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ESTIMATION OF EVAPOTRANSPIRATION AND WATER BALANCE OF IRRIGATED CROPS BY REMOTE SENSING: APPLICATION TO IRRIGATION MANAGEMENT IN THE MITIDJA PLAIN IN NORTHERN ALGERIA

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Abstract. In semi-arid areas, the conservation of water resources and use of recent technologies is a priority for agriculture. The objective of this work is to evaluate the functionality and accuracy of the SAMIR (SAtellite Monitoring of Irrigation) model outputs at the plot scale by estimating evapotranspiration and irrigation water volumes for agriculture in a semi-arid climate. Twenty-four (24) Sentinal2B images were used, covering an area of 60 hectares of citrus, located in the Mitidja plain and irrigated through a drip irrigation system. The images were captured during two seasons, dry (2020/2021) and wet (2017/2018). The irrigation volumes simulated by SAMIR were compared to the irrigation water volumes observed by the National Office of Irrigation and Drainage of Algiers. The results show a slight difference between the simulated and observed total volumes, 357038.55m3 and 305280 m3, for the dry year and 223063m3 and 190794.93m3 for the wet year with an overestimation varying from 10 to 20%. The results also reveal a consistency between the simulated ET and ET0 values throughout the growing season for all fields in both seasons of the study, which shows a good performance of the model in estimating evapotranspiration and confirms the feasibility of estimating pumping by remote sensing without calculating theoretical crop water requirements.

Keywords: remote sensing, irrigation, evapotranspiration

1.INTRODUCTION

Agricultural production is the largest water-consuming sector, accounting for 70% of all available freshwater (FAO, 2016). In recent years, agricultural regions have been under increasing water stress around the world. Severe droughts in Chile and the United States have affected agricultural production and reduced surface and groundwater reserves (OCDE, 2022). Furthermore, climate change, population growth and competition from other economic sectors have influenced crop water requirements, particularly in semi-arid regions. In North Africa, groundwater is overexploited by more than 50% (Kuper et al. 2016) and is largely used for irrigation.

Improving water management in agriculture and assessing irrigation performance, through accurate estimation of crop water use by means of efficient and innovative tools, is necessary to ensure the sustainability of a productive agri-food sector as well as the effective and sustainable utilization of water resources. Relevant to this, many theories and approaches have been developed to estimate water balance and evapotranspiration and determine crop needs.

High-resolution satellite imagery has provided a valuable source of data that, when implemented in well-tuned models, has the potential to estimate the rate of evapotranspiration with satisfactory accuracy (Derakhshandeh et al., 2022). The most practical and widely used approach to estimate crop water requirements is the FAO-56 method (Allen et al. 1998). It is based on the use of two crop coefficients (Kcb) and (Ke) to separate the respective contribution of plant transpiration and soil evaporation (Saadi et al. 2015).

Quantifying irrigation water efficiency at the field scale requires first accurate and high spatial and temporal resolution estimations of surface evapotranspiration (ET) (Zayed et al. 2016; Senay et al. 2016; Bai et al.2018). These measurements can provide a basis for making decisions about efficient and optimal irrigation management.

In this study, regional evapotranspiration and crop water consumption were estimated for an irrigated area (EL HAMIZ perimeter), located in the Mitidja plain (northern Algeria), using the SAtellite Monitoring of IRrigation (SAMIR) model fed by very high resolution satellite images. The Mitidja plain is the largest sub-coastal plain of Algeria. This plain is known by its agricultural production. During the last decades, drought has had a negative impact on availability of irrigation water. The objective of this work is to evaluate the functionality and accuracy of SAMIR outputs at the plot scale by estimating climatological variables such as evapotranspiration and irrigation water volumes for agriculture in a semi-arid climate. This approach has been widely used in many regions of the world where high resolution satellite imagery has made it possible to estimate evapotranspiration and crop water requirements for better irrigation management (Deines et al.2019; Karthikeyan et al.2020; Pradipta et al.2022; Bretreger et al.2022). The SAMIR model has given very satisfactory results in Morocco (El Hachimi el al.2022; Elfarkh et al. (2022)), in France (Cherif et al.2022), in Algeria (Tazekrit et al.2018), in Tunisia (Saadi et al.2015), and in Spain (Laluet et al.2022).

This study is very important from a practical point of view. It contributes to the exploration of possibilities to improve the mapping of evapotranspiration assisted by high resolution remote sensing data and evaluate, over two typical years, the water needs of crops in El Hamiz perimeter as well as the irrigation volumes that are extracted from the Mitidja aquifer. The results of this study can be a necessary decision support tool for policy makers and planners to optimize water consumption for agriculture and ensure agricultural productivity as well as food security.

Presentation of the study area

El Hamiz irrigation perimeter is located in the extreme east of the Mitidja plain and extends mainly over the Wilayas of Boumerdes, Algiers and Blida, covering an area of 17,000 hectares. It was built in 1879 following the construction of the Hamiz dam. It is divided into two parts: (1) The North Hamiz (coastline), located on the hills of the East Sahel; and (2) Hamiz plain which corresponds to the southern part of the perimeter which depends exclusively on the Hamiz dam for irrigation.

Rainfall patterns are highly variable in time and space with average annual rainfall varying between 600 and 900 mm. The average daily temperature is 18.05°C (minimum 12.1°C in January and maximum 24°C in August) (Figure 2). The relative humidity varies between 30% and 73%.

The daily reference evapotranspiration varies between 1.91 and 7.97 mm/d with an average estimated by the Penman-Monteith method at 2.65 mm/day (Figure 3). The dominant crops in this region are citrus (46%), orchards (25%) and market gardening (27%) (ONID, 2022).

The area studied during two seasons, one wet (2017-2018) and one dry (2020-2021), is about 60 ha of irrigated land, comprising 3 fields (C1; C2; C3) (Figure 1). The main crops in this area are citrus (C1 and C2) and peach (C3). The two agricultural seasons studied are characterized by special climatic conditions, notably rainfall (P) and reference evapotranspiration (ET0), which directly influence irrigation water requirements.

