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Satellite remote sensing for monitoring citrus orchards water requirements at the irrigation district scale

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Abstract
In Italy, irrigated agriculture is often managed by Reclamation Consortia, but they generally lack the proper tools for monitoring the irrigation water requirements (IWR), forbidding the required sustainability level by the European Water Framework Directive. In this context, the study aims at monitoring the IWR of citrus orchards of a Sicilian irrigation district by implementing a satellite-based methodological approach, during the irrigation seasons 2019 and 2020. Firstly, neural networks were implemented to map the citrus orchards, by using Normalized Difference Vegetation Index time series as input, and obtaining accuracy values of 94% and 87%, in 2019 and 2020, respectively. Then, the satellite-based ArcDualK$_c$ model was used to estimate crop evapotranspiration (ET$_c$) over the identified citrus orchards. The estimated ET$_c$ rates were validated at the farm scale in terms of irrigation volumes and compared to those obtained by the traditional FAO-56 approach. Then, the spatially distributed irrigation volumes estimated at district level were compared with those declared by the Reclamation Consortium, obtaining absolute error values of 3.28 Mm^3 (294%) and 7.08 Mm^3 (647%) for the years 2019 and 2020, respectively. The results of the study confirmed the usefulness of the satellite-based methodological approach for determining spatial distributed IWR estimates.

Key words: Sentinel-2; supervised classification; agro-hydrological models; irrigation volumes

Introduction

Global food security represents a fundamental sustainable development goal of the United Nations. In the near future, due to the increase in the growth rate of the world population, an increasing demand for food is expected which will lead to a greater demand for water resources (Mancosu et al., 2015). In this context, it becomes essential to optimize water resource management in order to increase the sustainability of irrigated agriculture, especially in semi-arid regions, where water scarcity negatively affects agricultural production (Consoli et al., 2006; Hsiao et al., 2007; Singh et al., 2017). In terms of production, citrus is one of the most important fruit tree crops in the world. Italy is one of the main citrus producing countries in the Mediterranean area (Consoli et al., 2023). In these environments, the success of citrus production largely depends on adequate irrigation supply (Vanella et al., 2021). The high-water demand that characterizes the citrus sector of the Mediterranean area makes necessary the adoption of precision irrigation strategies to limit water waste and increase the water use efficiency by crops (Vanella et al., 2023).

In Europe, specific measures have been adopted, including the Water Framework Directive (WFD; 2000/60/EC), which impose a significant increase of efficiency in the use of water resources in agriculture in the coming decades (Pelosi et al., 2021; Wriedt et al., 2009). In Italy, the Ministry of Agricultural, Food and Forestry Policies (MiPAAF) issued a Ministerial Decree on 31 July 2015, which requires the Italian regions to monitor and quantify the irrigated areas and irrigation volumes supplied. However, since the direct determination of this information is not always possible, for economic and logistical reasons, it is necessary to resort to indirect assessments (Pelosi et al., 2021).

In this context, the general aim of this study was to implement a methodological approach, based on satellite remote sensing, for supporting the main water management authorities to monitor the irrigation uses at the irrigation district scale, as highlighted in the scope of the WFD and of the Ministerial Decree of 31 July 2015 of the MiPAAF. In particular, the specific objectives of the study were: (i) to identify the irrigated citrus areas through the use of supervised classification techniques on high spatial resolution satellite images (Sentinel-2); and (ii) to estimate citrus irrigation water requirements (IWR) by combining an agro-hydrological model with satellite data.

Materials and methods

Study area

The study was conducted on the “Quota 102.50” irrigation district (14°57’9.664” E; 37°28’44.512” N; Figure 1) of the Eastern Sicily Reclamation Consortium, during the period 2019-20. The district is characterized by an irrigable area of 5,050 ha and an effectively irrigated area of approximately 2,300 ha. Within the district, citrus fruits represent over 95% of irrigated crops. The collective irrigation system consists of open channels and the delivery of water to individual farms takes place in irrigation turns. Each farm receives approximately 520-620 m^3 ha^{-1} per turn, for a total of 3-4 turns during the irrigation season (from May to October). The most frequent irrigation method is micro-irrigation.

Methodological approach

Figure 2 shows the methodological approach developed for the identification of the citrus irrigation areas of the irrigation district under study and the following estimate of their IWR, during the period 2019-20.

