MAGDA

INNOVATIVE SENSING FOR FARMING

METEOROLOGICAL ASSIMILATION FROM GALILEO AND DRONES FOR AGRICULTURE

Grant Agreement: 101082189

D6.3 Irrigation Advisory Results Validation

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Acronyms & Abbreviations

Term	Description
API	Application Programming Interface
CGLS	Copernicus Global Land Service
DEM	Digital Elevation Model
EO	Earth Observation
FAO	Food and Agricultural Organization
FMS	Farm Management System
GNSS	Global Navigation Satellite System
IAS	Irrigation Advisory Services
LAI	Leaf Area Index
MAD	Management Allowable Depletion
NDVI	Normalized Difference Vegetation Index
PCR	PCRaster
SSM	Surface Soil Moisture
SPHY	Spatial Processes in Hydrology
SWI	Soil Water Index
WRF	Weather Research and Forecasting
RMSE	Root Mean Square Error
DOY	Day Of Year

1 Introduction

1.1 Project background

1.1.1 Concept and aim

The MAGDA[1] project aims to deliver an integrated, modular system featuring advanced weather forecasting capabilities, along with a suite of enhanced tools and services that rely on the combination of satellite-borne, drone-borne and ground-based weather-observing technologies (Figure 1). The MAGDA weather forecasts are generated from a wide array of atmospheric data gathered from ground-based measurements, GNSS, and high-resolution meteodrones. The MAGDA weather forecasts will be generated through weather models that are able to ingest a wide array of atmospheric data gathered from ground-based measurements, GNSS, and high-resolution meteodrones. Enhanced weather forecasts are then used as forcings for supporting other advisory services of special interest for the agrofarming sector (e.g. the issuance of extreme weather warnings, or the detection of crop irrigation requirements). Irrigation Advisory Services (IAS), like the one aimed by MAGDA, play a critical role as agricultural extension tools and effective management instruments, helping optimize irrigation water use. By improving water efficiency, IAS contribute to increasing farmers' income while simultaneously reducing energy costs.

The warnings and irrigation advisories generated by MAGDA services will ultimately be channelled through a Farm Management System to ensure the capability to effectively reach farmers and agricultural operators.

Figure 1. MAGDA concept visualization

[1] https://www.magdaproject.eu/

1.1.2 MAGDA tools

MAGDA system rests on a suite of tools for the pre-processing of GNSS data, in-situ ground-based and meteodrone observations, and Copernicus data, as well as crop-simulation and front-end tools to support farm management (Table 1). A detailed description of MAGDA tools is provided in D3.1, section 4.1.9 and in D7.1.

Table 1. MAGDA tools description

Tools	Description	Developer
Atmospheric water vapor / soil moisture monitoring service	low-cost GNSS stations and BREVA cloud-based GNSS processing software	GRED
Meteodrone observation service	retrieval of high-resolution atmospheric measurements in vertical profiles	MM
In-situ sensors	collection of ground-based measurements of key meteorological variables	CAP2020
WRF-CIMA	generation of enhanced weather forecasts for early warning of extreme events and supporting irrigation advisory services	CIMA
IrriSPHY	quantification of crop water requirements and irrigation needs based on a crop-hydrological water balance model	FW
Farm Management System (FMS)	MAGDA's user-friendly operational dashboard (with APIs) to support an effective farm management	CAP2020

In the framework of MAGDA project, all these tools are fully integrated into a system (Figure 2) able to deliver operationally enhanced weather forecasts by assimilating the new spatial technologies and irrigation advisory direct to farmers and agriculture operators.

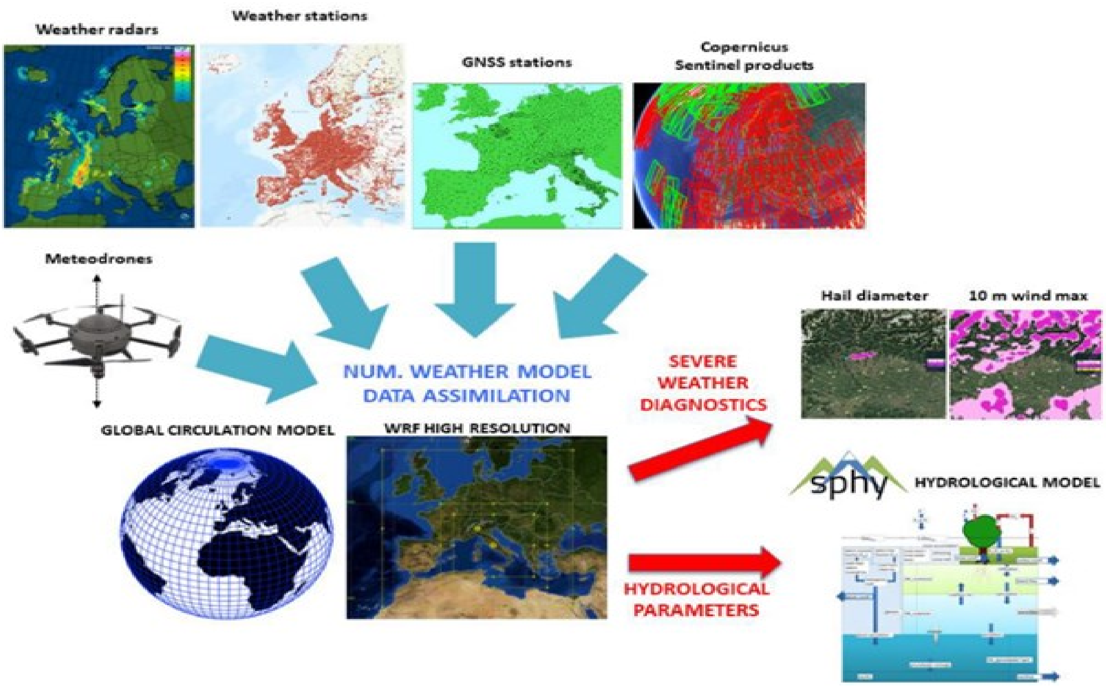

Figure 2. MAGDA forecast concept

1.1.3 Experimental settings

The target of the MAGDA project is to build a system based on hardware, software and data sources components to monitor and process environmental quantities, to deliver farmers with information and suggestions to improve the management of their farms.

The technological readiness of the system is continuously monitored through a set of overall and target-specific KPIs. The main targets are:

- Successful deployment of hardware systems (EGNSS receivers, meteodrones and in-situ sensors).
- Successful setting of pre-processing tools (GNSS data, in-situ data and Copernicus data).
- Successful setting and implementation of the weather and hydrological models.

The implementation of the MAGDA system (tools and services) has been tested in three experimental areas located in France, Italy and Romania (Figure 3).

Figure 3. Locations of the three pilot areas across Europe.

1.2 This report

1.2.1 Aim

Within the MAGDA project, FutureWater is leading the development of the irrigation advisory service through the *WP6 Hydrological modelling and Irrigation Advisory*. WP6 aims to demonstrate the feasibility of an operational irrigation advisory service able to deliver daily advice on irrigation water requirements at the farm level, based on the crop-hydrological model IrriSPHY (Spatial Processes in Hydrology).

WP6 is organized in three subtasks:

- 6.1: Simulating the water balance in SPHY, using remote sensing and in-situ data.
- 6.2: Implementation of operational irrigation advisory service.
- 6.3: Irrigation advisory results validation.

This report is the outcome of subtask 6.3: "Irrigation advisory results validation". The results of the irrigation advisory service pilot implementation are presented and discussed, as well as the validation process, through both comparison of the outcomes of IrriSPHY with soil moisture in-situ measurements and satellite-derived evapotranspiration.

