

RATIONALIZING RICE IRRIGATION STRATEGIES IN NORTHERN ITALY USING QGIS-SWAP-PADDY AND MODFLOW-6

RATIONALISATION DES STRATÉGIES D'IRRIGATION RIZICOLE AU NORD DE L'ITALIE À L'AIDE DE QGIS-SWAP-PADDY ET MODFLOW-6

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ABSTRACT

Rice-growing regions need irrigation strategies that meet crop water demand while sustaining groundwater recharge and improving resilience to water scarcity. Irrigation efficiency in these areas depends strongly on groundwater levels, which control percolation in fields and canals and affect flows from springs and watercourses. In Lomellina, northern Italy, a major rice-growing district (125,000 ha, 63,000 under rice), cultivation has traditionally relied on wet seeding and continuous flooding (WFL). In recent years, water-saving practices such as dry seeding with delayed flooding (DFL) and intermittent flooding (FTI) have increasingly replaced WFL, altering both the seasonal volume and timing of irrigation demand and groundwater recharge.

This study applies the QGIS-SWAP-Paddy framework, a spatialized version of the well-known SWAP model, integrated with a module simulating channel-network percolation, to assess these processes in Lomellina. The framework was calibrated for 2020 and validated for 2018 - 2019 using daily irrigation discharge data provided by the Irrigation User Association and the current irrigation management (PMR: 20% WFL and 80% FTI). Four scenarios - PMR, WFL, DFL, and AWD (wet seeding and alternate wetting and drying guided by a soil water status threshold) - were simulated for 2013 - 2023. Compared with WFL, the seasonal irrigation volume decreased by 18%, 30% and 32% under DFL, AWD and PMR, respectively. However, when considering peak irrigation discharge (June - July), the order of requirements was as follows: DFL > WFL > PMR = AWD. Percolation patterns mirrored the irrigation requirements. AWD was found to be a very promising strategy, promoting earlier groundwater recharge while reducing competition for irrigation during the peak months. The framework is currently being coupled with MODFLOW-6 to enable more accurate modelling of the complex interaction between groundwater levels and irrigation use.

Keywords: Irrigation strategies; crop water demand; water-saving practices; water scarcity; Irrigation efficiency.

RESUME

Les régions rizicoles exigent des stratégies d'irrigation qui répondent à la demande en eau des cultures tout en maintenant la recharge des eaux souterraines et en renforçant la résistance face à la pénurie d'eau. L'efficacité de l'irrigation dans ces zones dépend fortement des niveaux d'eau souterraine, qui contrôlent la percolation dans les champs et les canaux et exercent des impacts sur les débits des sources et des cours d'eau. À Lomellina, au nord de l'Italie, une importante région rizicole (125000 ha de terre, dont 63 000 ha de terre consacrée au riz), repose traditionnellement sur un ensemencement humide et des inondations continues (WFL). Au cours des dernières années, les pratiques d'économie

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d'eau telles que l'ensemencement à sec avec inondation différée (DFL) et les inondations intermittentes (FTI) ont de plus en plus remplacé le WFL, modifiant à la fois le volume saisonnier et le calendrier de la demande en irrigation et la recharge des eaux souterraines.

Cette étude applique le cadre QGIS-SWAP-Paddy, une version spatialisée du modèle bien connu SWAP, intégré à un module simulant la percolation canal-réseau, pour évaluer ces processus à Lomellina. Le cadre a été calibré pour l'année 2020 et validé pour la période 2018-2019 à l'aide des données de débit d'irrigation quotidien fournies par l'Association des usagers d'irrigation et la gestion actuelle de l'irrigation (PMR : 20 % WFL et 80 % FTI). Quatre scénarios - PMR, WFL, DFL et AWD (ensemencement humide et l'humidification et le séchage alternés guidés par un seuil d'humidité du sol) - ont été simulés pour la période 2013-2023. Par rapport à la méthode WFL, le volume d'irrigation saisonnier a diminué de 18%, 30% et 32% sous DFL, AWD et PMR, respectivement. Cependant, en ce qui concerne le débit d'irrigation maximal (juin-juillet), l'ordre des exigences était le suivant : DFL > WFL > PMR = AWD. Les modèles de percolation reflétaient les besoins en irrigation. L'AWD s'est révélée être une stratégie très prometteuse, favorisant une recharge plus précoce des eaux souterraines tout en réduisant la concurrence pour l'irrigation pendant les mois de demande maximum. Le cadre est actuellement lié à MODFLOW-6 pour permettre une modélisation plus précise de l'interaction complexe entre les niveaux d'eau souterraine et l'utilisation de l'irrigation.

