Bucket water mass balance model applied to the rice growing areas of Lower Mondego (Portugal) and Bafra (Turkey) Irrigation Districts

Authors: *Blanca Cuadrado-Alarcón*[1], *Melih Enginsu*[2], *Isabel Pedroso de Lima*[3], *Özgür Azapoglu*[2], *Romeu Gerardo*[3], *Luciano Mateos*[1]

Affiliation: [1] Instituto de Agricultura Sostenible, CSIC, 14004 Córdoba, Spain; [2] Black Sea Agricultural Research Institute, PK. 39 Samsun, Turkey; [3] University of Coimbra, 3041 Coimbra, Portugal.

Abstract

The MEDWATERICE project includes upscaling of the on-farm irrigation management improvements to the irrigation district scale. A 'bucket' mass balance approach was applied to two study cases in the project: i) Quinta do Canal, in the Lower Mondego irrigation district (Portugal), with 322 ha of rice production and supplied by the Mondego River; and ii) the west side of the Bafra irrigation district (Turkey), with 6200 ha of irrigated land (5100 ha devoted to rice cultivation), and supplied by the Kızılırmak River. In the two areas, water is supplied by a branched hierarchical open channel flow network, with no water reuse.

The application of the 'bucket' mass balance approach requires the conceptualization of the systems using topological flow diagrams. After that, the model computes daily water balances for the irrigation units, based on the aggregation of the paddy fields that are served by each secondary canal. The water balance components are evapotranspiration, percolation, surface drainage (if present), precipitation and irrigation. Available data of actual water supply were used to evaluate the model, which will be used to examine the impact at district scale of the implementation of on-farm water saving practices.

Keywords: 'bucket' model, water balance, irrigation, rice.

1. Introduction

The rice irrigation management improvements studied within the scope of the MEDWATERICE project include different options: dry seeding, AWD (alternate wetting and drying) irrigation, surface and subsurface drip irrigation, multi-outlet hybrid irrigation, or drainage water recycling.

To upscale those on-farm improvements to the irrigation district scale, different methodologies have been applied, including the 'bucket' mass balance approach (Mateos et al., 2000). This approach was applied to most of the study cases in the project. In this paper, we report the application to (i) Quinta do Canal, in the Lower Mondego irrigation district (Portugal), supplied by the Mondego River; and (ii) the west side of the Bafra irrigation district (Turkey), supplied by the Kızılırmak River.

The two areas are traditionally rice growing areas, and a good part of their economy is dependent on rice production. In both cases, water is supplied by a branched hierarchical open channel network, with no water reuse.

The Quinta do Canal pilot area devotes 322 ha to rice production (Figure 1), part of the 5000 ha of rice grown in the Lower Mondego irrigation district. Water is supplied by 4 secondary canals deriving for the district main canal. Quinta do Canal faces poor soil drainage and relatively high salinity. Rice cycle is around 5 months, typically from April/May to September/October. The area is characterized by a small size of the holdings (only about 20% of the agricultural holdings have an area larger than 2.5 ha) and relatively low yield (6 t/ha/year), which forces the need for a complementary family income. Irrigation is traditionally by flooding, and it is estimated that the current irrigation practice requires on average about 16,390 m^3/ha/year (e.g., Oliveira et al., 2022), at the irrigation district scale.

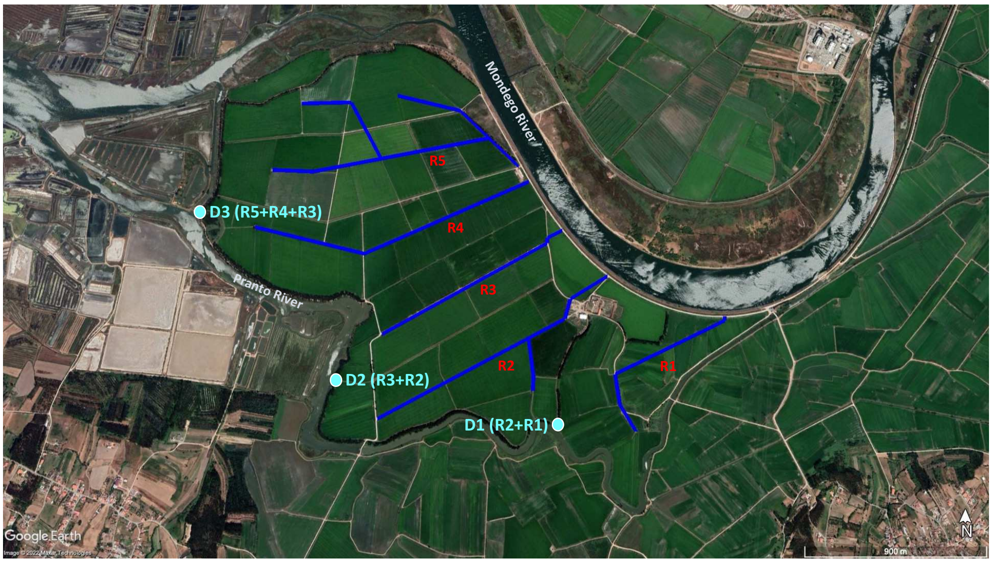

Figure 1. Area of Quinta do Canal and identification of the five inlets from the main irrigation canal, the secondary canals (R) and 3 drainage outlets (D) to the Pranto River (Source: Google Maps, 2022).

