BLOCK 5.

The MEDWATERICE project

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The MEDWATERICE project: objectives and expected impacts

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Abstract

The MEDWATERICE project (https://www.medwaterice.org/), started in April 2019, explores the sustainability of innovative water-saving irrigation strategies to reduce rice water consumption and environmental impacts, and to extend rice cultivation outside of traditional paddy areas to satisfy the increasing rice demand in Mediterranean countries. Innovative irrigation methods and technologies were implemented in experimental pilot farms of each country involved in the project (EG, IT, TR, ES, PT; Work Package 2). Tested water-saving irrigation methods were tailored to local conditions using a participatory action research approach through the establishment of Stake-Holder Panels (SHPs). For each irrigation solution, innovative technologies and the most appropriate rice varieties and agronomic practices were implemented to minimize impacts on yield quantity and quality. Experimental activities were conducted in the pilot farms for at least two agricultural seasons in the period 2019-2021. A dataset including agro-climatic data, soil physic-chemical properties, groundwater depth and salinity, irrigation water inflow and outflow, irrigation water salinity, grain yield and quality was produced in all Case Studies (CSs) and stored in a common FAIR and OpenAIRE compliant repository (https://dataverse.UMIL.it/). For some CSs, also GHGs emissions and nutrient and pesticides losses in surface waters and groundwater were measured. Datasets were used to assess water saving, yield and product safety and other environmental impacts for the wet seeding and continuous flooding (WFL, considered as the 'reference' irrigation in all CSs) and for the alternative irrigation solutions implemented, which are: alternate wetting and drying (AWD); dry seeding and delayed flooding (DFL), reduction in irrigation inflow/outflow (WIR), hybrid irrigation (HYBRID), multi-nozzle sprinkler irrigation (SPRINKLER), surface drip irrigation (DRIP), and subsurface drip irrigation (SDI). Moreover, the reuse of agricultural water drainage and waste water civil effluents, as well as the implementation of automated gates for optimising irrigation management in case of continuous flooding, were tested in specific experiments. A set of indicators for the quantitative assessment of the environmental and economic sustainability of the irrigation options were defined and applied to the datasets collected in the agricultural seasons 2019-2021. In addition, the social acceptability of the proposed water saving techniques was investigated through the Technology Acceptance Model (TAM) through questionnaires compiled by rice growers of the pilot areas, to explore barriers to the adoption and identify solutions to overcome them (Work Package 5). A particular focus is dedicated to the Egyptian situation, where rice is the second staple food after wheat (Work Package 4). Results achieved at the pilot farm scale are being extrapolated to the irrigation district level through agro-hydrological models of different complexity (heuristic, conceptual, physically-based), to support water management decisions and policies (Work Package 3). Results of the project are being disseminated through different channels (Work Package 6).

Keywords: Water-saving, Irrigation, Sustainability, Rice, Production, Mediterranean basin

1. Introduction

Rice is the world's most important food crop, since it is a staple food for more than half of the world's population and the world demand for rice is expected to increase by approximately 24-28% over the next 20-30 years (Nguyen and Ferrero, 2012; Alexandratos and Bruinsma, 2012). Rice is cultivated over about 1,300,000 ha in Mediterranean countries (FAOSTAT, 2019). Although in the Mediterranean region it is concentrated in specific areas, rice production has a great socio-economic and environmental importance due to the fact that rice is often a crucial product for internal consumption and export, and its cultivation uses important water volumes and has a strong link with biodiversity maintenance (many important rice areas are in river deltas, estuaries or coastal wetlands or, however, part of protected ecosystems such as the EU Natura-2000 network).

The most important rice-producing countries are Italy and Spain in Europe (72% of the EU production; 345,000 ha), and Egypt and Turkey among the non-EU countries (789,000 ha). Average crop yields range from 10 t ha^{-1} in Egypt (highest yield of rice worldwide, together with Australia and USA) to 6-7 t ha^{-1} in the European countries. Per-capita annual rice consumption ranges from 6–18 kg $person^{-1}$ $year^{-1}$ in southern Europe to 50 kg $person^{-1}$ $year^{-1}$ in Egypt. EU, Turkey and Egypt self-sufficiency rates are, respectively, 70%, 80% and almost 100%, but in all the countries human consumption is steadily increasing (World Atlas, 2016). In Egypt, rice is the most important staple food after wheat, and it is the second major foreign exchange-earning agricultural commodity.

Traditionally, rice is grown in paddies flooded from before sowing to before harvest, thus it requires much more irrigation water than non-ponded crops (Cesari et al., 2016). Under flooded conditions, significant amounts of nutrients may be lost by leaching and runoff, with important implications on water quality (Katoh et al., 2004). Like other important cereals, rice requires a great amount of chemicals, particularly fertilizers and pesticides, which may cause water pollution in a peculiar environment like paddy. Water management has been recognized as one of the most important factors that affect greenhouse gas emissions from paddy fields; in particular, rice paddies are one of the most important sources of atmospheric methane (CH_4), producing about 5-20% of the total emission from anthropogenic sources (USEPA, 2006) and approximately 30% of the global agriculture CH_4 emissions. Moreover, many important rice growing areas in the Mediterranean region are in environments where soil salinity is an important factor constraining production.

Mediterranean rice agro-ecosystems are nowadays facing numerous problems, such as the need to harmonize irrigation demand with the availability of the resource, the protection of the environment, the need to ensure an adequate income for rice producers, the impossibility of being introduced in agricultural areas characterized by a limited water availability despite the increase of rice consumption in the Mediterranean basin, and the lack of specific studies conducted in Mediterranean countries addressing environmental and socio-economic peculiarities of these areas. Due to these issues, the introduction of water management practices alternative to the continuous flooding is imperative to enhance water use efficiency and safeguard environmental quality in Mediterranean rice agro-ecosystems. However, these practices must be tested and adapted to country-specific conditions.

In the context of the MEDWATERICE project (https://www.medwaterice.org), seven case studies (CSs) were implemented in experimental pilot farms of the countries involved (EG, IT, TR, ES, PT). Tested water-saving irrigation strategies were tailored to local conditions using a participatory action research approach through the establishment of Stake-Holder Panels (SHPs). Data collected at the farm scale were up-scaled at the irrigation district level to support management and policy-making decisions. Indicators for the quantitative assessment of environmental, economic, and social sustainability of the irrigation options were defined and computed for each rice irrigation strategy for at least two agricultural seasons in the period 2019-2021.

2. Materials and methods

The general structure of the MEDWATERICE project is illustrated in Figure 1.

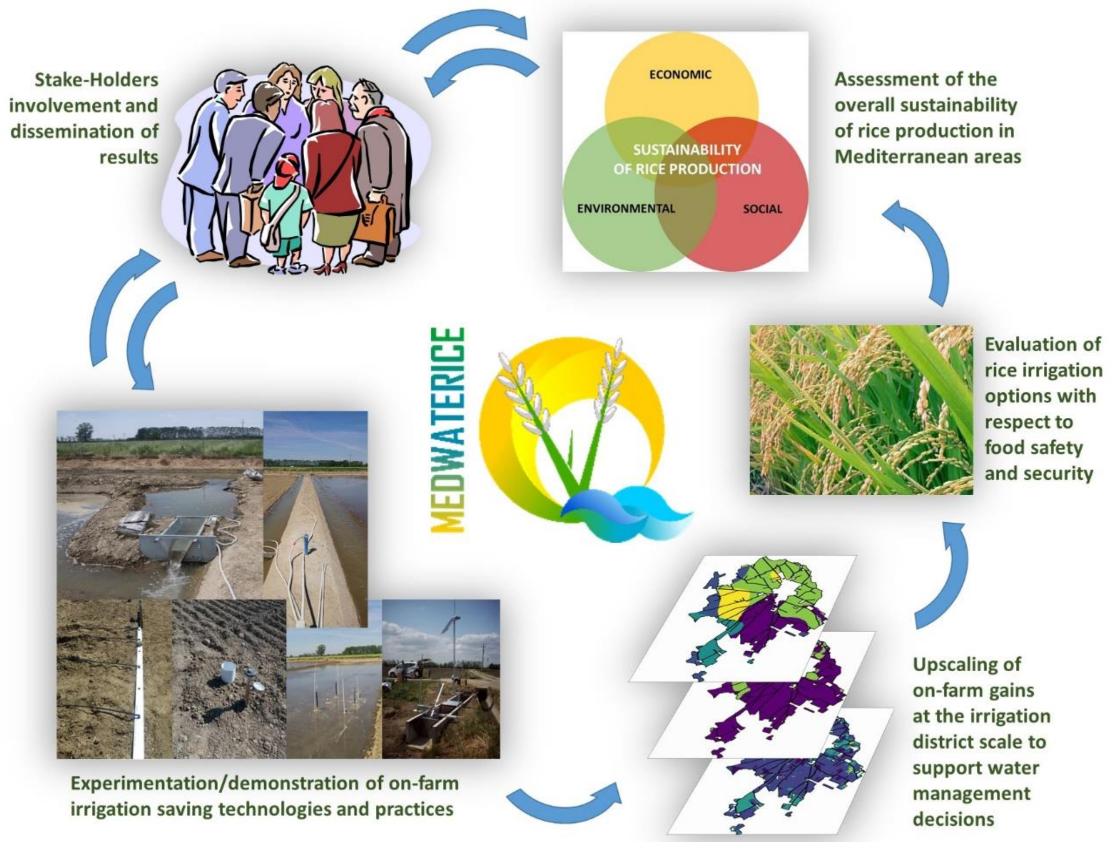

Figure 1: General structure of the project and main activities

Innovative irrigation methods and technologies were implemented in experimental pilot farms of each country involved in the project (EG, IT, TR, ES, PT; Work Package 2). For each irrigation solution, innovative technologies and the most appropriate rice varieties and agronomic practices were implemented to minimize impacts on yield quantity and quality.

The irrigation strategies experimented in the MEDWATERICE Case Studies (CSs) during the agricultural seasons 2019, 2020, and 2021, are illustrated in detail in Table 1.

Table 1: Irrigation strategies experimented in the MEDWATERICE Case Studies (CSs) during the agricultural seasons 2019, 2020 and 2021

Country and location	CS No	2019	2020	2021
Italy (Lomellina area, Pavia)	1	- Wet seeding and traditional flooding (pilot farm 1; subplots with 3 nitrogen treatments, and subplots untreated respectively with fungicides and herbicides are moreover included in the experiment) - Dry seeding and delayed flooding (pilot farm 1; subplots with 3	SAME AS IN 2019	- Dry seeding and traditional flooding implementing automated gates (pilot farm 2)

		nitrogen treatments, and subplots untreated respectively with fungicides and herbicides are moreover included in the experiment) - Wet seeding and alternate wetting and drying (pilot farm 1; subplots with 3 nitrogen treatments, and subplots untreated respectively with fungicides and herbicides are moreover included in the experiment)		
Spain (Baix Ter area, Pals, Girona)	**2**	- Wet seeding and traditional flooding (pilot farm 1) - Subsurface drip irrigation (pilot farm 2)	SAME AS IN 2019 + - Dry seeding and delayed flooding (pilot farm 1)	SAME AS IN 2019 + - Dry seeding and delayed flooding (pilot farm 1)
Spain (Guadalquivir marches, Seville)	**3**	- Wet seeding and traditional flooding (pilot farm 1) - Wet seeding and traditional flooding with a 15%-30% reduction of input water along the whole cycle with longer dry periods (considering the salinity level) (pilot farm 1) - Wet seeding and traditional flooding with a 15%-30% reduction of input water (considering the salinity level) along the whole cycle (pilot farm 1) - Wet seeding and traditional flooding with a 15%-30% reduction of input water (considering the salinity level) from day 100 after sowing (pilot farm 1) - Surface drip irrigation (pilot farm 2)	SAME AS IN 2019 (except for: Wet seeding and traditional flooding with a 15%-30% reduction of input water (considering the salinity level) along the whole cycle (pilot farm 1)	Two water saving options approved by the SHP were continued during the 2021 season: - Wet seeding and traditional flooding with a 15%-30% reduction of input water along the whole cycle with longer dry periods (considering the salinity level) (pilot farm 1) - Wet seeding and traditional flooding with a 15%-30% reduction of input water (considering the salinity level) from day 100 after sowing (pilot farm 1)
Portugal, (Lower Mondego Valley, Coimbra)	**4**	- Wet seeding and traditional flooding (pilot farm 1) - Wet seeding and alternate wetting and drying (pilot farm 1). *The test was abandoned due to weeds and pests affecting yield.* - Wet seeding and traditional flooding (pilot farm 2) - Wet seeding and alternate wetting and drying (pilot farm 2) *Both tests were invalidated by the low representativeness of the soil type.*	SAME AS IN 2019 (but changing location of pilot farm 2).	SAME AS IN 2020
Portugal (Lis Valley, Leiria)	**5**	- Wet seeding and traditional flooding (pilot farm 1) - Wet seeding and alternate wetting and drying (pilot farm 1): *Test was not carried out.* - Surface Drip Irrigation (pilot farm1): *Test was not completed.* - Subsurface drip irrigation with conventional water (in pots) - Subsurface drip irrigation with civil wastewater (in pots)	SAME AS IN 2019 (but the Surface drip irrigation plot was moved from pilot farm1 to a pilot farm 2.	SAME AS IN 2020

