Effects of the implementation of the Alternate Wetting and Drying (AWD) irrigation strategy in an Italian rice district: lesson learned by applying a semi-distributed agro-hydrological model

Authors: Giulio Gilardi[1], Alice Mayer[1], Michele Rienzner[1], Giovanni Ottaiano[1], Marco Romani[2], Elisa Cadei[2], Olfa Gharsallah[1], Arianna Facchi[1]

Affiliation: [1]Department of Agricultural and Environmental Sciences - Production, Landscape, Agroenergy (DiSAA), Università degli Studi di Milano, via Celoria 2, 20133 Milan (Italy); [2]Centro Ricerche sul Riso, Ente Nazionale Risi (ENR), 27030 Castello D'Agogna (Italy)

ABSTRACT

The north-western part of the Padana Plain in northern Italy is the most important rice district in Europe and the second in the Mediterranean basin after Egypt (230,000 ha in Italy and 450,000 ha in Egypt). Traditionally, rice irrigation was based on wet seeding and continuous flooding until to approximately three weeks before harvesting. Recently, due to an increased frequency of water scarcity periods and competition for water among agricultural and non-agricultural uses, water saving techniques are being introduced. Although these techniques must be firstly tested on a field scale, it is important to estimate their effects on the overall water resources system. In fact, especially in rice areas characterized by shallow aquifers, the strong interaction between traditional irrigation methods and phreatic aquifer levels leads to a re-use of the irrigation water which contributes to water flows in rivers and irrigation networks thus increasing the overall irrigation efficiency of rice areas.

An experimental platform was set up in the core of the Italian rice area (Castello D'Agogna, PV) to compare three rice irrigation management strategies over two agricultural years (2019-2020): wet seeding and traditional flooding (WFL), dry seeding and delayed flooding (DFL), and a 'safe' wet seeding and alternated wetting and drying irrigation (AWD-safe). Irrigation water use was monitored by the installation of flow meters, and all the other soil water balance components were quantified. At the field scale, water savings of AWD and DFL were found to be about 20% and 14% compared to WFL without penalizing rice production, while the temporal distribution of irrigation water needs and percolation fluxes changed as a function of the irrigation strategy.

Results achieved in the experimental fields were used in the parametrization of a semi-distributed and physically-based agro-hydrological model aimed at stimulating the overall irrigation system efficiency of a rice district (about 1000 ha) located close to the experimental platform. The modelling framework consists of three sub-models: i) one for the agricultural area, based on the physically-based SWAP model; ii) one for the channel network percolation; iii) one for the groundwater level dynamics. After investigating the current water dynamics and irrigation system efficiency for the period 2013-2020, the modelling system was used to explore the effects on the water resources system of some 'what-if scenarios', such as the adoption of a AWD-safe rice irrigation strategy in the whole district. The AWD-safe technique after wet seeding seems to be a good compromise solution in terms of recharging groundwater and reducing the peak irrigation request for rice.

This research was developed in the context of the MEDWATERICE (PRIMA-Section2 2018; https://www.medwaterice.org/) project.

Keywords: irrigation district; rice irrigation requirement; water-saving technology; agro-hydrological model; groundwater level; irrigation network efficiency

1. INTRODUCTION

Italy, with over half of the total European production grown on an area of more than 200 thousand hectares, is the most important rice producer in Europe and the second in the Mediterranean basin after Egypt. The most important rice-growing area of the country, located between Lombardy and Piedmont Regions, is featured by many peculiarities: an historical abundance of surface water, an extensive network of unlined irrigation and drainage channels and the presence of one of the largest aquifers in Europe.

Traditionally, rice irrigation was based on wet seeding and continuous flooding (WFL) up to about 30 days before harvesting. Recently, due to an increased frequency of water scarcity periods and competition for water among agricultural and non-agricultural uses, water saving techniques are being introduced in the area. However, their effectiveness over the territory need to be assessed.

