Scaling up to irrigation district level innovative on-farm water saving techniques for rice cultivation

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Abstract

The MEDWATERICE project - Towards a sustainable water use in Mediterranean rice-based agro-ecosystems – includes upscaling of on-farm efficiency and productivity gains at irrigation district scale. A common conceptual framework helped to understand water, salts and agrochemical fluxes in rice irrigation districts, and to identify modelling approaches for the upscaling of water use efficiencies and environmental effects of on-farm irrigation management practices. The modelling approaches were tailored to data availability in each specific study case. The study cases were characterized using Rapid Appraisal Process and DPSIR (Driving force, Pressure, State, Impact and Response) analysis. The selected modelling approaches were heuristic models; daily, semi distributed "bucket" mass balances; and physically-based distributed flow and transport models. The case studies were Lower Guadalquivir Marshes (Spain), the San Giorgio di Lomellina irrigation district (Italy), the Mas Plan farm in the Baix Ter (Spain), the Lower Mondego irrigation district (Portugal) and the left bank district in the Bafra valley (Turkey). The paper will present results of the application of the selected upscaling approaches to evaluate the impact of on-farm water saving techniques, such us alternate wetting and drying, dry seeding and delayed flooding, early drainage, drip irrigation and others, at district scale.

Keywords: rice; upscaling on-farm irrigation performance; water balance models

1. Introduction

This paper reports MEDWATERICE Work Package 3 ('Upscaling on-farm gains at irrigation district scale'), whose objective is to upscale the impact of on-field rice irrigation management technologies and practices at the district scale, and to assess district-level irrigation solutions aiming to water conservation.

The upscaling methods were developed/adopted based on data availability in each specific study case. The first step was the definition of a common conceptual framework for understanding water, salts and, when information was available, agrochemical fluxes in rice irrigation districts. The common framework helped to harmonise the characterization of district study cases. This characterization started with a DPSIR (Driving force, Pressure, State, Impact and Response) analysis, while the identification of water and other fluxes at the specific study cases was based on a Rapid Appraisal Process (RAP). The RAP served to collect basic information for the modelling activity, including the hydraulic arrangement and functioning of the study districts. The DPSIR was an independent activity that also served to fulfil the heuristic modelling approach, the simplest approach of the three selected, which are:

- Heuristic model;
- “bucket” mass balance model;
- physically-based water flow and pesticides transport models.

The application of models to assess water saving practices and make management decisions was preceded by three steps:

1. Stakeholders and knowledgeable managers were identified and committed to participate in the following steps;
2. the system was defined, its boundaries, main components (irrigation units) and connections, water sources and system exits, irrigated area, soil types, etc.;
3. the problem was stated. Depending on the study cases, the main problem was related to water scarcity, operating difficulties, salinity or diffuse pollution, etc.

Next, we explain the three modelling approaches, we describe the case studies (Figure 1), and we give an overview of the upscaling exercise in the case studies, which are the subject of specific articles in this conference, where they are presented in detail.

Figure 1. Location of case studies.

2. Modelling approaches

Three approaches were considered, heuristic method, “bucket” mass balance, and physically-based flow and transport models. The approach selected for each case study had to be functional, that is, it must give answer to the question of upscaling on-farm practices to system scale specific of each case study. The study case in Egypt followed the heuristic approach, although its application is not reported herein. The “bucket” mass balance approach was applied to case studies in Spain, Portugal and Turkey. Physically-based water flow and pesticides transport models were applied to one case study in Italy.

2.1. Heuristic method

Heuristic is any approach to problem solving based on experience. Heuristic use techniques and rules that are simple and practical; it may be alternative to complex decision-making models or a way for preliminary approximations. Heuristic relies on readily accessible (though not readily applicable) information to solve specific problems or improve process efficiency.

The heuristic method relied on the DPSIR and the RAP. DPSIR and RAP progressed simultaneously to understand the system functioning and specific weakness in project operation, management, resources, and infrastructure. Then, the heuristic method assessed the potential for water conservation at system scale and proposed specific management actions to benefit from on-farm efficiency gains and introduce system-scale water saving measures (Figure 2). The heuristic approach was applied to study cases where a comprehensive data-set at the irrigation district level was unavailable, so more complex approaches were unfeasible.