1.2.2 Relation to other tasks and deliverables

The position and interdependencies of WP6 within the project are shown schematically in Figure 4. Deliverable 6.3 corresponds to the final report of the work that has been done within WP6, presenting the irrigation advisory results validation. As can be seen from Figure 4, Work Package 6 receives inputs from several work packages (WP3, WP5 and WP7) and provides outputs to the Farm Management System Work Package (WP4).

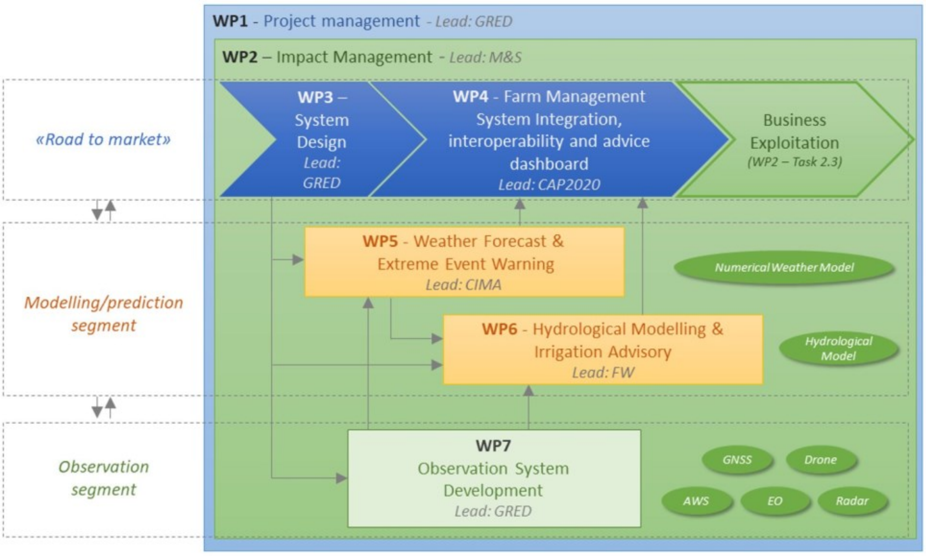

Figure 4. Overview of main activities within MAGDA

This deliverable is related to the following other MAGDA tasks and deliverables:

Receives inputs from:

Table 2. Input from other tasks and deliverables

Deliverable	Due Date	Input for D6.3
D3.1	30.04.2023	User requirements analysis (the farm location and farm characteristics) and system design
D4.1	31.10.2023	Report on MAGDA environment
D5.2	30.04.2024	Forecast system demonstrator data
D6.2	30.04.2024	Demonstrator methodology of operational irrigation advisory service
D7.1	30.11.2024	Results of observation system deployment for operational advisory evaluation

Provides outputs to:

Table 3. Output for other tasks and deliverables

Deliverable	Due Date	Output from D6.3
D4.3	31.12.24	Irrigation advisory data for the FMS

1.2.3 Reading guide

Chapter 2 provides an overview of the MAGDA Irrigation Advisory Service, detailing its approach and required input data. For further details on these aspects, refer to Deliverable 6.2. This chapter also covers the pilot implementation and calibration setup, focusing on the simulation domains, selected time windows, key parameters, and meteorological inputs for each site.

Chapter 3 presents the results and validation of the service, highlighting key findings from both irrigation water requirements and scheduling perspectives. Validation is conducted by comparing the service's outputs with in-situ measurements and satellite-derived variables. The chapter concludes with an explanation of the integration between the irrigation advisory service and the Farm Management System (FMS). It describes how data is shared via MAGDA's SFTP, the role of IrriSPHY, the crop-irrigation model, in feeding the FMS, and how the irrigation advisory tool's output data is displayed within the FMS.

Lastly, the conclusions are presented in chapter 4 and references in chapter 5.

2 Methodology and inputs

2.1 Approach

The flowchart of the MAGDA irrigation advisory service is shown in Figure 5. The backbone of the service rests on IrriSPHY, a crop-irrigation model that combines features from the FAO56 model (Pereira et al. (2015)) and novel components from the SPHY model[2] (Terink et al. (2015)).

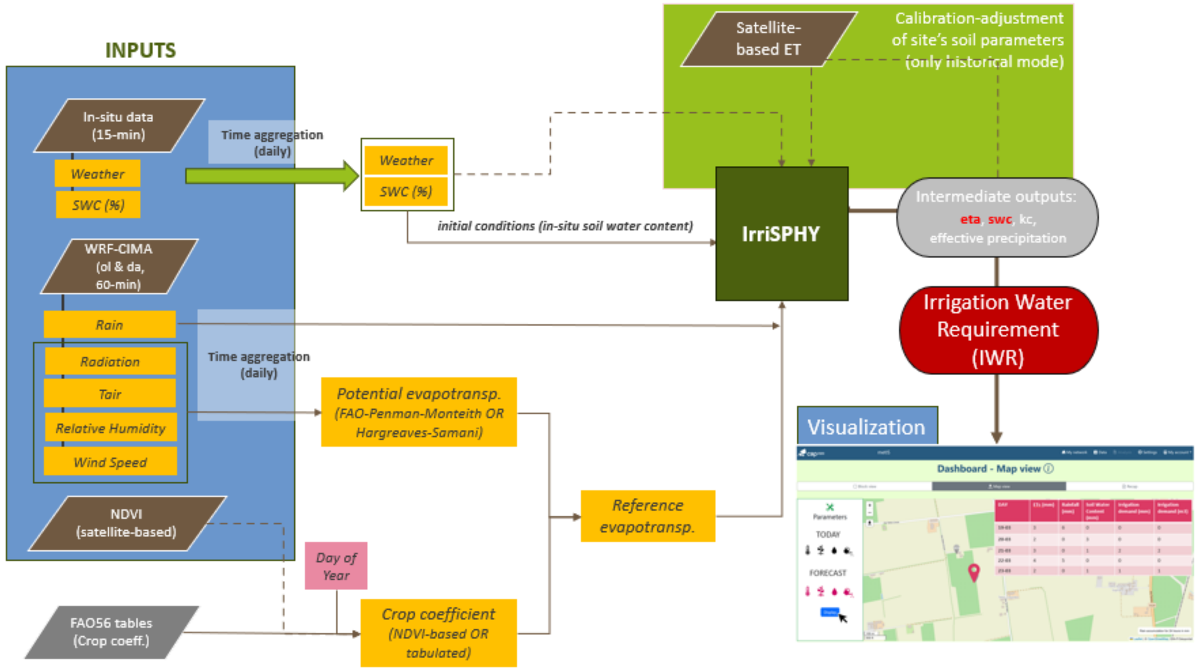

Figure 5. Flowchart of the irrigation advisory service.

In IrriSPHY, the Irrigation Water Requirement (IWR) is defined as the supplemental water needed to meet crop water demand that is not fulfilled by rainfall and existing soil moisture (Equation 1).

$$IWR = ET_c - \left(P_{eff} + ET_{sm}\right)$$

Equation 1

where ET_c is the crop evapotranspiration under non-stress conditions, and Etc_act is the actual crop evapotranspiration. P_{eff} is the effective precipitation, and ET_{sm} is the fraction of the soil water content at the root-zone that is taken by crops for evapotranspiration (also known as the Root Zone Water Supply). The component $P_{eff} + ET_{sm}$ is the total of water available from rainfall and soil moisture to meet the water needs of a crop. Under stress conditions for which P_{eff} + ET does not match ET_c, the $P_{eff} + ET_{sm}$ component may be similar to the crop evapotranspiration computed by using satellite-based evapotranspiration methods.

[2] For more information visit https://sphymodel.com/

IrriSPHY is a 1D leaky-bucket model that quantifies the most important water fluxes in the soil-plant-atmosphere continuum, the evolution of the soil water content in the root-zone domain, and the irrigation needs (Figure 6). In MAGDA, IrriSPHY has been run at the daily scale.