Water Application Efficiency, which is computed as the ratio between evapotranspiration and water inputs (WAE, %; Bouman et al., 2005), is a well-known index used to evaluate the irrigation management efficiency. However, WUE depends on the spatial scale at which the hydrological processes are observed. In fact, water fluxes which are considered non-beneficial losses at the field scale, such as percolation from the agricultural fields and from the irrigation channel network, can be partially recovered and reused on larger scales by fields located downhill, where shallow groundwater levels allow the reduction of percolation losses and the activation of capillary rise.

The objective of the hydrological modelling activity presented in this paper is to explore water dynamics and water use efficiencies of different irrigation management alternatives in a 1.000 ha irrigation district prevalently cropped with rice and located in the Lombardy portion of the Italian rice basin (Lomellina). In order to allow a clear illustration of the results, years 2013, 2016 and 2019, characterized by different agro-climatic conditions and availability of water resources in the district, are considered in the paper.

2. STUDY AREA AND DATA COLLECTION

The pilot rice district is located within the administrative boundary of San Giorgio di Lomellina (Pavia), about 45 km southwest of the city of Milan and extending over an area of about 1.000 hectares. The rice growing area of the district covers about 90% of the agricultural surface while the remaining 10% is mainly cropped with maize and poplar. Spatial distribution of the crops in the area were retrieved from the annual SIARL land-use raster maps provided by the Lombardy regional authority (ERSAF; 20 m x 20 m). The MNDWI index (Modified Normalized Difference Water Index; Xu, 2016) was calculated starting from satellite images (Landsat 7/8 and Sentinel 2) downloaded for the period April-May with the objective of identifying wet seeded and dry-seeded rice, following the procedure described in Mayer et al. (2019). Since the poplar area in the pilot district is very limited, poplar was randomly split into young (irrigated) and mature (rainfed), following a 40-60% ratio on the basis of indications from AIES.

A Ground Degree Days (GDD) model was developed and applied for dry seeded and wet seeded rice, using ground-based information provided by Ente Nazionale Risi (ENR). Rice crop biometric parameters were provided by ENR technicians, while crop coefficients were measured in a former experiments (Cesari de Maria et al., 2016, Chiaradia et al., 2015). Development stages and crop parameters for the other crops (maize and poplar) were defined according to the information reported in Mayer et al. (2019).

Soil hydraulic properties for the five most abundant types of soil in the area were estimated through PedoTransfer Functions (PTFs) based on the information reported in the 1:50.000 Lombardy Soil Map (ERSAF; 1: 50,000). The chosen PTFs were: i) Tomasella et al. (1998) for the soils Bulk Density (BD, not available in the Lombardy Soil Map); ii) Ungaro et al. (2005) for the soil water retention curve parameters and the saturated hydraulic conductivity. To take into account the compaction characterizing paddy soils, both BD and saturated hydraulic conductivity obtained by the PTFs were corrected following Mayer et al. (2019).

The agro-meteorological data were recorded at the ARPA station in Castello D'Agogna (a few kilometres from the district). The amount of rain fell from April to September in 2013, 2016 and 2019 was found to be 283, 331 and 281 mm, respectively. For the same years, in July the rainfall registered was 5, 75 and 54 mm.

The channel network within the district is managed by the Associazione Irrigazione Est Sesia (AIES); irrigation water comes almost exclusively from surface water bodies. Daily irrigation discharges conveyed to the district and used in this study were provided by AIES.

During the last years, dry seeding followed by an alternation of flooding and dry periods (a sort of rough Alternate Wetting and Drying - AWD - in which flooding periods are dictated by the irrigation turns scheduled by AIES on the basis of water availability in rivers) took the place of the traditional WFL practice. This change was triggered by new environmental conditions (e.g. greater probability of dry years) but, despite the simplified agronomic management and consequently the economic saving that dry seeding has brought to the farmers, this change is leading to different unexpected problems such as a lowering in GWL and increasing in competition for the water resources with other crops (especially maize) in June and July. The change (%) in rice irrigation management among the years 2013, 2016 and 2019 is shown in Table 1.