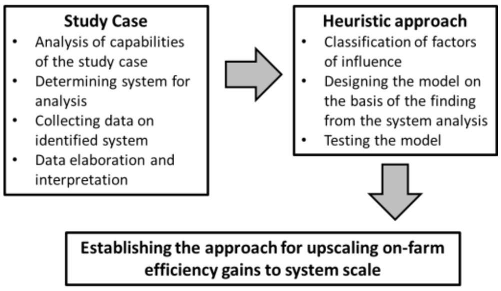

Figure 2. Diagram for the heuristic method for upscaling on-field irrigation efficiency gains to district level.

2.2. "Bucket" mass balance models

The arrangement of the units (fields, farms, sectors, districts...) in an irrigation system is determined by the hierarchical branched layout of the distribution network (Mateos et al., 2000; Mateos, 2008). A drainage network with a mirror image structure of the supply system can collect return flows from the irrigation units with the possibility that some return flow can be reused (Figure 3). The irrigation and drainage networks are then interconnected and the merged network is meshed. The solutes circulate with the water from irrigation unit to irrigation unit. Water and solute balances in the irrigation units (and drainage units, if so formulated), together with the water circulation defined by the interconnections in the network, serve to simulate the distribution of water and solutes according to the established management rules.

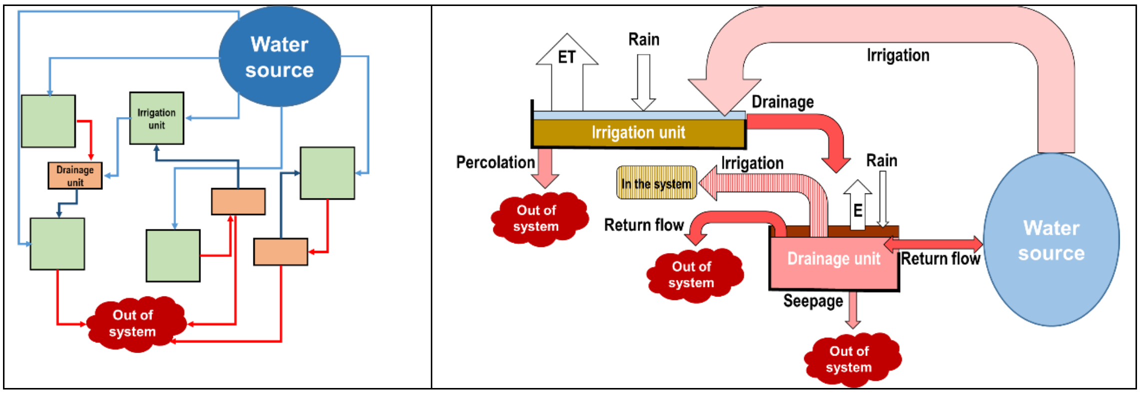

Figure 3. Diagrams of irrigation and drainage units interconnections (left) and water balance components (right).

2.3. Physically-based water flow model and pesticide fate model

The modeling approach set-up for the San Giorgio irrigation district to simulate water and pesticide flows in the current situation and in the case of scenarios considering the conversion of irrigation methods towards water saving techniques is explained below. Once the model was calibrated for the current situation, the following scenarios for the whole rice area within the district were taken into account: i) wet seeding and continuous flooding (WFL), ii) dry seeding and fixed turn irrigation (FTI), iii) dry seeding and delayed flooding (DFL) and iv) a safe Alternate

Wetting and Drying (AWD) technique following a wet seeding. Due to the limited space, this paper shows only results achieved in terms of water savings for WFL, FTI and AWD.

Physically-based water flow model

In the modelling framework developed, the SWAP model (Soil, Water, Atmosphere and Plant) (Kroes et al., 2008) is applied to the irrigation district following a semi-distributed approach. The district area is divided into zones which can be considered homogenous in terms of: crop cultivated, soil type and groundwater level condition. SWAP is designed to simulate one-dimensional vertical direction flow and transport processes at field scale, during growing seasons and for long term time series. The model employs the Richards equation including root water extraction to simulate soil moisture movement in variably saturated soils. Concepts are added to account for macro-porous flow and water repellency. Two empirical models complete the modelling framework, the former is used to estimate the monthly irrigation channel network percolation and the latter to simulate the mean monthly GWL over the district depending on the district percolation.

To simulate the current situation, the semi-distributed model was applied in the case of the San Giorgio di Lomellina district to 50 irrigation units obtained combining 5 crop types (rice with two irrigation management techniques, young and old poplar and maize), 5 soil types, and 2 groundwater level conditions (deep and shallow groundwater).