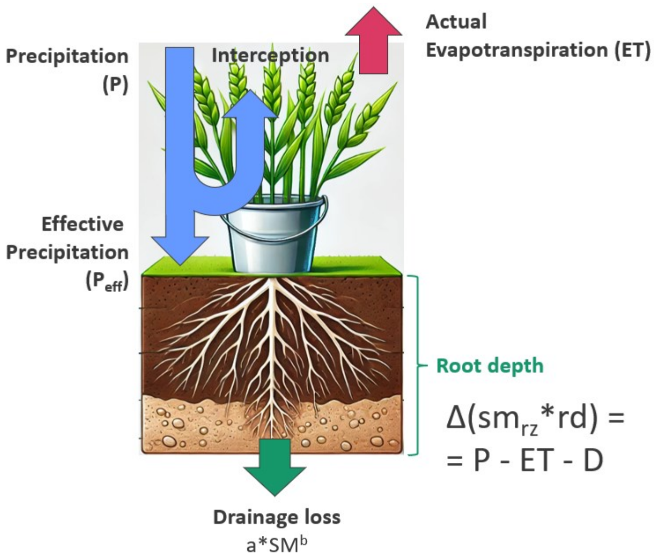

Figure 6. IrriSPHY conceptual model used in the Irrigation Advisory Service of MAGDA.

Compared to the model version described in Deliverable 6.2, two important improvements in the code have been recently added to provide a more reliable representation of the water fluxes in the soil-plant-atmosphere-continuum. The first improvement refers to how drainage is generated when soil moisture content in the root zone is beyond the soil field capacity (equation 8 in Deliverable 6.2). In the updated version, drainage loss is computed daily using a power-law relationship:

$$D = k * EWC^p$$

Equation 2

where EWC (Excess Water Content) is the amount of water (measured in mm/day) that exceeds the soil's field capacity after accounting for precipitation inflows within the root zone. Parameter k refers to the diffusivity coefficient (mm^2/day), while p is the moisture diffusivity exponent (dimensionless). Both parameters are soil and site-specific constants that define the soil water retention curve. Ideally these parameters should be calibrated from soil moisture measurements collected during small-moderate rainfall events and wet periods in which evapotranspiration losses are almost negligible. Due to the lack of data for an accurate calibration in the MAGDA project, typical values of k and p reported in literature were adopted in this study.

The second improvement refers to how actual evapotranspiration is computed when the soil moisture content is between the wilting point (wp) and field capacity (fc). As it is commonly adopted in other studies, a stress factor (F_{stress}) is introduced to account for the closure of the crop stomata when the soil moisture conditions in the root zone range between the wilting point and the field capacity of the soil (Figure 7).

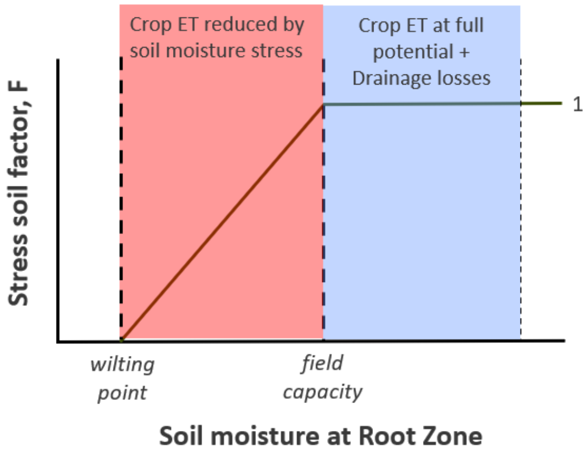

Figure 7. Influence of soil moisture conditions in the root zone on the crop evapotranspiration. Stomatal closure accounts when soil moisture in below the field capacity.

F_{stress} is a non-dimensional scalar that range from 0, when soil moisture is lower than the wilting point, to 1 when soil moisture exceeds the field capacity. Both soil parameters, wp and fc, can be set up based on laboratory analyses or derived from pedotransfer functions if data on soil texture and organic matter content are known. Finally, the ET_{sm} component in Equation 1 is computed as:

$$ET_{sm} = ET_c * K_c * F_{stress}$$

Equation 3

More details on the IrriSPHY model can be found in Deliverable 6.2 (section 2.1.2).

2.2 Selected pilot sites

The selection of pilot sites and experimental dates for the demonstrator phase are critical to evaluate the effectiveness and usefulness of the MAGDA system data for the irrigation service. The prototype of the MAGDA irrigation advisory tool has been tested in two Romanian and one Italian site where irrigation play an important role to produce crops. France will be not part of the experiments due to the lack of irrigated crops in the MAGDA pilot sites.

The selected demo sites at Romania and Italy consist of farms which have been monitored during the MAGDA project. MAGDA inputs include data from GNSS, meteodrone flights, weather stations and soil moisture sensors installed on the premises of the farm.

2.2.1 Romania

The Romanian experimental sites, SCDAB and ISMB, are located in the Brăila Plain-Danube River Floodplain and are owned by the Agriculture Research and Development Station Brăila[3]. This region is the most important agricultural hub in Romania, renowned for its highly fertile soils and the closeness

[3] https://www.scdabraila.ro/

of the Danube River that ensure water resources for irrigation that support extensive and productive farming.

Climate in the region is humid-subtropical (Cfa, according to the Köppen classification) characterized by warm, humid summers and mild winters. Mean Annual Precipitation is ~600 mm/year[4], and potential reference evapotranspiration of ~550 mm/year. Soils mostly have a loam or clayed-loam texture, and crops are irrigated during most of the year, except during the April-June period when capillary rise induced by high groundwater tables contributes to meet crop water requirements. In general, the irrigation system in the region consists of a channel network for water conveyance, electric pumping stations, and a network of buried pipes of various orders for water distribution. Irrigation water is delivered at specific outlets where farmers connect their overhead distribution equipment for applying sprinkler irrigation (centre pivots, front advanced lateral irrigation systems, travellers, etc.) in the field. The demonstrator has been tested in a typical summer crop (maize-grain at SCADB), and an autumn crop (cereals at ISMB). Figure 8 shows the location of the pilot sites and Figure 9 contains pictures of the different crops and locations involved.