A total of 127 Sentinel-2 satellite images (S2A and S2B, level 2A), distributed by the European Space Agency (ESA), was used. Specifically, 65 and 62 cloud-free images were selected during the years 2019 and 2020, respectively, from which the time series of the Normalized Difference Vegetation Index (NDVI; Rouse et al., 1974) were determined for each year, covering the period January-December. Furthermore, for the application of supervised classification algorithms, used to identify citrus growing areas, a dataset of over 500 ground truth points was created, acquired through field investigations and photointerpretation techniques (Figure 1). This dataset was divided into a “training” subset (70% of the total), for training the automatic classification algorithm and into a “testing” subset (the remaining 30%) for subsequent validation. In particular, the classification of the citrus orchard areas was performed by developing a neural network (NN) in the ENVI environment (Exelis Visual Information Solutions, Inc.) starting from the NDVI time series and the training subset. The NN architecture was made up of three layers, called “input”, “hidden” and “output”. The transfer function used was the sigmoid.

The estimate of the IWR for the citrus areas, during the irrigation season, was obtained through the application of the “ArcDualK$_c$” agro-hydrological model, developed in the ArcGIS© (ESRI) environment (Ramírez-Cuesta et al., 2018). The input data used for the application of ArcDualK$_c$

were: (i) Sentinel-2 satellite images; (ii) the agrometeorological data acquired from 4 different meteorological stations close to the irrigation district and managed by the Sicilian Agrometeorological Information Service (SIAS); and (iii) the agronomic, textural and irrigation characteristics (i.e. crop age, soil type and irrigation method) of 5 reference citrus farms located in the district (Figure 1).

In particular, the model uses the FAO-56 approach of the double crop coefficient (Kc, Allen et al., 1998) to estimate the daily rates of crop evapotranspiration (ET_c, mm), as follow:

$$ET_c = (K_{cb} + K_e) \cdot ET_0 \tag{1}$$

where ET_0 (mm) is the reference evapotranspiration, K_{cb} is the basal crop coefficient calculated as in Eq.2, and K_e is the soil evaporation coefficient calculated as in Eq.3.

$$K_{cb} = \frac{K_{cb,max}}{F_{c,max}} \left(\frac{SAVI - SAVI_{min}}{SAVI_{max} - SAVI_{min}} \right) \tag{2}$$

where $SAVI_{max}$ and $SAVI_{min}$ refer to the SAVI values of a high LAI and bare soil surfaces, respectively; $F_{c,max}$ is the maximum value of ground cover fraction (F_c) at which K_{cb} is maximal ($K_{cb,max}$). $K_{cb,max}$ values were obtained using the approach proposed by Allen et al. (1998), which adjusts K_{cb} at the middle and final stages, considering the local relative humidity (RH) and wind speed (u_2) conditions in the study area.

$$K_e = \left(K_{c,max} - K_{cb}\right) K_r \tag{3}$$

where, $K_{c,max}$ represents the maximum K_c value following precipitation or irrigation, adjusted for local RH and u_2 conditions, calculated as described by Allen et al. (1998). K_r is an evaporation reduction coefficient associated with the depletion of water in the topsoil (Allen et al., 1998), calculated as:

$$K_r = \frac{TEW - D_{e,i}}{TEW - REW} \tag{4}$$

where TEW (total evaporable water) is the maximum cumulative depth of evaporation from the soil surface layer when the topsoil has been completely wetted, calculated as in Eq.5; REW (readily evaporable water) is the maximum water depth that can evaporate from the soil surface layer during the energy-limited stage (tabulated values depending the soil type as in Allen et al., 1998); $D_{e,i}$ represents the cumulative depletion of evaporation from the soil surface estimated from a daily soil water balance, as in Eq.6.

$$TEW = 1000(\theta_{FC} - \theta_{WP})Z_e \tag{5}$$

where θ_{FC} and θ_{WP} denote the soil field capacity and wilting point in the study area, respectively; Z_e is the depth of the surface soil layer that is subject to drying through evaporation, fixed to 0.1 m as specified by Allen et al. (1998).

$$D_{e,i} = D_{e,i-1} - P_i - I_i + ET \tag{6}$$

where $D_{e,i}$ and $D_{e,i-1}$ refer to soil moisture depletion at the end of the day (i) and at the previous time steps (i-1); P_i and I_i refer to precipitation and irrigation on day i; capillary rise, deep percolation and runoff were instead disregarded as suggested by Consoli & Vanella (2014).