Pesticide fate model

The pesticide fate modelling approach used in MEDWATERICE at the district scale integrated three models originally developed by Waterborne Environmental, Inc. (USA): RICEWQ, RIVWQ and VADOFT.

RICEWQ was developed to simulate water and chemical mass balances associated with flooding, overflow, and controlled releases of water that are typical of rice production (Williams et al., 1999). Water mass balance considers precipitation, evaporation, seepage, overflow, irrigation, and drainage (Figure 4). Pesticide mass balance can accommodate dilution, advection, volatilization, partitioning between water/sediment, decay in water and sediment, burial in sediment, and re-suspension from sediment. RICEWQ does not consider pesticide losses through leaching, which could be a significant dissipation path for certain pesticides under field conditions. In order to describe adequately both leaching and runoff processes, an interface between RICEWQ and the vadose zone fate and transport model (VADOFT) model was built (Carsel et al., 1998; Miao et al., 2003a). VADOFT performs one-phase, one-dimensional transient or steady state simulations of downward water flow and chemical solute transport in variably saturated porous media (Figure 4). The VADOFT solves the Richards' equation, the governing equation for infiltration of water in the vadose zone. RICEWQ also provides daily summaries of the amount of pesticide and water lost from paddies' system due to runoff/overflow. These losses can be used as a water and pesticide mass input for the chemical transport model for riverine environments (RIVWQ) (Figure 4). RIVWQ was developed to evaluate time-varying water and chemical mass balance in river networks as a result of point-source and nonpoint-source chemical loadings (Miao et al., 2003b).

Soil and crop parameters and water fluxes to set up the RICEWQ and VADOFT are provided by the physically based water flow simulation.

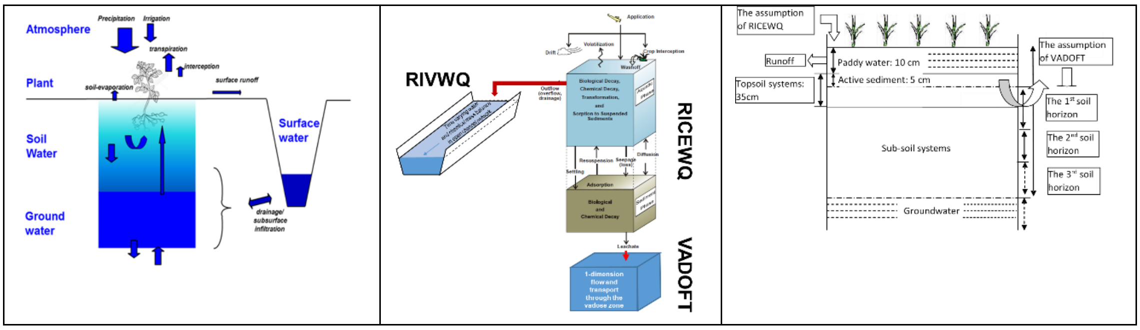

Figure 4. From left to right: Graphical description of SWAP (taken from the SWAP webpage (https://www.swap.alterra.nl/) graphical description of the models RICEWQ, VADOFT and RIVWQ and their coupling; and detail of the soil layers considered in VADOF and their connection with RICEWQ.

3. Study cases

The case studies presented in this paper are: Lower Guadalquivir Marshes (Spain), where we modelled the right bank district; the San Giorgio district (Italy), the Mas Plan farm in the Baix Ter (Spain), Quinta do Canal farm in the Lower Mondego district (Portugal) and the left bank district in the Bafra valley (Turkey).

The San Giorgio district is located in the most important rice-growing area of Italy, in the Padana plain, 45 km southwest of Milan. It covers 990 ha bounded by the rivers Agogna and Erbognone (Figure 5). The landscape is mainly flat except for some sand depositions of fluvial origin. The phreatic groundwater surface varies in space and time and is very shallow in some areas. Soils are generally sandy-loam or loamy-sand. The irrigation and drainage networks are managed by the Associazione Irrigazione Est Sesia (AIES). Water comes almost exclusively from surface water bodies (Arbogna and Po river through the Cavour channel). The main channels are the 'Canalino', the 'Cavo Isimbardi' and the 'Roggia Comunale di San Giorgio'. During the last decade, dry seeding followed by a delayed flooding, or by an alternation of flooding and dry periods, has been taking the place of the traditional wet seeding and continuous flooding. The shift to dry seeding is contributing to the decline of groundwater levels until mid-June, which affects the water supply of other crops.

