Efficient Water Use in Citrus Orchards in the Context of Water Scarcity: A Comprehensive Approach with the AquaCitrus Model

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***Abstract*—Efficient water use in irrigated agriculture is essential, particularly in water-scarce regions. Accurately measuring and managing crop water requirements is key to enhancing water use efficiency. This research presents a new approach implemented in the AquaCitrus model, which separately calculates crop transpiration using the basal crop coefficient and soil evaporation through the Ritchie model. The proposed methodology was applied to calculate the water requirements of drip-irrigated mature citrus trees (*Citrus sinensis*) during the 2015 irrigation season in the semi-arid climate of eastern Spain (Valencia), one of the country's major citrus producing regions. Key parameters, including crop coefficients, transpiration rates, evaporation rates were compared with values from alternative approaches and previous studies, showing high concordance and underscoring the robustness of the developed approach. A significant finding was the clear differentiation between beneficial water use (transpiration, 83.7%) and non-beneficial water loss (evaporation, 16.3%), which is crucial for optimizing irrigation water management in arid and semi-arid areas. The results demonstrate that this methodology is both valuable and practical for improving water use efficiency due to its simplicity and minimal data requirements, making it feasible for calculating local values effectively.**

Keywords-water scarcity; irrigation management; water use efficiency; prennial crops.

I. INTRODUCTION

Agriculture is the largest consumer of freshwater, accounting for approximately 70% of global freshwater use. With increasing water scarcity driven by population growth, industrialization, intensified agriculture, and climate change, the need for efficient water use in agriculture is more urgent than ever. Optimizing water use in agriculture is essential in water-scarce regions, such as much of the Iberian Peninsula. A key element in achieving this optimization is accurately quantifying crop water requirements, specifically crop EvapoTranspiration (ET_c), which balances irrigation needs while conserving water resources [1].

Several methods are used to determine water requirements in irrigated agriculture, including energy balance, eddy covariance, remote sensing, and crop coefficient approaches [2]. Among these, soil water balance (SWB) models based on the FAO56 method [3] are widely recognized and used. The FAO56 method estimates ET_c by multiplying the crop coefficient (K_c) with reference evapotranspiration (ET_o), calculated using the FAO Penman-Monteith equation [4]. Since the publication of FAO24 in the early 1980s, numerous SWB models have been developed, establishing a foundation in the field of crop water requirements and irrigation scheduling [1]. Most of these models are based on the FAO K_c-ET_o approach, with notable examples including ISAREG [5], BUDGET [6], MOPECO [7], and swbEWA [8]. Although effective, the single crop coefficient K_c, which assumes a unified value for both crop transpiration (T_c) and soil evaporation (E_s), can lead to inaccuracies by not adequately capturing the E_s component, particularly in arid and semi-arid climates where soil evaporation is significant.

To address this limitation, a dual crop coefficient approach ($K_c = K_{cb} + K_e$) was developed [1], [3], which separates the basal crop coefficient (K_{cb}) for transpiration from the soil evaporation coefficient (Ke), thus allowing independent estimation of E_s and T_c. This approach enhances the accuracy of ET_c estimation and better reflects field conditions and irrigation practices [1]. Although various models, such as AquaCrop [9], SALTMED [10], and SIMDUALKc [11], implement this dual approach, most are designed for annual crops, with few options tailored for woody crops like citrus. Additionally, K_{cb} values can be highly site-specific, limiting their transferability [12]. To improve accuracy, [13] developed a method to estimate K_{cb} based on factors like crop height, stomatal control, and canopy cover fraction, making it more adaptable to different orchards and locations.

In this study, we developed a methodology to accurately estimate the water requirements of citrus crops, a critical consideration given the high irrigation demands and growing pressures from climate variability. This approach, implemented in the AquaCitrus model [14], separately calculates E_s using the Ritchie model [15] and T_c based on Allen and Pereira's method [13] for estimating site-specific K_{cb} values. This model is designed to meet the specific needs of citrus crops in water-scarce environments, such as Valencia, Spain—a major citrus-producing region that contributes over 56% of the European Union's citrus production [16].

This article is organized as follows: after the introduction, the materials and methods section describes the AquaCitrus model and its approach to calculating crop water requirements

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(ET_c). This is followed by a presentation of the results and a discussion of key findings. Finally, we conclude with important insights drawn from the study.

II. MATERIALS AND METHODS

A. *AquaCitrus Model*

AquaCitrus is a soil water balance model explicitly designed for citrus cultivation. It aims to enhance irrigation efficiency by simulating water fluxes within the soil-plant-atmosphere system. Key components considered by AquaCitrus include effective precipitation, infiltration, runoff, soil evaporation, drainage, and crop transpiration, while accounting for soil heterogeneity. This model contributes to optimizing water use efficiency in water-scarce regions, computes irrigation requirements, evaluates a given irrigation schedule, and aids in simulating climate change scenarios. The is currently under development, incorporating production function that account for various factors, including the physiological characteristics of citrus crops.