Egypt (Nile Delta: East, North, West)	**6**	North Delta site: - Traditional flooding with high (fresh)and low (agricultural drainage) quality water (pilot farm 1; 2 cultivation methods and 6 varieties are moreover experimented in different plots) - Traditional flooding (pilot farm 2; 4 cultivation methods and 8 varieties are moreover experimented in different plots) East Delta site: - Traditional flooding (pilot farm 1; 3 cultivation methods and 5 varieties are moreover experimented in different plots) West Delta site: - Traditional flooding (pilot farm 1; 3 cultivation methods and 8 varieties are moreover experimented in different plots)	North Delta site: - Traditional flooding compared with hybrid irrigation method (pilot farm 1; 2 water qualities, 3 cultivation methods and 5 varieties are moreover experimented in different plots) East Delta site: - Traditional flooding (pilot farm 1; 3 cultivation methods and 5 varieties are moreover experimented in different plots) - Surface drip irrigation (pilot farm 1; 3 cultivation methods and 5 varieties are moreover experimented in different plots) - Hybrid irrigation (pilot farm 1; 3 cultivation methods and 5 varieties are moreover experimented in different plots) - Multi-nozzle irrigation (pilot farm 1; 3 cultivation methods and 5 varieties are moreover experimented in different plots) West Delta site: - Traditional flooding compared with hybrid irrigation method (pilot farm 1; 2 water qualities, 3 cultivation methods and 5 varieties are moreover experimented in different plots)	SAME AS IN 2020
Turkey (Bafra Valley)	**7**	- Wet transplanting and traditional flooding (pilot farm 1; 2 rice varieties experimented) - Wet transplanting and alternate wetting and drying – considering a 1st soil water content depletion rate (pilot farm 1; 2 rice varieties experimented) - Wet transplanting and alternate wetting and drying – considering a 2nd soil water content depletion rate (pilot farm 1; 2 rice varieties experimented) - Wet transplanting and alternate wetting and drying – considering a 3rd soil water content depletion	- Dry seeding and traditional flooding (pilot farm 1; 2 rice varieties experimented) - Dry seeding and alternate wetting and drying – considering a 1st soil water content depletion rate (pilot farm 1; 2 rice varieties experimented) - Dry seeding and alternate wetting and drying – considering a 2nd soil water content depletion rate (pilot farm	Only two irrigation techniques were implemented to determine Green-House Gas emissions (CH4 and N2O) under two irrigation practices at the Bari farm: - Traditional flooding (pilot farm 1) - Alternate wetting and drying – considering the 3rd soil water content depletion rate (pilot farm 1)

		rate (pilot farm 1; 2 rice varieties experimented) - Wet transplanting and surface drip irrigation, considering a 1st soil water content depletion rate (pilot farm 1; 2 rice varieties experimented) - Wet transplanting and surface drip irrigation, considering a 2nd soil water content depletion rate (pilot farm 1; 2 rice varieties experimented)	1; 2 rice varieties experimented) - Dry seeding and alternate wetting and drying – considering a 3rd soil water content depletion rate (pilot farm 1; 2 rice varieties experimented) - Dry seeding and surface drip irrigation, considering a 1st soil water content depletion rate (pilot farm 1; 2 rice varieties experimented) - Dry seeding and surface drip irrigation, considering a 2nd soil water content depletion rate (pilot farm 1; 2 rice varieties experimented)	

In the pilot farms, many data were measured directly in the field, while others were the result of estimations carried out using simple models. With the objective to allow a comparison among results obtained in the different pilot farms, the MEDWATERICE participants collected a minimum common set of data (called 'minimum dataset') for each farm. The 'minimum dataset' was collected both for the traditional flooding irrigation ('reference' irrigation management) and for the experimented water-saving irrigation strategies. The 'minimum dataset' includes: agro-climatic data, soil physico-chemical properties, soil water status data, groundwater level and quality data, irrigation volumes and quality data, water balance components, crop development, yield and product quality. Datasets were collected in each CS for at least two agricultural seasons in the period 2019-2021. In some pilot farms, additional data were measured, such as those needed to compute the soil nutrient balance, the soil salt balance and other environmental impacts (e.g. water pollution due to the use of pesticides, greenhouse gas emissions); these results will allow a better investigation of specific environmental aspects involved in rice cropping.

Data collected during the lifetime of the project are being stored in a FAIR and OpenAIRE compliant repository called DATAVERSE (https://dataverse.unimi.it/) offered by UMIL (Università degli Studi di Milano - University of Milan), following the best practices and standards available. DATAVERSE is a repository software platform created by Harvard University to support universities and research institutions to facilitate the management and archiving of research data according to FAIR principles. After an embargo period of 2 years, data access will be 'opened' under a Creative Common (CC) licence.

A set of indicators for the quantitative assessment of the environmental and economic sustainability of the irrigation options were defined and applied to the datasets collected in the agricultural seasons 2019-2021. The social acceptability of the proposed water saving techniques was investigated through the Technology Acceptance Model (TAM) through questionnaires compiled by rice growers of the pilot areas, to explore barriers to the adoption and identify solutions to overcome them. A particular focus is dedicated to the Egyptian situation, where rice is the second staple food after wheat.

Results achieved at the pilot farm scale are being extrapolated to the irrigation district level through agro-hydrological models of different complexity (heuristic, conceptual, physically-based), to support water management decisions and policies.

3. Results

The main results obtained so far are listed below and will be illustrated during the MEDWATERICE workshop and in specific papers published in the workshop e-book.

- Identification, with the support of SHPs set up in each project rice area, of the most suitable irrigation solutions which were implemented in pilot farms alongside the traditional irrigation technique (continuous flooding). Experimental activities in the pilot farms were carried out at least for two years in the period between 2019-2021.
- Definition and collection of a 'common set of experimental data' both for the traditional flooding ('reference') and for the innovative irrigation management options in all the pilot farms for at least for two experimental years in the period between 2019-2021.
- Definition of a database structure to store data collected in the pilot farms, creation of a FAIR and OpenAIRE compliant repository (https://dataverse.UMIL.it/) where data collected from the experimental pilot farms during the agricultural seasons 2019-2021 were uploaded. This common repository, at the end of the project, will allow to benchmark data from different countries and different technologies and practices.
- Conduction of a literature review on the current irrigation technologies and practices in Egypt, and design and distribution of 300 questionnaires to rice farmers to investigate their practices.
- Conduction of a literature review on the existing methodologies to assess techno-economic, environmental and social sustainability of agricultural production, with a focus on rice systems (Gharsallah et al., 2021).
- Development of a novel indicator-based methodology to assess the overall sustainability of rice systems at the on-farm scale, and design of a questionnaire to collect data for the assessment. Application of the methodology to the MEDWATERICE pilot farms for at least two experimental years in the period between 2019- 2021. Data obtained at farm scale are being used for the district scale.
- Development of guidelines (in local languages) for the irrigation solutions tested in MEDWATERICE characterized by the higher technical/technological degree of readiness, and therefore judged to be suitable to be disseminated among farmers. For the same solutions, development of fact-sheet (in English) to support their international dissemination.
- Definition of a novel conceptual framework to upscale water use efficiencies and environmental impacts of traditional and innovative irrigation strategies at the irrigation basin scale. The framework is adaptable to the complexity, information availability and expertise of each area and is under implementation for each project CS.
- Organization of numerous SHs meetings and farm field days, more than 40 contributions to national and international seminars and congresses, 4 papers in scientific journals, and 4 articles in trade journals were produced so far. The final meeting will be held in Albacete, Spain on 5-7 September 2022 (https://crea.uclm.es/crea/SUPWASConference)
- Development of MEDWATERICE website (www.medwaterice.org) and update of its contents every 6 months. All the results and material produced are constantly uploaded to the website. The website will be maintained for a minimum of 3 years after the closure of the project, in order to guarantee a long-term impact of project results.

4. Conclusions

MEDWATERICE is successfully investigating the introduction of innovative water-saving irrigation techniques/technologies tailored to local conditions in the rice sector of the Mediterranean basin, assessing their overall sustainability (economic, environmental, and social) at the on-farm and irrigation district scales.

The most innovative achievements of the project, are: (1) introduction of participatory action research as an innovation strategy in the Mediterranean rice sector to explore the applicability of non-conventional irrigation-efficient methods tailored to local conditions; (2) production of a field-proved, ready-to-be-adopted set of water-saving techniques unique in the Mediterranean basin: first, because of the ground-breaking nature of some of them, and second, because the transnational research approach used confers them strength and robustness; preparation of fact-sheets for their dissemination and guidelines for their implementation; (3) use of state-of-the-art hydraulics, low cost sensors, and ICTs to set-up integrated multi-sensor system for the continuous monitoring of water dynamics in rice fields under different irrigation regimes; (4) development of a comprehensive multidisciplinary indicator-based tool to assess the overall sustainability (economic, environmental, and social) of rice systems at the on-farm and irrigation district scales; (5) building of a novel framework for computing effective water efficiency and productivity by up-scaling farm efficiency data to the irrigation district scale, in order to prevent fake or rebound effects of water saving measures; few studies in the literature deal with these complex phenomena in rice areas.

The project implemented several dissemination actions, including the preparation of fact-sheets and guidelines, and the involvement of the Stake-Holder Panels in each project step. The indicator system developed for the sustainability assessment, and the modelling framework to upscale water savings at the irrigation district scale, are novel tools that will be appropriately described in technical and scientific publications since they are expected to survive to the project and be available to the technical and scientific communities working in rice areas.

More in general, outcomes produced by MEDWATERICE are expected to inject tailored and updated knowledge to improve the sustainability of rice production in the Mediterranean countries, with a particular attention to the adoption of water-saving techniques.

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Irrigation strategies alternative to continuous flooding to decrease water use and increase water productivity in Mediterranean rice-based agroecosystems

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Abstract

In the Mediterranean basin, rice is cultivated over an area of 1,300,000 hectares. The most important rice-producing countries are Italy and Spain in Europe (72% of the EU production; 345,000 ha), and Egypt and Turkey among the extra-EU countries (almost totality of the production; 789,000 ha). Traditionally, in these areas, rice is cultivated under continuous flooding; thus, it requires much more irrigation than non-ponded crops. On the other hand, rice is strategic for food security in some countries and its consumption in the whole Mediterranean basin is steadily increasing.