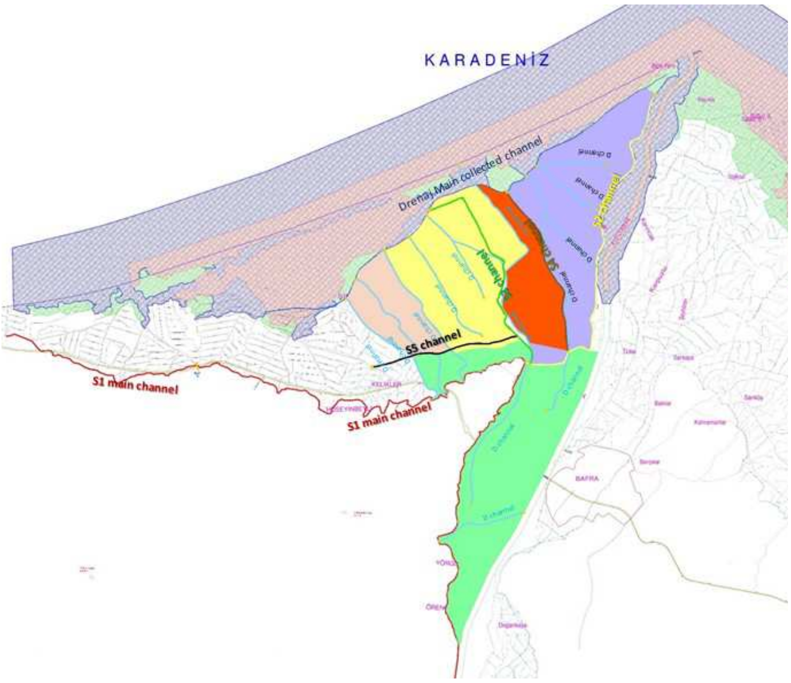

Figure 2. Bafra plain and irrigation sectors (in colour) in the Bafra Plain west side Irrigated Area.

The west side of the Bafra irrigation district (Figure 2) encompasses 6200 ha of irrigated land, including rice, maize, and horticulture, of which 5100 ha are devoted to rice cultivation.

Irrigation water used in the flooded irrigated rice fields is about 24,000 m^3/ha according to the General Directorate of State Hydraulic Works. The fields are bordered to prevent surface drainage, while a subsurface drainage system evacuates field water percolation through a drainage ditch network. Crop rotation is a common practice in the area mainly to prevent the soil from a long exposition to anaerobic conditions. Usually, rice is cultivated continuously during 5 to 7 years, and then the land is rotated to another crop.

2. Materials and methodology

Water circulation in the two study sites has been modelled with the 'bucket' mass balance approach (Mateos, 2008). The application of the 'bucket' approach requires first a conceptualization of the systems using topological flow diagrams. This diagram is determined by the layout of the hierarchical branched distribution networks and of the drainage network that collects return flows from the fields. The fields that share irrigation canal and drainage ditch are aggregated into irrigation units.

The water balance model computes daily balance components for each irrigation unit. These components are evapotranspiration, percolation, surface drainage (if present), precipitation and irrigation. Figure 3 shows a diagram of the water balance components computed for an irrigation unit.

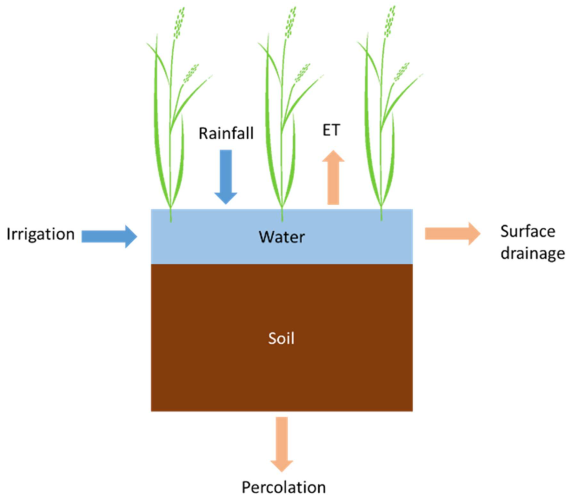

Figure 3. Water fluxes in a paddy field.