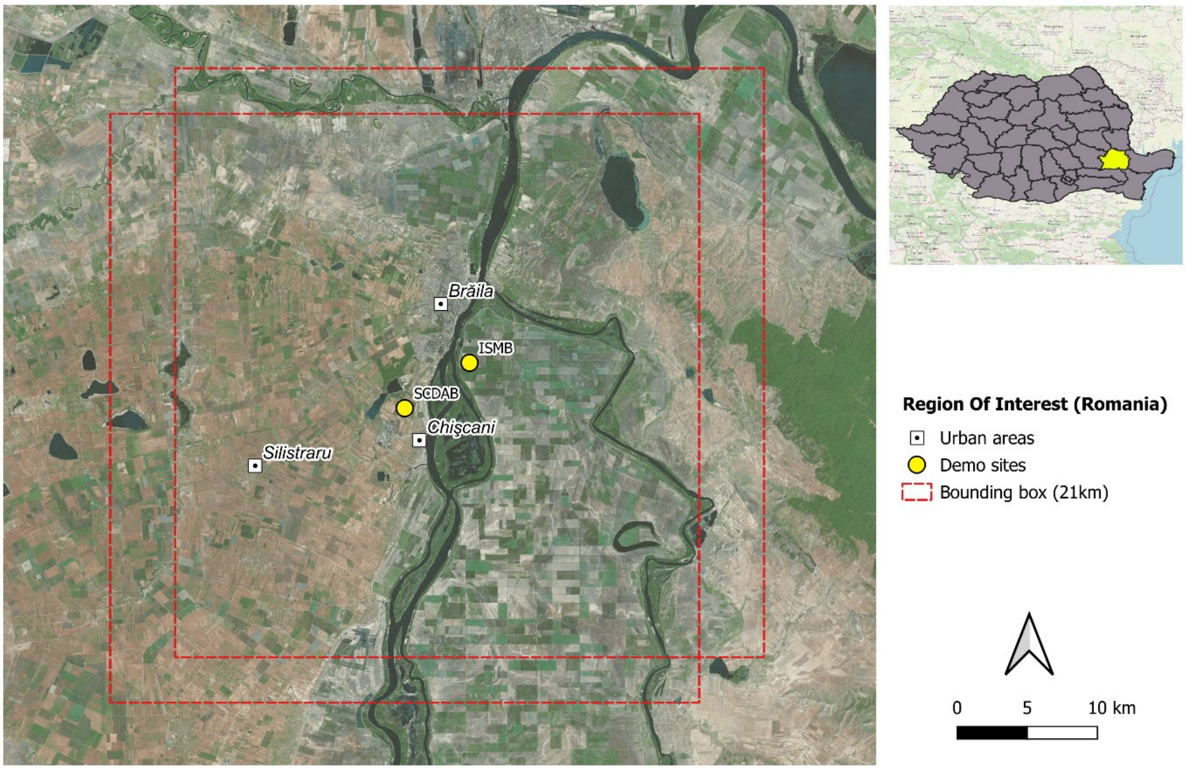

Figure 8. Selected pilot sites in Braila region (Romania). Dotted boxes define the bounding box of 21x21km around each pilot site.

[4] https://weatherandclimate.com/romania/braila

Figure 9. Photos of pilot sites in Romania (left: SCDAB pilot site – maize, right: ISMB pilot site – autumn cereals)

2.2.2 Italy

The Italian case refers to the Tetto-Bernardo pilot site located in Piedmont region (NW Italy) which has been proposed by the Italian Confederation of Farmers – Cuneo section (ICF-C). This region between Cuneo and Saluzzo is recognized as a major hub for fruit production in both Italy and Europe.

The area has a moderately continental climate (Cfb, according to Köppen-Geiger classification) characterized by cold winters and warm summers. Mean Annual Precipitation is ~990 mm/year, and potential reference evapotranspiration of ~600 mm/year. Soils in the valley mostly have a loamy texture. Crops in the region are dominated by cereals, sunflowers, and fruit trees and vegetables. Irrigation is an important component of the whole agrosystem. The region has a well-developed network of canals and irrigation channels that distribute water from rivers and reservoirs to the farms. At the farm level, surface and sprinkler irrigation are the most prominent techniques, followed by drip irrigation in high-value crops. The experimental site selected consists of an apple orchard located at the Tetto-Bernardo farm, where irrigation is localized, and “watermark” soil moisture sensors are already in place. Figure 10 shows the location of the farm and Figure 11 contains some pictures taken during the site inspection.

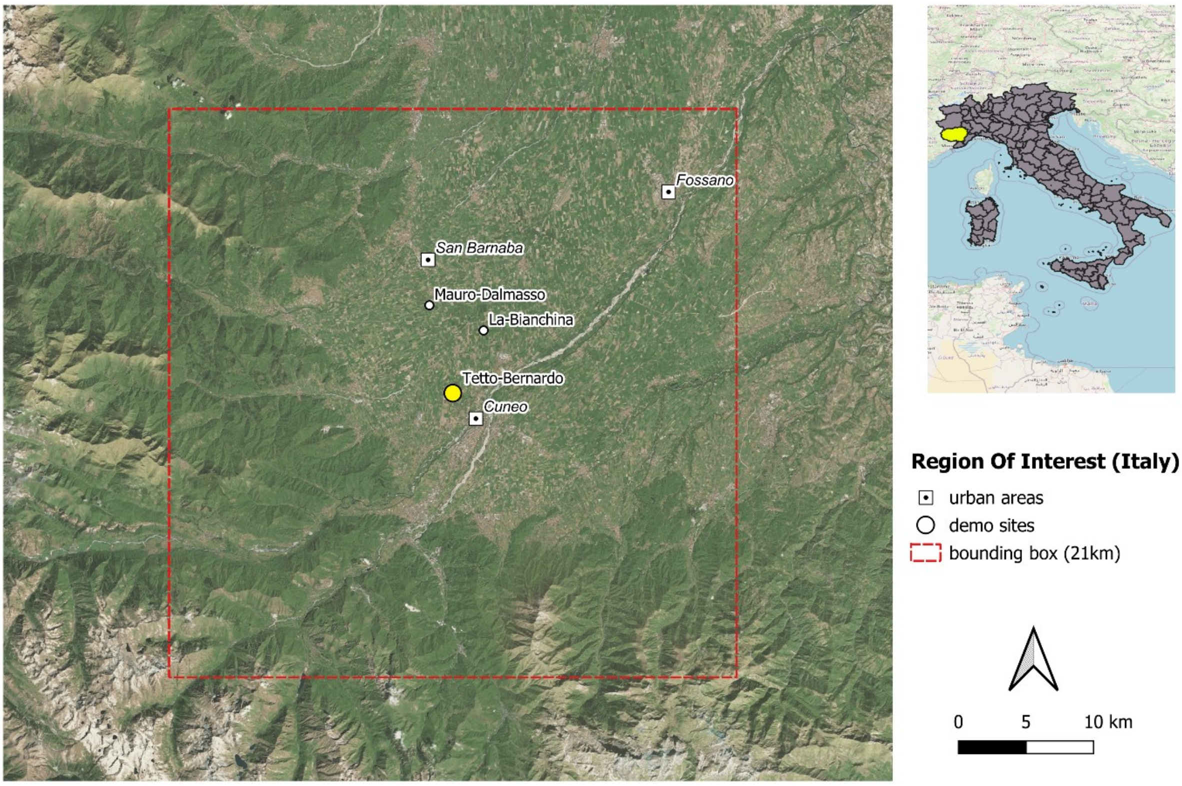

Figure 10. Location of Tetto-Bernardo pilot site in Piedmont region (Italy). Dashed box defines the 21km-side bounding box around the site.

Figure 11. Photos of Tetto-Bernardo farm

2.3 Input data

2.3.1 Site-specific parameters

The most critical site-specific parameters for the irrigation advisory service are listed in Table 4. Some additional brief notes on the sites are provided below.

Table 4. Site parameters used in the irrigation advisory service (*SOS = Start of the Crop Season)

	Romania		Italy
Site name	SCADB	ISMB	Tetto-Bernardo
Lat, Lon (EPSG:4326)	(45.2061, 27.9199)	(45.2318, 27.9830)	(44.4138, 7.5231)
Altitude (m a.s.l.)	13.5	2.5	527
Crop type	Maize-grain	Autum cereals	Apple
Planting date	1 April	15 October	1 July
Root depth (m)	0.5	0.5	1.0
Soil texture	Loam	Clay-loam	Loam
Total porosity (%)	0.85	0.85	0.85
Soil wilting point (vol/vol)	0.15	0.22	0.15
Soil field capacity (vol/vol)	0.35	0.48	0.35
Soil diffusivity coefficient, k (mm^2/day)	0.2	0.2	0.2
Soil moisture diffusivity exponent, p (dimensionless)	1.5	1.5	1.5

2.3.2 Meteorological data

Weather forecasts

Two types of weather forecasts provided by consortium partner CIMA were ingested into the crop-irrigation model:

- **Open loop forecasts** (no data assimilation, WRF-CIMA-ol). These datasets do not assimilate the MAGDA system data from in-situ sensors, GNSS and/or Meteodrones. These forecasts are considered here as the benchmark scheme.
- **MAGDA forecasts** (with data assimilation, WRF-CIMA-da). These forecasts assimilate diverse data sources, depending on availability: radar data, GNSS data, in situ temperature data and Meteodrones data. The impact of assimilation is expected to contribute mainly to the beginning of the forecasted window, and its impact can vary between cases due to several factors such as available observations, atmospheric conditions at assimilation timing, event types, etcetera. It is assumed that forecasts with data assimilation may provide higher potential for water savings, as they account better for the local conditions at the plot level. Detailed methodology is explained in D5.2.