The ArcDualK$_c$ model was validated in the reference citrus farms in terms of irrigation volume, and subsequently, implemented at the scale of the irrigation district to estimate the water requirements of citrus orchards.

In detail, the IWR (mm) of citrus orchards were calculated as follow:

$$IWR = ET_c - P_{eff} \tag{7}$$

where P_{eff} (mm) represents the portion of rainfall that is accessible to the crop and does not contribute to runoff (Döll and Siebert, 2002):

$$\begin{cases} P_{eff} = P \cdot (4.17 - 0.2 \cdot P) \,/\, 4.17, \; P < 8.3 \text{ mm/d} \\ \qquad P_{eff} = 4.17 + 0.1 \cdot P, \; P \geq 8.3 \text{ mm/d} \end{cases} \tag{8}$$

Later, IWR was converted into irrigation volume (IV; m^3) as follow:

$$IV = \frac{IWR \cdot A}{\mu} \cdot 10^{-3} \tag{9}$$

where, A is the irrigated crop surface (m^2), μ is the irrigation system efficiency and 10^{-3} is a coefficient for converting the obtained volume from liters to cubic meters. Irrigation efficiency indicates the proportion of water effectively used by crops compared to the total water applied during irrigation. In this study, given that drip irrigation is the predominant method in the Quota 102.50 irrigation district, a tabulated μ value of 0.90 was used (Howell, 2003).

Analysis of the results

The reliability of the results obtained from the implementation of the NN for the classification of citrus orchard areas was evaluated with the "k-fold cross validation" method on the testing subset. The overall accuracy was assessed by dividing the number of correctly classified pixels by the total pixel count. Additionally, a confusion matrix was constructed by matching the location and class of each ground truth pixel with its corresponding location and class in the classification image. The results were then presented as percentages for each ground truth category.

The ET_c rates, estimated in the reference citrus farms with the ArcDualKc model, were initially compared qualitatively with those obtained through the traditional FAO-56 approach (using the tabulated K_c). Subsequently, the results were validated using a linear regression analysis to compare the IV estimated by both models with those supplied by the farmers. The coefficient of determination (R^2) was calculated with the intercept forced to 0 to assess how well the models fit the observed data. Additionally, the root mean square error (RMSE, m^3) and the percent bias (PBIAS, %) were computed to quantitatively describe the accuracy of the applied approaches. The significance level was assessed in terms of p-value (≤ 0.001). The estimated IV were also compared with the actual volumes provided by the farmers in terms of absolute error (AE).

Finally, the IV obtained at the district scale with the satellite-based approach were compared in terms of AE to those declared by the Reclamation Consortium.

Results and Discussion

Identification of citrus growing areas

Figure 3 shows the maps of the citrus growing areas in the "Quota 102.50" irrigation district, for the period 2019-20, obtained through the implementation of NN on the NDVI time series. From the comparison of these results with the testing subset, accuracy values (in classifying the citrus orchard areas) of 94.3% and 87.4%, respectively in the years 2019-20, were obtained. These values are in line with those obtained in recent studies that employ supervised classification techniques starting from NDVI time series, detected with sensors on board both Sentinel-2 and Landsat-8 satellite platforms (Bolognesi et al., 2020; Htitiou et al., 2019; Magidi et al., 2021).

Estimation of irrigation water requirements

Figure 4 shows the comparison between the ET_c rates estimated with the spatially distributed agro-hydrological model ArcDualK_c and those obtained by applying the traditional FAO-56 approach in the reference citrus farms for the years 2019-2020.

Table 1 presents the validation of both agro-hydrological models at the reference citrus farms. In 2019, similar results were observed for the ArcDualK$_c$ model and the traditional FAO56 approach, achieving R^2 values of 0.98 and 1.00, RMSE values of 9510m³ and 9338 m³, and PBIAS values of -44.36% and -44.86%, respectively. In 2020, the ArcDualK$_c$ model outperformed the traditional FAO56 approach, with R^2 values of 0.99 and 1.00, RMSE values of 3904 m³ and 4828 m³, and PBIAS values of -20.95% and -26.39%.

Table 2 shows the comparison, in terms of absolute error (AE), between the IV estimated by the satellite-based ArcDualKc model and the FAO-56 approach, and the observed IV at the reference citrus farms. The lowest AE was observed for the satellite-based ArcDualK$_c$ model, with values of about 306,257 m^3 and 149,712 m^3, respectively, during 2019-20. These results highlight how the ArcDualK$_c$ model, due to the use of satellite images, is able to capture the site-specific conditions, in terms of K_{cb}, of the different citrus groves under study (Longo-Minnolo et al., 2020).