Crop evapotranspiration (ET_{ci}) is calculated with the single crop coefficient method. The daily crop coefficient will be considered as 1.05 when the paddy is flooded and before rice plants emerge above the water surface, increasing to 1.20 when the crop is fully developed, and dropping to 0.6, just before harvest, according to FAO (Allen et al., 1998). The **rainfall daily value (R_i)** and crop evapotranspiration daily value (ET_{ci}) are expressed in cubic meters in the irrigated unit. The i subindex in all the equations represents the day in the balance, and $i-1$ indicates the value of the day before. Daily data for reference evapotranspiration and daily rainfall is available in both study cases from nearby weather stations.

Percolation (P_i) is estimated from a daily rate (K) introduced as a soil property expressed in mm of percolation per day and unit of area. P_i , expressed in cubic meters, is:

$$P_i = Area * K$$

When the soil is saturated, percolation rate is equal to *K*, and when it is not saturated, percolation rate is considered zero.

For the balance purposes, the profile is divided into two layers, (1) the soil layer, which has a **soil water content (SWC_i)**, expressed in cubic meters, and (2) the free water layer, with a volume named **free water volume (FWV_i).**

The water balance accounts for management practices, through a parameter **called target free water depth ($TFWD_i$)** that measures the level of required free water layer in the field. This is a daily management input that varies depending on the area and the farmer. The $TFWD_i$ is transformed into **a target free water volume ($TFWV_i$)** using the area of the irrigation unit.

In the Quinta do Canal case study, **surface drainage (D_i)** is only used when the paddy field needs to be emptied. Then, the model simulates drainage by lowering $TFWD_i$ along 14 days. In the Bafra case study, there is no surface drainage (fields are emptied through percolation).

The daily **irrigation needs (I_i)** are calculated through the water balance with the objective of reaching $TFWV$ of the day:

$$I_i = TFWV_i - FWV_{i-1} + SWC_{SAT} - SWC_{i-1} + ETc_i - R_i + P_i + D_i$$

However, the resulting **irrigation (I_i)** is subjected to two conditions:

- ✓ If the value obtained is lower than 0, then I_i remains 0.
- ✓ If the value obtained is higher than the maximum supply capacity, I_i will be the maximum supply capacity.

Finally, SWC_i and FWV_i are calculated as follows:

$$SWC_i = SWC_{i-1} + FWV_{i-1} - ETc_i - P_i + R_i + I_i - D_i$$

If $SWC_i < SWC_{SAT}$, then $FWV_i = 0$

If $SWC_i > SWC_{SAT}$, then $SWC_i = SWC_{SAT}$

and $FWV_i = FWV_{i-1} - SWC_{SAT} + SWC_{i-1} - ETc_i - P_i + R_i + I_i - D_i$

Data used to run the model included cropped area by irrigation unit, weather data from a nearby station, and some measurements of soil texture. In Quinta do Canal, Sentinel-2 satellite imagery of the study area, with 10 m full spatial resolution and already atmospheric corrected, was downloaded from the Copernicus open-access website (https://sci-hub.copernicus.eu) and used to derive site specific crop coefficients derived from the vegetation index NDVI (Mateos et al., 2013; González-Dugo et al., 2013).

Irrigation district estimations of the water supply for the different irrigation units were used to evaluate the results of the model.

3. Results and discussion

3.1. Conceptualization of the case studies

Figures Figure 4 and Figure 5 represent the layout of the two case studies modelled with the 'bucket' approach.

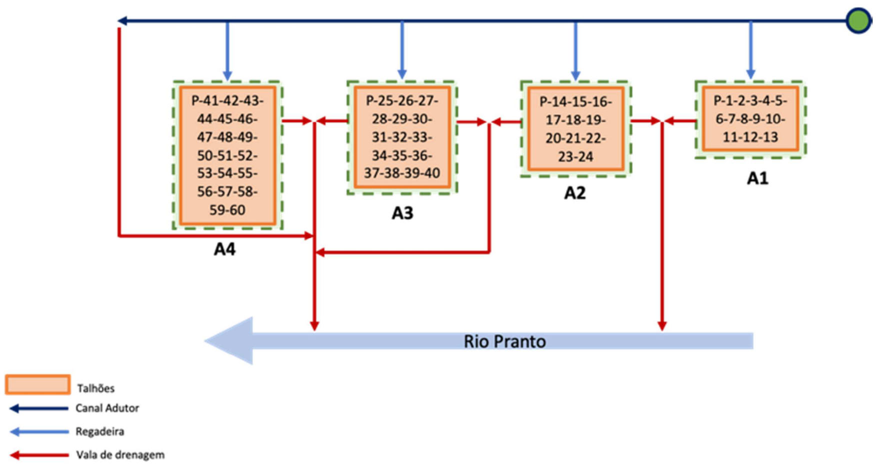

Figure 4. Conceptual layout of the hydraulic arrangement for the 'bucket' modelling approach applied to the Quinta do Canal. See Figure 1 for relating the case study map with the mass circulation diagram.