The phreatic groundwater surface varies in space and time and is very shallow in some areas of the district. Four piezometer wells were installed in the district area, and the groundwater level (GWL) was measured weekly from 2015 by AIES. Figure 1 shows the average daily GWL measured by the piezometers installed in the district (the 2013 GWL was reconstructed using the modelling system described in this paper; see Mayer et al. 2019). The figure clearly shows how the rice irrigation management conversion in the district affected the daily average GWL values, with a general lowering of the groundwater table and an evident delay in reaching high GWLs at the beginning of the agricultural season (April-June).

Year	Dry seeded (%)	Wet seeded (%)
2013	40.1	59.9
2016	92.5	7.5
2019	100.0	0.0

Table 1. Irrigation management strategies adopted in the years 2013, 2016 and 2019. Percentage where computed from the soil land use raster maps used in the simulations (see Section 2 for more details).

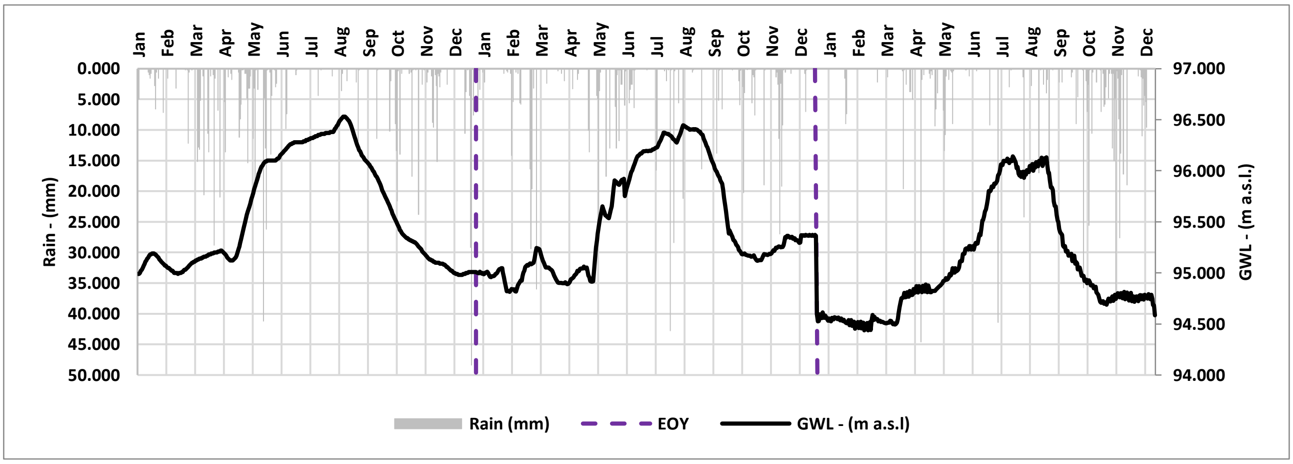

Figure 1. Average daily GWL over the district in the years 2013, 2016 and 2019. The 2013 GWL was reconstructed using the modelling system described in the paper after its calibration.

3. MODELLING SYSTEM AND SIMULATED SCENARIOS

In the modelling framework developed, the SWAP model (Soil, Water, Atmosphere and Plant; Kroes et al., 2008; 2017) is applied to the irrigation district following a semi-distributed approach (SMDAA). The district area is divided into 40 different homogeneous zones, considering: 4 crop types cultivated in the area (rice, maize, young and old poplar), 5 soil types and 2 groundwater level conditions.

With respect to GWL conditions, two zones having shallow and deep GWLs are defined by attributing to the first zone the areas that, in the daily spatial interpolation obtained using all data measured in GW wells, showed a GWL shallower than -1 m on July 15th of each year. Two groundwater depth series (shallow and deep) are moreover generated for the two zones averaging the daily GWLs in each zone (further details are reported in Mayer et al., 2019).