Mots-clés : Stratégies d'irrigation; Besoins en eau des cultures; Pratiques d'économie d'eau; Pénurie d'eau; Efficacité de l'irrigation.

INTRODUCTION

Most of the world's rice is produced on irrigated land (Gassman et al., 2022). However, water scarcity threatens the sustainability of rice production, as excessive water use and possible future shortages could further impact these heavily irrigated systems (Silalertruksa et al., 2017). A current research topic investigated by many groups worldwide, including in Europe (Gharsallah et al., 2023; Gonçalves et al., 2022; Zoffoli et al., 2023), is exploring alternative irrigation strategies to conventional continuous flooding (WFL) that improve irrigation efficiency at field and district levels while maintaining traditional gravity-based irrigation systems.

Spanning over 125,000 hectares in the Lombardy region (Figure 1), more than half of Lomellina's surface area is devoted to rice paddies (63,000 hectares). Bordered by the rivers Po, Sesia and Ticino, and by the Piedmont region to the north, it forms part of Italy's main rice-growing region (220,000 hectares of rice), alongside Basso Novarese and Vercellese in the Piedmont region. The National Rice Authority (ENR) (<https://www.enterisi.it/>) oversees rice agronomic practices in all this area. The main crops in Lomellina are rice, maize and poplar. The area has a complex geomorphology and hydrogeology and hosts one of Europe's largest aquifers. The gravity-fed irrigation system receives water mainly from the Po, Sesia, and Ticino rivers, and is managed by the Water Irrigation Association AIES (<https://www.estsesia.it/>). Groundwater is vital to the hydrology of the Lomellina region (Mayer et al., 2019), since the shallow water table facilitate a semi-natural water reuse by interacting with the irrigation system (flooded paddies and unlined canals): percolation raises the groundwater level, supports river and canal flows and reduces the need for rice irrigation by decreasing vertical water losses from paddies during the growing season. Traditionally, rice in the Lomellina region was cultivated using the wet seeding and continuous flooding (WFL) method, which requires large volumes of water (Miniotti et al., 2016; Monaco et al., 2021). However, due to increasing water scarcity and competing demands over the past 15 - 20 years, farmers have shifted towards water-saving techniques such as dry seeding with delayed flooding (DFL) or turn-based irrigation (FTI). However, although dry seeding reduces costs and saves time, it appears to prevent an increase in groundwater levels early in the season, thereby decreasing water availability downstream. Furthermore, competition for irrigation between rice and other crops, such as maize, seems to intensify during the central months of the season (June and July). In fact, DFL delays initial flooding until June, requiring more water to fill the paddy fields at that time due to drier soil and lower groundwater levels.