Figure 4 shows the four irrigation units defined for the Quinta do Canal case study. Water flow from the main canal is represented with a dark blue arrow, and the flow diverted into the four secondary canals is represented with light blue arrows. The fields supplied by each secondary canal were grouped into irrigation units A1 to A4. Surface drainage and percolation that ends up in the surface drainage network through lateral fluxes is represented by the red arrows that lead to the Pranto River.

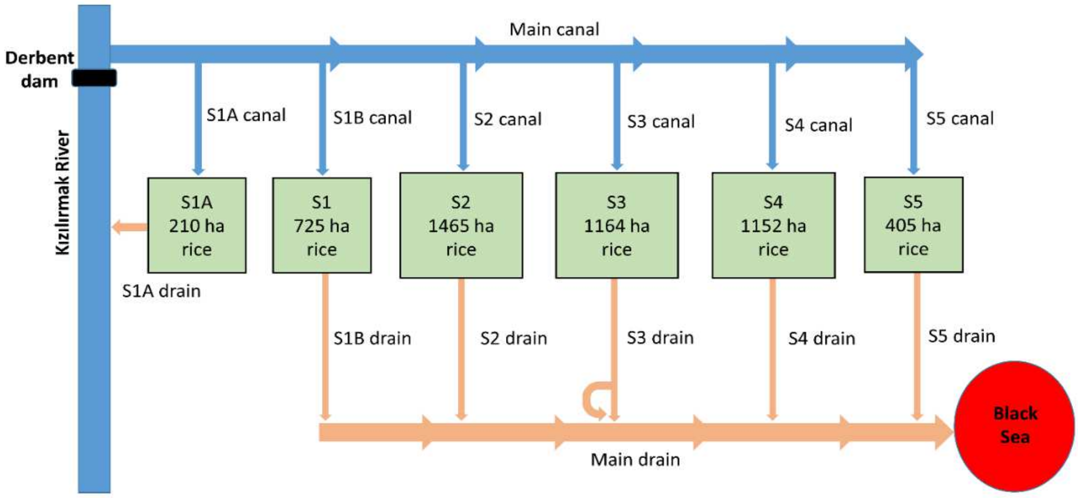

Figure 5. Conceptual layout of the hydraulic arrangement for the 'bucket' modelling approach applied to the Bafra Plain west Side Irrigated Area. See Figure 2 to relate with case study map.

Figure 5 shows the six irrigation units defined for the Bafra Plain west side case study. Water flows from the main canal and is diverted into six simplified secondary canals (represented by light blue arrows). The secondary canals serve the irrigation units S1A to S5. Percolation that ends up in the drains through lateral fluxes is represented by the orange arrows that lead to the Kızılırmak River or to the Black Sea.

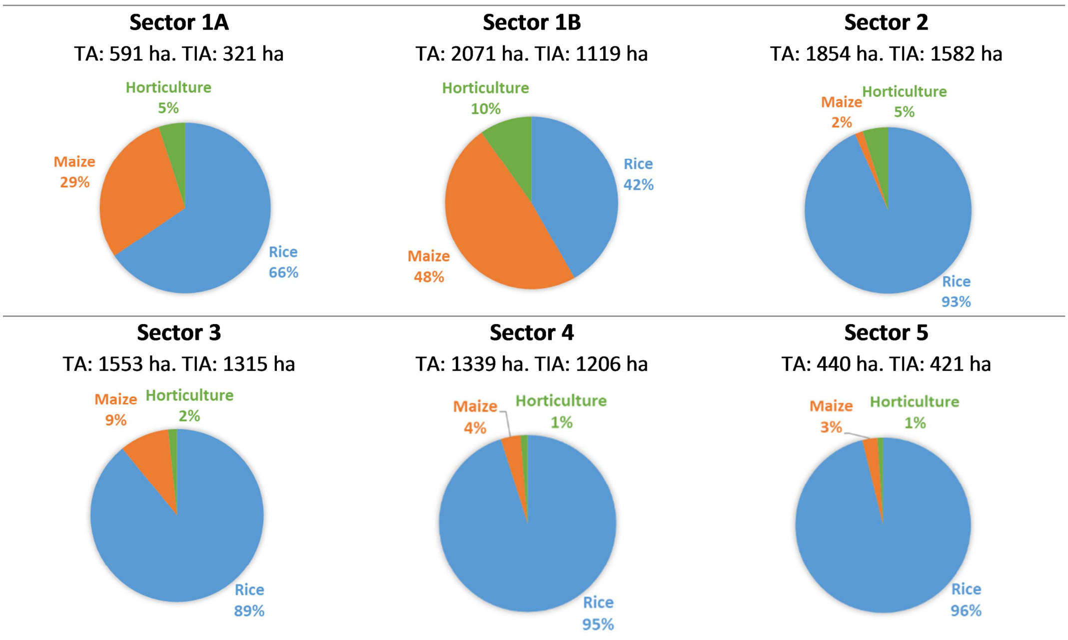

Figure 6. Irrigated crop distribution in the 6 irrigation units of Bafra Plain west side. TA refers to total area, and TIA is the total irrigated area.