Figure 5 shows the IV of the citrus orchard areas of the "Quota 102.50" irrigation district, determined by applying the ArcDualK$_c$ model with the satellite data, and the IV declared by the Reclamation Consortium during the period 2019-20. Specifically, absolute error values of 3.28 Mm^3 (294%) and 7.08 Mm^3 (647%), were observed, respectively, for the years 2019 and 2020. Large overestimations were also observed by Pappalardo et al. (2022), confirming how these overestimates can be attributed to the use of private water sources (e.g., wells and reservoirs). In Sicily, in fact, autonomous irrigation, managed by private consortia or by company owners using private wells, represents a widespread reality (Zucaro et al., 2014).

Conclusions

In this study, a satellite-based approach was developed for mapping citrus orchards and determining their IWR. The application of supervised classification techniques (NN) and the agro-hydrological model, using satellite data as input (ArcDualK$_c$), allowed to map citrus growing areas with high accuracy and reliably estimate their IWR. The consistency of the results obtained at the irrigation district scale suggests that the proposed methodological approach is a valid tool to support various water management authorities in fulfilling the obligations of the WFD and the Ministerial Decree of 31 July 2015 of MiPAAF, thereby improving the sustainability of irrigated agriculture.

However, it is crucial to consider some limitations of the proposed procedure. Firstly, the supervised classification methodology, although accurate, can be influenced by the quality and resolution of the available satellite images. Furthermore, the approach used to estimate crop evapotranspiration (ET_c) and consequently the IWR relies on models that, despite being validated with satisfactory results, may present inherent uncertainties due to the variability of local conditions. Additionally, another potential source of error in the model validation could be the IV provided by the farmer, which does not always correspond to the actual crop water requirements. These limitations could have contributed to the observed absolute errors in the IV estimates.

At the district scale, the high absolute error observed in the comparison between the estimated IV and those declared by the Reclamation Consortium can be attributed to various factors, including the use of private water sources (e.g., wells and reservoirs) not always accounted for in the official data. In Sicily, autonomous irrigation, managed by private consortia or farm owners using private wells, is a widespread reality.

For future research, it would be beneficial to integrate additional data sources to improve the accuracy of estimates and reduce errors, for instance, by using in-situ sensors to monitor soil moisture and crop evapotranspiration in real-time. Moreover, the adoption of more advanced machine learning techniques could further enhance the classification of irrigated areas and the estimation of IWR.

Despite these limitations, this study provides a solid foundation for the adoption of precision irrigation strategies, contributing to the optimization of water resource management and improving the sustainability of agriculture in semi-arid regions.

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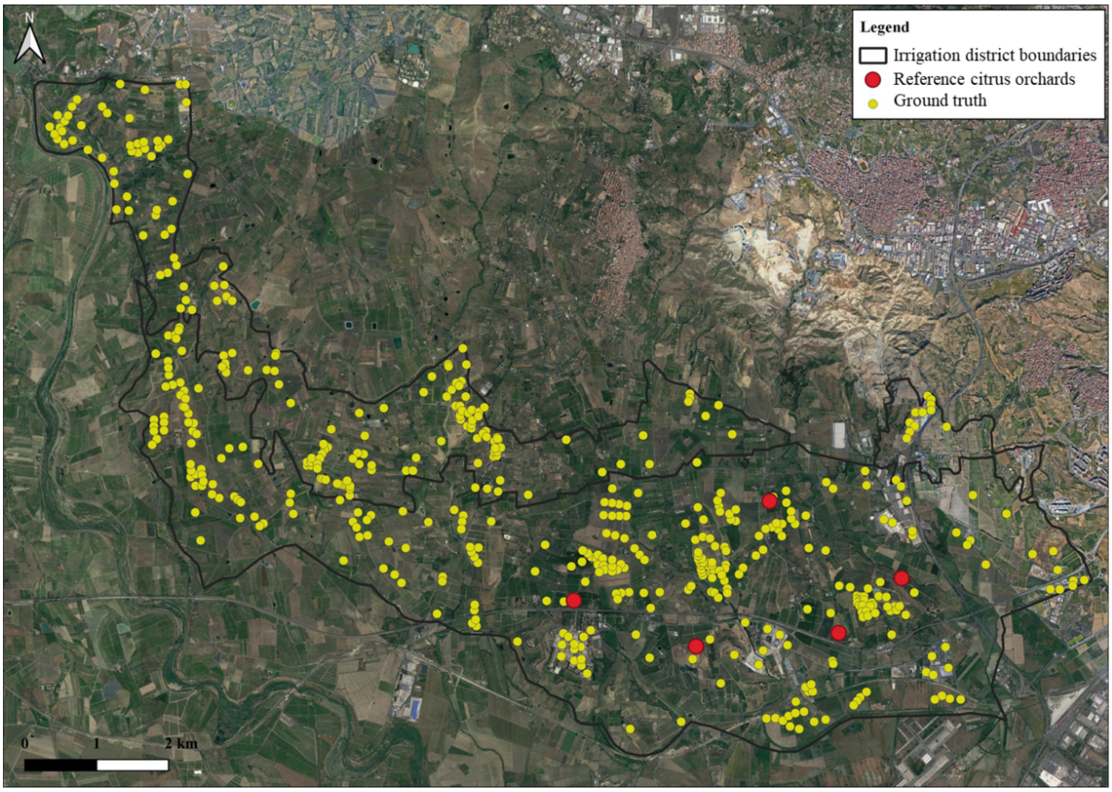