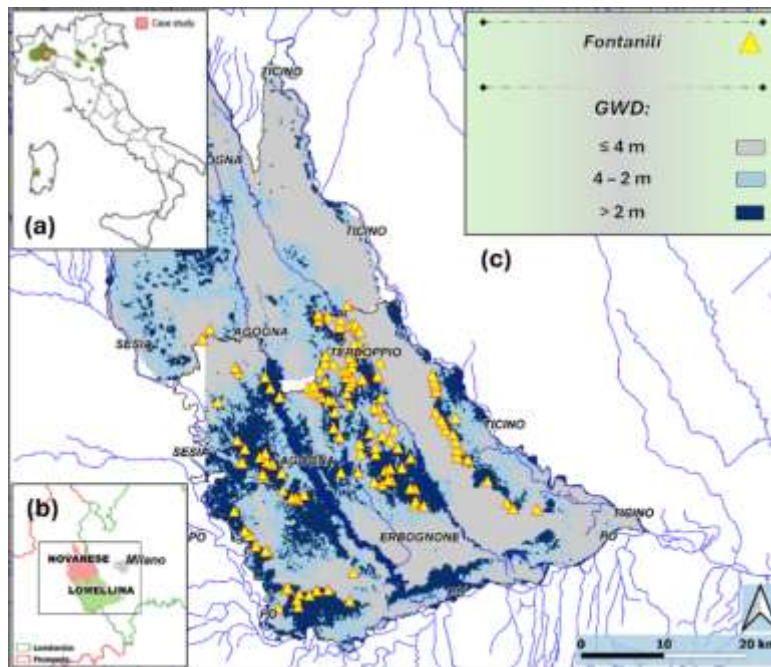


Figure 1. (a) General overview of rice-growing areas in Italy (source: ENR); (b) Novarese (Piedmont) and Lomellina (Lombardy) rice districts; (c) Surface hydrography, groundwater table depth (GWD, negative), and depression springs ('Fontanili').

The recent QGIS-SWAP-Paddy framework (Gilardi, 2025; Gilardi et al., 2026) leverages open-source QGIS (<https://qgis.org/>) to convert GeoPackage (<https://www.geopackage.org/>) spatial data into field-level simulations using the SWAP (<https://www.swap.alterra.nl/>) agro-hydrological model. It moreover integrates an irrigation channel network model. The tool streamlines the setup of simulations, supporting the implementation and analysis of alternative irrigation strategies to assess water requirements and percolation in lowland agricultural districts. In this work, the framework has been parameterized for the entire Lomellina area and used to conduct a scenario analysis to estimate irrigation requirements and groundwater recharge. Simulated scenarios are: PMR (the 'current situation', WFL and FTI), WFL, DFL, and AWD (Carrijo et al., 2017). Work is currently underway to explicitly integrate QGIS-SWAP-Paddy with MODFLOW6, in order to enable a more accurate assessment of the effects of these scenarios on the entire water resources system (Baják et al., 2026).

MATERIALS AND METHODS

Area Description

According to the Castello D'Agogna agro-meteorological station, the average rainfall from April to September between 1993 and 2024 was 322 mm, the average air temperature was 20.6 °C, the average wind speed was 1.5 m/s and the average daily solar radiation was 233.3 W/m².

In terms of soil, the study area encompasses 60 Cartographic Units (UCs) as defined in the 1:50,000 Lombardy Region Soil Map, which was produced by ERSAF (<https://www.ersaf.lombardia.it/>) and is detailed in the LOSAN soil database (<https://www.losan.ersaf.lombardia.it/>). The soils generally have a coarser texture (ranging from loam to sandy loam) and higher vertical percolation rates (0.7 - 2.3 cm/d) than those found in many other rice-growing areas worldwide (Gassman et al., 2022).

The soil hydraulic parameters for rice soils of the Lomellina were estimated using PedoTransfer Functions (PTFs) identified in a recent UNIMI-DiSAA investigation (Gilardi, 2025). A typical paddy soil profile consists of three layers: 1) a muddy top layer (20–30 cm); 2) a compact hardpan that restricts water flow; and 3) subsoil that eventually reaches the aquifer. Water percolation during flooding depends

on the hydraulic conductivity, thickness and depth of the hardpan. For non-paddy soils, hydraulic properties were estimated using PTFs developed by Rawls and Brakensiek (1989), which are commonly adopted for soils in Lombardy (Cazzaniga et al., 2026).