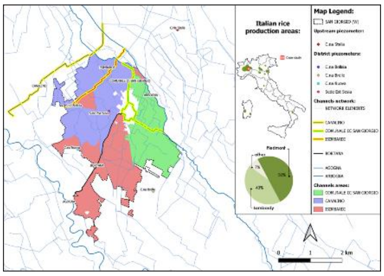

Figure 5. San Giorgio district case study (Italy); colors indicate areas served by the three irrigation canals.

The Baix Ter irrigation district is located in the Nord-eastern of Catalonia (Spain). With a Mediterranean climate, it conforms an alluvial plain with Xerofluvents soils that represent the main agricultural area of the internal basins of Catalonia region. Rice production in the Baix Ter is included in the Reg del Molí de Pals irrigation Consortium (Figure 6a), with an irrigable area of about 3,500 ha, mainly devoted to corn, alfalfa and apple trees. Irrigation water is derived from river Ter and distributed through open channels and pipes. Paddy fields are irrigated by continuous flooding and occupy around 1,200 ha. The critical issues related to the water resources management in the Baix Ter irrigation district are strong competition for water use;

risk of contravening the limits set by the EU Water Framework Directive due to high concentrations of chlorides, nitrates and sulfates in the groundwater; and high environmental and natural relevance of the area. The upscaling exercise was carried at the Mas Pla farm (Figure 6), that covers 120 ha of paddy rice and represents the growing conditions of this crop in the district.