Software used

Satellite monitoring of irrigation (SAMIR) is a software package for the spatialization of evapotranspiration (ET) and water balance of irrigated crops over large areas. It is a software application that uses the following three main groups of information: (1) Climatological data to obtain the reference evapotranspiration (ET0); (2) Land cover to spatialize the results; and (3) Phenological data or crop parameters to obtain the crop coefficient (Kc) (single crop coefficient). Moreover, it is based on the use of satellite imagery tracking daily changes in soil water storage based on effective rainfall and irrigation inputs as well as actual evapotranspiration (Simonneaux et al.2009; Kharrou et al. 2021).

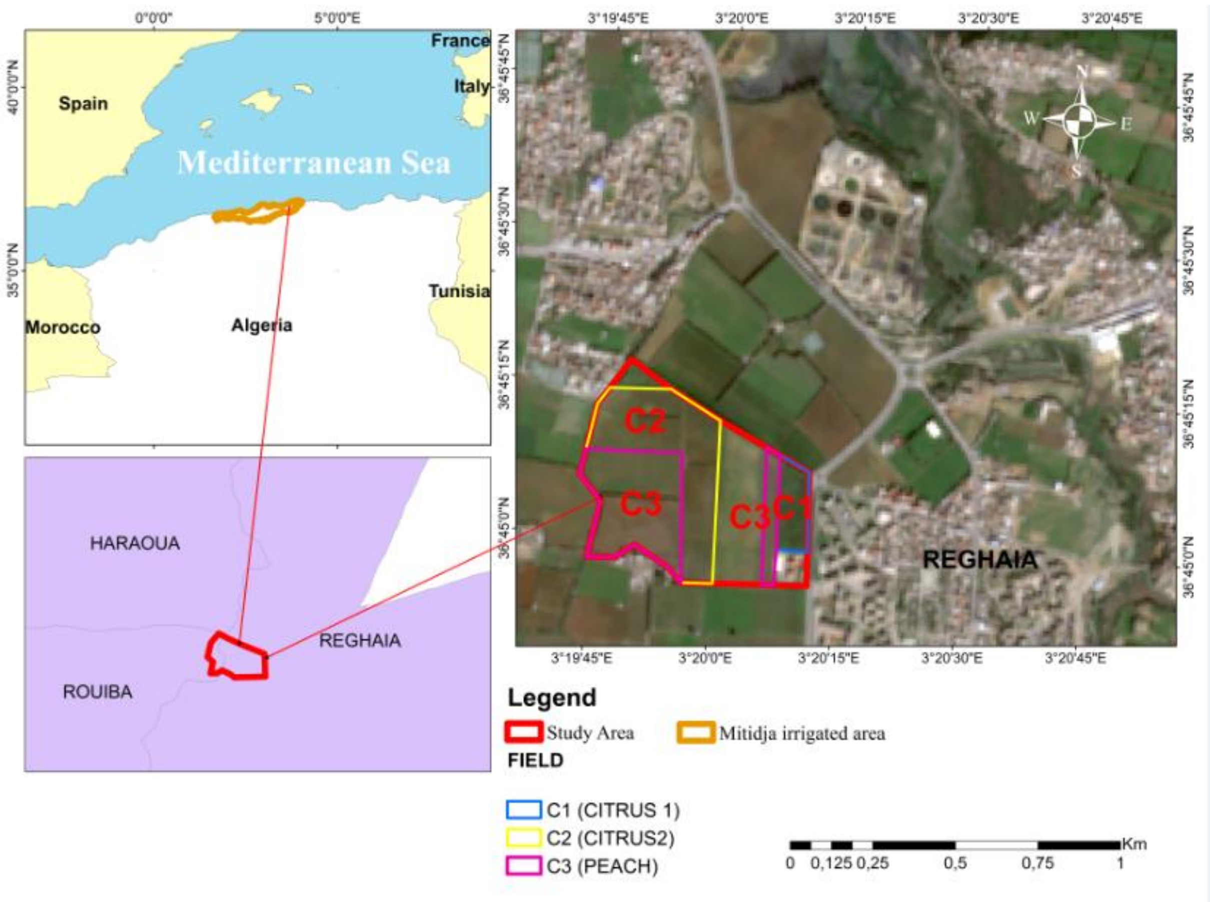

Figure 1. Location of the study area

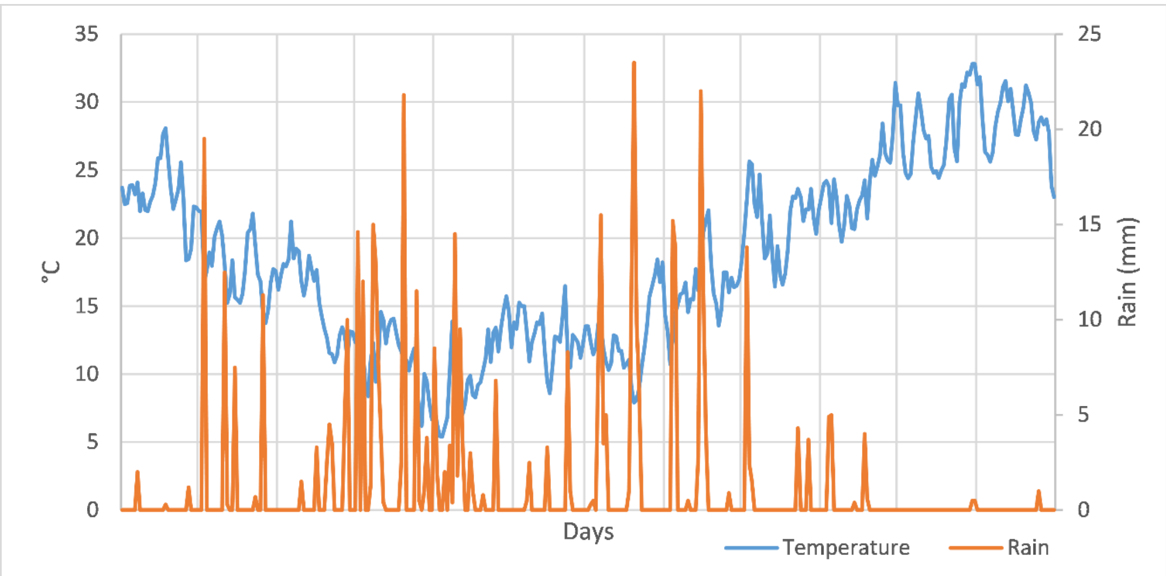

Figure 2. Rainfall and temperature at Dar el Beida station: September 2020 - September 2021 (NMO 2021).