The Lombardy Region Geoportal (<https://www.geoportale.regione.lombardia.it/>) provides soil use databases, including DBGT, DUSAAF 7.0 and SIARL (2020), for the study area. These datasets were merged to generate a unified map for the simulation period. FTI rice and maize sites were identified where DBGT arable land overlapped with the predominant rice or maize cells in SIARL. ENR wet-seeded rice data (2020) helped to identify WFL-managed areas since regional databases do not distinguish between irrigation methods. Poplar sites from Dusaf were categorised as young (irrigated) or mature (non-irrigated) using a split of 40 - 60%, as in Mayer et al. (2019). Figure 2 displays productive soil uses. Non-productive uses include fallows (arable land in DBGT that is not marked as rice or maize in SIARL), riparian vegetation (deciduous forests in Dusaf) and urban or unclassifiable areas (bare soil). Gilardi et al. (2023) developed and calibrated a crop development model for wet-seeded (WFL and AWD) and dry-seeded (FTI and DFL) rice, based on 2020 data and ENR expertise. The irrigation scheduling in the rice model was improved to allow time-dependent ponding thresholds and to integrate fixed and crop-specific management at the field scale. WFL fields maintain ponded water from one week before seeding until drying, with short dry periods. FTI uses typical northern Italian practices involving dry seeding, one week of flooding and fixed rotational irrigation from tillering onwards. The AWD protocol (RISOSOST project) begins cycles at tillering once the soil water potential reaches -10 kPa at a depth of 5 cm, which is considered safe (Carrijo et al., 2017); continuous flooding after panicle initiation lasts 20–30 days to reduce grain cadmium content (Vitali et al., 2024), AWD then continues until final drying. Maize is grown from April to September and is parametrized as described by Mayer et al. (2019); it receives 200 mm of border irrigation after 70% RAW depletion. Poplar follows a generic forest model: young trees receive two irrigations of 200 mm, while mature trees are rain-fed. Data for fallow land, riparian vegetation and bare soil are taken from SWAP demo crops.

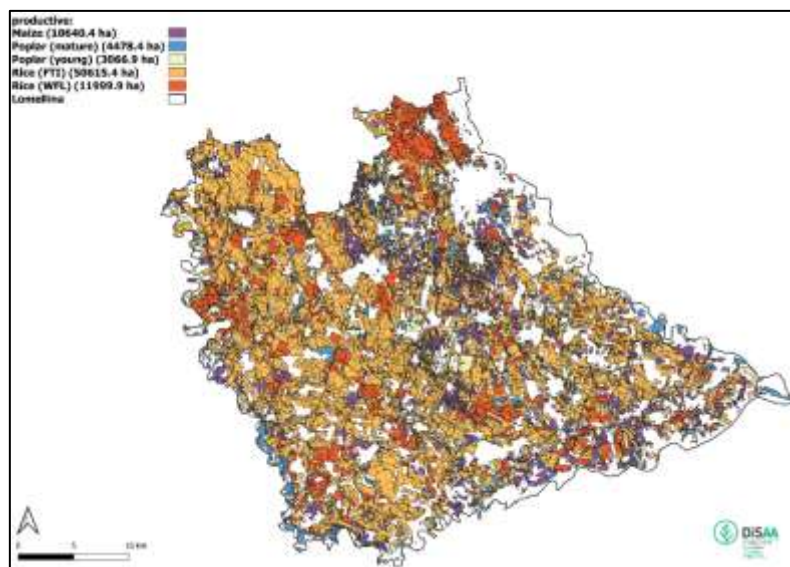


Figure 2. Spatial distribution of productive soil uses within the Lomellina region (PMR scenario). Selected soil uses (WFL, FTI, maize, young and mature poplar) are listed in the legend (soil use name and area covered in hectares).

Piezometric groundwater data for the phreatic aquifer in the study area is available from the Lombardy Region Geoportal. This data is based on surveys conducted in May and September 2014. The Digital Terrain Model (DTM), which is also available through the Geoportal, provides elevation information. By combining the piezometric data and the DTM, the depths of the groundwater were determined for the simulated domain. Data from September 2014 were selected to reflect levels influenced by summer irrigation. The classification proposed by Mayer et al. (2019) for shallow (≥ -1 m) and deep (< -1 m) groundwater depth areas (GWD) was adopted. While recent groundwater level measurements from

Lomellina are being analysed, the daily GWD temporal patterns observed by Mayer et al. (2019) for San Giorgio di Lomellina are assumed to be representative of the 'shallow GWD' and 'deep GWD' areas of Lomellina.