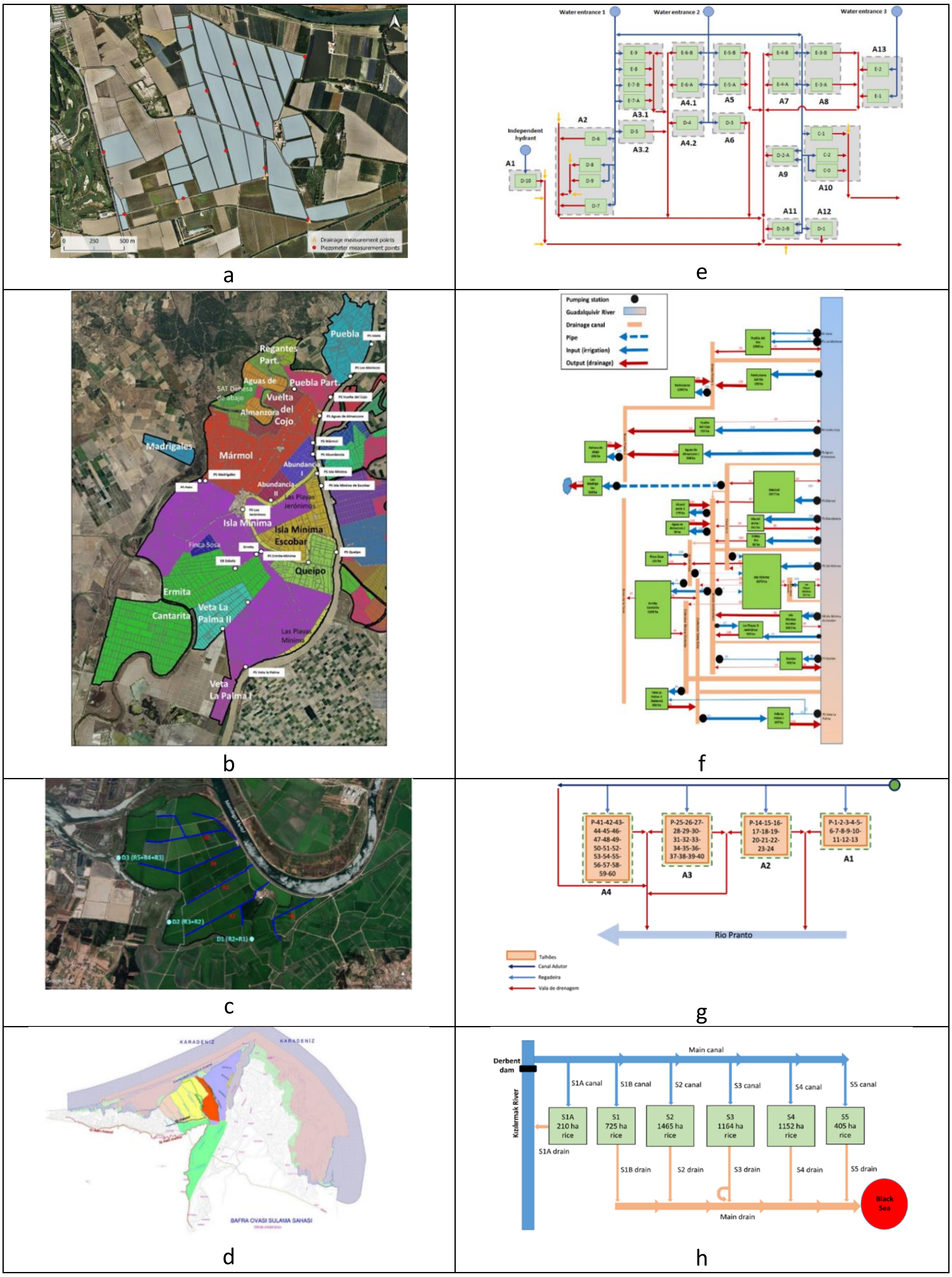

Figure 6. From top to bottom, on the left, map of the case study districts Mas Pla (Spain), Right Bank of Lower Guadalquivir Marshes (Spain), Quinta do Canal (Portugal) and Bafra Plain Left Side Irrigated Area (Turkey), and on the right, their respective topological flow diagrams.

The Lower Guadalquivir Marshes (Spain) case study is the rice-growing area on the right bank of Lower Guadalquivir Valley. The area comprises about 22,000 ha of marshes located between the estuary of the Guadalquivir River and Doñana National Park (Figura 6b). Rice production is traditional in the region; it generates significant rural employment and direct and indirect economic activity (rice industry, machinery, agrochemicals, transport). Land productivity is high thanks to the environment and high cropping intensity. Irrigation is by flooding, requiring 10,000 m^3/ha/year at district scale, although individual fields may receive four times as much. The irrigation water comes from the general regulation system of the Guadalquivir River basin: water released for irrigation is pumped directly from the estuary. Salinity is therefore a problem which severity depends on the rate of water release and the tides. Water restrictions due to rainfall and reservoir storage variability is the main threat for rice production in the Guadalquivir marshes. The salinity problem is not uniform across the area, but it is spatially distributed, increasing downstream along the estuary.

Rice production is a tradition in the Lower Mondego Valley (Portugal). About 5,000 ha are dedicated to rice cultivation, which constitutes about 40 % of the irrigated land in the Lower Mondego irrigation district. The irrigation water is conveyed by the main irrigation canal that runs along the Mondego river, which is regulated by several upstream dams. The selected case study is one sector (Quinta do Canal) of 335 ha devoted to rice (Figure 6c). The sector is bounded to the north by the Mondego River, to the south by the Pranto River and to the west by the Mondego River estuary. Quinta do Canal is amongst the most downstream irrigated land of the Lower Mondego irrigation district. The water delivered to the area is controlled by the Local Farmers Association and is shared between 38 farmers. Drainage water and excess water of the irrigation canal are discharged to the Pranto river. The proximity of Quinta do Canal to the Atlantic Coast and the sea tidal water intrusion that affects the Mondego and Pranto rivers explain the high salinity of the surface and ground waters, which is compensated by the good quality of the irrigation water. Competition for water among the users in the Mondego Basin and limitations in the upstream reservoirs' storage capacities are threats to rice production.

The irrigation district of Bafra (Turkey) covers an irrigated surface of 21,550 ha. It is composed by two different areas, Bafra Plain Right Side Irrigated Area, with 11,550 ha, and Bafra Plain Left Side Irrigated Area, with 10,000 ha, devoted mainly to rice. The upscaling of on-farm water saving practices in the Bafra plain was carried out by modelling water circulation in the Left Side Irrigated Area (Figure 6d). Rice is cultivated under continuous flooding irrigation. The main water source is the Kızılırmak River, regulated by the Derbent and the Altınkaya dams. The water uptake uses is a weir in the Kızılırmak river that diverts water to the main irrigation canal. The distribution network is ramified, it has a network of 5 secondary canals and many smaller tertiary canals. The Bafra Plain Left Side Irrigated Area has three main drainage channels that dump the water to the sea. The insufficiency of the drainage system and the shallow groundwater table cause salinity problems.