Figure 1. Irrigation district under study, with the reference citrus farms used for the calibration of the agro-hydrological model (red dots) and the ground truth points (yellow dots) for the implementation and validation of the supervised classification algorithm.

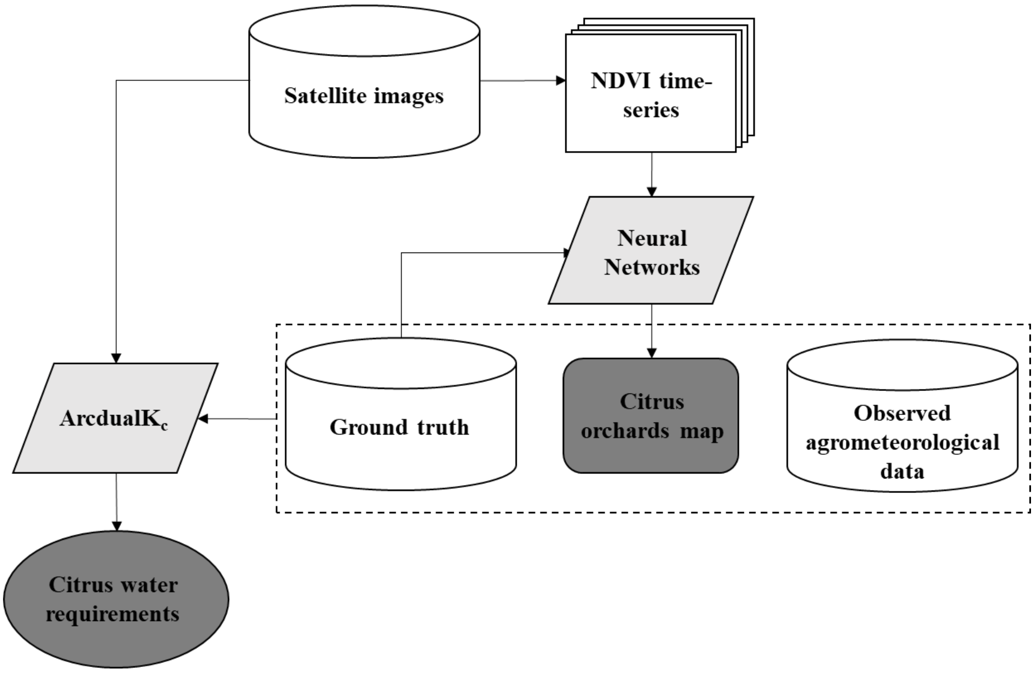

Figure 2. Satellite based methodological approach for mapping the citrus orchard areas of the irrigation district under study and estimating their irrigation needs.