Only measured irrigation discharge data conveyed by AIES to the Lomellina district from 2018 to 2020 was available. Information from the regional database Catasto Utenze Idriche di Regione Lombardia (CUI), which covers supplies from surface water not managed by AIES, depression springs and private wells, was also taken into account. Both datasets were provided by the AIES consortium and were used to calibrate the modelling framework.

QGIS-SWAP-Paddy

QGIS-SWAP-Paddy (Figure 3) addresses two distinct groups of processes that occur within the simulation domain: I) processes that take place in the agricultural area, and II) processes involving the channel network. The first group of processes relies on a semi-distributed application of the well-known SWAP (<https://www.swap.alterra.nl/>) model to estimate both irrigation requirements and deep percolation within the agricultural area. The second group of processes incorporates an ad hoc algorithm developed to estimate channel percolation and, consequently, the net and/or gross discharge circulating within the channel network.

In simulations based on historical data, the measured gross irrigation discharge at the inlet of the simulation domain, provided by AIES, is used as input to derive the corresponding net irrigation requirement (i.e. irrigation water availability for the agricultural area). Conversely, in scenario analyses where historical data are unavailable, the framework starts with the estimated net irrigation requirement coming from the agricultural area and computes the corresponding gross discharge (i.e. net irrigation plus channel network percolation).

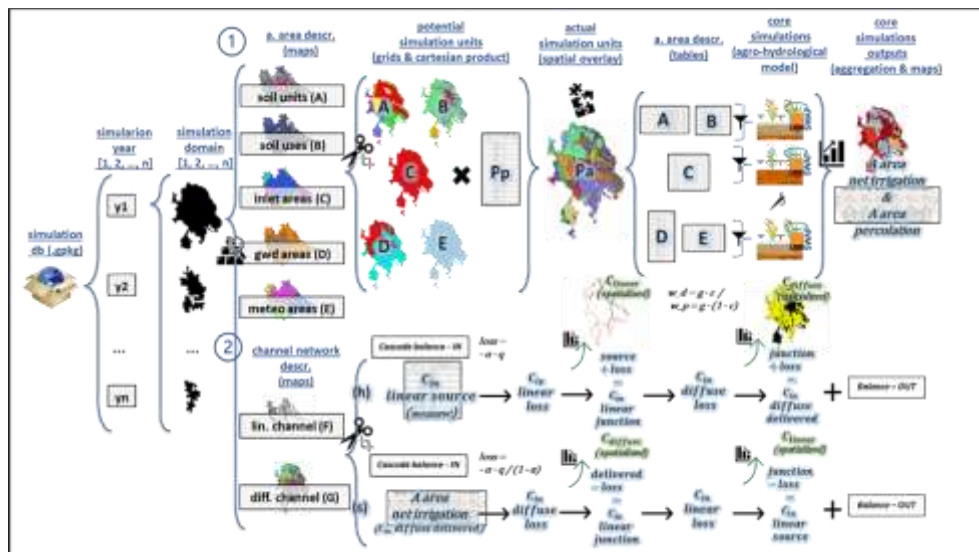


Figure 3. A schematic overview of the steps followed by the framework to: (1) semi-distribute the SWAP model within the agricultural area, and (2) describe the channel network of a simulation domain; both for a user defined simulation year.

Model Performance Assessment and Irrigation System Performance Evaluation

QGIS-SWAP-Paddy was calibrated and validated for the PMR scenario. Calibration, carried out for the year 2020, focused on adjusting irrigation management parameters for the rice crop and soil hydraulic properties of the hardpan, with the aim to minimize differences between simulated net irrigation requirements ($A_{area \text{ net irrigation}}$, m3/s) and estimated net irrigation availability, this latter corresponding to the channel network net discharge delivered to the district ($C_{network \text{ net discharge}}$,

m³/s). The year 2020 was chosen for calibration because Lomellina had sufficient irrigation water, which justifies the assumption that the territory's irrigation requirements matched its irrigation availability. The years 2018 and 2019 were used for validation. AIES suggested a 10- to 12-day irrigation rotation for FTI. In 2019, however, the turns were longer due to drought (rotations reached 25 - 30 days). Based on information provided by AIES, channel efficiency was assumed to average 60% during the irrigation season and 80% in the remaining months.