The MEDWATERICE project (https://www.medwaterice.org/) includes 7 case studies (CSs) representative of different rice agroecosystems in 5 Mediterranean countries (Italy, Spain, Portugal, Egypt and Turkey). Innovative irrigation strategies alternative to the traditional wet-seeding and continuous flooding (WFL) were tested and tailored to local conditions in each CS, including: alternate wetting and drying (AWD), dry-seeding and delayed flooding (DFL), subsurface drip irrigation (SDI), surface drip irrigation (DRIP), reduction of water input (RWI), hybrid irrigation (HYBRID) and multi-nozzle sprinkler irrigation (SPRINKLER). In each CS, strategies were compared to WFL and field trials were carried out at least for two years during the period 2019-2021. A minimum dataset including agroclimatic data, soil physico-chemical properties, groundwater depth and salinity, irrigation water inflow and outflow, irrigation water salinity, grain yield and quality was collected and analyzed in all case studies.

Results suggest that AWD and DFL might be sound alternatives to WFL in Lomellina (IT), Baix Ter (SP), Lower Mondego and Lis Valleys (PT), and Bafra Valley (TR), leading to an increase in water productivity up to 30%. SPRINKLER and HYBRID irrigation tested in the Nile Delta (EG) resulted in an increase in water productivity of about 50% in both cases. Surface and subsurface drip irrigation systems have a great potential in reducing water use, while maintaining yield production as demonstrated in the Nile Delta (EG), Bafra Valley (TK), and Baix Ter (ES), where water productivity increased from 40 to 100% compared to WFL. Nevertheless, when adopting drip irrigation techniques, special attention must be paid to the irrigation system design and

management, by considering the site-specific soil hydraulic properties and agroclimatic conditions.

This communication describes the main aspects affecting rice production in each area participating in the MEDWATERICE project, and quantifies the water use and the quantity and quality of the rice production achieved with the traditional irrigation method (WFL) and the innovative irrigation solutions tested in each CS.

Keywords: Water-saving irrigation; Water productivity; Mediterranean basin; Alternate Wetting and Drying (AWD), Dry-seeding and Delayed Flooding, Surface and subsurface drip irrigation, Hybrid irrigation; Multi-nozzle sprinkler irrigation

1. Introduction

Growing rice requires, in general, two to three times more water than other cereals (Kijne, 2006; Marcos *et al.*, 2018). The Mediterranean basin, where rice is cultivated over an area of 1,300,000 hectares, due to its high population and semi-arid climatic conditions, is among the most water-scarce regions, posing serious constraints on irrigation (Harmanny and Malek, 2019). Additionally, there is a strong competition for water use with other economic sectors, such as urban, industrial, environmental, recreational and touristic (Zikos and Hagedorn, 2016). Simultaneously, water scarcity in this region is being aggravated by the climate change, which is increasing temperatures and modifying the precipitation patterns (Iglesias and Garrote, 2015).

In the Mediterranean region, rice is traditionally grown under continuous flooding. Due to the threat of less water availability, alternative water management and irrigation systems, which may allow reducing water input to grow rice, are of great interest. Different research has been carried out worldwide to introduce strategies and technologies for reducing irrigation water at the field scale while maintaining yield. Nevertheless, most results show that rice yield declines as soon as the soil water content is below saturation (Bouman and Tuong, 2001). Different irrigation strategies alternative to the wet seeding and continuous flooding irrigation (WFL) have been tested to reduce water inputs in paddy fields (Tuong et al., 2005). Among them: Alternate Wetting and Drying (AWD), Dry-seeding and Delayed Flooding (DFL), different intensities and timings of Reduction of Water Input (RWI), Surface and subsurface drip irrigation (Drip and SDI), Hybrid irrigation (HYBRID) and Multi-nozzle sprinkler irrigation (SPRINKLER). Carrijo et al. (2017) analyzed available scientific literature focused on AWD and estimated that it led to a reduction in water use compared with WFL from 15% to 33%, depending on the severity of application of this technique. The same study revealed that the average water productivity (WP) was about 24% higher in AWD than in WFL. Nevertheless, information about the irrigation water needs and crop productivity using these innovative irrigation technologies is very scarce, and only a few studies were conducted in the Mediterranean region. Among these, Cesari de Maria et al. (2017), using DFL in western Po valley (Italy), observed an average reduction of 20% of the irrigation needs compared with WFL, while reduction in yield was only 3%.

The objective of this study is to describe the main characteristics of each CS involved in the MEDWATERICE project, quantify the water use, yield, and water productivity achieved with the traditional irrigation method (WFL), considered as the “reference” irrigation method for all CSs, and compare these results with those achieved with the tested innovative solutions in each CS.

2. Material and Methods

2.1. Description of the case study areas (CS) and experimental sites

Case studies (CSs) were implemented in pilot farms of the main rice producer countries around the Mediterranean basin (Italy, Spain, Portugal, Turkey and Egypt). For each irrigation solution, the experimental activities were conducted during at least two agricultural seasons in the period 2019-2021. Tested alternative irrigation methods and technologies adopted in each CS were tailored to local conditions using a participatory action research approach through the establishment of Stake-Holder Panels in each country, which included regional authorities, water managers, farmers' associations and consultants, and private companies of the rice production supply chain.

CS1, Italy: The main rice cultivated area in the country is located in the upper Po Valley, between the Piedmont and Lombardy regions, with about 120,000 ha, which contributes to about 92% of the total rice Italian production (Zampieri *et al.*, 2019). The experimental tests were carried out at the ENR Rice Research Centre's experimental farm located at Castello d'Agogna, Pavia, within the traditional rice production area.

During the period 2019-2020, the maximum and minimum temperatures within the cropping season were 4.2°C and 37.5°C, with an average precipitation of 287.5 mm and a potential evapotranspiration of 670.2 mm. Soil texture of the first soil layer was silty-loam and groundwater depth was about 200 cm at the beginning of the irrigation season and 15-20 cm in the center of the season (80 cm as an average). The different irrigation options were tested in six plots of about 20 m x 70 m each, with two replicates for each option.

CS2, Baix Ter, Spain: This area includes a surface devoted to rice of about 1,000 ha. Being a small surface within the total 105,000 ha of rice cultivated in Spain (Gómez de Barreda *et al.*, 2021), it is well-known by the quality label "Arròs de Pals" (Empordà Gastronòmic, 2022).

In the period 2019-2021, the maximum and minimum temperatures within the cropping season were 5.7°C and 35.5°C, with an average precipitation of 128.0 mm and a potential evapotranspiration of 508.2 mm. The soil texture of the first layer was loam to silty-clay-loam and average groundwater depth was 45.9 cm. The experimental tests were carried out in different fields of an area ranging from 0.4 to 1.1 ha. The soil texture at the first layer in the WFL field was silty-clay-loam, the DFL was loam and the two SDI fields were silty-clay and sandy-loam.

CS3, Guadalquivir Marshes, Spain: It is the main rice production area in Spain with 39,635 ha dedicated to rice in 2019, and the one with the highest average yield, around 8.6 t/ha (Gómez de Barreda *et al.*, 2021).

During the period 2019-2020, the maximum and minimum temperatures within the cropping season were 6.8°C and 37.8°C, with an average precipitation of 63 mm and a potential evapotranspiration of 733 mm. The soil texture at the upper layer was from clay to silty-clay and groundwater depth was about 60 cm. Furthermore, it is noticeable that the water quality level is low in terms of salinity, with an average electrical conductivity of 3.46 dS/m. The experimental fields had a mean area of 5.8 ha, except the drip irrigation experiment that had 0.4 ha.

CS4 and CS5, Lower Mondego and Lis Valley, Portugal: These areas are in the center of Portugal, near the Atlantic coast, with a total rice crop cultivation area of about 6,000 ha.

In the period 2019-2021 the maximum and minimum temperatures within the cropping season were 10.0°C and 36°C for Mondego Valley, and 4.8°C and 34.0°C for Lis Valley, with an average precipitation of 62.8 mm and a potential evapotranspiration of 565.0 mm. Soils are mainly alluvial, some of them poorly drained with waterlogging and salinization risks, especially in downstream areas. In Lis Valley the average groundwater depth was 64 cm and an electrical conductivity of 1.46 dS/m, no data are available for Mondego Valley. The irrigation water had good quality with an average electrical conductivity of 0.068 dS/m and 0.286 dS/m, for Mondego and Lis valley respectively. Soil textures vary from silty-clay to clay-loam. Experimental fields had an area ranging from 0.5 to 3.2 ha, except the drip-irrigated plot, which had an area of 240 m^2.

CS6, Delta Nile, Egypt: The Nile Delta covers an agricultural area of approximately 1.8 million ha, irrigated by a complex network of waterways. Rice growing area is about 500,000 ha with a national average yield of 10 t/ha.

During the period 2019-2021, the maximum and minimum temperatures within the cropping season were 20.3°C and 41.1°C, with an average potential evapotranspiration of 976.0 mm; there was no precipitation being recorded in this period. Groundwater is shallow, aquifers have an average salinity of 4.6 dS/m. The predominant soil texture is clayey, with poor drainage. In 2020 and 2021 agricultural seasons, the experimentation was conducted in three experimental sites. The data presented in this study are focusing on the field experiment located at the east Nile Delta. The tests were performed in 3 x 10 m^2 plots, with three replications of each treatment. All the data considered in the present study correspond to the Hybrid Rice-EH1 variety irrigated with freshwater (0.53-0.76 dS/m). The WFL treatment was practiced with raised-beds surrounded by small basins. Drip irrigation was designed with 4 l/h emitters spaced 0.3 m and driplines 0.5 m apart. Hybrid irrigation method consisted of a pressurized system delivering water to each experimental plot with a single outlet, 2" diameter, and a discharge of 6-9 m^3/h operating at 100 kPa. SPRINKLER irrigation used multi-nozzle impact sprinklers with 5 nozzles of 2.5-7 m^3/h at operating pressures of 200-500 kPa. The sprinklers were spaced 12 x 12 m apart, with an overlapping of 100%.

CS7, Bafra Valley, Turkey: It is a Delta plain located on the middle part of the Black Sea coast, with approximately 16,000 ha devoted to rice cultivation.

In the period 2019-2021, the maximum and minimum temperatures within the cropping season were 8.7°C and 33.0°C, with an average precipitation of 153.4 mm and a potential evapotranspiration of 481.6 mm. The soil texture at the first layer was silty-clay and average groundwater depth was about 114 cm. Also, it is noticeable the low water quality in terms of salinity, with an electrical conductivity of 1.63 dS/m. The field experiments were carried out in 5 x 5 m^2 plots, in a total of 36 plots, including 3 replications of each treatment x 6 irrigation treatments x 2 rice varieties.

In the particular case of CS7 (Bafra Valley), the WFL traditional technique refers to transplanted rice with continuous flooding in 2019 and dry seeding plus immediate flooding with about 2-3 mm of water level till emergence and then continuous flooding (about 8-10 mm) in 2020 and 2021; in this study, both cases have been included as WFL (**Table 2**).

2.2. Tested alternative irrigation strategies

Innovative irrigation strategies tested in the pilot farms were compared with wet seeding and continuous flooding (WFL), which is considered as the 'reference' irrigation method in all CSs.

The tested alternative irrigation strategies and methods were (**Table 1**): dry seeding and delayed flooding (DFL), alternate wetting and drying (AWD), reduction in water inflow/outflow (RWI1: 26% during the whole crop cycle, RWI2: reduction from 100 days after sowing, RWI3: 30% reduction with longer drying periods), hybrid irrigation (HYBRID), multi-nozzle sprinkler irrigation (SPRINKLER), surface and sub-surface drip irrigation (DRIP and SDI). For each irrigation solution, innovative technologies and the most appropriate rice varieties and agronomic practices were implemented to minimize impacts of irrigation water reduction on yield quantity and quality.