The cropping pattern in the Bafra west side case study included: rice, barley, Vicia sativa, maize, melon, cauliflower, wheat, and many others. Some crops are not irrigated, although some supplementary irrigation might be applied when the weather is not optimal for the crop development. To model the water balance, irrigated crops have been classified in three groups: rice, maize, and horticulture. The cropping areas obtained are shown in Figure 6.

3.2. Water balance results in Quinta do Canal

The water fluxes obtained with the application of the water balance model to each irrigation unit of Quinta do Canal are presented in Figure 7. And the aggregated values are presented in Figure 8.

Table 1 presents total values for the modelled year. The average irrigation obtained is 1,442 mm/year.

Surface drainage occurs at two times, in June for pesticides treatment and before harvest. Irrigation has the higher peak at the beginning of the season when the paddies are filled up with water.

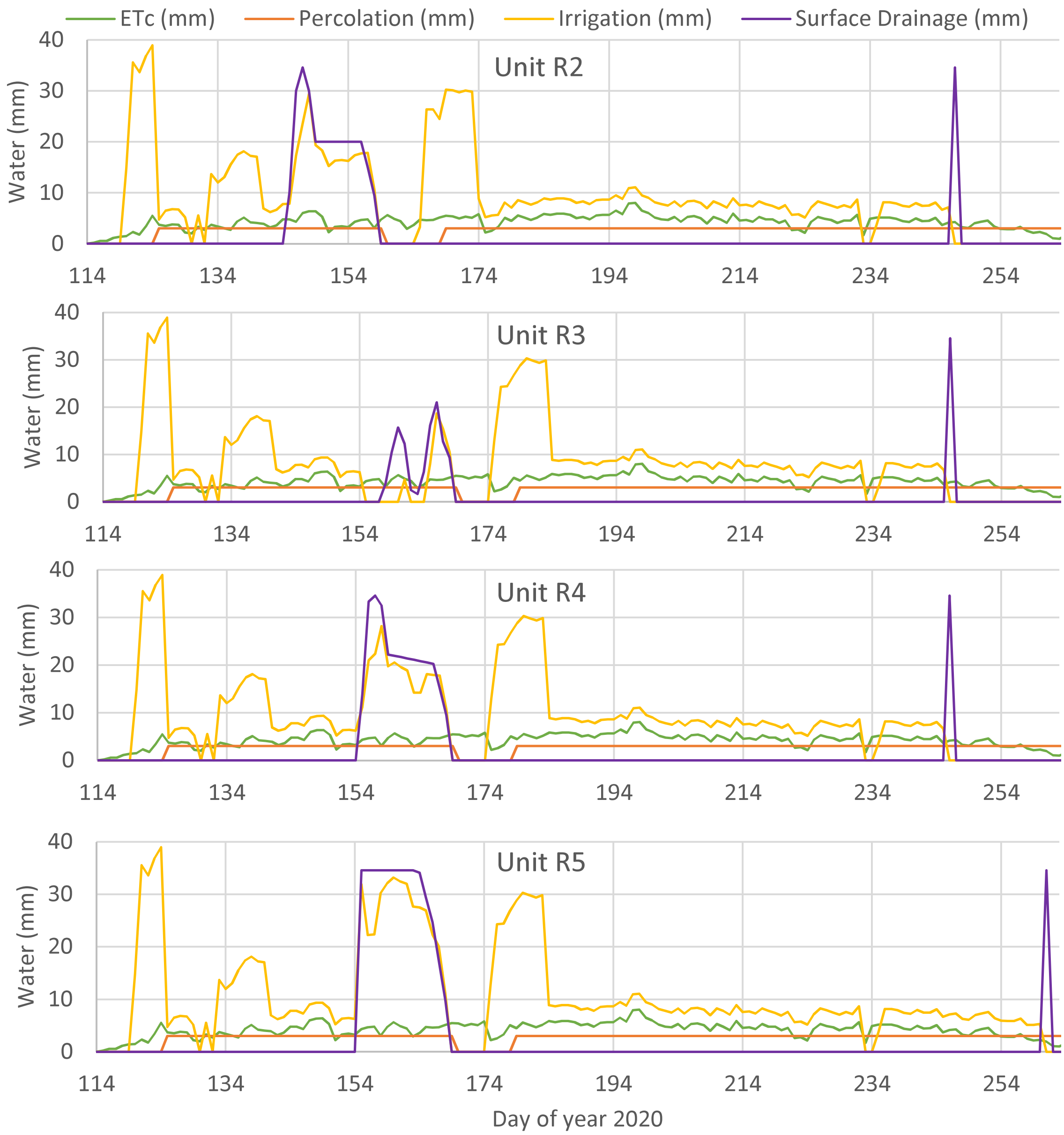

Figure 7. Water balance results for irrigation units in Quinta do Canal (Portugal).