SAMIR is developed in IDL (*Interactive Development Language*), like ENVI, and uses the specific features of ENVI. At least IDL 6.4 (ENVI4.4) is required. The main originality of SAMIR lies in its use of a remotely sensed NDVI time series for monitoring vegetation development from which crop coefficients and plant fraction coverage are derived instead of using standard values (Simonneaux et al.2009 ; Kharrou et al. 2021).

The SAMIR model uses the FAO-56 algorithm according to Simonneaux et al. (2009), equation 1:

$$ETc = ET0 \times Kc \; \ldots\ldots\ldots\ldots \; (1)$$

Where Kc is the crop coefficient, ET0 is the daily reference evapotranspiration; it is calculated according to the FAO Penman-Monteith method (Allen et al. 1998).

ETc can be calculated using another method that takes into account variations in soil water availability, inducing either water stress or soil evaporation. It is presented by the following equation:

$$ETc = ET0 \times (Kcb \times Ks + Ke) \ldots\ldots\ldots\ldots (2)$$

Where K_{cb} is the base crop coefficient derived from NDVI (Allen et al.1998; González-Piqueras, 2006; Pôças et al.2020). K_e is the evaporation coefficient of the bare soil fraction. K_s is the water stress coefficient calculated from the water status of the soil compartment and the maximum evaporation of the plant taking into account the reduction of transpiration due to lack of water in the root zone. K_{cb} is adjusted by the water stress coefficient K_s.

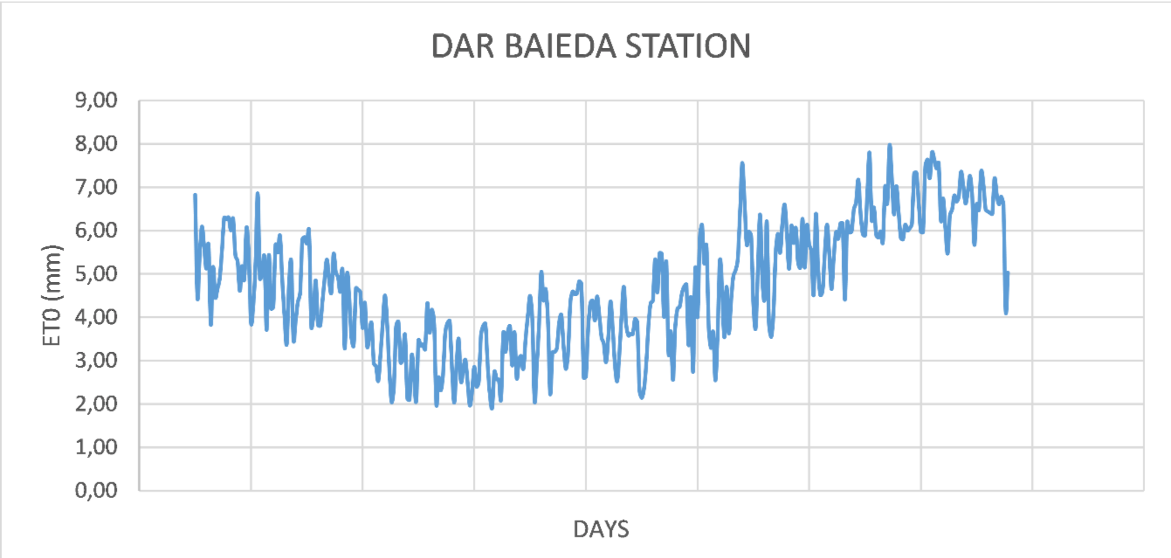

Figure 3. Reference evapotranspiration at Dar el Beida station. September 2020 - September 2021 (NMO 2021)

K_e and K_s are computed on the basis of daily water balance calculated in the surface soil evaporation layer of effective depth (Z_e) and in the root zone (Z_r), respectively, according to Allen et al. (1998). The coefficient Ks is considered to be 0 when the three soil compartments are filled and 1 when they are empty. The drying of the three compartments is assumed to be linear (Simonneaux et al.2009; Tazekrit et al.2018).

SAMIR calculates daily water balance ensuring the conservation of water volumes in the soil. The equation used by SAMIR to calculate the water balance of each pixel of the land cover map is given by Eq(3) Simonneaux et al. (2009):

$$ET + DSW = R + I \ldots\ldots\ldots\ldots (3)$$

Where R represents precipitation, I is irrigation and ET is evapotranspiration, and DSW is the variation in soil water content.

SAMIR software (Simonneaux et al. 2009) executes the irrigation simulation according to the evolution of the water stored in each pixel of the land cover image, taking into account the basic data defined by the operator :

- Initial water content before the start of irrigation;
- The soil moisture fraction, depending on the system used.
- The rooting depth is about 1 m;
- A dewatering rate that allows irrigation to start;
- The irrigation recharge rate and the value of K_{cb}, which indicates the end of the vegetative cycle and of any irrigation.

Study data

For the purposes of the study, land use maps of the study area were produced based on multi-source data:

- Field campaigns, in which training sites were identified on which to base the classification of captured scenes.
- Sentinel-2 image series acquired in 2017-2018 and 2020-2021, downloaded for free from the website https://scihub.copernicus.eu/ of ESA (*European Space Agency*) to provide NDVI time series. The images were chosen so that the scenes covering the study area were free of clouds and spots (Toumi

et al.2013 ; Menasria et al.2021 ; Salles.2022). Figure 4 shows the dates of acquisition of the satellite images used.