Selected forecasting windows

The MAGDA irrigation advisory service was tested on different time windows during summer and autumn of 2024. For the selection of dates, the occurrence of rainfall events, and the highest availability of MAGDA data from GNSS, meteodrone flights, and/or weather and soil moisture sensors at field scale were considered. The dates finally selected are listed in Table 5.

Table 5. Demo sites and dates of the demonstrator

Site	Windows of Forecast	SCDAB	ISMB	Tetto-Bernardo
Romania	29 Jun – 3 Jul 2024	10.5	12.9	
	22 – 26 Jul 2024	3.2	22.3	
	5 – 8 Aug 2024	5.0	9.4	
	7 – 11 Sep 2024	12.1	10.2	
Italy	20 - 24 Jun 2024			43.7
Total (evaluated period)		**30.8**	**54.8**	**43.7**

For the selected forecasted windows, the two types of forecasts (DA and OL) were received containing 5 days of predictions in a moving window of one day, meaning that forecasts were launched on each day within the event of interest covering the next five days (Figure 12).

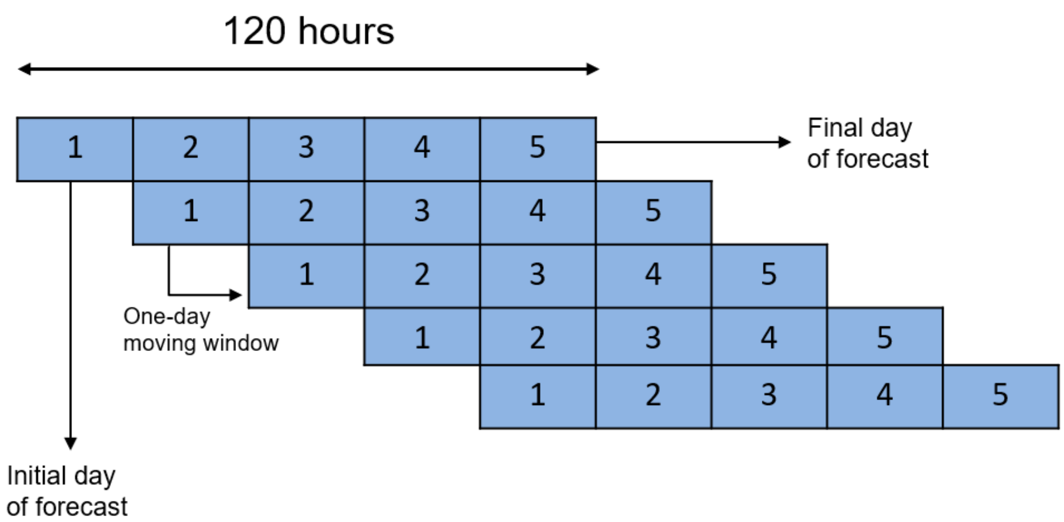

Figure 12. Forecasts structure

The demonstrator exercise consists of forcing the crop-hydrological model with both types of forecasts and compare the outputs in terms of accumulated values of Irrigation Water Requirement and Potential Evapotranspiration at the end of the forecasted window.

Spatial variability

An important point of consideration when working with these forecasts is spatial variability. For verification, as meteorological variables such as precipitation are areal quantities (Ghelli & Lalaurette François (2000)), it is advisable to adopt an up-scaling approach in order to compare in situ meteorological values (point-based, from sensors) and spatially distributed values (pixel-based, from WRF). Slight shifts in the spatial pattern of a meteorological forecast can lead to big differences when checking a single point value. Figure 13 shows an example of this effect. Below are five predictions of rainfall for 3 July 2024, forecast date is indicated on each individual image. It can be noticed that slight shifts in the spatial patterns can lead to significant changes on the point-value of the in-situ station (yellow dot).

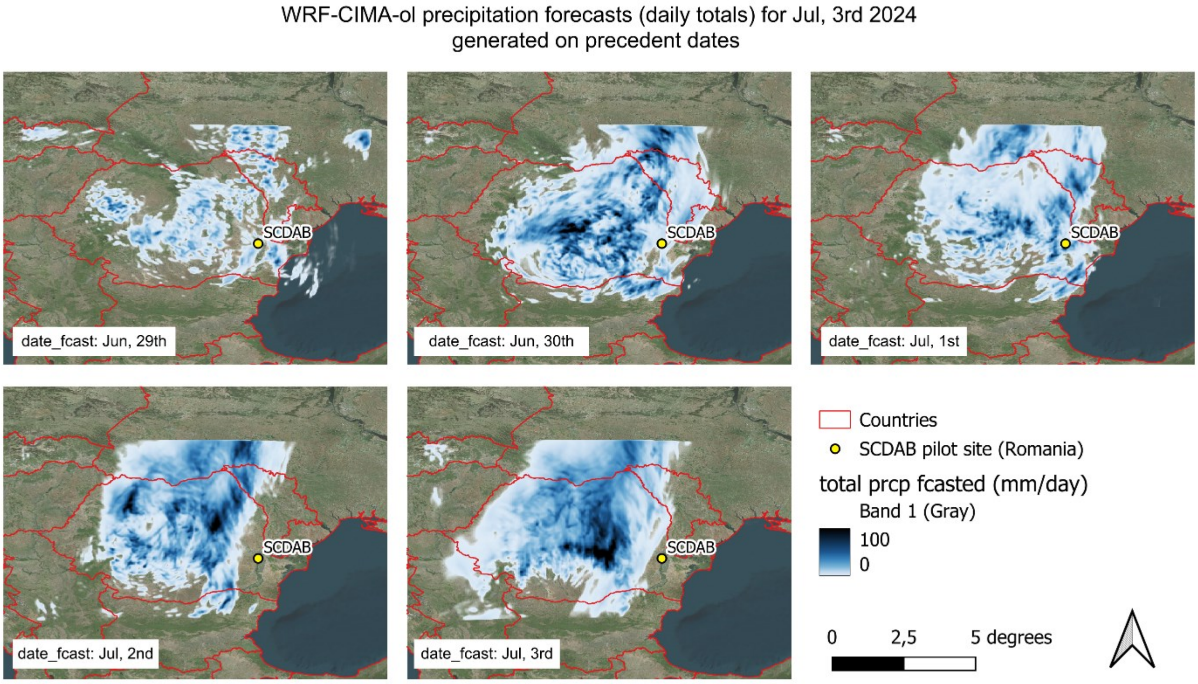

Figure 13. Spatial distribution of total daily precipitation forecasted for July 3rd by the WRF-CIMA-ol model, with forecasts generated on each of the five preceding days.

To avoid this issue, a defined area is considered – a box, covering 7x7 grid points (21x21 km) – centered on the in-situ station (Figure 14). IrriSPHY is then forced with these 49 paired-value vectors of precipitation and potential reference evapotranspiration forecasts. This approach allows to obtain different values of irrigation advice, which are used to compute different metrics such as the mean, maximum/minimum and percentile values within the grid in order to provide a range of values, to cope with this spatial variability.