4. Results

Examples of results obtained with the application of "bucket" model to three case studies are presented in this section. Their detailed descriptions including a fourth case study are available in separate presentations at this workshop (Cuadrado-Alarcón et al., 2022a; Cuadrado-Alarcón et al., 2022b; Cufí et al, 2022).

Figure 7 shows the typical output representing water fluxes obtained with the application of the "bucket" model to Quinta do Canal in 2020.

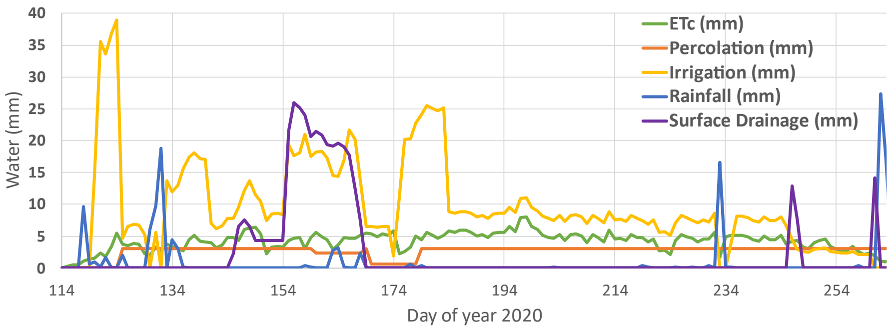

Figure 7. Daily water balance components at Quinta do Canal (Portugal).

A second example of application of the "bucket" model is in Figure 8, that shows simulation results of upscaling two alternative irrigation practices (increased and decreased water reuse) in the Right Bank of the Lower Guadalquivir Marshes, compared to management practices in 2020. The maps show the distribution of salinity averaged over the growing season of 2020. Overall, it may be observed an increase of salinity from north to south, determined by the salinity of the river water and the reuse of drainage water. Current scenario resulted in a surface drainage fraction of 0.52; the result assuming an increase in water reuse was a surface drainage fraction of 0.72; while a reduction in water reuse yielded a drainage fraction of 0.4. Comparing the three maps, it may be observed a clear effect of salt redistribution when water reuse within the system is increased.

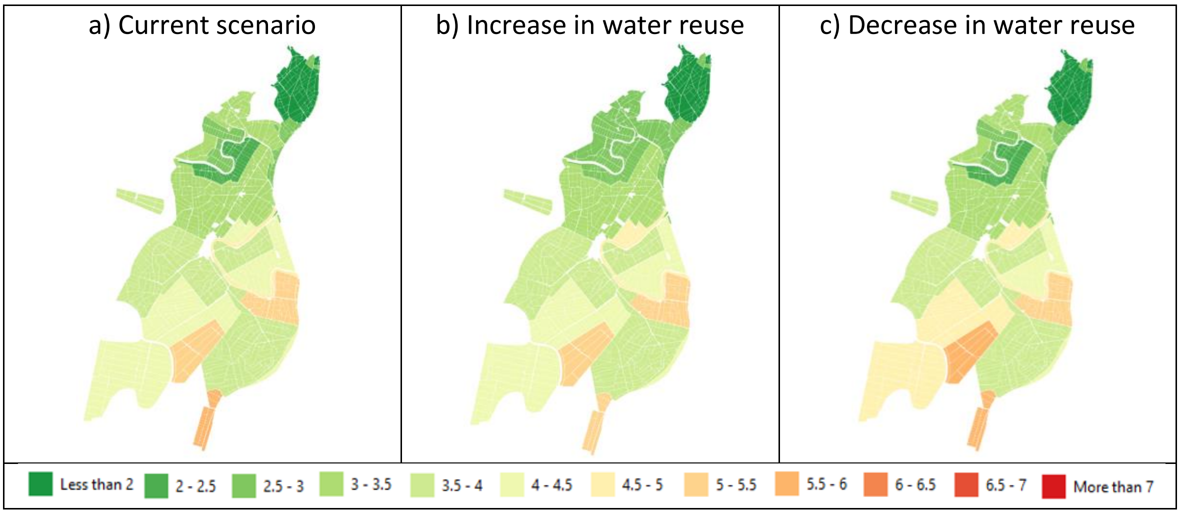

Figure 8. Spatial distribution of salinity in the input water for irrigation. Average value for year 2020 (dS/m). Rice growing areas on the right riverbank of the lower Guadalquivir marches (Spain).