Table 1: Summary of irrigation strategies tested in the project experimental areas

Innovative irrigation strategy	**Italy (Lo mell ina) CS1**	**Spain (Baix Ter) CS2**	**Spain (Guadalquivir marches) CS3**	**Portugal (Lower Mondego Valley) CS4**	**Portugal (Lis Valley) CS5**	**Egypt (Nile Delta) CS6**	**Turkey (Bafra Valley) CS7**
Wet-seeding and traditional flooding (WFL)	X	X	X	X	X	X	X
Alternate Wetting and Drying (AWD)	X			X	X		X
Dry-seeding and Delayed Flooding (DFL)	X	X					
Reduction of Water Input (RW1, RWI2+RWI3)			X				
Subsurface Drip Irrigation (SDI)		X					
Surface Drip Irrigation (DRIP)			X		X	X	X
Hybrid irrigation (HYBRID)						X	
Multi-noozle sprinkler irrigation (SPRINKLER)						X	

RWI1 – 26% reduction in water inflow/outflow during whole crop cycle, RWI2- reduction of water inflow 100 days after sowing, RWI3 - longer drying periods and inflow/outflow reduction (30%).

2.3. Data collection and statistical analysis

Average yield, irrigation water, crop evapotranspiration (ETc), percolation and Water Productivity (WP), Relative Water Supply (RWS), and contents of cadmium and arsenic accumulated in the husked grain are reported for WFL, considering all available years. For the other irrigation treatments, and considering the limited space of this communication, only the increase or decrease of each of these parameters compared with WFL for each CS is provided in the following sections.

Statistical analyses were carried out using SPSS Statistics software v.28 (IBM, New York, USA). Tukey's pairwise comparison test was used for assessing if averages were significantly different with a probability of 0.05 or less.

3. Results and discussion

3.1. Wet seeding and continuous flooding (WFL)

Results showed in **Table 2** indicate great differences in the irrigation water use, percolation, and grain yield among the different CSs. Therefore, the comparisons of innovative irrigation systems with WFL were made for each CS.

Table 2: Water balance components, WP and RWS indicators, grain yield, total arsenic and cadmium grain contents for WFL in the different case studies (average ± standard deviation over the years of experimentation).

CS	Rice varieties	Irrigation water (m^3/ha)	ETc (m^3/ha)	Percolation (m^3/ha)	Grain yield (t/ha)	WP $_{I+R}$ (kg/m^3)	RWS (m^3/m^3)	Grain Cd (mg/kg)	Grain As (mg/kg)
CS1	Centauro	24,750 ±1,004 b	6,640 ±141 bc	20,505 ±1,648 a	10.6 ±0.88 a	0.39 ±0.06 c	4.1 ±0.2 b	0.006 ±0.001	0.240 ±0.059
CS2	Bahia/Onice/Mare	13,055 ±583 d	5,529 ±707 c	10,058 ±1276 b	6.5 ±141 c	0.46 ±0.05 bc	2.6 ±0.2 c	0.081 ±0.103	0.128 ±0.152
CS3	J. Sendra/Puntal	23,346 ±5,474 bc	8,835 ±1321 a	1,507 ±25 d	8.9 ±0.4 ab	0.35 ±0.03 cd	2.9 ±0.1 ab	0.020 ±0.000	0.271 ±0.070
CS4	Ariete	14,168 ±2,420 cd	6,805 ±223bc	NA	9.2 ±0.5 ab	0.61 ±0.08 b	2.2 ±0.3 c	0.012 ±0.007	NA
CS5	Ariete	14,586 ±1,749 cd	6,618 ±430 bc	7,203 ±1,858 bc	6.6 ±0.8 c	0.43 ±0.05 c	2.4 ±0.3 c	0.010 ±0.000	0.313 ±0.140
CS6	Hybrid-EH1	12,395 ±2,176 d	8,199 ±1 ab	4,635 ±664 cd	10.2 ±0.8 a	0.83 ±0.09 a	1.5 ±0.3 c	0.239 ±0.232	0.259 ±0.045
CS7	Osmancik/Rekor	38,937 ±4,435 a	5,283 ±408 c	NA	7.9 ±0.7bc	0.19 ±0.0d	7.7 ±1.0 a	0.038 ±0.008	0.023 ±0.005

WP_{I+R}: Water productivity considering irrigation plus precipitation, RWS: Relative water supply defined as Irrigation plus rain / ETc. Different letters mean that there were significant differences ($p<0.05$) in the average values of each parameter for each CS.

Depending on the CS, WFL irrigation inputs ranged from 12,395 to 38,937 m^3/ha; ETc ranged from 5,283 to 8,835 m^3/ha; percolation ranged from 1,507 to 20,505 m^3/ha; grain yield ranged from 6.5 to 10.6 t/ha; WP_{I+R} ranged from 0.83 to 0.19 kg/m^3 and RWS ranged from 1.5 to 4.7 m^3/m^3.

As can be observed, most of the values in Table 2, except for the Cd and As contents, resulted to be significantly different among CSs. Therefore, in the following, the effects of the tested irrigation solutions were assessed considering the WFL results achieved in each CS.

3.2. Alternate Wetting and Drying (AWD)

When adopting AWD irrigation and comparing results with WFL, it can be observed that: no yield reductions were found in Lomellina and Mondego Valley, while 9% and 12% yield reductions were obtained in Lis and Bafra Valleys, respectively. In addition, water saving was around 20% in Lomellina, 2% in Mondego Valley, 10% in Lis Valley and 26% in Bafra Valley. Percolation was reduced by 24% in Lomellina, and 29% in Lis Valley. On the other hand, Water Productivity (WP_{I+R}) was increased by 23% in Lomellina and 19% in Bafra Valley, while it was similar to WFL in Mondego and Lis Valleys. Finally, Relative Water Supply (RWS) was reduced by 17% in Lomellina, 11% in Lis Valley and 23% in Bafra Valley while it was similar to WFL in Mondego Valley.

According to these results, AWD can be considered a promising irrigation technique for rice cultivation in the Mediterranean basin, as it allowed to achieve a reduction in water consumption which barely penalized the yield.

3.3. Dry Seeding and Delayed Flooding (DFL)

In comparison with WFL, yield with DFL increased by 13% in Baix Ter and reduced by 5% in Lomellina. The yield improvement in the Baix Ter can be probably explained by the more homogeneous distribution of the seeds, as seed-drill was used. This fact facilitated a good establishment of the plants before the tillering stage, and consequently an efficient competition of rice with the weeds. The amount of irrigation water was reduced by 14% in Lomellina, but it was increased by 6% in the Baix Ter. Percolation was reduced by 15% in Lomellina and was maintained in the Baix Ter. This can be explained by the greater amount of irrigation in DFL compared with WFL in the Baix Ter, probably because the DFL field was sandier that the WFL field. Water Productivity (WP_{I+R}) increased in both CSs, by 8% in Lomellina and 6% in the Baix Ter. Relative Water Supply (RWS) was reduced by 9% in Lomellina and 2% in the Baix Ter.

According to the obtained results, DFL can be considered a promising irrigation technique which can be considered as an alternative solution to the WFL; the results have been positive in both case studies as the application of DFL increased water productivity. However, a massive adoption of the DFL technique could slow down the rising of the groundwater level of about one month in rice areas thus reducing the water reuse; how acceptable this may be is to be assessed from case to case.

3.4. Reduction of Water Input (RWI1, RWI2 and RWI3)

Compared with WFL, reduction irrigation treatments RWI1, RWI2 and RWI3, applied in CS3 reduced yield by 6%, 7% and 8%, with a corresponding irrigation reduction of 14%, 31% and 7%, respectively. Percolation was barely affected in the different irrigation treatments. Water Productivity (WP_{I+R}) was increased, especially in RWI2, achieving a 30% gain compared with WFL, while RWI1 and RWI3 produced small increases of WP, 16% and 5%, respectively. Relative Water Supply (RWS) was reduced by 32%, 28% and 16% for RWI1, RWI2 and RWI3, respectively.

Among the RWI treatments, the best results were obtained with the strategy RWI2 (reduction of water inflow 100 days after sowing), as it reduced the irrigation volume more than the other treatments and showed a very small effect on yield.

3.5. Subsurface drip irrigation (SDI) and surface drip irrigation (DRIP)

SDI irrigation: SDI was tested in two different fields in CS2, one with sandy-loam texture (SDI_SaL) and deep groundwater and another one with silty-clay texture and shallow groundwater (SDI_SiC). The results have been quite different for the two fields. When adopting SDI, and comparing results with WFL, it can be observed that: yield was reduced by 45% and 4.5% in SDI-SaL and SDI-SiC, respectively. The yield obtained with SDI in the silty-clay soil was quite similar to the one obtained with WFL. The amount of irrigation water was reduced by 30% and 42% in SDI-SaL and SDI-SiC, respectively. Percolation was reduced by 40% and 66% with SDI-SaL and SDI-SiC, respectively. Water Productivity (WP_{I+R}) was reduced by 29% in SDI-SaL and increased by 58% in SDI-SiC. Relative water supply (RWS) was reduced by 22% and 39% in SDI-SaL and SDI-SiC, respectively.

The positive results obtained in SDI-SiC demonstrated that irrigation water volume can be reduced by 40% without affecting yield and reducing deep percolation about 60-70%. The poor results in SDI-SaL were probably due to an inefficient design: different dripline spacings were tested (66 cm and 75 cm) but they might be excessive for this coarse soil.

DRIP irrigation: Compared with WFL, yield was reduced by 64% in Guadalquivir marshes, 38% in Lis Valley and 5% in Bafra Valley. Instead, it increased by 10% in Nile Delta. The amount of irrigation water was maintained in Guadalquivir marshes and reduced by 35%, 38% and 75% in Lis Valley, the Nile Delta and Bafra Valley, respectively. Percolation was reduced by 32% and 90% in Lis Valley and the Nile Delta (percolation was not available for Guadalquivir marshes and Bafra Valley). In addition, Water Productivity (WP_{I+R}) was reduced by 66% and 6% in Guadalquivir marshes and Lis Valley; on the contrary, it was increased by 78% and 268% in Nile Delta and Bafra Valley, respectively. Relative Water Supply (RWS) was increased by 4% Guadalquivir Marshes and reduced by 26%, 32% and 73% in Lis Valley, the Nile Delta and Bafra Valley, respectively.

In summary, contradictory results were found for DRIP irrigation in different contexts: while in yield increased by 10% in the Nile Delta and it was maintained in Bafra Valley, in Lis Valley and Guadalquivir marshes it was dramatically reduced by 38% and 64%, respectively.

It must be highlighted that SDI and DRIP are very innovative irrigation techniques for rice cultivation. These tests pioneered the application of these technologies in rice irrigation. Difficulties in selecting the appropriate design of the irrigation system adapted to agro-climatic conditions and soil type (depth of driplines, emitter and dripline spacings and emitters flowrate), irrigation management criteria to be adopted for drip-irrigated rice, lack of experience in weed control when rice grows under aerobic conditions, were a challenge in many of the CSs. Nevertheless, the experience gained in the framework of this project and the positive results in some of the design and management options show that drip is a very promising technique which can be adopted in water scarce areas and for extending the rice production out of the traditional paddy areas.

3.6. Hybrid irrigation (HYBRID)

The results obtained in CS6 with HYBRID irrigation compared with WFL revealed that rice yield was increased by 23%, irrigation water was reduced by 18%, percolation was reduced, Water Productivity (WP_{I+R}) was increased by 49% and, Relative Water Supply (RWS) was reduced by 18%.

According to the reported results, hybrid irrigation can be considered as a valid alternative irrigation solution to WFL, as it increased yield and reduced irrigation water and percolation. Water Productivity with Hybrid irrigation achieved 1.24 kg/m^3, being among the highest found in the project.

3.7. Sprinkler irrigation (SPRINKLER)

Sprinkler irrigation in CS6 increased rice grains yield by 10% compared to WFL. The amount of irrigation water was reduced by 25%, percolation was reduced, Water Productivity (WP_{I+R}) was increased by 46%, Relative Water Supply (RWS) was reduced by 23%.