Two empirical models complete the modelling framework, the former is used to estimate the monthly irrigation channel network percolation (PC) and the latter to simulate the mean monthly GWL over the district (PGL) depending on the district percolation. In this way, by following a recursive computation scheme (5 iterations are generally sufficient to obtain stable GWL series), the modelling system is able to simulate scenarios and/or past years for which GWL data series are not available (e.g. GWLs for 2013).

The PC model has the following characteristics:

$$Pc(t) = Qc(t) \cdot a(t); \qquad \text{with } t = \text{monthly time index} \tag{1}$$

where the monthly irrigation channel network percolation Pc(t) is a function of the mean monthly irrigation discharge Qc(t) and of a loss factor a(t), which varies between 0.0 and 0.4 depending on the GWL during the agricultural season, while it is set to 0.2 outside the irrigation season when the smaller canals are dry. In the scenarios, in which irrigation discharges are not measured and only the field irrigation requirements simulated by SWAP (Ir(t)) are known, equation 1 is converted into:

$$Pc(t) = [a(t) \cdot Ir(t)] / [1 - a(t)] \tag{2}$$

The theoretical formulation of the PGL model is illustrated below:

$$Yd(t) = f(Pd(t); Yupstream(t); Yd(t-1)); \quad \text{with } t = \text{monthly time index} \tag{3}$$

where Yd(t) is the mean monthly GWL over the district, Pd(t) is the district total monthly percolation (i.e. sum of Pc(t) and the percolation from the agricultural fields), Yupstream(t) is the regional monthly GWL data measured at the Cascina Stella piezometer located NE, upstream of the district, along the main groundwater flow direction with respect to the study area (being a sort of NE boundary condition).

The entire framework was calibrated considering the historical soil use, irrigation management and irrigation water availability for the period 2013-2016. Further details about the calibration of the three models presented here and about the developing of the PC and PGL models can be found in Mayer et al. (2019).

The objective of this study was to compare the following rice irrigation management scenarios: i) fixed turn irrigation (FTI) after a dry seeding, ii) wet seeding and continuous flooding (WFL), iii) a safe AWD technique following a wet seeding. The FTI scenario, characterized by a turn of 8 days and 120 mm per irrigation event, is designed accordingly to AIES information, to be representative for the FTI strategy proposed by AIES in condition of good water availability. For the traditional WFL irrigation management, 120 mm of ponding water is kept on the fields from a few days before the emergence to rice maturity, apart from three dry periods needed for the agronomic practices. In the case of AWD, rice irrigation is managed as for WFL in the first part of the season and undergoes intermittent flooding from the tillering stage; in particular, after tillering flooding is applied to reach 120 mm of ponding water only when the soil reaches a critical moisture level (set in SWAP as: pore water pressure -100 cm at 5 cm below the soil surface). As a matter of fact, this irrigation strategy was tested directly in experimental parcels set up at Ente Nazionale Risi during the 2019-2020 agricultural seasons and led to an average water saving of about 20% for safe-AWD with respect to WFL.

Water Application Efficiency (WAE) was calculated as:

$$WAE = (E + T) / (I + R) \times 100 \tag{5}$$

where E, T, I and R are evaporation, transpiration, net irrigation and rainfall, respectively. It shall be noted that WAE is the inverse of the Relative Water Supply (RWS) indicator, defined as the available water (I + R) over the crop evapotranspiration (E+T) within the agricultural season (Yildirim et al. 2007; Kuscu et al. 2009).

Channel Efficiency (CE) was computed as the ratio between the irrigation water reaching the agricultural fields (Q_{DEL}) and the water entering the district through the irrigation conveyance network (Q_{IN}):

$$CE = Q_{DEL} / Q_{IN} \times 100 \tag{6}$$

In the scenario analysis, Q_{IN} is not known since it is not possible to rely on historical measures. Because of that, Q_{IN} is set to be equal to the sum of the simulated irrigations and the estimated channel percolation, while Q_{DEL} is set equal to the simulated irrigations. Thus, in this case, Q_{IN} must be considered as the minimum amount of water that the district would need to guarantee the simulated water requirements ('minimum' because it is assumed that the irrigation water conveyed to the district is used with maximum efficiency in all months, so that it is never discharged into drainage channels exiting the district).