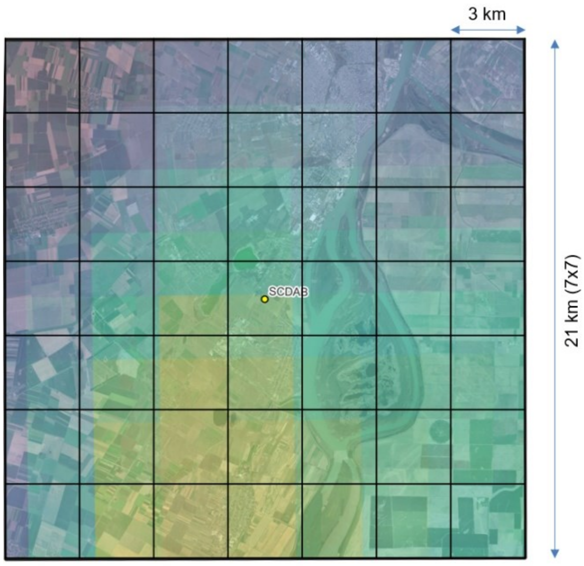

Figure 14. Box covering 7x7 pixels (21x21 km) around the in-situ station, colour scale corresponding to precipitation values. Romanian pilot site of SCDAB.

Figure 15 is a different representation of the importance of the spatial variability matter. The histograms show the 49 values (7x7 grid) of forecasted precipitation (x-axis) for the days preceding a rainfall event (y-axis), for the three different sites. The date of the event is indicated in the title of each graph and the observed value of the forecasted date measured from in-situ sensors is represented as red-dashed vertical line. Significant variability can be observed across time and space among the forecasted values within the grid. By adopting an up-scaling approach in which spatial statistics are computed, the correlation with the in-situ measurements increases. The figure also shows the spatial distribution for both forecasts (with and without assimilation). However, having only few events per site, it is not possible to derive strong conclusions about which forecast performs better. For more details on the impacts of data assimilation on the weather forecasts, please refer to Deliverable 5.3.

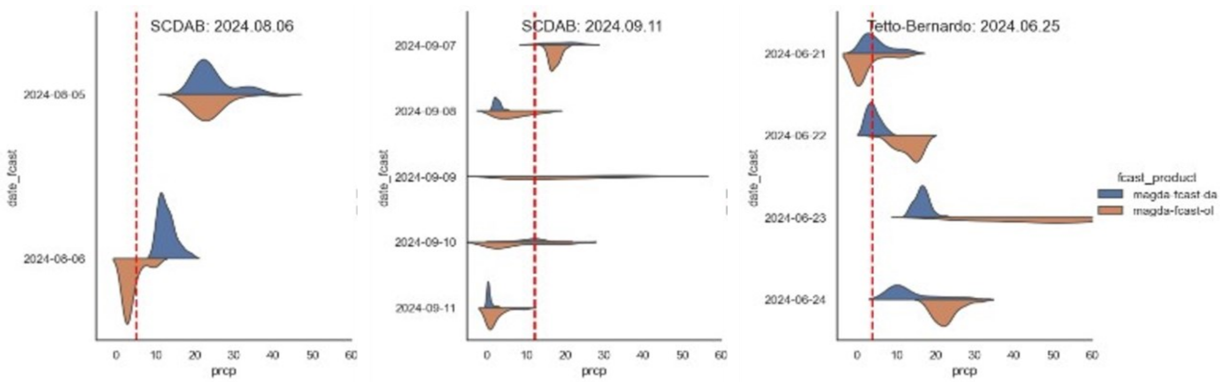

Figure 15. Histograms of rainfall forecasts (x-axis) in precedent days (y-axis) to rainfall-observed events (vertical dashed red line), for the three different sites. The date of the event is indicated in the title of each graph. Blue and orange histograms refer to wrf-cima-da and wrf-cima-ol forecast products, respectively.

2.3.3 In-situ sensor data

In-situ sensors data are produced by CAP2020. The output format of the files is CSV, and the acquisition frequency is 15 minutes. However, for irrigation purposes, the variables provided by sensors are aggregated to a daily timestep. Among the wide range of variables provided, only a small subset of them have been used for the irrigation advice computation, for establishing initial conditions:

- Soil Water Content: soil moisture (vol/vol in %) at 30cm depth. Values are used to initialize IrriSPHY at the beginning of each forecasting window.
- Meteorological variables (rain, air temperature, air relative humidity, and wind). Only used for calibration purposes and hindcast analyses[5].

Data from the in-situ sensors is made available to MAGDA's partners through an API and on a shared SFTP server, in near real time.

[5] During an forecasting-operational setup, potential evapotranspiration is directly estimated from meteorological forecasts.

2.3.4 Satellite-derived Actual Evapotranspiration

Satellite-based actual evapotranspiration in MAGDA was retrieved by Meteo Romania using the TSEB model, a Surface Energy Balance algorithm which combines optical-satellite (MSI-Level2 from Sentinel-2), thermal-satellite (LST product from the Sentinel-3), and reanalysis meteorological data (from ERA-5 dataset). The TSEB model was implemented using the Guzinski et al. (2020) algorithm, and by using the SNAP Toolbox. MAGDA's ETa values are generated with a temporal resolution of 10 days, and spatial resolution of 20 meters. This dataset is used as an independent source of information for validation and intercomparison against IrriSPHY outputs (see validation results in section 3.3.1)

2.4 Site-specific calibration

The site-specific calibration of MAGDA irrigation model is essential for accurately estimating soil moisture dynamics in the root zone and forecasting crop irrigation needs during dry periods. A key parameter in this calibration is root zone depth, which influences soil water storage and evapotranspiration losses.

To determine the optimal root depth at the plot scale, soil moisture data from drying spells longer than 15 days is analysed. The model runs with different root depth values, and the best fit is selected based on correlation and RMSE metrics between observed and simulated soil moisture.

A more detailed description of the MAGDA's IrriSPHY site-specific calibration can be found in Deliverable 6.2 (section 2.1.3).

3 Results and Validation

3.1 Irrigation Water Requirements

IrriSPHY provides farmers with estimates of daily Irrigation Water Requirements (IWR) in m³/ha/day for short-term (2-day ahead) and medium-term (5-day ahead) forecast windows. These IWR estimates represent the supplementary water that farmers may apply as irrigation to meet the crop's daily water needs. The calculations are based on meteorological conditions, crop development stage, and soil moisture levels in the root zone.

Table 6 and Table 7 present recommendations of irrigation, i.e. IWR values, issued at SCDAB and Tetto-Benardo pilot sites for all selected selected forecasting periods. The relative contribution of IWR to the crop reference evapotranspiration (IWR/ET_c ratio) is also reported for comparison purposes.

Assuming an operational scheme like the one envisioned for the MAGDA service, these forecasts would be delivered to farmers every two days, providing predictions for the next 2-day and 5-day periods. The forecasts were based on weather forcings generated by forecasting models, both with and without the assimilation of in-field, GNSS, and Meteodrone measurements. Spatial average is applied over the 7x7 pixels box around the in situ station.

In SCDAB, with a higher sample size of forecasts than in Tetto-Bernardo, estimates of IWR and IWR/ET_c ratios derived from weather forecasts with data assimilation (DA) were consistently higher than those retrieved for the benchmark case (OL) for all selected events. However, in Tetto-Bernardo, no clear difference was observed during the single testing period evaluated. These results suggest DA forecasts better captures water needs, by accounting for better on-ground conditions.

The results show that, in the SCDAB testing site, short-term (2-day ahead) forecasts of IWR and IWR/ET_c were consistently higher than in medium-term (5-day ahead) forecasts (0.32–0.23 vs. 0.29–0.19, for DA-OL configurations, respectively) in the SCDAB testing site. No differences were detected in the Tetto-Bernardo site.