The performance of the model during calibration and validation was assessed using the indices recommended by Moriasi et al. (2007), specifically: Nash-Sutcliffe Efficiency (NSE, -), RMSE-observations standard deviation ratio (RSR, -), and Percent Bias (PBIAS, %). The indices were calculated only for months that strictly fall within the irrigation season (May to September). In the scenario analysis, irrigation system performance was evaluated using the Relative Water Supply (RWS) indicator, which is widely adopted worldwide (Ahmad et al., 2024). RWS was calculated during the irrigation season (April to October) when net irrigation was greater than zero, to avoid non-representative results from months with low irrigation and minimal crop water requirements (generally April and October).

RESULTS AND DISCUSSION

Figure 4 provides a monthly comparison between A_{area} net irrigation and $C_{network}$ net discharge aggregated over the entire simulation domain for 2018 - 2020. The calibration and validation efficiency indices are reported in Table 1. For the calibration year 2020, all performance metrics showed a high level of agreement between the estimated and observed values. As might be expected, the validation values are less favourable. In 2019, AIES reported that irrigation was abundant in May but critical thereafter, especially in June, and the observed discrepancy between crop requirements and available water was then expected. In 2018, irrigation issues mainly occurred in September when demand was low due to the crops being ready to harvest. During the main growing season (May - September), 2018 had the highest average maximum temperature (30.53 °C), followed by 2019 (29.46 °C) and 2020 (28.47 °C). Minimum temperatures showed a similar trend. The warmth in 2018 sped up crop development, leading to an early harvest. When considering the entire 2018 - 2020 period, the 'clean' version of the dataset (obtained by excluding the identified critical months of September 2018 and May - June 2019) yielded markedly improved results (NSE = 0.771, RSR = 0.479, PBIAS = 3.68%, all rated very good). Considering the complexity of the modelling task, the performance assessment was considered satisfactory.

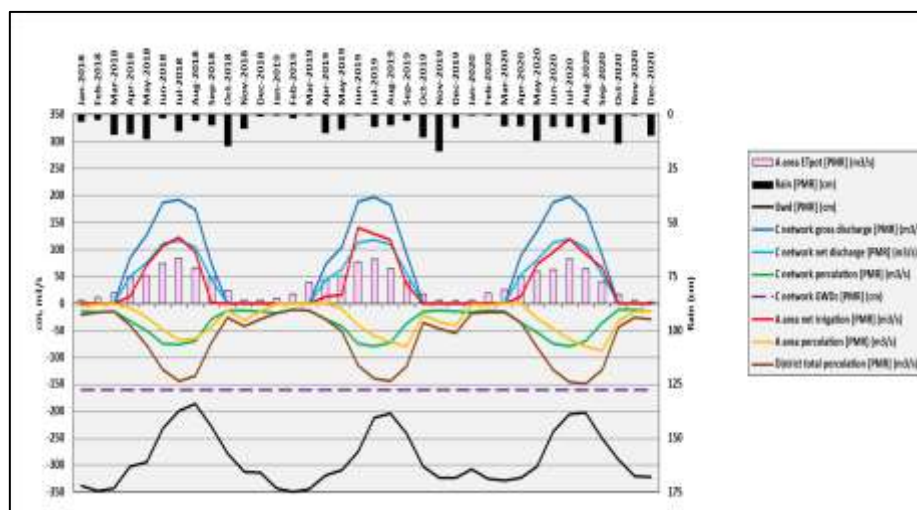


Figure 4. Calibration (2020) and validation (2018-2019) results for the Lomellina irrigation district. Values reported for the agricultural area are monthly aggregated data for the entire simulation domain. Rain is shown as black histograms at the top of the graph, and the average GWD as a black line at the bottom.