4 RESULTS

The simulated groundwater table depth (GWD = GWL minus level of the soil surface taken by a Digital Terrain Model) for all the scenarios are shown in Figure 2, while net irrigation and channel percolations for the years 2013, 2016 and 2019 are reported in Table 2 and 3. Figure 2 shows that the dry seeding technique adopted in FTI leads to a dramatic decrease in GWD in first months of the season, slowing the rise of the water table towards its maximum peak values of about one-two months. On the contrary, the GWD values under the AWD irrigation strategy overlap with WFL in the first part of the season, starting to diverge in June.

With respect to the net irrigation demand (Table 2), the WFL scenario shows the highest irrigation water required, not only during the entire irrigation season (April-September) but also for the critical month of July. AWD seasonal values of WAE are strongly influenced by the wet seeding technique, however AWD performs better in July when compared to FTI as a result of a more efficient use water (irrigations are scheduled to take place only when soil reaches a critical moisture level). Shallow groundwater has a strong effect on WAE values, especially in WFL scenarios where it never falls under 40% both in April-September and July (see in Table 2 the values reported in brackets on the left).

When considering the percolation from the channel network, the AWD scenario shows to produce the highest values of percolation from the channel network during the period April-September, even if they are not very dissimilar to FTI values. However, in July FTI values of percolation overtake both AWD and WFL. Channel Efficiency (CE) values show obviously an opposite trend: channel network percolation depends not only on the irrigation discharge conveyed in the channel network, but also from the GWD; thus, the higher CE values for WFL can be explained by the GWD behaviour in the three years (Figure 2).

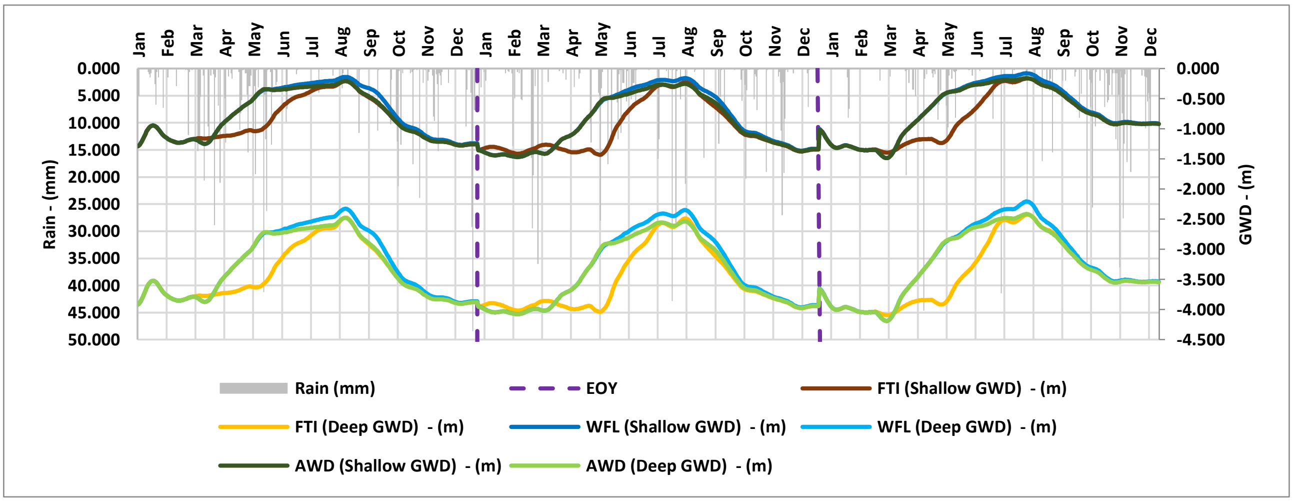

Figure 2. Groundwater depths (GWD) calculated by the PGL model for the years 2013, 2016 and 2019 and provided to the SDMAA model during the last iteration adopted in the simulation (five iterations were used for every year in all the scenarios).