According to the reported results, sprinkler irrigation can be a sound irrigation alternative to WFL as it increased yield, reduced irrigation water needs and percolation. Water Productivity achieved 1.21 kg/m^3, being among the highest observed in the project.

3.8. Grain quality: Arsenic and Cadmium contents for all irrigation treatments

Experimental results showed that in the case of AWD, DRIP and SDI Arsenic in rice grain tended to decrease while Cadmium tended to increase compared to WFL in most of the CSs, but these differences were not statistically significant at $p<0.05$. No clear patterns were observed for the other irrigation solutions.

In particular, AWD Cadmium rice content increased by 0.01 mg/kg in Lomellina, decreased by 0.01 mg/kg in Mondego Valley and remained nearly the same as in WFL in Mondego Valley and Bafra Valley. As expected, due to the soil aerobic conditions characterizing AWD, Arsenic in the rice grain decreased by 0.02 mg/kg in Lomellina and by 0.01 mg/kg in Bafra Valley; however, it was 0.03 mg/kg higher than WFL in Lis Valley.

In the case of SDI (Baix Ter), Cadmium rice content was lower compared to WFL of 0.071 mg/kg in SDI-SaL and 0.061 mg/kg in SDI-SiC. Arsenic content in the rice grain increased in SDI-SaL by 0.017 mg/kg and decreased by 0.015 mg/kg in SDI-SiC with respect to WFL. It must be considered that irrigation water for SDI-SaL was pumped from a well in which Arsenic content was higher than in the water used to irrigate the SDI-SiC and WFL fields, provided by an open channel.

When considering DRIP irrigation, Cadmium rice content was nearly the same as in WFL in the Guadalquivir marshes, it increased by 0.018 mg/kg and 0.008 mg/kg in the Delta Nile and Bafra Valley, and reduced by 0.018 mg/kg in Lis Valley. Arsenic content in the rice grain was lower than WFL by 0.191 mg/kg in Guadalquivir marshes, 0.213 mg/kg in Lis Valley, 0.003 mg/kg in Bafra Valley, while it was 0.052 mg/kg higher than WFL in the Nile Delta.

4. Conclusions

Yield quantity, irrigation water use, percolation and corresponding Water Productivity and Relative Water Supply using the conventional irrigation system for rice (WFL – wet seeding and continuous flooding) were found to be significantly different for the experimental sites (CSs) around the Mediterranean basin considered in the MEDWATERICE project. The agroclimatic and soil characteristics, the groundwater table depth, the irrigation and agronomic practices adopted, the presence of salinity problems in some rice areas are probably responsible of what observed. Therefore, the comparisons shown in this paper among WFL and tested innovative solutions were carried out within the same CS.

AWD irrigation technique is found to be a sound alternative to WFL to reduce irrigation inputs (CS1, CS4, CS5 and CS7). Even though, slight reductions of yield compared to continuous flooding irrigation might happen, especially when this technique is adopted considering more severe soil water content thresholds. Water Productivity increases when compared to WFL and DFL.

DFL can be seen as an interesting alternative to WFL, which can facilitate many agronomic practices to the farmer. Literature reports an irrelevant decrease in yield and a slight reduction in irrigation water input adopting DFL. In MEDWATERICE we observed: i) the same yield with a slight reduction of irrigation water input (CS1), and ii) a slight increase in irrigation water needs, yield and Water Productivity (CS2).

Reduction of water input irrigation strategies RWI1, RWI2 and RWI3 may be interesting alternatives when the available water for irrigation is limited. The best results in the experimentation were achieved with the strategy RWI2 (reduction of water input after the day 100 after seeding), which was characterized by a reduction of about 30% of the total irrigation input compared to WFL during the last development stages of the rice cropping cycle. This irrigation practice showed to have no negative impacts on yield, neither on rice quality. The main concern may be water quality in terms of salinity, which may affect yield when water input is reduced. If water quality is not an issue, reduction of water input after the day 100 after seeding can considered as a sound water saving alternative to WFL.

Hybrid irrigation and sprinkler irrigation showed to be interesting alternatives to WFL as they increased yield, reduced deep percolation and irrigation water (by 18% and 25%, respectively) compared to WFL in the Nile Delta.

Surface and subsurface drip irrigation systems (DRIP and SDI) showed that if the irrigation system is properly designed and managed (CS2, CS6 and CS7), acceptable yield reduction can be achieved with a high water saving (up to 50% and more), leading to an important increase in WP. However, further research needs to be carried out to have best insight on: i) the choice of the most favorable rice varieties which could better adapt to aerobic conditions; ii) the proper design of the irrigation system to take into account site-specific soil conditions (e.g., flowrate, lateral and emitter spacing); and iii) the setup of an irrigation scheduling taking into consideration local agroclimatic conditions, soil hydraulic properties, crop physiology, and irrigation water quality.

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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.

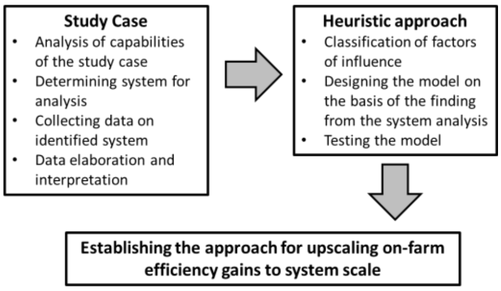

Figure 2. Diagram for the heuristic method for upscaling on-field irrigation efficiency gains to district level.

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.

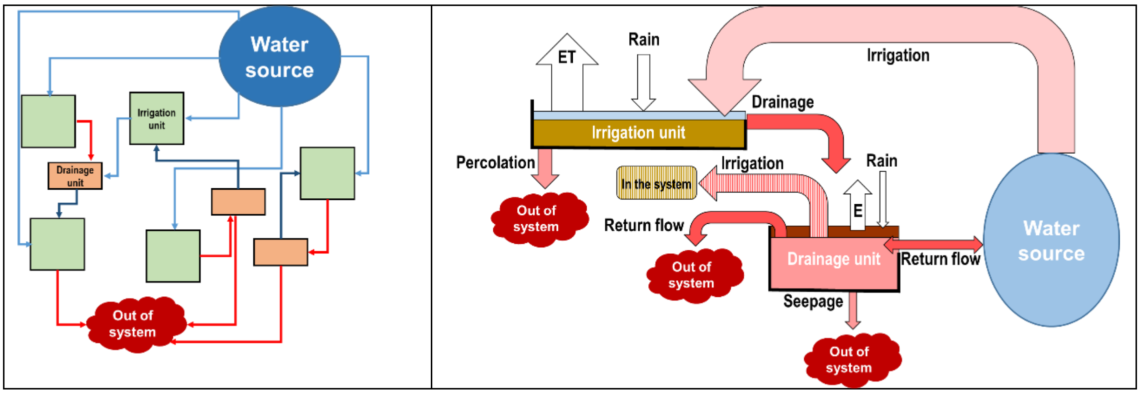

Figure 3. Diagrams of irrigation and drainage units interconnections (left) and water balance components (right).

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.

<u>Physically-based water flow model</u>

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).

<u>Pesticide fate model</u>

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.

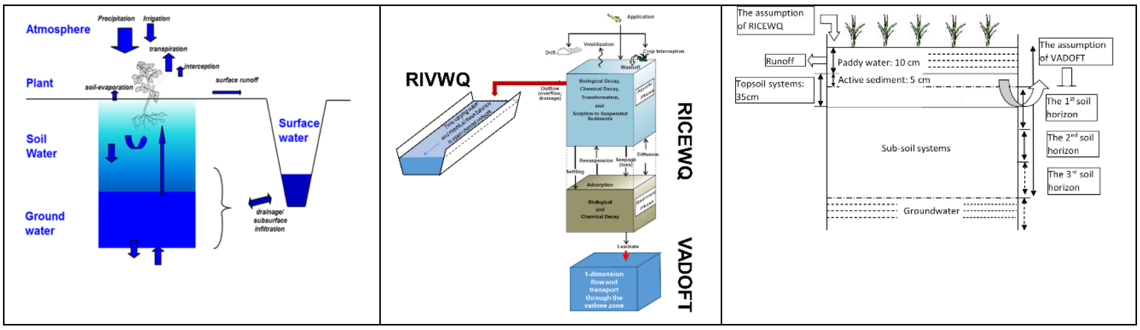

Figure 4. From left to right: Graphical description of SWAP (taken from the SWAP webpage (https://www.swap.alterra.nl/) graphical description of the models RICEWQ, VADOFT and RIVWQ and their coupling; and detail of the soil layers considered in VADOF and their connection with RICEWQ.

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.

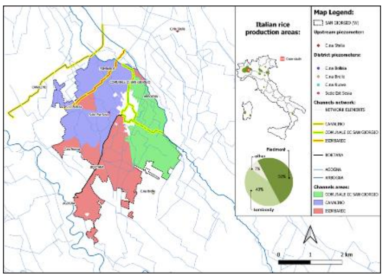

Figure 5. San Giorgio district case study (Italy); colors indicate areas served by the three irrigation canals.

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.

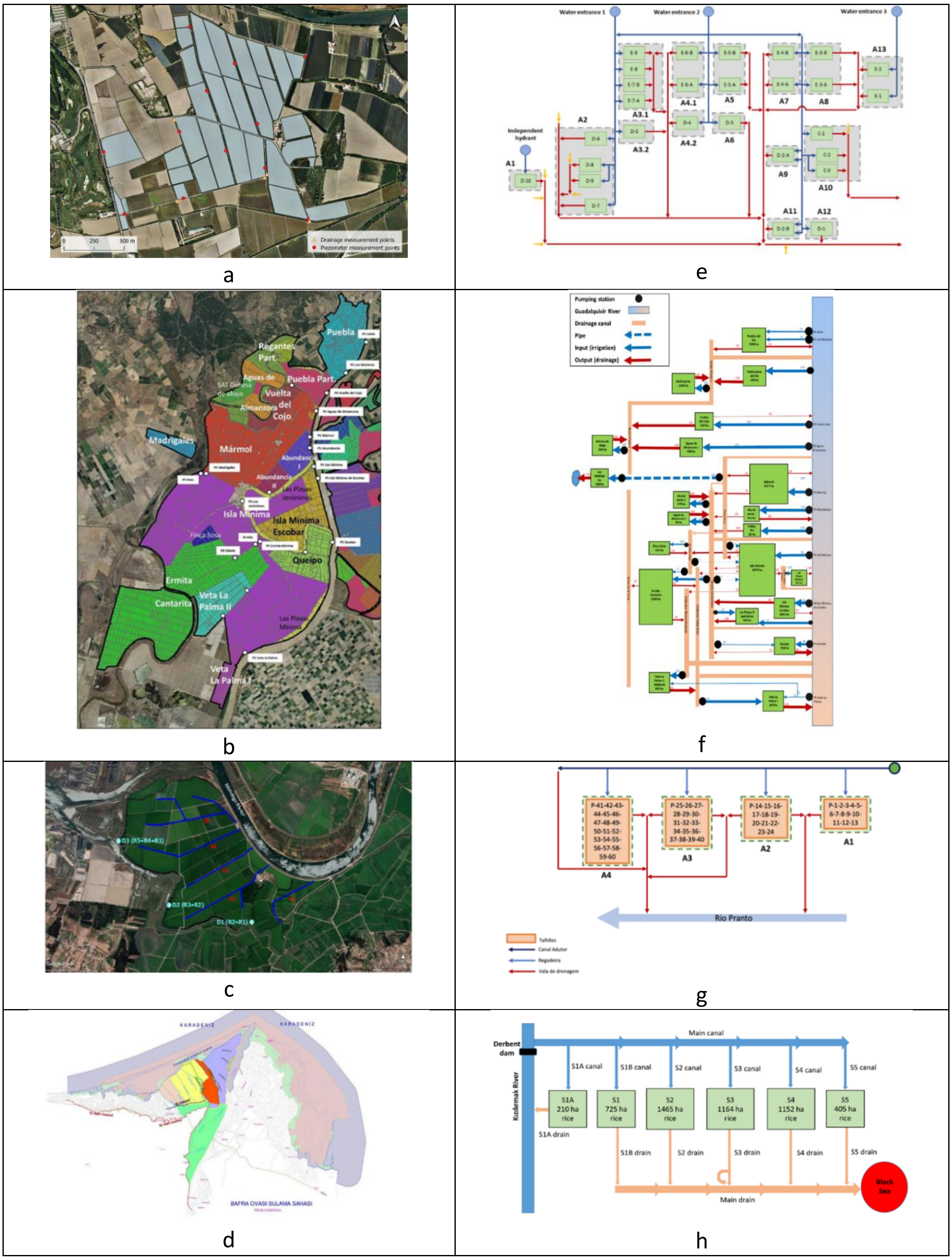

Figure 6. From top to bottom, on the left, map of the case study districts Mas Pla (Spain), Right Bank of Lower Guadalquivir Marshes (Spain), Quinta do Canal (Portugal) and Bafra Plain Left Side Irrigated Area (Turkey), and on the right, their respective topological flow diagrams.