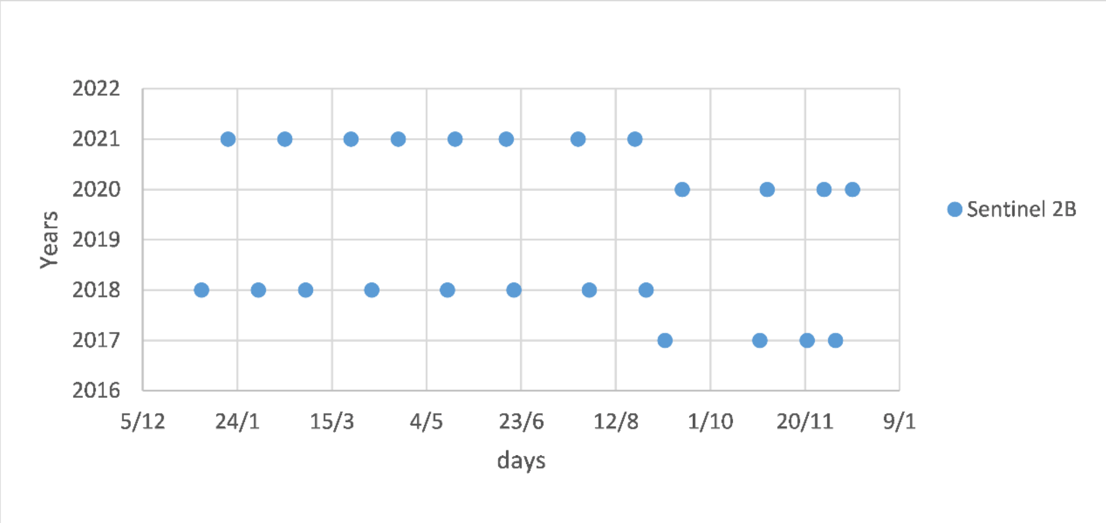

Figure 4. Dates of downloading satellite images from the website https://scihub.copernicus.eu/.

Irrigation data was collected from the National Office of Irrigation and Drainage in Algiers (NOID of Algiers).

The daily values of the climatic parameters used for the calculation of ET0 were obtained from the meteorological station of Dar el Beida managed by the National Meteorological Office (NMO). Daily precipitation (expressed in mm) and temperature (expressed in °C) series were used.

2.METHODOLOGY

Land cover was applied through supervised classification of satellite images using the ENVI maximum likelihood algorithm. In this research, the normal NDVI vegetation index was calculated for the fields C1, C2, C3 (seasons 2017-2018 and 2020-2021), using Envi 4.4, following the expression (4):

$$NDVI = \frac{Band\ 8 - Band\ 4}{Band\ 8 + Band\ 4} \ldots\ldots\ldots\ldots (4)$$

Where the red and near-infrared bands are equivalent to bands 4 and 8 respectively

Estimated irrigation at the level of the irrigated areas was compared to the volumes of water actually used by the farmers in the same fields.

The relation between *Fc* and *NDVI* is considered to be linear (Simonneaux et al. 2009; Tazekrit et al. 2018**;** Kharrou et al. 2021). The *Fc* factor was calculated using formula 5:

$$Fc = 1{,}14 \times NDVI - 0{,}15 \ldots\ldots\ldots\ldots (5)$$

The variation of *Kcb* is obtained using the relation 6 for the fields C1 and C2 (Er Raki al. 2010) and the relation 7 for the field C3 (Pôças et al.2020)

$$Kcb = 0{,}1930 \times Fc + 0{,}3570 \ldots\ldots\ldots\ldots (6)$$

$$Kcb = 1{,}5500 \times Fc \ldots\ldots\ldots\ldots (7)$$

For a better evaluation of the results obtained, the mean relative error (MAPE) for the two seasons studied was used. It is calculated by formula 8:

$$MAPE = \frac{1}{N}\sum_{1}^{N}\left|\frac{Xobs(i) - Xsim(i)}{Xobsi}\right| \ldots\ldots\ldots\ldots (8)$$

Where ($X_{obs(i)}$) corresponds to the observed values and ($X_{sim(i)}$) corresponds to the estimated values.

The SAMIR model was performed on the three fields during two seasons: dry (2020/2021) and wet (2017/2018), using sentinel image time series. The soil of the fields was considered homogeneous. The initial water content of the soil was estimated taking into account previous rainfall and was initially set at 35% of available water in the soil. The depth of the evaporation layer (*Ze*) and the proportion of readily available water (p) were set in accordance with FAO 56 (Allen et al. 1998). SAMIR software parameters used are shown in Table 1.

Table 1. Parameters used to run SAMIR and estimate evapotranspiration (ET)

Parameters	Definition	Values			Source
		C1	C2	C3	
	Soil parameters:				
θfc **(m^3/m^3)**	Maximum water holding capacity of the soil	0,36	0,36	0,36	Ground observation
θwp **(m^3/m^3)**	The soil moisture at which the plant can no longer take up water	0,25	0,25	0,25	Ground observation
Ze (mm)	Depth of the evaporation compartment	125	125	125	FAO56
REW	Easily usable capacity for evaporation	4	4	4	Calibration
Init_RU (%)	Initial soil condition in percent	35	35	35	ONID
Z_tot (mm)	Total depth of the soil compartment	2000	2000	2000	FAO56
Zr_min (mm)	Minimum Root Depth	800	800	800	Calibration
Zr_max (mm)	Maximum Root Depth	1000	1000	1000	Calibration
p	Soil water depletion fraction for no stress	0,65	0,65	0,65	FAO56
Dif	Diffusion between deep and root layers	10	10	10	Calibration
	Irrigation parameters :				
Kcb_off (%)	Kcb threshold to stop irrigation (% de Kcbmax)	0	0	0	FAO56
Ir_max (mm)	Maximum irrigation rate	100	100	100	FAO56

3. RESULTS AND DISCUSSION
Estimation of Evapotranspiration (ET)

The results of daily evapotranspiration estimated by the SAMIR model are shown in figures 5 and 6. These figures reveal daily evolution of the simulated real ET compared to the reference evapotranspiration as well as the precipitation recorded during the dry and wet seasons. During the dry season, the estimated ET values vary between 1.61 and 7.98 mm, 1.66 and 8.29 mm, and 1.61 and 8.06 mm for fields C1, C2 and C3, respectively. Moreover, during the wet season, the estimated ET values vary between 0.82 and 6.39 mm for field C1, 0.91 and 6.01 mm for field C2, and 1.06 and 6.81 mm for C3.