Table 2. Net irrigation and WAE values for the agricultural fields within the district, both for the whole season (April to September) and for July only. In brackets: WAE indices computed separately for shallow and deep GWL zones, respectively.

Scenario	Year	Seasonal Net Irrigation (mm)	Seasonal WAE (%)	Net Irrigation of July (mm)	WAE of July (%)
FTI	2013	991.3	43.0 (46.9, 41.1)	310.8	49.3 (58.6, 45.3)
	2016	919.9	43.7 (50.0, 40.8)	368.7	34.9 (42.6, 31.8)
	2019	923.9	46.0 (51.0, 43.8)	395.2	36.6 (42.3, 34.3)
WFL	2013	1954.5	28.3 (41.8, 24.0)	499.6	33.0 (51.6, 27.6)
	2016	1930.4	28.0 (41.2, 23.8)	432.8	31.6 (50.9, 26.2)
	2019	1931.5	29.1 (42.6, 25.1)	470.1	32.8 (53.6, 27.5)
AWD	2013	1554.9	34.4 (48.8, 29.6)	408.0	40.4 (55.4, 35.2)
	2016	1539.6	33.8 (44.7, 29.9)	327.9	39.9 (51.1, 35.7)
	2019	1594.3	34.3 (47.1, 30.2)	309.4	47.3 (77.5, 39.5)

Table 3. Channel percolation and CE values for the whole season (April to September) and for July only.

Scenario	Year	Seasonal Channel perc. (mm)	Seasonal CE (%)	Channel perc. of July (mm)	CE of July (%)
FTI	2013	402.6	71.1	114.0	73.2
	2016	382.4	70.6	114.2	76.4
	2019	336.6	73.3	122.2	76.4
WFL	2013	546.3	78.2	56.5	89.8
	2016	652.8	74.7	29.9	93.5
	2019	577.4	77.0	16.1	96.7
AWD	2013	613.5	71.7	102.4	79.9
	2016	738.8	67.6	74.2	81.6
	2019	652.5	71.0	51.1	85.8

Figure 3 illustrates a comparison between the simulated Q_{IN} (irrigation discharge entering the district, obtained as the sum of net irrigation and percolation from the channel network) and the corresponding discharge conveyed to the district by AIES in 2016 ($Q_{IN-AIES}$). The idea is to verify the difference in gross irrigation needed under the three different irrigation management strategies, compared to the real irrigation water availability for the district. For sake of simplicity, only year 2016 is shown in Figure 3. As shown in Table 1, in 2016 only the 7.5% of the rice surface was still irrigated by wet seeding and continuous flooding; moreover, based on personal communications of AIES, during the central months of the 2016 season irrigation turns had to be extended up to 10-12 days because irrigation water was not sufficient for 8-day turns. This explains why the red lines is above the black line in June and July. Figure 3 shows that the FTI gross irrigation requirement significantly differs from WFL and AWD in the months of April and May because of the dry seeding technique adopted.