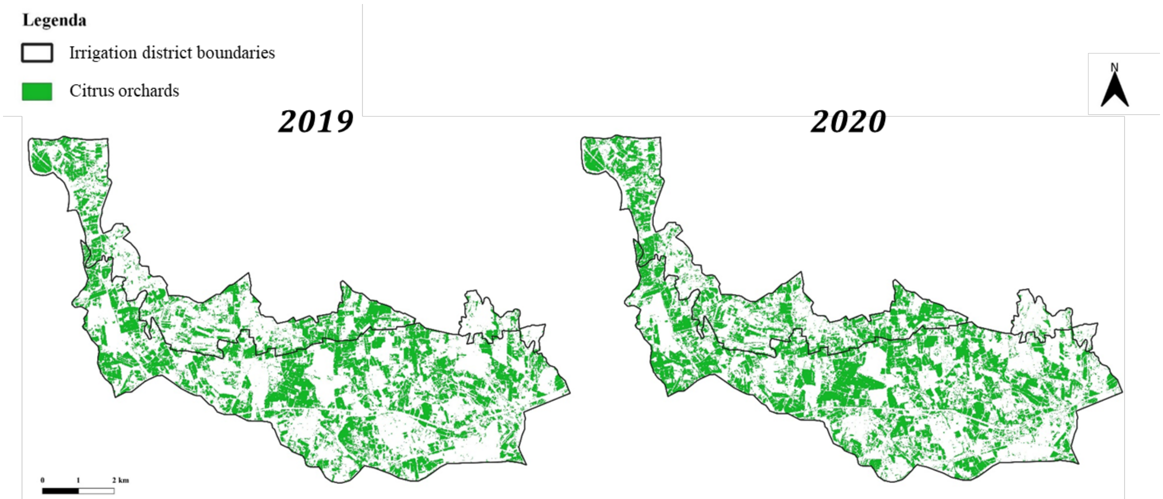

Figure 3. Maps of the citrus growing areas of the “Quota 102.50” irrigation district for the period 2019-20.

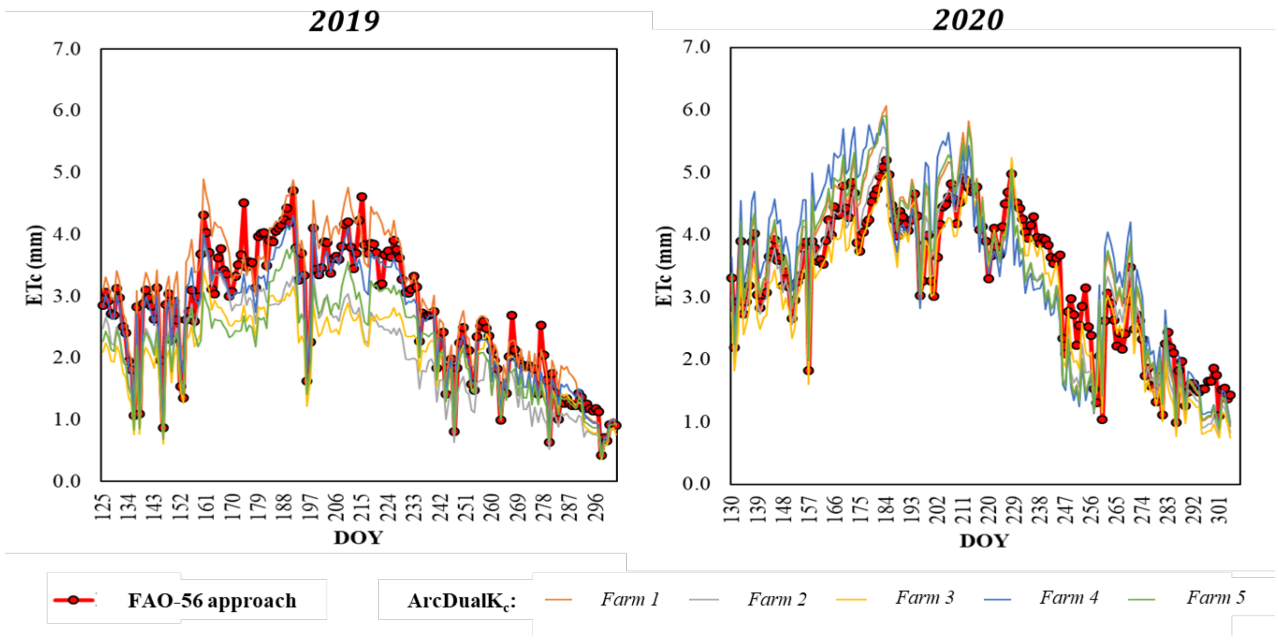

Figure 4. ET_c rates estimated with the spatially distributed agro-hydrological model ArcDualK_c and those obtained by applying the traditional FAO-56 approach over the 5 citrus farm, during the years 2019-20.