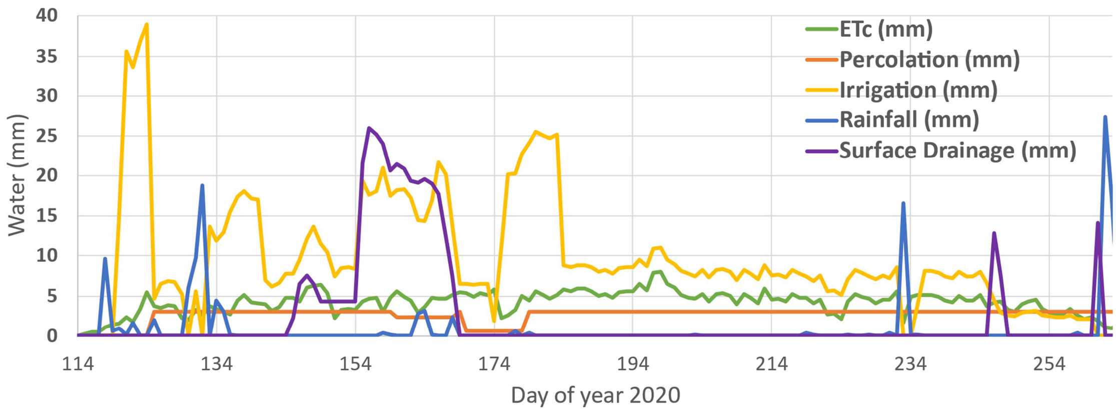

Figure 8. Results for total daily water fluxes obtained from the mass balance in Quinta do Canal (Portugal).

Table 1. Modelled water balance fluxes for the irrigation season 2020 in Quinta do Canal.

Total values	Water (mm)
ETc	633
Rainfall	134
Percolation	402
Surface drainage	358
Irrigation	1442
Increase in water content	183

3.3. Water balance results in Bafra

Table 2 shows total simulated water balance fluxes for year 2020. The values presented in the table encompasses all three simulated crop types. Average supply modelled for rice is highest, with an average value of 3,508 mm/year.

Table 2. Modelled water balance fluxes for the irrigation season 2020 in Bafra plain west side.

	ETc (m^3/ha)	Perc (m^3/ha)	Irrig (m^3/ha)	Rain (m^3/ha)
S1A	534	1,153	17,42	85
S1B	525	3,845	43,96	87
S2	541	1,625	22,99	78
S3	542	2,593	32,71	80
S4	544	1,662	23,48	78
S5	545	1,681	23,79	78

Detailed graphs of water balance components for the different irrigation units are presented in Figure 9. Daily values resulting from the water balance are shown in Figure 10. FWV represents the variation of the water level in the rice fields (determined by management decisions) and explains the three peaks that appear in the irrigation curve, to fill up the paddies.