Table 6. Short-term forecasts of precipitation (P_{fcast}), crop reference evapotranspiration (ET_c), and Irrigation Water Requirement (IWR) derived from different weather forecast products (DA and OL) at different testing dates and sites. IWR and ET_c in m3/ha/day. Total rainfall in the period measured at the site (P_{obs}) and forecasted (P_{fcast}) are in mm.

Site	Testing period	P_obs	2-days							
			DA				OL			
			P_fcast	ETc	IWR	IWR/ETc	P_fcast	ETc	IWR	IWR/ETc
SCDAB	29 Jun – 3 Jul 2024	10.5	10.8	110.71	37.60	0.34	14.0	103.63	28.42	0.27
	22 – 26 Jul 2024	3.2	7.6	108.39	50.34	0.46	14.7	94.06	29.29	0.31
	5 – 9 Aug 2024	5	12.3	86.81	20.26	0.23	12.0	75.97	12.44	0.16
	7 – 11 Sep 2024	12.1	20.7	29.83	0.00	0.00	19.4	29.18	0.00	0.00
	Average	7.7	12.8	83.94	27.05	0.32	15.0	75.71	17.54	0.23
Tetto-Bernardo	20 – 24 Jun 2024	43.7	28.6	39.03	1.72	0.04	24.7	40.63	1.74	0.04

Table 7. Medium-term forecasts of precipitation (Pfcast), crop reference evapotranspiration (ETc), and Irrigation Water Requirement (IWR) derived from different weather forecast products (DA and OL) at different testing dates and sites. IWR and ETc in m3/ha/day. Total rainfall in the period measured at the site (Pobs) and forecasted (Pfcast) are in mm.

Site	Testing period	P_obs	5-days							
			DA				OL			
			P_fcast	ETc	IWR	IWR/ETc	P_fcast	ETc	IWR	IWR/ETc
SCDAB	**29 Jun – 3 Jul 2024**	10.5	16.2	108.3	30.1	0.28	20.9	102.8	21.3	0.21
	22 – 26 Jul 2024	3.2	18.3	104.6	44.6	0.43	20.2	92.5	22.9	0.25
	5 – 9 Aug 2024	5	10.6	86.8	20.3	0.23	19.5	76.0	12.4	0.16
	7 – 11 Sep 2024	12.1	13.5	30.9	0.0	0.00	24.8	29.8	0.00	0.00
	Average	7.7	14.7	82.7	23.8	0.29	21.4	75.3	14.1	0.19
Tetto-Bernardo	**20 – 24 Jun 2024**	43.7	50.8	41.5	4.5	0.10	52.9	17.9	3.9	0.22

3.2 Irrigation scheduling

The MAGDA irrigation advisory service provides a flexible and precise framework for optimizing irrigation scheduling and fine-tuning irrigation inputs at the farm scale. This benefit stems from its near-real-time simulation of soil water content in the root zone and its ability to quantify the soil moisture available to meet crop water demands.

Figure 16 shows IWR assuming irrigation at the full crop water requirement (Business-as-Usual (BAU) practice) for crop reference evapotranspiration estimated by using two different inputs for weather forcings:

- Black line: reference crop evapotranspiration calculated using in-situ measurements of weather data (potential evapotranspiration) and the crop's development stage (crop coefficient). This case is considered as the benchmark case, to be enhanced by using MAGDA forecasts.
- Red line: reference crop evapotranspiration calculated using forecast (open loop) weather data (potential evapotranspiration) and the crop's development stage (crop coefficient).

The difference between the lines and bars represent the potential water savings achievable when improved forecasts and/or in situ measurements are considered.

The potential for water savings varies depending on the level of data assimilation and the accuracy of input weather forcings, particularly precipitation. Additionally, short-term forecasts (2-day ahead) can significantly outperform mid-term forecasts (5-day ahead), benefiting from MAGDA's improved forecasting capabilities with data assimilation. In general, irrigation needs from forecasts with data assimilation are consistently higher than forecasts without assimilation. Despite slightly higher ETc, forecast IWR values are conservative, suggesting precipitation-dominated supply.

Regarding benchmark IWR (from in situ measurements only), it is consistently higher than IWR produced by forecasts, as no incoming precipitation for the next days is being considered. This analysis demonstrates the potential water savings that can be achieved when anticipating crop water requirements based on forecasts, leading to a more efficient irrigation scheduling.

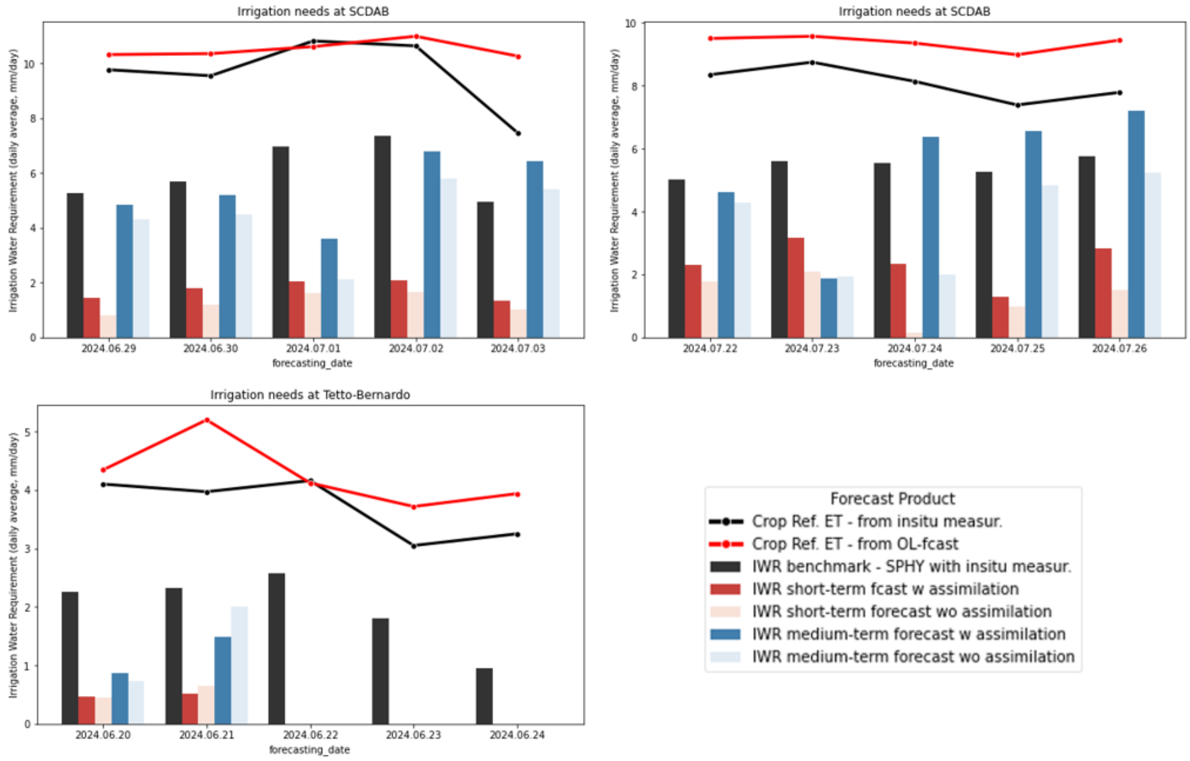

Figure 16. Examples or reference crop evapotranspiration (ETc) and irrigation water requirements (IWR) issued at SCDAB site for periods 29 June - 03 July and 22-26 July, and at Tetto-Bernardo for period 20-24 June. All values in water depth (mm/day). Irrigation needs represent the daily average over the forecasting window (black bar, used as benchmark), 2-day (reddish bars) and 5-day (blueish bars) forecasting periods, based on weather forecasts with (dark, WRF-CIMA-DA) and without (light, WRF-CIMA-OL) data assimilation. Lines represent ETc values retrieved from in-situ measurements (black) and weather forecasts (red).