The simulated ET curves indicate variability close to that of ET0 for the two seasons 2020-2021 (fig. 5) and 2017-2018 (fig. 6). These results require a comparison with observed values in reality, which was not carried out in this study due to the lack of measuring instruments (Eddy covariance) which are complex and not available in our study area.

Consistency is observed between the simulated ET and ET0 values throughout the growing season for all fields, suggesting a good performance of the model in estimating evapotranspiration. These results corroborate with those obtained by Saadi et al. (2015 and 2018) in Tunisia. The results are also comparable to those found by Elfarkh et al. (2022) in the traditionally irrigated area of the High Atlas Mountains of Morocco. Kharrou et al. (2021), in the Haouz plain in central Morocco, also have found evapotranspiration values close to those we obtained.

Monthly modeled irrigation values were calculated for the fields of the study area for which validation data were available. The results are presented in table 2.

During the dry season, the irrigated quantity is around 1037.15 mm for field C1, 1079.17 mm for field C2, and 1013.67 mm for field C3, with an average excess estimated at 11.32% as drainage equivalent to 120 mm. During the wet season, the irrigated quantities are 634.02 mm, 639.09 mm, and 723.56 mm for fields C1, C2 and C3 respectively, with an estimated average excess of 45% as drainage equivalent to almost 300 mm.

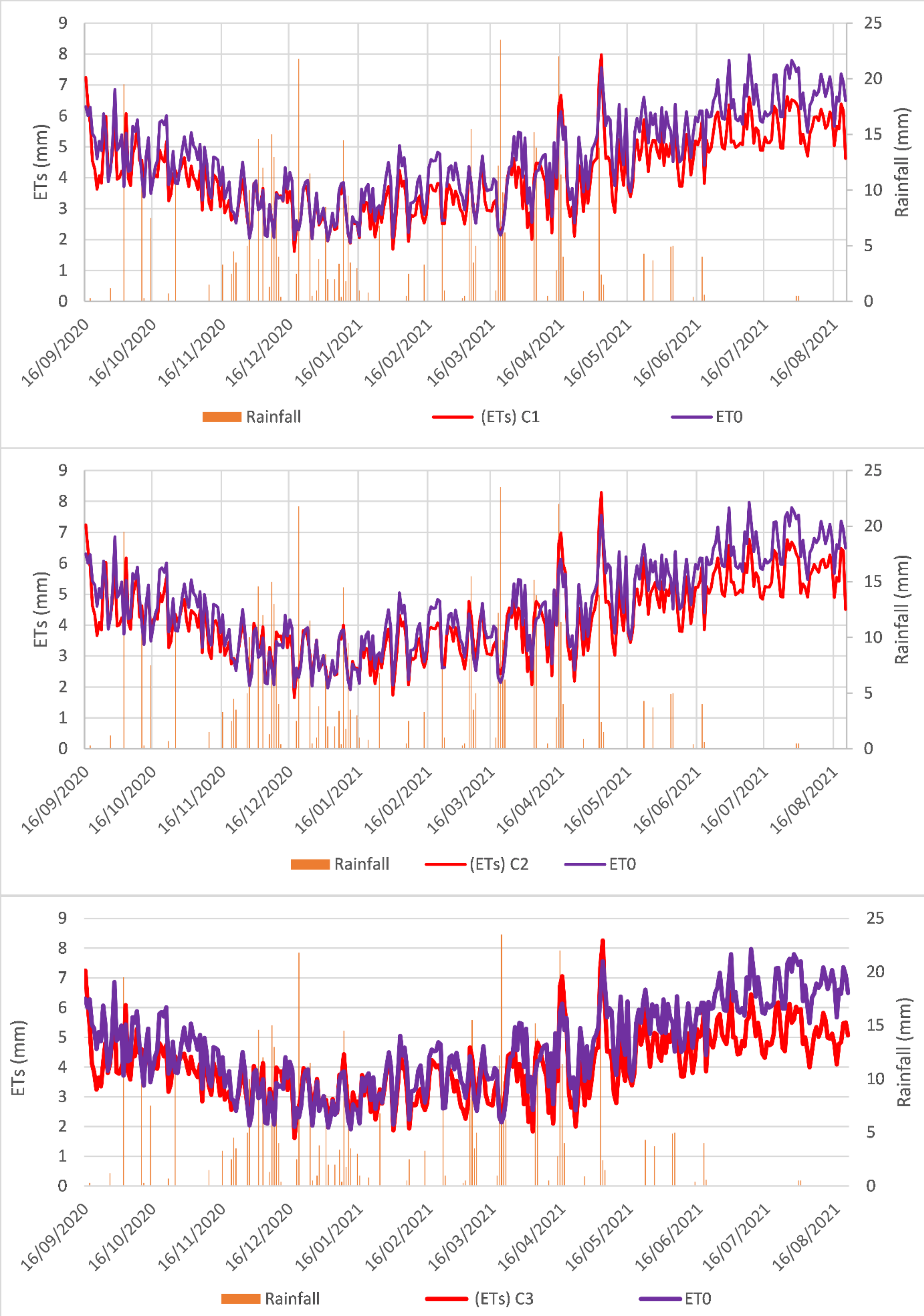

Figure 5. Variation of simulated ET and measured ET0 on fields in the study area during the dry season (2020-2021)