Table 1. Model evaluation for the years 2020 (calibration) and 2018/2019 (validation). The 'clean' version of the dataset is obtained by excluding the critical months September 2018 and May - June 2019.

Index	Value	Moriasi et al. (2007)
2018		
NSE (-)	0.439	Unsatisfactory
RSR (-)	0.749	Unsatisfactory
PBIAS (%)	12.736	Good
2019		
NSE (-)	0.008	Unsatisfactory
RSR (-)	0.996	Unsatisfactory
PBIAS (%)	4.831	Very good
2020		
NSE (-)	0.766	Very good
RSR (-)	0.483	Very good
PBIAS (%)	5.312	Very good
2018 - 2020 (clean)		
NSE (-)	0.771	Very good
RSR (-)	0.479	Very good
PBIAS (%)	3.681	Very good

Figure 5 shows the monthly averages of irrigation requirements and groundwater recharge for each scenario (PMR, WFL, DFL and AWD) across the simulation domain for the period from 2013 to 2023. In terms of the annual district irrigation requirement, the WFL scenario shows the highest overall usage (1,152.5 m³/s), followed by DFL (945.5 m³/s, -18.0%), AWD (812.0 m³/s, -29.6%) and PMR (787.1 m³/s, -31.7%). The highest water usage is seen in June for WFL and DFL, with DFL exceeding WFL and both being significantly higher than PMR and AWD. July is a key month for AWD and PMR, with AWD usage surpassing that of PMR, though remaining lower than that of DFL and WFL. AWD also shows a notable drop in usage in June compared to the other methods. Wet seeding scenarios (WFL and AWD) require more irrigation in the early season than dry seeding (PMR and FTI). District percolation monthly patterns largely mirror irrigation requirement patterns.

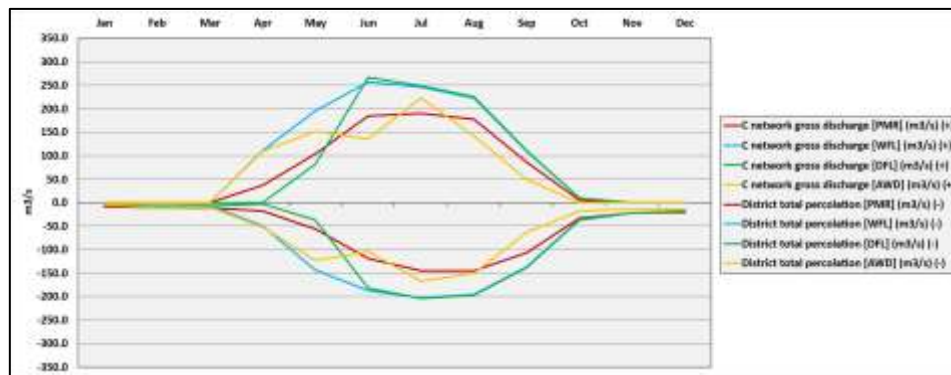


Figure 5. Average monthly $C_{network}$ gross discharge and district total percolation (both in m³/s) for all the simulated scenarios (PMR, WFL, DFL, and AWD) in 2013 – 2023.

The average monthly values of RWS (Figure 6) from 2013 to 2023 are consistent with the simulated district total requirements. The lowest yearly RWS is achieved by AWD (2.8), followed by PMR (2.9), WFL (3.8) and DFL (3.9). In terms of annual performance, the AWD scenario is very close to the PMR scenario, despite requiring a greater total volume of irrigation (812.0 m³/s vs 787.1 m³/s). This is largely due to AWD's exceptional performance in June (RWS: 2.2 vs 3.0), resulting from the alternating wetting and drying irrigation management strategy applied in this scenario. Additional gains are observed in the

latter part of the season (August - October). However, AWD underperforms relative to PMR in the early season (April - May) due to the wet seeding practice applied across the entire rice-growing area, and again in July, when re-flooding occurs during the flowering stage.