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.

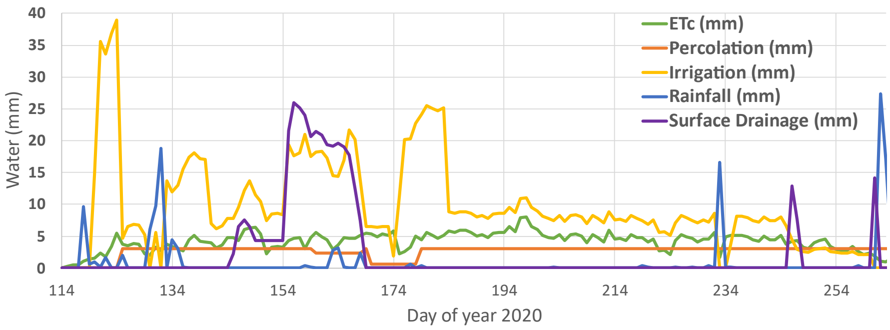

Figure 7. Daily water balance components at Quinta do Canal (Portugal).

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.

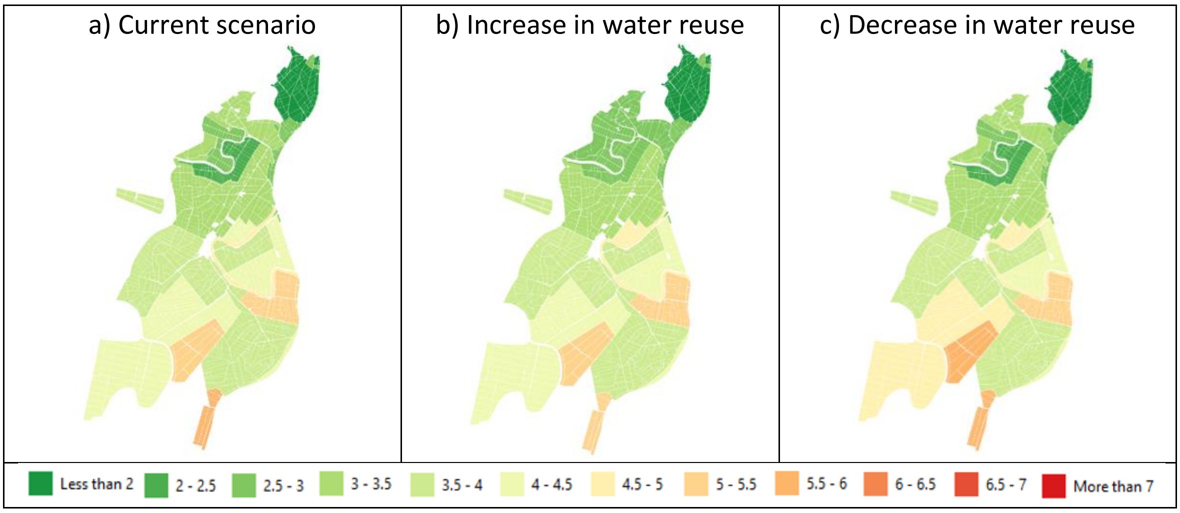

Figure 8. Spatial distribution of salinity in the input water for irrigation. Average value for year 2020 (dS/m). Rice growing areas on the right riverbank of the lower Guadalquivir marches (Spain).

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).

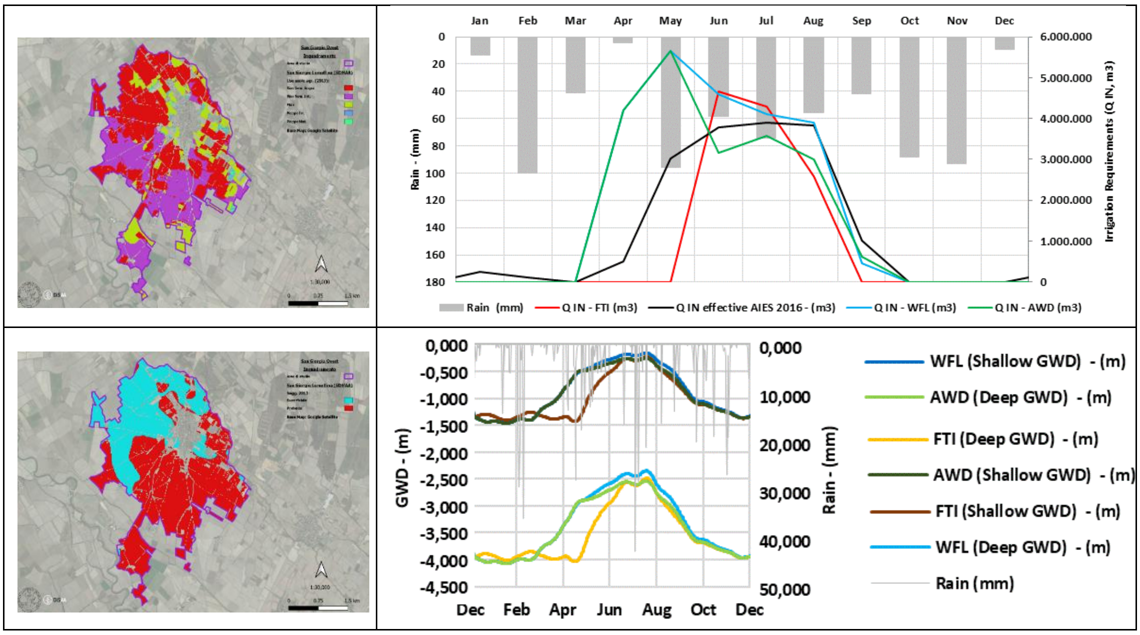

Figure 9. Land use (upper left), shallow and deep GWD areas (bottom left), irrigation requirements (upper right) and groundwater levels for the San Giorgio district, Italy (year 2016).

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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Economic, environmental, and social sustainability of water-saving solutions for the rice sector in the Mediterranean basin

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Abstract

In the Mediterranean basin, rice has important economic and social implications, especially in areas where it is a staple food such as Egypt. On the other hand, the peculiar flooding conditions in which rice is traditionally grown lead to the use of huge volumes of water, as well as to the potential release of greenhouse gases and pesticides into the environment. The introduction of water-saving irrigation strategies could reduce water consumption and decrease the harmful environmental impacts while maintaining yield and rice quality. However, the environmental, economic and social sustainability of these strategies must be adequately evaluated.

To explore the overall sustainability of innovative water-saving irrigation strategies, several experimental farms were selected in the main rice producer countries of the Mediterranean basin (EG, IT, TR, ES, PT) in the context of the MEDWATERICE project (https://www.medwaterice.org/). In particular, the alternative irrigation strategies compared to the wet seeding and continuous flooding (considered as the 'reference' irrigation in all CSs), were: alternate wetting and drying (AWD); dry seeding and delayed flooding (DFL), water input reduction after day 100 from sowing (WIR), hybrid irrigation (HYBRID), multi-nozzle sprinkler irrigation (SPRINKLER), surface drip irrigation (DRIP), and subsurface drip irrigation (SDI).

A set of indicators for the quantitative assessment of the environmental and economic sustainability of the irrigation options were defined, which includes: Farm Profitability (Net Income); Labour Productivity; Productivity (Grain yield); Water Productivity; Relative Water Supply; Percolation to Groundwater; Energy Productivity; Nutrient (N, P, K) Use Efficiency; Greenhouse Gas Emission (CH_4 and N_2O); Environmental Potential Risk Indicator for Pesticides (EPRIP); Food Safety (Arsenic and Cadmium grain rice content). The social acceptability of the irrigation strategies was investigated through the Technology Acceptance Model (TAM) by involving rice growers of the pilot areas, barriers to the adoption of the irrigation strategies were assessed and ways to overcome them identified. The indicator set was applied to datasets collected in the experimental farms during the agricultural seasons 2019-2021, and results are being extrapolated to the irrigation district level to support water management decision makers and policy planners. The methodologies developed and the results achieved are illustrated and discussed in this paper.

Keywords: Water-saving irrigation strategies, Indicators, Sustainability, Rice, Social acceptability

1. Introduction

Rice cultivation is considered a source of environmental harm due to the flooding conditions in which rice traditionally grows. From 1961 to 2019, the rice area harvested globally increased from about 115 million ha to about 162 million ha, with significant conversions of natural to arable lands. Methane emissions of rice areas are estimated to have increased from 17,400 to 24,100 kilotons in the same period (FAOSTAT 2021). Yield production increased with the introduction of high yielding crop varieties, farm mechanization, and various types of chemical fertilizers and pesticides. Farmers, with respect to agronomic inputs, often adopt the attitude of 'more is better' to increase yield production, regardless of economic and environmental costs (Stuart et al., 2018; Huelgas et al., 2010).

On the other hand, rice cultivation has important economic and social implications in many areas of the word and also in the Mediterranean basin, in which it is cropped over an area of 1,300,000 hectares. The most important rice-producing countries in the Mediterranean area are Italy and Spain in Europe (72% of the EU production; 345,000 ha) and Egypt and Turkey among the extra-EU countries (almost totality of the production; 789,000 ha). In the Mediterranean area, the peculiar flooding conditions in which rice is traditionally cultivated lead to the use of huge volumes of water, as well as to the potential release of greenhouse gases and pesticides into the environment. For this reason, the introduction of water-saving irrigation strategies could reduce water consumption and decrease the harmful environmental impacts linked with rice cropping, while maintaining yield and rice grain quality. However, the environmental, economic, and social sustainability of these strategies must be adequately evaluated.

In the context of the MEDWATERICE project (https://www.medwaterice.org; 01/04/2019 - 31/03/2023), seven case studies (CSs) were implemented in experimental pilot farms of each country involved in the project (EG, IT, TR, ES, PT). Tested water-saving irrigation methods were tailored to local conditions using a participatory action research approach through the establishment of Stake-Holder Panels (SHPs). For each irrigation solution, innovative technologies and the most appropriate rice varieties and agronomic practices were implemented to minimize impacts on yield quantity and quality. Experimental activities were conducted in the pilot farms during at least two agricultural seasons in the period 2019-2021, to evaluate the economic, environmental and social sustainability of the water-saving techniques introduced. A literature review of the existing methodologies applied all over the world to assess economic, environmental and social aspects connected to rice production was carried out in Gharsallah et al. (2021). The review was the base for the selection/development of a set of economic and environmental indicators and a social analysis procedure then applied to the MEDWATERICE CSs. The current paper presents the methodologies adopted and the main results achieved so far.

