower soil water content (Tian et al., 2017). Additionally, the organic matter content is lower than 1%. The latter condition, when combined with the sandy soil type, results in poor water retention (Sun et al., 2017). In fact, the decrease in water-holding capacity and the rise in infiltration capacity are typical when sand content is high compared to clay content (Yang et al., 2019).

Following the FAO 56 single approach, daily crop coefficient values and for different stages were derived. The crop coefficient values reported in Allen et al. (1998) and the derived $K_{c\ act}$ values from the experiment follow more or less the same pattern but are not equal. It is visible that Allen et al. (1998) overestimate the crop coefficient reflecting the crop demand. This overestimation reaches 9%. Different results from studies focusing on the calibration of citrus ET_a based on the single crop coefficient (Maestre-Valero et al., 2017) and the dual crop coefficient (Er-Raki et al., 2008) are gathered in Table 2. These recommended K_c values show a clear discrepancy. One way to explain so is that crop coefficients depend on variable factors. They integrate climatic factors (Yang et al., 2003), plant biophysical characteristics (Consoli and Papa, 2013), irrigation management, and soil evaporation (Maestre--Valero et al., 2017). These factors and processes are directly impacted by agricultural practices.

Another comparison helping to locate this experiment's results is comparing the derived $K_{c\ act}$ values to different values reported for citrus orchards from multiple published studies (Table 2). From the collected values, there is an immense contrast between the same values computed in one country (Er-Raki et al., 2008; Heitz et al., 2011). Bouazzama et al. (2008) indicate entirely different results. The values from Er-Raki et al. (2008) in the table are as they were cited in Jamshidi et al. (2020).

A range of crop coefficient values has also been suggested as a result of numerous studies looking at citrus ET_c based on the dual K_c approach (Er-Raki et al., 2008; Peddinti and Kambhammettu, 2019). The diversity and complexity of meteorological conditions, irrigation control, plant physical and biological characteristics, and soil evaporation rates are probably to blame for these differences in the reported Kc values. The requirement for local calibrations is further highlighted by the inherent anomalies in Kc coming from its empirical determination, particularly under drought circumstances. Maestre-Valero et al. (2017) employed the EC approach, which was linked to soil water balance (FAO56) by Er-Raki et al. (2009). Also, different approaches were utilized to estimate evapotranspiration values for citrus. Castel (2000) combined data from drainage and weighing lysimeters using the SWB technique ($K_{cmid} = 0.55$).

In Spain, water use efficiency was assessed by the analytic hierarchy process (AHP) technique and a new synthetic irrigation efficiency index (IEI) was elaborated (Poveda-bautista et al., 2021). This study emphasized the significance of assessing the effectiveness of irrigation water use. In the Moroccan context, Nassah et al. (2018) adopted relative deep percolation ratio. The result recorded an average annual DP_R value of 43% in the Haouz region of Morocco – the same value recorded in this experiment for the first year. In other studies, DP_R equals about 11% in arid and semi-arid climates (García Petillo and Castel, 2007), lower than the obtained DP_R.

Irrigation assessment leads to the necessity of appropriate irrigation scheduling. Even when micro-irrigation distribution systems and water-saving management strategies are used, the hydrological models can be thought of as an accessible tool for indirect evaluations of soil and crop water status targeted at identifying irrigation schedule parameters (Rallo et al., 2017). The FAO-56 paper contains some ambiguity, especially in citrus orchards where crop water use is influenced by tree light interception or crop load (Consoli et al., 2006; Rallo et al., 2021). Moreover, the importance of monitoring the soil-plant-atmosphere continuum to identify precise thresholds of permissible soil depletion for precision irrigation scheduling was demonstrated by the ecophysiological linkages in Puig-Sirera et al. (2021). The same study determined a threshold of depletion factor ($p = 0.41$) to create a site-specific irrigation scheduling protocol for Citrus.

The Eddy Covariance allows the measurement of H_{sonic} and LE for an area of few hectares, depending on the wind speed (Ezzahar et al., 2007). However, the measurement of the net radiation (R_n) and the soil flux (G) remain a punctual information (Allen et al., 2011). Indeed, the dual K_c approach could have been better to use (Allen et al., 2011). Currently, it needs more time to do the new simulations.

5. Conclusions

The study is the first application of the EC technique in citrus farming in the Souss-Massa region, characterized by a semi-arid climate worsened by water scarcity. Generally, the meteorological conditions are similar to the ones of the Mediterranean area, characterized by a semi-arid climate. The latter leads to reference evapotranspiration values being high, reflecting a considerable climatic demand. Nevertheless, the annual average rainfall is lower than the crop water requirement, meaning there is an obvious need to supply water through irrigation. The ET_o values computed following the Penman-Monteith equation from the FAO-56 paper can be reliable for elaborating an irrigation protocol, allowing the adjustment of crop coefficient values. The derived Kc act values for the citrus orchard at the three-growth stage (initial, mid, and late-season) are 0.64, 0.58, and 0.64, respectively. On the other hand, the research investigates DP in citrus orchards using drip irrigation in a semi-arid climate and develops a method based on the FAO-56 model for defining irrigation schemes and optimizing irrigation under the region's specific conditions. The results demonstrate that the water balance equation gives a very high DP of about 813 mm/year, with a rough DP_R value of 52% percent. It is in line with the measured soil water moisture level.

The FAO-56 simple approach was employed to determine the proper irrigation amounts. The results reveal that, by considering rainfall, the model proposes a far lower quantity of irrigation than the farmer allocates. According to the model calculations, it appears that, on average, around 55% of the water supply may be saved. This research has shown

Table 2
Mean K_c values reported for Citrus orchard in published studies.

Month	Local $K_{c\ act}$ values	(Rana et al., 2005)	(Er-Raki et al., 2009)	(Bouazzama et al., 2008)	(Heitz et al., 2011)	(Consoli and Papa, 2013)	(Maestre-Valero et al., 2017)
1	0,62	0,90	0,50		0,75	0,70	1,80
2	0,49	0,90	0,60	0,54	0,60	0,88	0,80
3	0,56	1,10	0,70	0,50	0,65	0,57	0,60
4	0,62	1,10	0,75	0,55	0,65	0,52	0,40
5	0,63	1,10	0,75	0,80	0,65	0,58	0,54
6	0,64	1,10	0,75	0,88	0,70	0,60	0,49
7	0,61	1,00	0,75	0,88	0,70	0,61	0,49
8	0,63	0,95	0,60	0,88	0,70	0,68	0,58
9	0,65	0,90	0,50	0,54	0,70	0,84	0,74
10	0,72	0,90	0,40	0,54	0,70	0,86	1,06
11	0,63	0,90		0,54	0,65	0,95	1,15
12	0,76	0,90			0,65	0,61	1,12

that, for sustainable water management, a tailor-made drip irrigation schedule is required. Indeed, drip irrigation reduces water losses to evapotranspiration. However, losses to deep percolation need to be lowered through the control of water flow into the system.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

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