To accurately calculate the citrus evapotranspiration, the model AquaCitrus combines the equations proposed by Allen and Pereira [13], for crop transpiration estimation and the model introduced by Ritchie [15], for soil evaporation determination.

B. *Crop Transpiration Approach in AquaCitrus*

Crop transpiration (Tr, mm.d^{-1}) in AquaCitrus is estimated using the crop coefficient method. The potential transpiration of citrus crops is determined by multiplying K_{cb} by the reference evapotranspiration (ETo, mm.d^{-1}) as illustrated in equation (1) and (2). The model considers various factors like plant physiology, development stages, and environmental conditions to calculate the basal crop coefficient.

$$T_r = K_{cb} * ET_o \qquad (1)$$

K_{cb} is computed by multiplying the density coefficient (K_d) by a maximum basal coefficient representing full cover conditions (K_{cb_full}), following the formula proposed by Allen and Pereira [13]:

$$K_{cb} = K_{c\,min} + K_d * (K_{cb\,full} - K_{c\,min}) \qquad (2)$$

where, $K_{c\,min}$ is the minimum crop coefficient for bare soil, approximately equal to 0.15 under typical agricultural conditions, as suggested by Allen and Pereira [13]. The $K_{cb\,full}$ is the maximum crop transpiration coefficient during peak plant growth with nearly full ground cover. This coefficient is initially calculated based on the crop height, accounting for climatic variations, and subsequently adjusted for stomatal control in trees using a reduction factor (F_r) derived from mean leaf stomatal resistance [13]. Allen and Pereira's study [13] provides extensive insights, for a detailed understanding of these equations.

C. *Soil Evaporation Approach in AquaCitrus*

The model computes soil evaporation (E_s, mm.d^{-1}) using the Ritchie model [15]. This approach divides the process of evaporation into two stages, distinguishing between the evaporative processes of wet and dry soil zones and recognizing the irregular distribution of soil moisture resulting from localized irrigation practices.

Mathematically:

$$E_s = \begin{cases} E_{s,pot} & if \quad \sum E_s \le U \\ \alpha\left(\sqrt{t} - \sqrt{t-1}\right) & if \quad \sum E_s > U \end{cases} \qquad (3)$$

where, $\sum E_s$ is the cumulative soil evaporation, $E_{s,pot}$ (mm.d^{-1}) is the potential soil evaporation amount, t (days) is the time since the start of stage two, and α (mm.d$^{-0.5}$) is the Ritchie coefficient and it depends on soil hydraulic characteristics.

The model accounts for irrigation and precipitation events that re-wet the soil surface, potentially causing a transition back to stage one from stage two. The potential evaporation in stage one is calculated as follows:

$$E_{s,pot} = [\Delta / (2.45 * (\Delta + \gamma)] * R_{ns} \qquad (4)$$

where, Δ (kPa ºC^{-1}) is the saturated water vapor pressure slope, R_{ns} (MJ.m^{-2}.d^{-1}) is the net radiation at the soil surface, and γ (kPa ºC^{-1}) is the psychrometer constant.

III. RESULTS AND DISCUSSION

A. *AquaCitrus Model Evaluation*

AquaCitrus was evaluated using soil moisture data from various depths within a citrus plot in Valencia (Spain), a region known for its Mediterranean climate and Spain's main citrus-producing region. The model's performance was commendable, demonstrating a significant correlation between the simulated and observed values (Fig. 1). The results showed high levels of agreement across different soil depths, with coefficients of determination (R^2) ranging from 0.78 to 0.91. These findings validate the model's ability to predict water balance in citrus crops accurately, confirming its potential as an effective tool for irrigation management and water conservation in arid and semi-arid regions, particularly under the challenges posed by water scarcity.

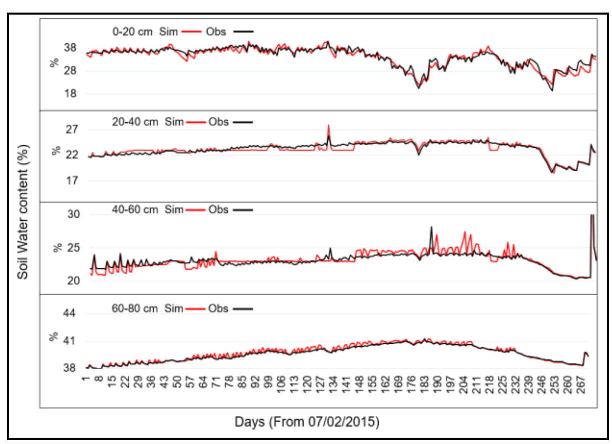

Figure 1. Simulated and observed soil water content at various depths: 10 cm, 30 cm, 50 cm and 70 cm.