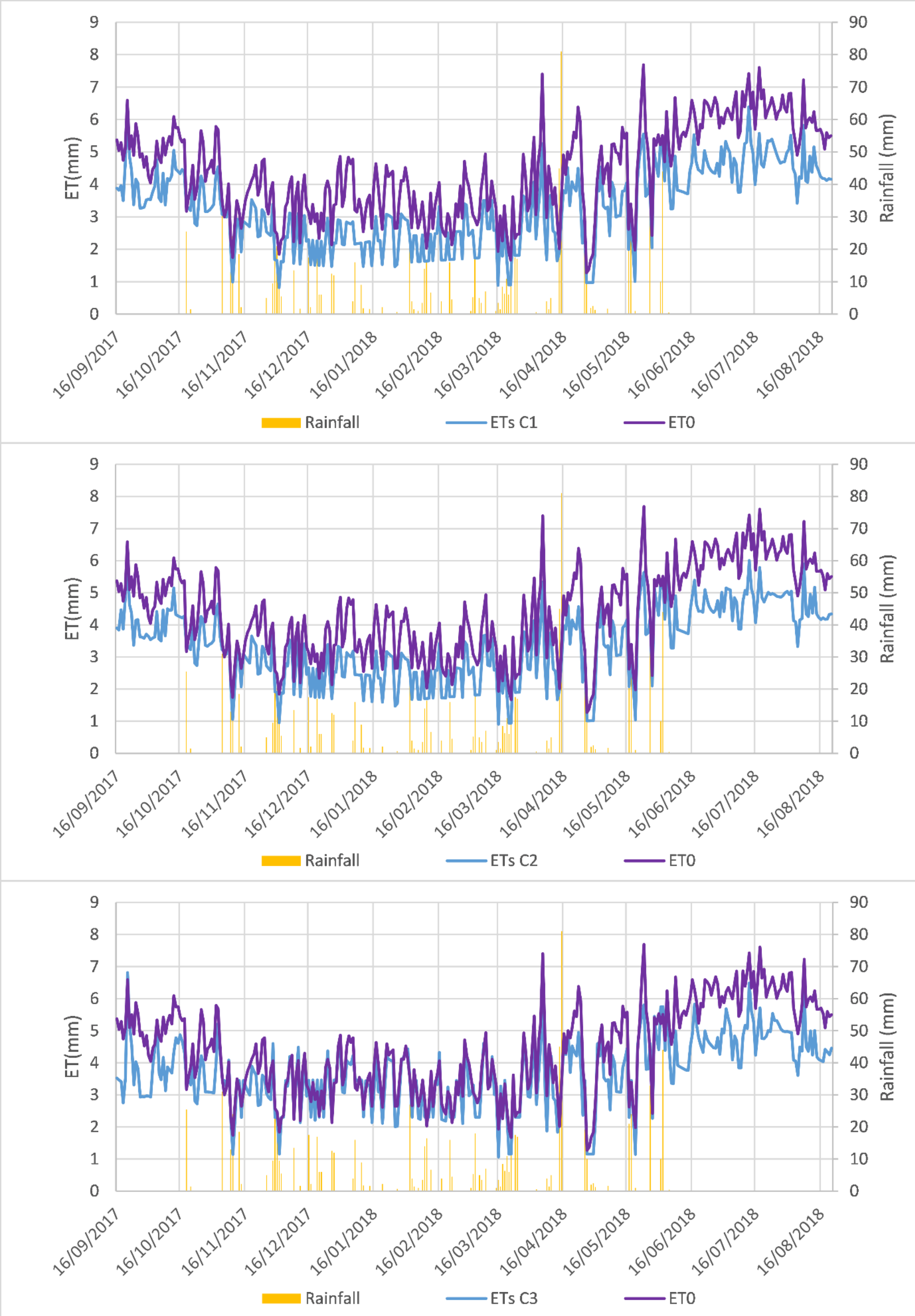

Figure 6. Variation of simulated ET and measured ET0 on fields in the study area during the wet season (2017-2018)

It can be noticed that the amount irrigated in the wet period is less than that irrigated in the dry period (by 40% for citrus and 30% for peaches). Generally, the wettest months are the least irrigated. A difference in estimated evapotranspiration is noted between the dry and wet periods (13% for citrus and 1% for peaches). This difference can be explained by the variation in temperature and humidity recorded during the two seasons. Overall, the inputs (Rain and Irrigation) are close to the evaporative consumption (ET) for both seasons (Figure 7). The variation in soil water content is greater in wet periods than in dry periods.