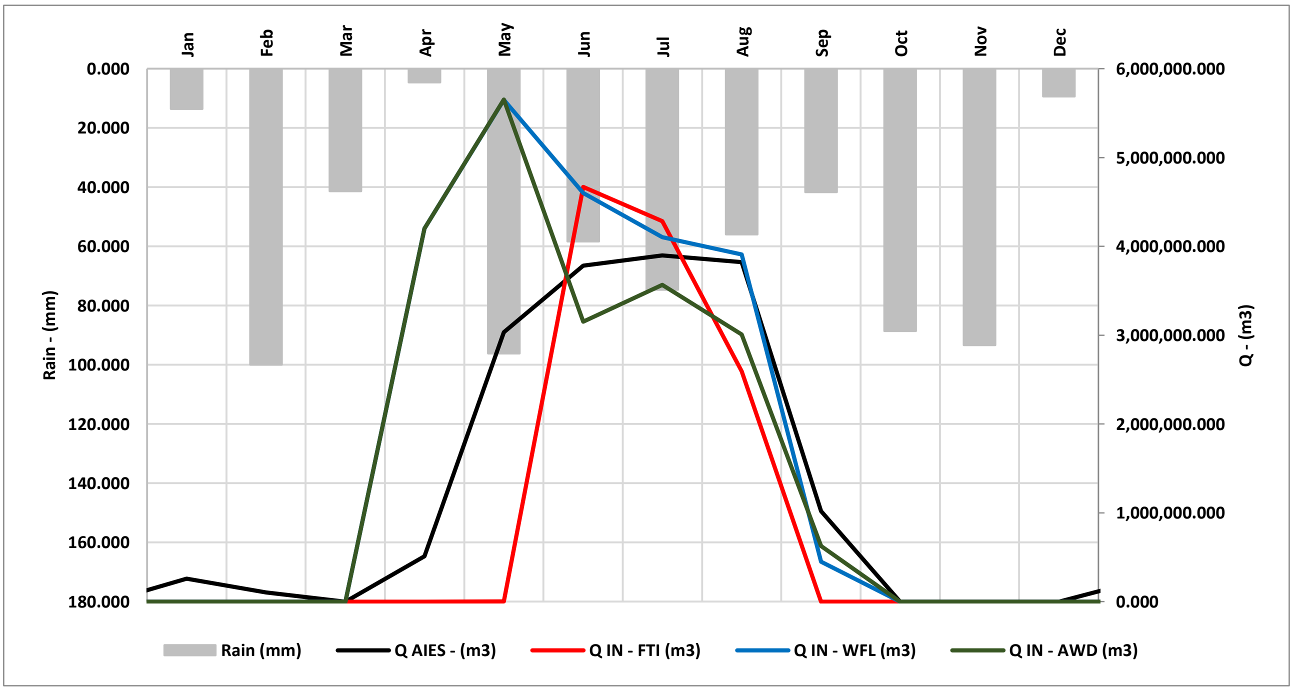

Figure 3. Simulated gross irrigation requirements (Q_{IN}) for the year 2016 for all the scenarios simulated (FTI, red; WFL, blue; AWD, green). In black, the discharges conveyed to the district by AIES ($Q_{IN-AIES}$) in the same year.

The great difference between $Q_{IN-AIES}$ and WFL and AWD in these two months is obviously explained by the fact that only a small percentage of wet seeded rice was still cultivated in 2016, and the dry seeding of rice was heavily prevalent in the district. However, $Q_{IN-AIES}$ is higher than FTI in the first months of the season, and this is due to the fact that even with a turned irrigation after a dry seeding, the irrigation channel network needs to reach a sufficient water discharge availability well in advance with respect to the irrigation season.

Both FTI and WFL irrigation requirements in the central part of the irrigation season (June-July) are higher than the available ones, while AWD would guarantee a lower use of the water resource if compared to the irrigation water availability. In the last months of the irrigation season, $Q_{IN-AIES}$ generally is higher than the irrigation requirement of the agricultural territory; water in excess is discharged in the drainage network exiting the district.

5 CONCLUSIONS

The modelling activity conducted in the context of MEDWATERICE highlights, once more, the strong connection existing between irrigation and groundwater table depth in rice areas, and how complex is to estimate the actual irrigation water need and efficiency of an irrigation strategy when considering large portions of agricultural territory.

Recently, the study area is facing a lowering in GWLs due to the massive conversion to dry seeding and turned irrigation. However, even if the FTI strategy can reduce the overall irrigation volume used during the agricultural season, it does not allow to decrease the irrigation need in the central months of the season, leading to an even higher irrigation requirement compared to the WFL in June and July for the three years covered by this study. This is explained by the fact that, although the field irrigation requirement decreases in June and July adopting FTI, the lowering of the GWLs leads to an increase in the channel network percolation losses.