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B. Crop Evapotranspiration

The citrus basal crop coefficient (K_{cb}) was calculated daily using the methodology developed in this study, with monthly averages computed for comparison. These values ($K_{cb\ sim}$) were compared with FAO standard values for citrus crops under similar conditions (50% canopy cover, 3-meter crop height, and no active soil cover): 0.60 at the initial stage, 0.55 at mid-season, and 0.60 at the late season (Fig. 2). Unlike the FAO values, which represent generalized standards, the calculated Kcb values in this study are site-specific.

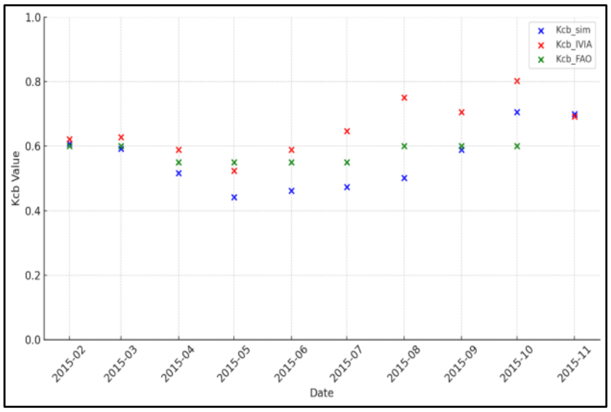

Figure 2. Monthly Kcb values from diffrent approaches.

The study also compared the calculated $K_{cb\ sim}$ with values provided by the Valencian Institute of Agricultural Research (IVIA) ($K_{cb\ IVIA}$) [17]. Despite similar edaphoclimatic conditions between the study and IVIA plots, $K_{cb\ IVIA}$ values were consistently overestimated, particularly during late spring and summer when temperatures are higher. This discrepancy is attributed to two factors: (1) $K_{cb\ IVIA}$ assumes a canopy cover of 70% or more, whereas the canopy cover in this study was 50%; and (2) the methodology developed in this study incorporates an adjustment factor (F_r) to account for the plant's stomatal regulation, which reflects citrus crops' ability to control stomata under conditions of high humidity, wind, and elevated temperatures. This stomatal adjustment enhances the accuracy of the proposed method, making it highly applicable for calculating citrus water requirements.

In addition, crop evapotranspiration (ET_c) was evaluated using research data from the Valencian Institute of Agricultural Research (IVIA) [17], ET_c values simulated by the model were compared with observed values under conditions similar to those of the study plots. This comparison demonstrated a strong correlation, with a coefficient of determination (R^2) of 0.86 (Fig. 3), further affirming the model's reliability in replicating actual agricultural water use scenarios.

During the 2015 irrigation season, the evaporation fraction determined in this study accounted for 16.3% of the total crop evapotranspiration (ET_c), while transpiration represented 83.7%. Evaporation constitutes a non-beneficial water loss for the crop, emphasizing the importance of accurately quantifying this component of ET_c. Such quantification is essential for devising strategies to minimize evaporation losses, thereby enhancing overall water use efficiency in irrigation management.

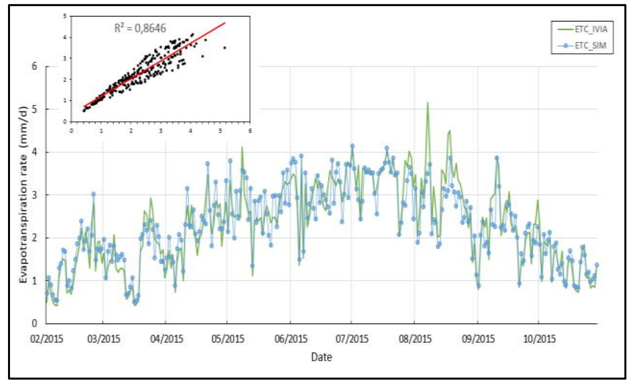

Figure 3. Daily values of ETc sim and ETc IVIA.

IV. Conclusion And Future Work

Accurate measurement and management of crop transpiration and soil evaporation are critical for improving water use efficiency, particularly in arid and semi-arid regions where water scarcity pose significant challenges. The methodology developed in this study offers a more precise understanding of citrus crop water requirements, enabling the implementation of targeted and efficient irrigation strategies.

One of the key advantages of this method is its simplicity and minimal data requirements, making it practical and accessible for diverse agricultural contexts. This approach is integrated into the AquaCitrus model, which also incorporates key factors such as root distribution and soil heterogeneity to calculate the soil water balance and optimize crop water use. While the model shows promise, its development is ongoing, and further testing and refinement are necessary to address additional challenges such as site-specific parameterization and model validation under diverse climatic and soil conditions. Future work will focus on enhancing the model's functionality and usability to support sustainable water management in citrus orchards. The final version of AquaCitrus will be made available upon completion.

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