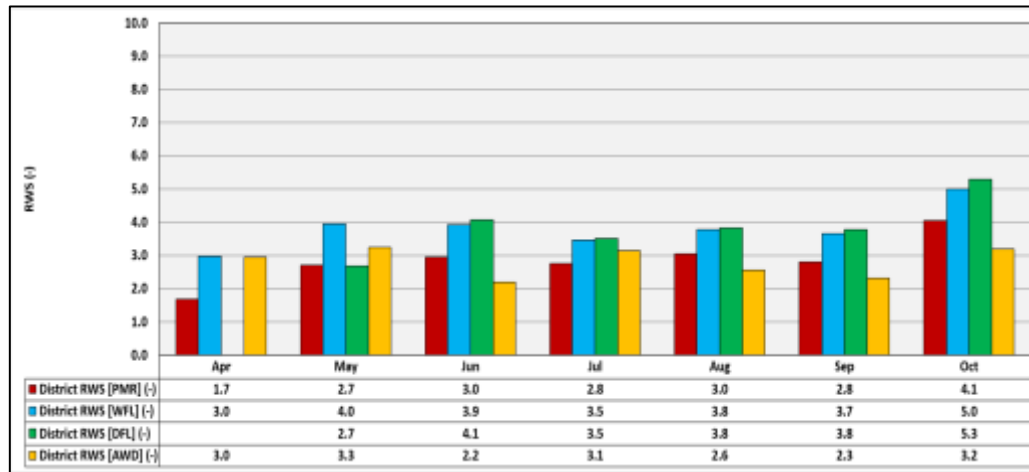


Figure 6. Average monthly values of the Relative Water Supply - RWS (-) index for all the simulated scenarios (PMR, WFL, DFL, and AWD) in the period 2013 – 2023.

CONCLUSIONS AND FUTURE RESEARCH

The QGIS-SWAP-Paddy framework was developed to streamline simulation setup, support alternative irrigation strategies, integrate relational database functions, and featuring an irrigation channel network model to assess water requirements in lowland districts. Its architecture directly addresses the need for a multi-scale, physically based agro-hydrological model to be used in rice areas (Siad et al., 2019; Uniyal and Dietrich, 2021).

QGIS-SWAP-Paddy, parameterized with recently identified soil PTFs for rice areas in northern Italy, was calibrated/validated and successively applied to the entire Lomellina. Four scenarios (PMR, WFL, DFL, and a safe AWD) were simulated. AWD showed to cut annual water requirements by 29.6% compared to WFL. The RWS for AWD was 2.8, substantially lower than the 3.8 - 3.9 of WFL and DFL, indicating a significant reduction in oversupply. In the critical month of June, AWD achieved an average RWS of 2.6 in June and July, outperforming the other three scenarios. AWD was then found to be a very promising strategy, promoting earlier groundwater recharge while reducing competition for irrigation during the peak months.

The framework is currently being coupled with MODFLOW-6 to enable more accurate modelling of the complex interaction between groundwater levels and irrigation use. The MODFLOW-6 model adopts the same spatial extent as the QGIS-SWAP-Paddy model and is discretized using a structured grid of 31,747 active cells with a resolution of 200 × 200 m. Initial groundwater heads were derived from the 2014 Lombardy Region groundwater level map. MODFLOW-6 uses QGIS-SWAP-Paddy's percolation rates as inputs, to simulate seasonal and interannual groundwater dynamics across the domain, including interactions with the Sesia, Ticino, and Po rivers, together with minor surface water bodies, for the period 2018 - 2020. Groundwater levels measured by AIES at 21 piezometers were used for calibration. The model reproduces observed seasonal fluctuations, associated with irrigation, typically reaching (+1.5) - (+2) m in summer, corresponding to the peak irrigation season, and (-1) m off the irrigation season. However, complete coupling between the two models needs to be improved further to more accurately reproduce the effect of irrigation strategies on groundwater dynamics and vice versa.

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