The AWD-safe technique after wet seeding, currently tested only in experimental plots, seems able to reduce irrigation requests starting from the rice tillering phase (first half of June), thus constituting a compromise solution in terms of recharging the water table and reducing the peak irrigation request for rice. When compared to WFL, AWD-safe leads to a water saving of about 20% for the period April-September and 25% for the month of July.

REFERENCES

Papers

Bouman, B. A. M., Peng, S., Castañeda, A. R., & Visperas, R. M. (2005). Yield and water use of irrigated tropical aerobic rice systems. Agricultural Water Management, 74(2), 87–105.

Cesari de Maria, S., Rienzner, M., Facchi, A., Chiaradia, E. A., Romani, M., & Gandolfi, C. (2016). Water balance implications of switching from continuous submergence to flush irrigation in a rice-growing district. Agricultural Water Management, 171, 108–119.

Chiaradia, E. A., Facchi, A., Masseroni, D., Ferrari, D., Bischetti, G. B., Gharsallah, O., Cesari de Maria, S., Rienzner, M., Naldi, E., Romani, M., & Gandolfi, C. (2015). An integrated, multisensor system for the continuous monitoring of water dynamics in rice fields under different irrigation regimes. Environmental Monitoring and Assessment, 187(9).

Kuscu, H., Bölüktepe, F. E., Demir A. O., 2009. Performance assessment for irrigation water management: A case study in the Karacabey irrigation scheme in Turkey. African Journal of Agricultural Research Vol. 4 (2), pp. 124-132. http://www.academicjournals.org/AJAR

Mayer, A., Rienzner, M., Cesari de Maria, S., Romani, M., Lasagna, A., & Facchi, A. (2019). A Comprehensive Modelling Approach to Assess Water Use Efficiencies of Different Irrigation Management Options in Rice Irrigation Districts of Northern Italy. Water, 11(9), 1833.

Tomasella, J., & Hodnett, M. G. (1998). Estimating soil water retention characteristics from limited data in Brazilian Amazonia. Soil science, 163(3), 190-202.

Ungaro, F., Calzolari, C., & Busoni, E. (2005). Development of pedotransfer functions using a group method of data handling for the soil of the Pianura Padano–Veneta region of North Italy: water retention properties. Geoderma, 124(3-4), 293–317.

Xu, H. (2006). Modification of normalised difference water index (NDWI) to enhance open water features in remotely sensed imagery. International Journal of Remote Sensing, 27(14), 3025–3033.

Yildirim, M., Cakmak, B., Gokalp, z., 2007. Benchmarking and Assessment of Irrigation Management Transfer Effects on Irrigation Performance in Turkey. Journal of Biological Sciences 7(6). DOI: 10.3923/jbs.2007.911.917

Manuals/Books

de Wit, A.J.W., System description of the WOFOST 7.2 cropping systems model, Wageningen: Wageningen Environmental Research. 2020.

DiSAA – Department of Agricultural and Environmental Sciences, IdrAgra Technical manual - version 2.0, University of Milan, 2021.

Kroes, J. G., van Dam, J. C., Groenendijk, P., Hendriks, R. F. A., & Jacobs, C. M. J. Swap version 3.2: theory description and user manual. Wageningen: Alterra, 2008.

Kroes, J. G., van Dam, J. C., Bartholomeus, R. P., Groenendijk, P., Heinen, M., Hendriks, R. F. A., Mulder, H. M., Supit, I., & van Walsum, P. E. V. (2017). SWAP version 4. Wageningen: Wageningen Environmental Research, 2017.

Institutions/Web sites

AIES, https://www.estsesia.it/.

ARPA, https://www.arpalombardia.it/.

ENR, https://www.enterisi.it/.

ERSAF, https://www.ersaf.lombardia.it/.