As a final example of the application of the "bucket" model, two simulation scenarios for the Baix Ter case study are presented: current irrigation practices in Mas Pla (dry seeding with delayed flooding irrigation: scenario A); the traditional practice in the area (wet seeding and continuous flooding irrigation: scenario B). Calculation of irrigation performance indicators showed higher irrigation and total water efficiencies under Scenario A (Table 1).

Table 1. Irrigation performance indicators of the simulated scenarios in 2021, Mas Pla, Baix Ter case study (Spain).

Performance Indicator	Scenario A	Scenario B
Irrigation efficiency	0.47	0.36
Runoff fraction	0.00	0.17
Deep percolation fraction	0.50	0.33

As an example of the application of the physically-based water flow model, Figure 9 shows for the San Giorgio di Lomellina district the crop distribution and the areas characterized by shallow and deep groundwater level depths (GWD) in 2016, together with the effect of a massive conversion of irrigation methods on irrigation requirements and groundwater levels for the same year. For this case study, simulations have been carried out for the period 2013-2020. A detailed description of this application is in separate presentation at this workshop (Gilardi et al., 2022).

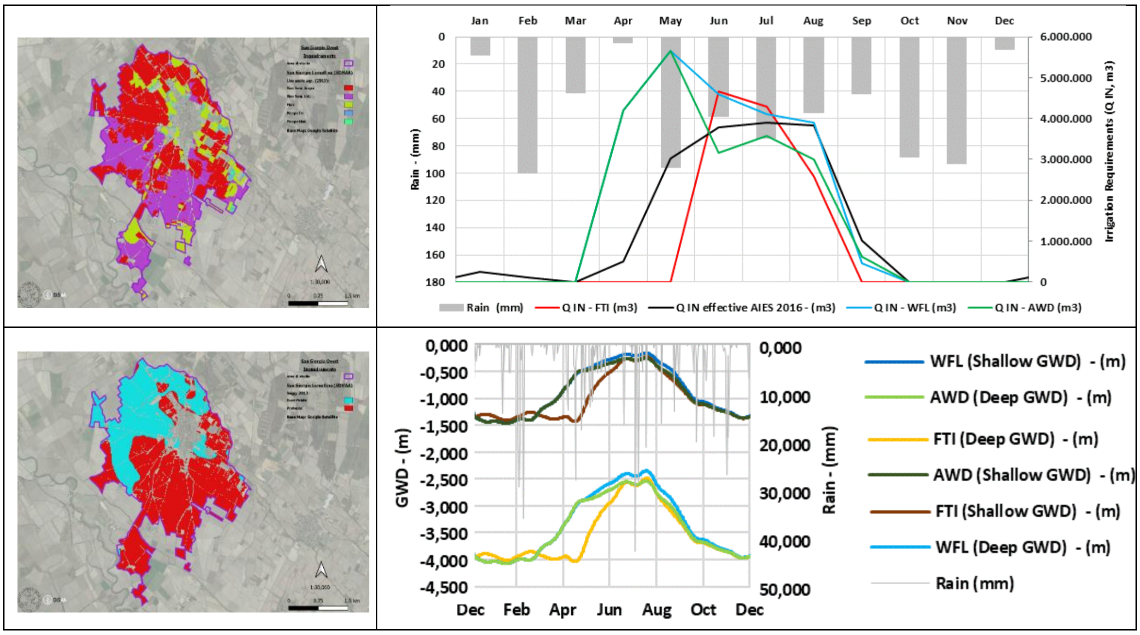

Figure 9. Land use (upper left), shallow and deep GWD areas (bottom left), irrigation requirements (upper right) and groundwater levels for the San Giorgio district, Italy (year 2016).

5. Conclusions

All case studies in MEDWATERICE performed the RAP and DPSIR analysis that allowed the identification and analysis of the main physical and management characteristics of the studied irrigation systems. The application of the "bucket" mass balance modelling approach to cases in Spain, Turkey and Portugal proved the usefulness of the approach for the upscaling purpose; while the physically-based flow and transport models implemented in Italy showed the potential of simulation analysis using such complex models. The next steps (until March 2023, closing date for the MEDWATERICE project) will be refining the application of the models selected for each case study and applying common irrigation performance indicators for comparison at the Mediterranean basin scale. The set of indicators will include: water productivity, relative water and irrigation supply, irrigation consumptive use coefficient, distribution efficiency, and variation of groundwater depth.

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