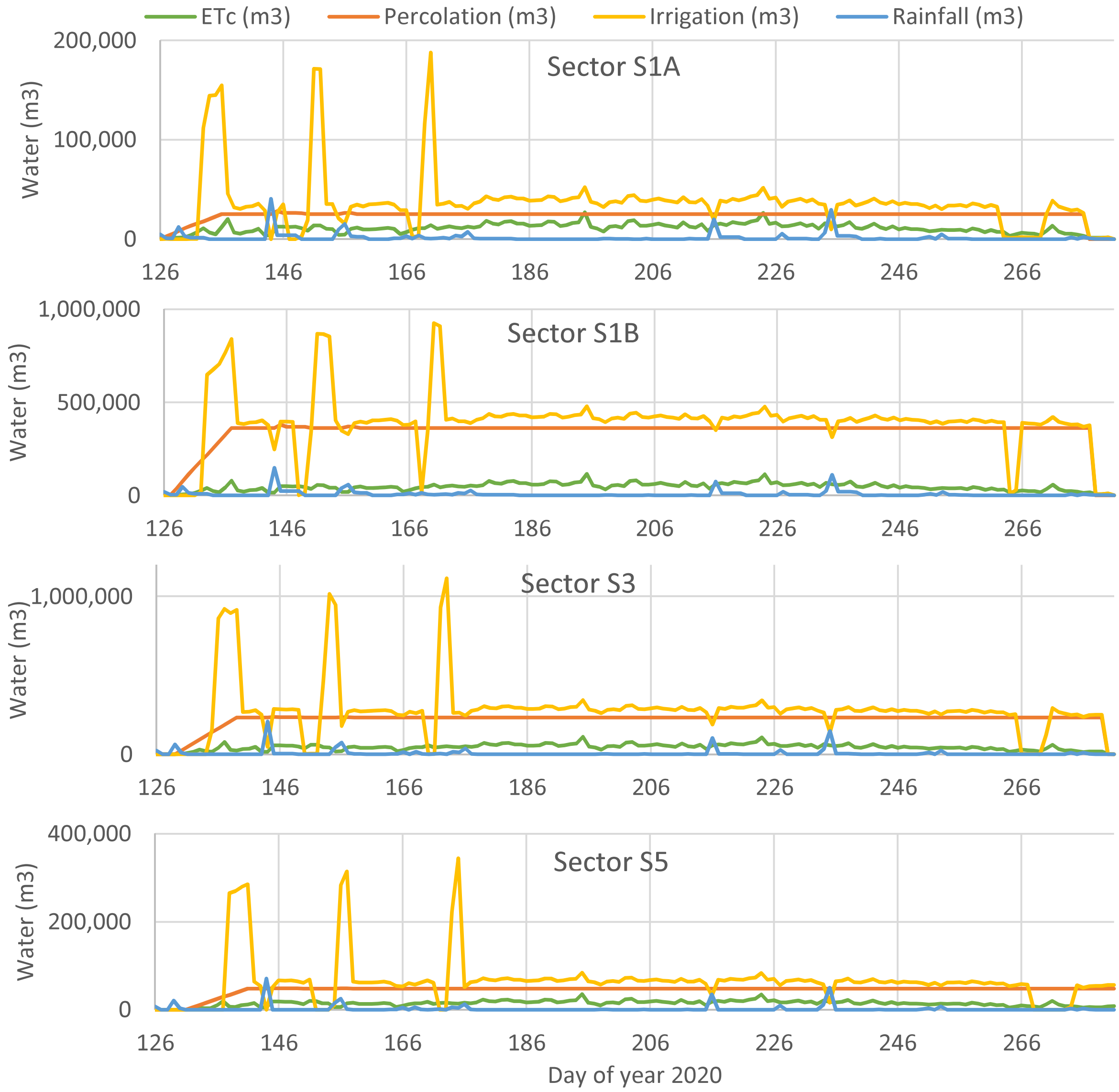

Figure 9. Results of the daily water balance in some of the sectors in Bafra Plain left Side (Turkey).

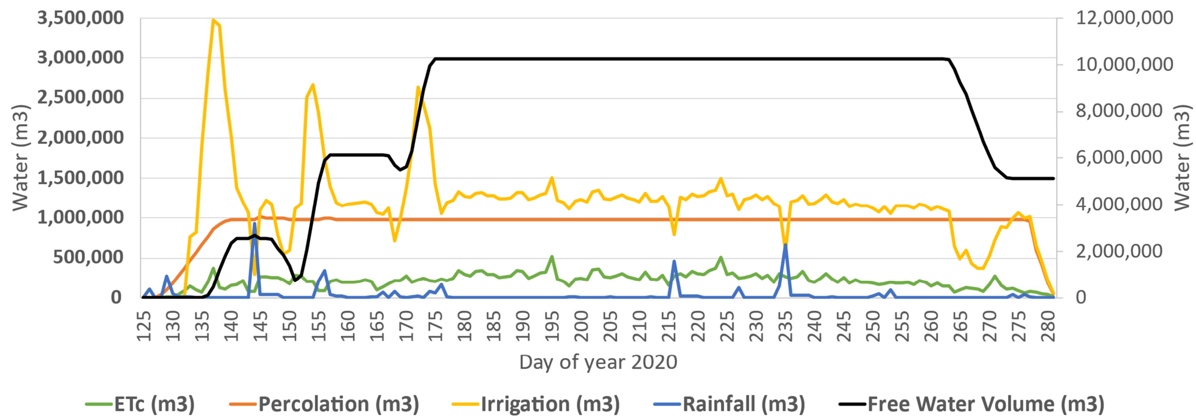

Figure 10. Results of the total estimated daily water fluxes after the mass balance in Bafra Plain west side (Turkey). Free water volume (FWV) values correspond to the y axis on the right, the rest of the results represented correspond to the y axis on the left.

3.4. Discussion

Available data on estimated water supply were used to evaluate the model, which could be used to upscale on-farm current management at district scale. Daily supply data in the Quinta do Canal case study was compared with the modelled irrigation requirement (Figure 11).