2. Materials and methods

2.1. Indicator framework

Among the indicators found in the literature, the following economic and environmental indicators proposed by the Sustainable Rice Platform (SRP; https://www.sustainablerice.org/) were selected to be adopted in MEDWATERICE: Farm Profitability (Net Income); Labour Productivity; Productivity (Grain yield); Water Productivity (WP); Greenhouse Gas Emission (CH_4 and N_2O); N and P Use Efficiency (SRP Performance Indicators Version 2.0, 2019). A K Use Efficiency indicator was added, considering the same approach proposed by SRP (2019) for N and P Use Efficiency. To evaluate the effect of the irrigation strategies in terms of water saving, the indicator Relative Water Supply was included (Sanchez et al., 2015). Furthermore, to investigate the amount of energy consumed during the agronomic and irrigation operations, the Energy Productivity indicator was added to the indicator set (Rao et al., 2017). For the evaluation of the pesticides impact, the Environmental Potential Risk Indicator for Pesticide (EPRIP) described in Padovani et al. (2004) was selected and modified to account for rice specific growth conditions (Voccia et al., 2022). To evaluate the effect of irrigation strategies on the groundwater recharge, the indicator Percolation to Groundwater (PG) was built. Finally, an indicator describing the Food Safety risk (Cadmium and Arsenic content in rice grain) was developed. Social acceptability of the irrigation strategies proposed in the project was evaluated through a qualitative approach based on the Technology Acceptance Model (TAM) (Davis 1989). Selected indicators and approaches are shown in Figure 1.

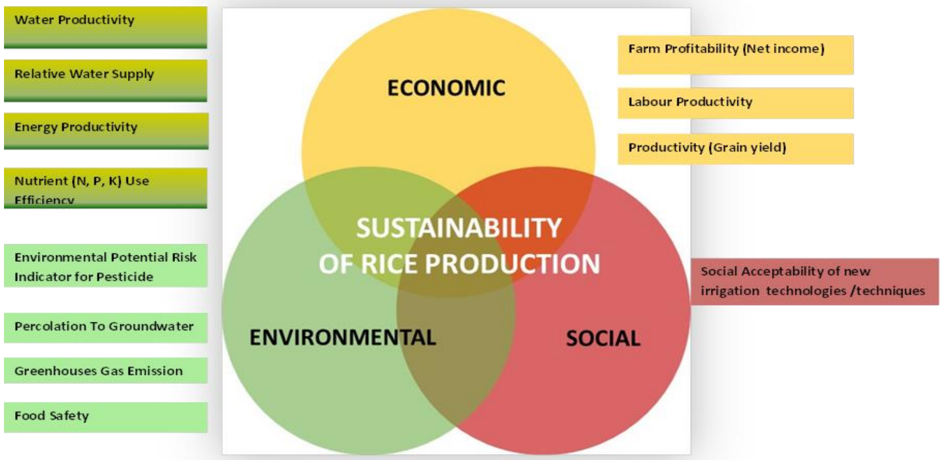

Figure 1: Indicators and approaches for the sustainability assessment of rice production under different irrigation strategies in MEDWATERICE

2.2. Data collection

All economic and environmental indicators were computed through data collected from the experimental fields in the MEDWATERICE pilot farms, and through questionnaires developed for on-farm data collection compiled by farmers hosting the experimentations with the support of the project researcher and technical staff. For each pilot farm, only fields cropped with rice were considered in the questionnaire, and a separate questionnaire was compiled for each rice irrigation strategy tested in the farm. In the questionnaire, all the processes involved in rice production from the land preparation till post-harvesting were taken into account. Social acceptability was evaluated using an additional questionnaire compiled through face-to-face interviews with a sample of rice growers in the study areas involved in MEDWATERICE.

3. Results and discussion

The most promising water-saving irrigation solutions explored in the CSs were: AWD in CS1 (Lomellina, Italy); DFL and SDI in CS2 (Baix Ter, Spain); WIR in CS3 (Guadalquivir marshes, Spain); AWD in CS4 (Lower Mondego Valley, Portugal); AWD and DRIP in CS5 (Lis Valley, Portugal); HYBRID, SPRINKLER, and DRIP in CS6 (Nile Delta, Egypt); AWD and DRIP in CS7 (Bafra Valley, Turkey). Results achieved for each water-saving technique were compared with the traditional continuous flooding (WFL) which was considered as the 'reference' irrigation strategy in all CSs. Average values of the indicators over the period 2019-21 are reported in this paper; all values are referred to 1 ha of rice surface. Only the calculation of Environmental Potential Risk Indicator for Pesticides (EPRIP) and the analysis of Social Acceptability are still in progress for all CSs except than CS1.

In the project, next steps will be: 1) to generalize results obtained in the experimental farms in order to make them representative for a 'typical farm' of the investigated rice areas; 2) to extrapolate water saving results demonstrated in the pilot farms at the irrigation district level to support water management decisions and policies. For both activities, final results will be available in the next months. Preliminary results in terms of water saving indicators at the irrigation district level for some CSs are reported in Gilardi et el (2022) for CS1, in Cufi et al. (2022) for CS2, in Alarcon et al. (2022a) for CS3, and in Alarcon et al. (2022b) for CS4 and CS7.

The main results achieved in the MEDWATERICE pilot farms are discussed in the following sections.

3.1. CS1 (Lomellina, Italy)

AWD: Alternate Wetting and Drying (AWD) was found to be a promising irrigation technique for rice cultivated in northern Italy, economically reliable, which allowed a reduction of water consumption without penalizing the rice yield or strongly influencing the rice grain quality (Cadmium and Arsenic content in rice grain). The main aspects emerged are the following:

- Farm Profitability of AWD was slightly higher than that of WFL, with an increase of about 22 euro/ha; rice yield was similar (11 t/ha).
- Labour Productivity of AWD was slightly lower than that of WFL (175 hour/ha in AWD *versus* 203 hour/ha in WFL). This was in particular due to the difference in hours spent for irrigation operations (22 hour/ha in WFL, 31 hour/ha in AWD) since AWD required more labour for the manual management of gates during the drying and wetting events. All the other agronomic operations conducted in the agricultural season were similar.
  Labour required to manually manage the inlet and outlet gates maintaining a constant ponding water level in the fields, increased under the AWD regime with respect to WFL, may be reduced through the adoption of automatic gates controlling the irrigation inflow on the base of the in-field ponding water level; a preliminary application in northern Italy is illustrated by Gangi et al. (2022).
- AWD showed a water saving of 20%, an increase in Water Productivity (WP) of 20%, a decrease in Relative Water Supply (RWS) of 21.5%, and a reduction in Percolation (PG) of 24% compared to WFL.
- AWD showed a similar Energy Productivity and Nutrient (N, P, K) Use Efficiency than WFL. Following the estimates done in the project, AWD allowed the reduction of CH_4 emissions by about 18% while increased N_2O emissions by about 39%.
- AWD decreased inorganic Arsenic content in rice grain and increased rice Cadmium content. Considering the EU Regulation 2015/1006, the maximum inorganic As content allowed in the non-parboiled milled rice is 0.20 mg/kg, in the parboiled and husked rice is 0.25 mg/kg, and in rice for baby-food is 0.10 mg/kg. Maximum admissible Cadmium content in rice is 0.15 mg/kg (Commission Regulation 2021/1323) while in rice for baby-food it is reduced to 0.04 mg/kg (Commission Regulation 2014/488). For CS1, inorganic Arsenic content was found to be below the legal limit for both irrigation strategies, while Cadmium content was even below the limit for baby food.
- Regarding the Environmental Potential Risk Indicator for Pesticides (EPRIP), AWD showed a similar EPRIP values than WFL. In particular, for the AWD the Predicted Environmental Concentration (PEC) showed the same probability to exceed Risk Point 3 (EXC_PROB_3%) than WFL. Details are illustrated in Voccia et al. (2022).
- Farmers of the Lomellina rice area declared their willingness to adopt AWD if requested since they were persuaded of the advantages for the environment; however, they declared they would need financial, technical, and, if possible, technological support (i.e. devices to guide the wetting and drying cycles). As a matter of fact, they must reintroduce water seeding, while now almost the whole territory has switched to wet seeding and delayed flooding.

3.2. CS2 (Baix-Ter, Spain)

DFL: Dry-seeding and Delayed Flooding (DFL) showed to be a valid technique to be adopted in Northern Spain. In particular, experimental activities conducted in the pilot farm showed that:

- DFL increased Farm Profitability by 45%. This was mainly related to the high yield obtained (8 t/ha *versus* 6.5 t/ha in WFL), as production costs were quite similar. The yield improvement in DFL can be explained by a more homogenous distribution of seeds, as the seeding operation was conducted through a seed-drill and this facilitated a better establishment of the plants before the tillering stage and consequently a more efficient competition of rice with the weeds.
- Labour Productivity of DFL was higher than for WFL. This was due to: i) the difference in yield production, and ii) the difference in hours spent to conduct agronomic and irrigation operations, since water seeding, pesticide treatments, and fertilizations required more time when conducted in flooded fields.
- No water saving was observed, WP increased by 6%, RWS decreased by 2%, and no PG reduction was found.
- DFL increased Energy Productivity and Nutrient (N, P, K) Use Efficiency. It reduced slightly CH_4 emissions (3%) while N2O emissions increased (23%).
- DFL showed quite a similar Cadmium grain content and a lower Arsenic grain content compared to WFL, and both were below the EU limits.

SDI: Sub-surface Drip Irrigation (SDI) showed to be a promising water-saving technique; however, in the specific CS, it demonstrated not to be economically profitable. Details are illustrated below:

- SDI experimented in the Cobert pilot farm showed to be not economically profitable. In particular, Farm Profitability was found to be about -2576 euro/ha; this was due to:
  - a low yield production obtained with SDI (3.5 t/ha), explained by: i) difficulties in designing and managing the SDI irrigation system (depth of driplines, spacing of drippers and driplines and emitter flowrates) in such a challenging conditions (sandy-loam texture and deep groundwater); ii) difficulties in controlling weeds in case of rice grown under aerobic conditions; and iii) need to select appropriate rice varieties for SDI: Onice variety produced 2.64 t/ha in 2019 and 2.65 t/ha in 2021, Furia variety produced 5.28 t/ha in 2020 and this demonstrated that a yield improvement could be achieved with a change in rice variety.
  - a total cost of the SDI irrigation system (irrigation materials, installation, sensors, yearly service for remote connection, user software), which was found to be 1424 euro/ha/year considering a lifespan of the SDI irrigation system of about 7 years.
  - the high cost of the electricity used (kW/ha) by the pumping system.
- Due to the low yield (3.5 t/ha), a low Labour Productivity value was obtained despite the lower amount of labour required to grow one ha of rice adopting SDI (24 hour/ha) compared to WFL (36 hour/ha).
- Compared to WFL, SDI showed a water saving of 30%, an increase of WP of 29%, a decrease of RWS of 22%, and a PG reduction of 85%.
- SDI decreased the Nutrient (N, P, K) Use Efficiency. CH_4 emissions were not considered, due to the aerobic field conditions, while N_2O emissions increased compared to WFL.
- When considering rice grain quality, rice Cadmium content was lower, while Arsenic content was higher compared to WFL.
- The experiment was repeated in 2021 in the Benzinera farm, characterized by a heavier soil, with the rice variety Bahia, obtaining a yield reduction of only 4.5% compared to WFL. Economic and environmental indicators will be calculated for this additional dataset in the next months.