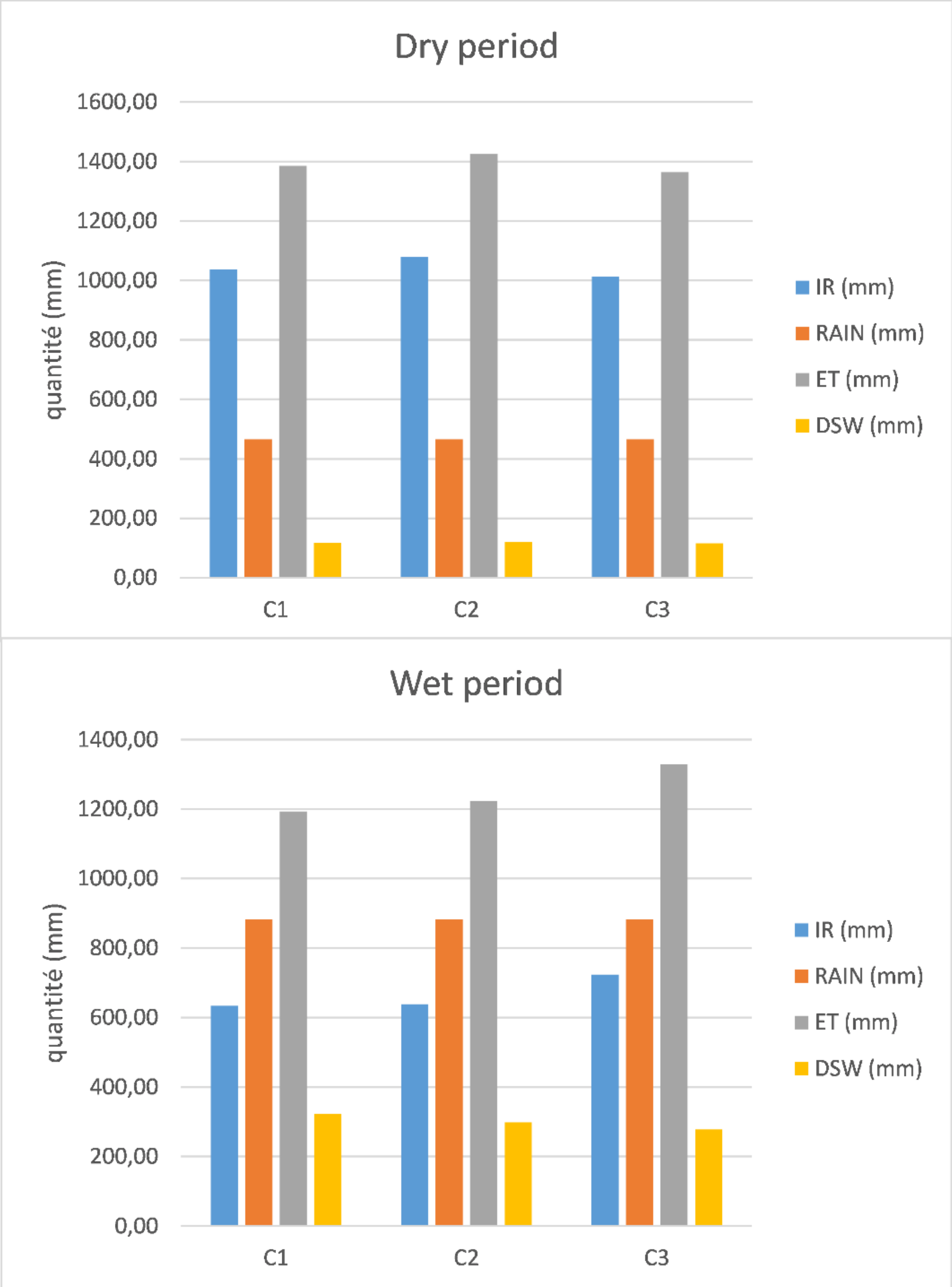

Figure 7. Water balance for the three fields in dry and wet periods

Table 2. Monthly values of irrigation and evapotranspiration modeled by SAMIR

Months	DRY			WET			Diff Wet/Dry	
	rain (mm)	IR (mm)	ET (mm)	rain (mm)	IR (mm)	ET (mm)	IR %	ET %
Field C1								
Sept.	3,5	124,74	73,93	23,6	137,12	105,83	9,93	43,16
Oct.	51,8	108,37	135,67	27	104,41	118,02	-3,66	-13,01
Nov.	30,3	80,02	102,34	136,2	32,42	86,46	-59,49	-15,52
Dec.	109,1	0,00	92,07	124,4	0,00	66,98	-	-27,25
Jan.	57,2	19,05	84,93	35,3	0,00	73,96	-100,00	-12,92
Feb.	15,6	71,99	90,66	98,7	0,03	60,09	-99,95	-33,72
Mar.	85,6	32,92	104,71	127,6	0,00	74,56	-100,00	-28,80
April	70,6	53,06	113,59	170,9	0,00	89,52	-100,00	-21,19
May	25,7	123,29	148,56	82	13,64	110,21	-88,93	-25,82
June	14,9	131,72	150,61	54,5	76,19	132,69	-42,15	-11,90
July	1	176,94	174,54	1	142,89	151,21	-19,25	-13,37
August	1	115,06	113,49	1	127,32	123,18	10,66	8,54
SUM	**466,3**	**1037,15**	**1385,10**	**882,2**	**634,02**	**1192,70**	**-38,87**	**-13,89**
Field C2								
Sept.	3,5	119,81	74,89	23,6	145,93	107,55	21,80	43,61
Oct.	51,80	111,51	138,66	27	101,11	118,90	-9,33	-14,25
Nov.	30,3	97,44	106,85	136,2	30,99	90,90	-68,19	-14,93
Dec.	109,1	0,15	96,42	124,4	0,00	76,82	-100,00	-20,33
Jan.	57,2	18,83	87,48	35,3	0,00	78,52	-100,00	-10,24
Feb.	15,6	82,29	95,82	98,7	0,07	62,29	-99,91	-34,99
Mar.	85,6	33,20	111,18	127,6	0,00	77,06	-100,00	-30,69
April	70,6	56,24	118,42	170,9	0,00	91,54	-100,00	-22,69
May	25,7	128,00	151,83	82	17,79	112,72	-86,10	-25,76
June	14,9	137,42	153,24	54,5	74,87	133,62	-45,52	-12,81
July	1	175,54	176,28	1	149,81	150,64	-14,66	-14,55
August	1	118,73	114,20	1	118,52	122,26	-0,18	7,06
SUM	**466,3**	**1079,17**	**1425,27**	**882,2**	**639,09**	**1222,83**	**-40,78**	**-14,20**
Field C3								
Sept.	3,5	126,07	68,94	23,6	121,75	100,41	-3,43	45,66
Oct.	51,80	99,78	132,26	27	105,95	116,68	6,18	-11,78
Nov.	30,3	74,70	102,76	136,2	47,96	98,03	-35,80	-4,60
Dec.	109,1	0,93	98,71	124,4	0,00	97,47	-100,00	-1,25
Jan.	57,2	44,77	93,65	35,3	48,36	105,61	8,01	12,78
Feb.	15,6	70,55	94,22	98,7	11,93	81,92	-83,08	-13,06
Mar.	85,6	33,55	105,18	127,6	0,00	92,73	-100,00	-11,83
April	70,6	44,22	111,47	170,9	2,96	101,92	-93,30	-8,57
May	25,7	127,36	146,69	82	36,90	118,13	-71,02	-19,47

June	14,9	131,77	147,35	54,5	77,49	136,96	-41,19	-7,05
July	1	161,97	163,27	1	151,81	155,48	-6,27	-4,77
August	1	98,00	99,50	1	118,45	122,69	20,87	23,30
SUM	**466,3**	**1013,67**	**1363,99**	**882,2**	**723,56**	**1328,03**	**-28,62**	**-2,64**

The annual water balance was calculated for both seasons (Figure 8) and revealed that: for the dry season (2020/2021): the cumulative irrigation simulated by the SAMIR model is around 357038.55 m^3, whereas the irrigator used 305280 m^3 , i.e. 14.5% less than the volume estimated by the model. Rainfall was 466.3mm. The difference between the simulated and observed volumes is around 12%, 16% and 10% for fields C1, C2 and C3, respectively.

For the wet season (2017/2018): Rainfall is around 882.2mm. The simulated irrigation is estimated at 223063.00m^3, whereas the volume used in reality is 190794.93m^3; i.e. 14.47% less than the model. The differences between the simulated and observed volumes are estimated at 10%, 12% and 21% for fields C1, C2 and C3 respectively.