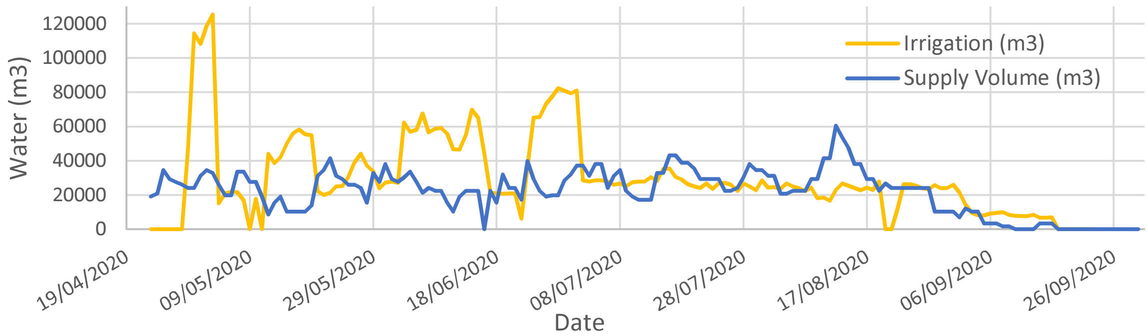

Figure 11. Comparison of estimated and modelled data on irrigation supply for Quinta do Canal, rice cultivation season 2020.

Table 3. Modelled and estimated total supply volumes in Quinta do Canal, season 2020.

	R2 (m^3)	R3 (m^3)	R4 (m^3)	R5 (m^3)	Total (m^3)	Total (m^3/ha)	Total (l/s/ha)
Estimated	639,360	453,600	864,000	1,595,592	3,552,552	11,033	0.829
Simulated	962,036	571,138	998,688	2,110,644	4,642,506	14,418	1.084

Table 3 includes the seasonal estimated and modelled water supply for each irrigation unit and the total value. Estimated supply values (11,033 m^3/ha/year for the entire study area) were lower than simulated ones, 3,400 m^3/ha/year on average. This difference could be due to inaccurate estimation of the percolation rate, which has been estimated from two soil texture analyses. But it could also be caused by an inaccurate estimation of the water supplied to the irrigation units, used to evaluate the model. As mentioned in the introduction section studies such as Oliveira et al. (2022) estimate rice irrigation in the area in 16,390 m^3/ha/year whereas our estimates reach only 11,033 m^3/ha/year. A better understanding of percolation in the area would help understand if the water balance model is simulating correctly the processes occurring in the field.

Table 4. Estimated and modelled water flows, irrigation season 2020 in Bafra plain west side.

Sector	Irrigated area (ha)	Estimated water supply (m^3/ha/year)	Modelled water supply (m^3/ha/year)	Total volume of estimated supply (m^3/year)	Total volume of modelled supply (m^3/year)
S1A	320.9	79,416	17,422	25,484,586	5,590,818
S1B	1118.6	79,416	43,958	88,834,710	49,171,720
S2	1581.8	36,086	22,989	57,081,024	36,364,653
S3	1315.4	31,201	32,715	41,041,728	43,033,490
S4	1206.0	18,776	23,479	22,643,712	28,315,293
S5	421.0	59,388	23,794	25,002,432	10,017,151
Global	5963.7	43,611.9	27,393	**260,088,192**	**172,493,126**

In the Bafra plain west side case study, available supply data were an average seasonal value of discharge in the distribution open channels, based on the design of the channels and assuming a constant water depth. The comparison between the estimated and modelled values is shown in

Table 4. Globally, modelled supply water was lower than the estimated supply. One possible reason for this discrepancy is that the channels might not always work at their full capacity.

Nevertheless, simulated results are of the same order than the supply data, but the quantity differs by more than a third. Particularly, sector S1A and S1B have very high estimates, which might be because those estimates correspond to the main channel, that continues further where the irrigation system is still under construction, thus its capacity overestimates actual discharge.

In general, crop water allocation is higher in Bafra plain than in Quinta do Canal, which is consistent with their climates and their water stress. Moreover, percolation is higher in Bafra plain than in Quinta do Canal, which will reinforce the difference in irrigation needs between the two areas.

4. Conclusions

The study cases of Quinta do Canal (Portugal), with 322 ha, and the west side of the Bafra irrigation district, with 6200 ha, have been modelled with the 'bucket' mass balance approach. A conceptualization of each system was first carried to apply the model. Results for the irrigation season 2020 showed a response to climate conditions and soil characteristics. Modelled results estimate irrigation needs of 14,420 m^3/ha/year for the Quinta do Canal area and 27,393 m^3/ha/year for the west side of the Bafra irrigation district.

Comparison with available supply data show a discrepancy with the modelling results, but the order of magnitude is the same. The reason for this gap is unknown due to the uncertainty in the estimated supply data available for model evaluation, and in some of the parameters used for the modelling exercise, which would in some cases require a more intense monitoring activity; this is particularly true for the percolation rates.

There is a considerable amount of potential work to be carried in the two areas to improve the results and obtain more information, such as monitoring discharges and solutes at certain locations upstream and downstream; this would allow to improve the water mass balance and introduce the solute mass balance in the modelling process.

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