3.3. CS3 (Guadalquivir marshes, Spain)

WIR: Water Input Reduction (WIR) after day 100 from the sowing date showed to reduce water consumption, without penalizing significantly yield production, and without reducing rice grain quality. In particular, it can be reported that:

- Farm Profitability was about 1347 euro/ha, with a yield production about 8 t/ha.
- Labour Productivity of WIR was slightly lower than WFL. This difference was in particular due to the difference in yield production (about 1 t/ha), as labour input required to conduct agronomic and irrigation operations was similar for the two strategies.
- Water saving was found to be about 31% with respect to WFL, WP increased by 29% and RWS decreased by 28%.
- Energy Productivity was slightly lower than WFL, mainly due to the reduction of yield production, as the amount of carburant consumed to conduct agronomic operations was similar (92 l/ha). Nutrient (N, P, K) Use Efficiency was slightly lower than for WFL, CH4 emissions were slightly reduced compared to WFL (WFL had a few more days of flooding compared to WIR), N2O emissions were similar to WFL since very similar irrigation and fertilizer management strategies were adopted for the two irrigation solutions (i.e. flooding irrigation regime, with one single field drainage, and similar nitrogen treatments).
- Cadmium and total Arsenic contents in the rice grain remained unchanged.

3.4. CS4 (Lower Mondego Valley, Portugal)

AWD: Alternate Wetting and Drying (AWD) showed indicators quite in line with WFL, no significant water saving was achieved and no effect on yield production was observed. Main results are:

- Farm Profitability of AWD was about 2846 euro/ha, no significant reduction in yield production was found for AWD compared to WFL (about 9 t/ha).
- Labour Productivity was lower for AWD (271 kg/hour for WFL *versus* 244 kg/hour for AWD). This was in particular due to the increase of labour required by AWD for the irrigation management.
- Water consumption was slightly lower than for WFL (about 2%). No significant changes were observed in WP and RWS, while PG was reduced by about 8%.
- Energy Productivity was similar to WFL, since the amount of fuel consumed to conduct agronomic operations was similar (135 l/ha) for both irrigation strategies (AWD and WFL). Nutrient (N, P, K) Use Efficiency was slightly lower for AWD than for WFL. No significant changes in CH_4 and N_2O emissions were observed.
- Cadmium and total Arsenic content in rice grain remained similar to WFL, under the EU limits.

3.5. CS5 (Lis Valley, Portugal)

AWD: Alternate Wetting and Drying (AWD) showed to be a promising irrigation technique for the Lis Valley, reducing water use with a slight yield production loss. The main observed results are:

- Farm Profitability was about 1755 euro/ha, yield production was reduced by about 9%.
- Labour Productivity was lower than for WFL (199 kg/hour for WFL *versus* 149 kg/hour for AWD). This was in particular due to the difference in yield production, as well as in labour input, as AWD required more labour for the irrigation management compared to WFL.
- Water saving was found to be about 10% with respect to WFL. No significant change was observed for WP, while RWS decreased by 11%, and PG by about 29%.

- Energy Productivity was lower than for WFL, due to the reduction of yield production, since the amount of fuel consumed for agronomic operations was similar (140 l/ha) in both irrigation strategies (AWD, WFL). Nutrient (N, P, K) Use Efficiency was slightly lower than for WFL, CH_4 emissions decreased by about 23% and N_2O emissions were slightly higher than for WFL.
- No changes were found in Cadmium and Arsenic content in rice grain.

3.6. CS6 (the Nile Delta, Egypt)

HYBRID: Multi-outlet Hybrid irrigation was found to be a very promising water-saving technique, with a high economic reliability. In particular, when considering the Hybrid variety, it was highlighted that:

- Farm Profitability was about 2153 euro/ha, increased by 30% when compared to WFL. Yield production was incremented by 17% achieving 12.5 t/ha. The cost of the multi-outlet hybrid irrigation system was about 325 euro/ha, considering a lifetime of 15 years. Therefore, the initial investment (325 euro/ha) could be covered in the first year.
- Labour Productivity was highly increased when compared to WFL. This was in particular due to the increase in yield production, and to the decrease in labour input of 22%, as HYBRID required less labour hours to conduct agronomic and irrigation operations.
- Water saving was found to be about 25% with respect to WFL. WP increased by 54%, RWS decreased by 25%, and a relevant PG reduction was achieved.
- Energy Productivity was found to be higher than WFL, as the consumed energy was reduced by 35% and the production was increased. Nutrient (N, P, K) Use Efficiency was incremented with respect to WFL. No changes were observed in CH_4 and N_2O emissions.
- Cadmium and Arsenic rice content were slightly decreased with respect to WFL.

SPRINKLER: Multi-nozzle Sprinkler irrigation demonstrated to be an appropriate water-saving irrigation technique, economically profitable, that could be adopted as an alternative to the traditional continuous flooding in the rice area of the Nile Delta. It was highlighted that:

- Farm Profitability achieved was 1421 euro/ha. Yield production was incremented by 5% with respect to WFL, achieving 11.3 t/ha. Cost of the multi-nozzle sprinkler irrigation system was about 725 euro/ha and the considered lifetime was estimated to be 8.5 years. Therefore, it can be concluded that the initial investment could be covered in the first year.
- Labour Productivity was incremented due to the increase in yield production and to the reduction of labour input by 18%, since SPRINKLER required less labour hours for agronomic and irrigation operations.
- Water consumption was reduced by 31% with respect to WFL, WP increased by 51%, and RWS decreased by 29%, while an important PG reduction was achieved.
- Energy Productivity decreased due to the increase of the energy input required for pump functioning in the sprinkler irrigation system. Nutrient (N, P, K) use Efficiency and N_2O emissions increased, and CH_4 emissions were not considered due to the aerobic condition.
- Cadmium and Arsenic contents in rice grain were slightly increased, with a few samples above the EU legal limit for As concentration.

DRIP: Surface Drip irrigation showed to be an innovative water-saving irrigation technique that could be adopted in rice cultivated areas of the Nile Delta, guaranteeing a high water saving without penalizing yield production. The main results obtained are:

- Farm Profitability was found to be 1158 euro/ha. Yield production was incremented by 5% and it attained 11.3 t/ha. The total cost of the surface drip irrigation system was about 1000 euro/ha.

Therefore, it can be deduced that the initial investment could be economically covered in the first few years of rice production, taking into consideration that the system lifetime was estimated to be about 7.5 years.

- Labour Productivity increased when compared to WFL, due to the labour input reduction (about 18%), as DRIP irrigation required less labour hours for agronomic and irrigation operations.
- Water consumption highly decreased (about 43%) with respect to WFL, WP highly increased (84%), RWS was reduced by 37%, and PG decreased of about 90% when compared to WFL.
- Energy Productivity decreased, as the consumed energy was incremented by 57% with respect to WFL, due to the energy input required for the pumping system. Nutrient (N, P, K) Use Efficiency and N_2O emissions increased with respect to WFL, and CH_4 emissions were not considered due to the aerobic conditions of rice.
- Cadmium content in the rice grain was similar to WFL, while Arsenic rice content decreased, with values below the EU legal limit.

3.7. CS7 (Bafra Valley, Turkey)

AWD: Alternate Wetting and Drying (AWD) showed to be a promising irrigation technique reducing water consumption without important yield production losses, and improving the impact of rice production on the environment. The Alternate Wetting and Drying (AWD) strategy was tested in the Bafra Valley adopting three severity degrees AWD (-5cm), AWD (-10cm) AWD (-15cm); details are reported in Enginsu et al. (2022). Indicators were calculated for the three cases, but average values are reported in this paper. The main results are:

- Farm Profitability was found to be 2100 euro/ha (1825-2361 euro/ha for the three AWD severity options). Yield production was reduced by 12% (7-16%), achieving about 7 t/ha (6.7-7.4 t/ha).
- Labour Productivity was slightly lower than for WFL due to the slight reduction of yield production. Labour input for AWD was found to be similar than that for WFL.
- Water saving was about 26% (19-32%) when compared to the traditional flooding, WP increased by 19% (17-21%), and RWS decreased by 24% (17-31%).
- Energy Productivity was higher than for WFL, due to the lower use of electricity for water pumps taking water from the irrigation channel used in AWD. Nutrient (N, P, K) Use Efficiency was slightly decreased, total CH_4 emissions were rather reduced, while N2O emissions incremented.
- Cadmium content in the rice grain was comparable to WFL, while Arsenic content significantly declined; however, concentrations were widely below the EU legal limits.

DRIP: Surface Drip irrigation showed to be a promising water-saving irrigation technique in the Bafra Valley area. It was experimented under two management strategies (DRIP-1.75 and Drip 2.0); details are reported in Enginsu et al. (2022). Both trials gave similar results, average values were considered in this paper.

- Farm Profitability reached approximately 1700 euro/ha (1676-1731 euro/ha). Yield production slightly decreased to about 7.5 t/ha (7.4-7.6 t/ha). The cost of the surface drip irrigation materials was about 1394 euro/ha; the initial investment could be economically covered in the first few years of rice production, taking into consideration that the system lifetime was estimated to be about 3 years.
- Labour Productivity was highly incremented, due to the huge reduction of labor input (about 83%) spent in agronomic and irrigation operations.
- Water saving was about 75% when compared to the traditional flooding, WP highly increased by 270% (248-287%) and RWS decreased of 73% (71-75%).

- Energy Productivity was higher than that for WFL, due to the lower electricity consumed in DRIP to pump water from the irrigation channel. Nutrient (N, P, K) Use Efficiency was slightly lower than for WFL, total CH4 emissions were not considered due to the aerobic field conditions, and N_2O emissions resulted to be highly incremented.
- Cadmium content in the rice grain slightly increased and Arsenic content was found to be lower than for WFL, although values were always widely below the EU legal limit.

4. Conclusions

Water management practices alternative to continuous flooding are highly required to enhance water use efficiency and safeguard environmental quality in rice agro-ecosystems. In the MEDWATERICE project, a novel and multidisciplinary approach to evaluate the overall sustainability (economic, environmental, and social) of water-saving irrigation techniques/technologies alternative to the traditional continuous flooding is proposed and applied to a set of alternative irrigation strategies experimented in pilot farms of project participating countries. The results achieved highlight its effectiveness in summarizing the main economic, environmental and social aspects that emerged from the application of the innovative techniques/technologies in the different geographical contexts.

As regards the specific results achieved in the MEDWATERICE pilot farms, it can be noted that, although general trends can be observed for the indicator values when used to analyse the same irrigation strategy compared to WFL in different geographical areas, absolute values are strongly dependent on the individual Case Study. This is undoubtedly due to the specific environmental conditions, to the rice variety used, to the design, realization and management of irrigation systems at the field and farm level, and to the agronomic and irrigation practices adopted locally.

In general, it emerged that Alternate Wetting and Drying (AWD), Dry-seeding and Delayed Flooding (DFL), Water Input Reduction from day 100 after sowing (WIR), and HYBRID irrigation can be seen as interesting alternatives to the traditional flooding method, ready to be spread among farmers, which could substitute the traditional technique in all the Mediterranean rice area allowing a slight to moderate water saving and a reduction of environmental impacts without radically modifying the irrigation systems. Surface drip (DRIP), subsurface drip irrigation (SDI) and SPRINKLER are promising irrigation solutions to be adopted in geographical context where water resources are limited, which would allow to extend the rice cultivation areas and consequently satisfy the growing product demand; however, it must be taken into account that the high water savings achievable with these techniques is often paid through high investments for the irrigation systems (irrigation equipment, installation, periodic maintenance, sensors to support the irrigation management if any, etc.) and energy costs. Thus, to achieve yield productions able to cover the high investment and energy costs, particular attention must be paid to: i) the choice of appropriate rice varieties adapted to aerobic conditions; ii) the choice of a proper irrigation system design (laterals and emitters spacing, flow rates, etc.) and management (irrigation schedule and duration), taking into consideration site-specific soil hydraulic properties, crop water requirements, and irrigation water quality (salinity, etc.); iii) the consideration of solar-powered pumping systems to reduce energy inputs; and iv) the use of the irrigation system for other profitable crops after the end of the rice season.

The specificities of each technique and the best practices to be adopted for its implementation in the different geographical contexts to minimize economic and environmental drawbacks are described in guidelines and fact-sheets produced during the project and uploaded to the project website (https://www.medwaterice.org/downloads/).

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