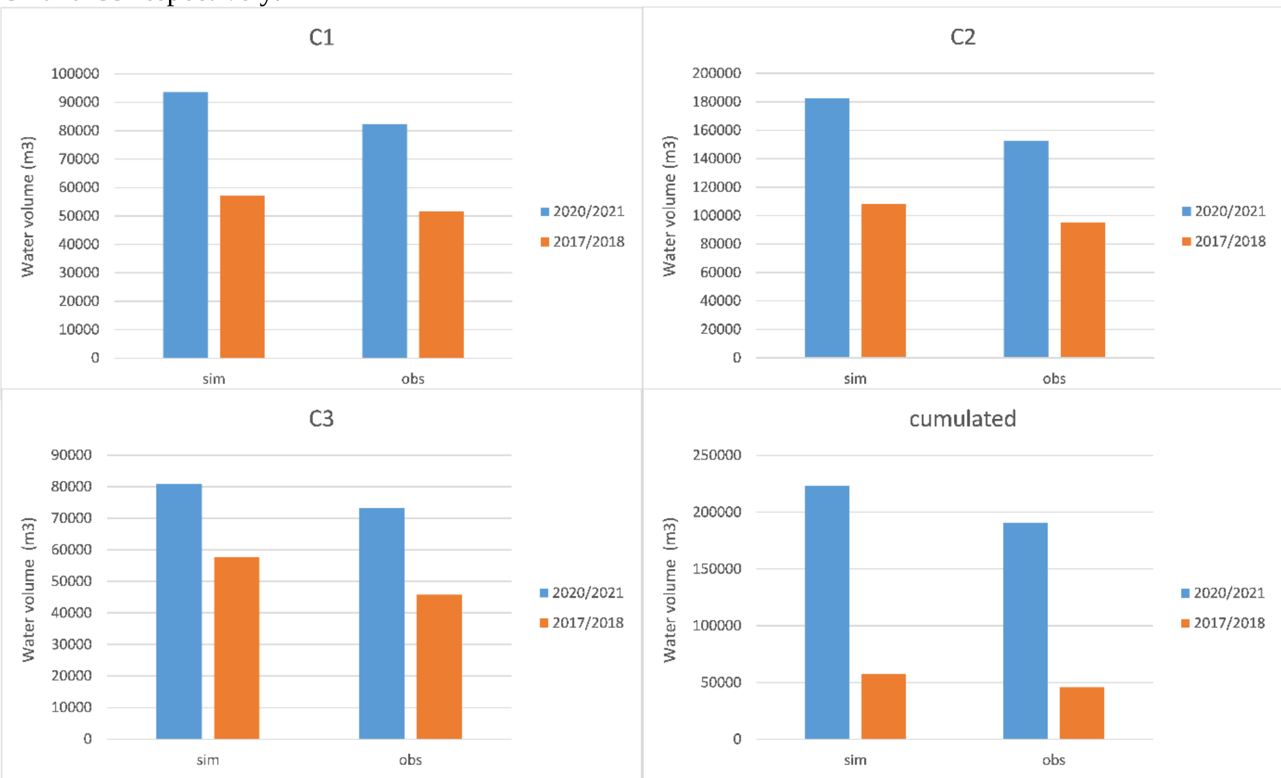

Figure 8. Water balance for the three fields in the study area during both periods

The approach used in SAMIR is simple and very effective for both the estimation of evapotranspiration and the elaboration of water balance of irrigated crops in order to ensure optimal irrigation and better yield. This approach has been used and validated in other studies conducted in similar and different regions (Er-Raki *et al.* 2009 ; Kharrou et al. 2021; Saadi et al. 2015). A study on the water requirements of citrus was carried out in Egypt by Nizinski et al. (2014) using the Penman-Monteith method. They found an annual irrigation depth of 994.3mm which is slightly different from our simulated results.

Toureiro et al. (2017) found that SAMIR overestimates irrigation requirements by about 20% for maize grown in a Mediterranean climate, which is consistent with our results. Another study was carried out by Tazkerit et al. (2018) on citrus fruits in a plot located in Macta watershed, west of Algeria, under a Mediterranean climate. It gave an estimated annual irrigation of 950.18mm for a rainfall of 320mm, which is slightly different from our simulated results. The results obtained by Saadi (2015) in the plain of Kairouan in Tunisia are also close and comparable to our results.

Irrigation levels estimated by SAMIR are generally satisfactory, with the exception of December, when values are very low. This is probably due to the amount of rain that fell during this month, which represents the maximum of the year. Compared to the ET, the modeled irrigations are low, especially in summer.

The results of this work can be used in the management of irrigation in the current perimeter as they can also be extrapolated to other perimeters where the problem of water availability is noticed. Currently, the availability of water resources poses major problems for ensuring adequate irrigation to provide the optimum production necessary for the country's food security. Based on this concern, the results of this work are supposed to be of considerable value to decision makers and managers of water resources and irrigation in this region as well as in other regions.

4. CONCLUSION

In this study, we used remote sensing and SAMIR software to estimate evapotranspiration and determine irrigation volumes at the plot level in a semi-arid area. The absolute percentage differences found through this study vary between 10% and 16% for the dry season with an average value of around 14.5% and between 10% and 20% for the wet season with an average value of around 14.47% which indicates that the seasonal and annual volumes estimated by this method are acceptable. A strong consistency is observed between the simulated ET and ET0 values throughout the growing season with very close variation curves.
Remote sensing has been shown to be an effective tool for monitoring irrigation volumes and determining the spatial and temporal distribution of crop water requirements at field level using soil water balance models. The SAMIR model has also shown its ability to provide good estimates of irrigation water requirements and could be applied to assess irrigation water use in large-scale irrigated areas (Perimeter and above). It is important to note that this study shows the possibility of combining monitoring information (rainfall, temperature, ET0, pedology,...) with a water balance model based on remote sensing to propose an approach that can be a necessary decision support tool for irrigation managers to improve irrigation scheduling for efficient and cost-effective water management for agricultural irrigation, especially in arid and semi-arid areas.

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