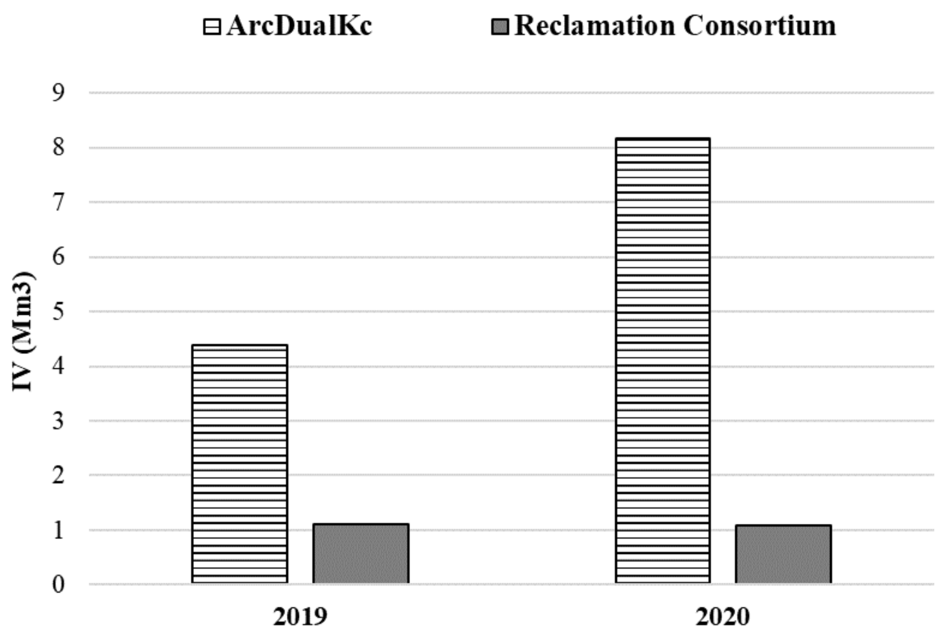

Figure 5. Irrigation volumes (IV; Mm3) of the citrus orchards of the irrigation district under study estimated by the satellite-based model ArcDualK_c and supplied by the Reclamation Consortium, during the period 2019-20.

Table 1. Statistical performance of the ArcDualK$_c$ model and the traditional FAO-56 approach to estimate the irrigation volumes (IV) at the reference citrus farms.

	ArcDualK$_c$			**FAO56 approach**		
	R^2	**RMSE (m^3)**	**PBIAS (%)**	**R^2**	**RMSE (m^3)**	**PBIAS (%)**
2019	0.98*	9509.66	–44.36	1.00*	9337.57	–44.86
2020	0.99*	3903.74	–20.95	1.00*	4828.23	–26.39

*p≤0.001

Table 2. Comparison, in terms of absolute error (AE), between the irrigation volumes (IV) estimated by the satellite-based ArcDualK$_c$ model and the FAO-56 approach, and the observed irrigation volumes at the reference citrus farms.

		IV (m^3)				
		ArcDualKc	**FAO-56**	**Observed**	**$AE_{ArcDualKc}$ (m^3)**	**AE_{FAO-56} (m^3)**
2019	Farm 1	72,759.42	64,384.65	126,480.00	-53,720.58	-62,095.35
	Farm 2	61,799.15	62,918.58	123,600.00	-61,800.85	-60,681.42
	Farm 3	79,054.69	87,230.81	150,796.80	-71,742.11	-63,565.99
	Farm 4	151,473.10	151,615.46	260,610.00	-109,136.90	-108,994.54
	Farm 5	19,060.28	14,538.47	28,917.00	-9,856.72	-14,378.53
	Total	**384,146.63**	**380,687.97**	**690,403.80**	**-306,257.17**	**-309,715.83**
2020	Farm 1	100,202.08	86,440.41	126,480.00	-26,277.92	-40,039.59
	Farm 2	128,283.80	113,066.90	165,440.00	-37,156.20	-52,373.10
	Farm 3	110,156.52	104,756.37	134,886.40	-24,729.88	-30,130.03
	Farm 4	204,196.03	202,241.03	258,930.00	-54,733.97	-56,688.97
	Farm 5	22,103.16	19,518.80	28,917.00	-6,813.84	-9,398.20
	Total	**564,941.58**	**526,023.50**	**714,653.40**	**-149,711.82**	**-188,629.90**