3.3 Validation

An analysis was performed at the site level to verify the outputs generated by IrriSPHY. The analysis did not aim to provide a comprehensive validation exercise, but only a first-order intercomparison-verification assessment between MAGDA simulations and other independent sources of data. The target variables for the intercomparison exercise were:

- actual evapotranspiration: comparison between simulated values and values retrieved from the application of the TSEB model with Sentinel-2/3 and reanalyses data.
- soil moisture: comparison between simulated vs observations during the 5-days forecasting window of interest.
- irrigation water applied: comparison between simulated irrigation water requirements and actual irrigation water applied (only at SCDAB pilot site, where real quotas were provided by farmers for the 2024 crop season).

3.3.1 Actual evapotranspiration

Simulated values of actual evapotranspiration (*eta*) derived from the IrriSPHY model used in MAGDA and the satellite-based TSEB model are shown in Table 8 and Figure 17. Values of *eta* from IrriSPHY in Table 8 refer to the overall average computed from all the simulated values generated during the forecasting windows of interest for each pilot site.

In general, satellite-based values are higher than those derived from IrriSPHY, with absolute differences between models that range between 1.0 in Tetto-Bernardo and 2.3 mm/day in ISMB. Except for the ISMB case, differences in eta values between both sources in SCDAB and Tetto-Bernado are less than 20%, which is around the typical uncertainties found in eta from eddy-covariance measurements.

Table 8. Comparison of daily actual evapotranspiration values estimated by IrriSPHY and the satellite-based TSEB model for the three sites. Values refer to the mean for all simulations.

Site	IrriSPHY		eta_tseb	Absolute Diff.	
	eta_da	eta_ol		da - tseb	ol - tseb
ISMB	0.278	0.275	2.602	2.324	2.327
SCDAB	3.379	3.509	3.786	0.407	0.277
Tetto-Bernardo	3.759	3.733	4.71	0.951	0.977
			Average	1.227	1.193

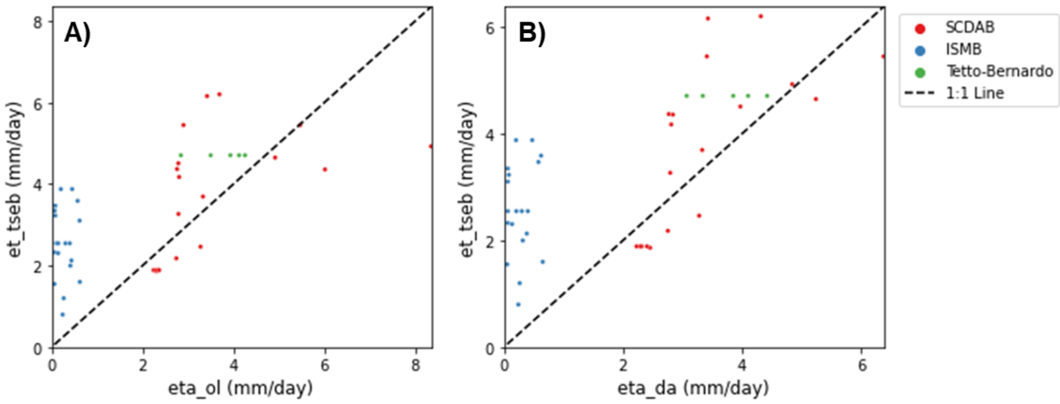

Figure 17. Scatterplots between actual evapotranspiration values from the satellite-based TSEB model (y-axis) and simulated from MAGDA's IrriSPHY (x-axis). Left: forced with open-loop weather forecasts (eta_ol), right: forced with weather forecasts with data assimilation (eta_da)

3.3.2 Soil moisture

Results from the comparison between simulations of soil moisture and in-situ measurements are shown in Table 9 and Figure 18.

When simulated values of soil moisture are grouped and averaged at the site level, predictions using weather forecasts with data assimilation are slightly closer to in-situ observations than simulations derived from open-loop weather forecasts.

Table 9. Comparison of soil moisture values estimated by IrriSPHY and in-situ measurements. Values refer to the mean for all simulations generated in the forecast windows evaluated.

Site	IrriSPHY		sm_obs	Absolute Diff.	
	sm_da	sm_ol		da - obs	ol - obs
ISMB	0.240	0.251	0.234	0.007	0.017
SCDAB	0.204	0.199	0.234	0.029	0.035
Tetto-Bernardo	0.420	0.419	0.475	0.055	0.056
			Average	0.030	0.036

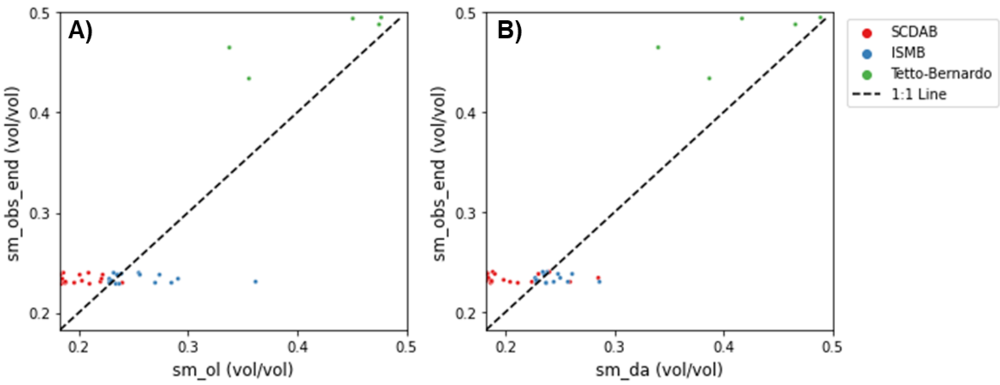

Figure 18. Scatterplots between soil moisture in-situ measurements (y-axis) and simulated values from MAGDA's IrriSPHY (x-axis). Left: forced with open-loop weather forecasts (sm_ol), right: forced with weather forecasts with data assimilation (sm_da).

3.3.3 Irrigation Water Applied

As part of an intercomparison analysis or model verification exercise, recommendations of irrigation from IrriSPHY have been compared against quotas of irrigation applied at the SCDAB pilot site during the 2024 crop season. Irrigation at SCDAB is applied according to the ICITID Baneasa-Giurgiu method (Grumeza N. et al (1989), a traditional method widely used in the region. This method rests on monthly mean values of potential evapotranspiration derived from the Thornthwaite method (1948), crop-specific coefficients previously adjusted for the typical crops in the region (maize, sunflower, soybean, and wheat), and in situ soil moisture measurements. The method provides the time and amount of irrigation to be applied in the loamy soils of the Braila region based on the Management Allowed Depletion (MAD) concept. MAD is defined in this method as the difference between the field capacity and the wilting point. For irrigated maize, the method states 50% of the MAD as the threshold for applying irrigation. When soil moisture is below this threshold, irrigation for applying is the total volume of water needed to reach the field capacity of the soil. Theoretical recommendations for irrigation are finally adjusted to the particular and complex irrigation system of the Braila County, where irrigation is applied less often but with high quotas per irrigation. During the 2024 summer season, maize was irrigated five times between May and August, accounting for a total of 2250 m^3/ha (Table 10). The ICITID method does not consider precipitation forecast or in situ meteorological forcings. In order to compare this traditional method with IrriSPHY outcomes, irrigation quotas actually applied in SCDAB were scaled to daily values to cover the same testing forecasting windows simulated in this study.

Table 10. Actual values of Irrigation Water Applied (IWA, m3/ha) at different dates at SCDAB pilot site for maize crops during the 2024 season.

Date	IWA
27 May 2024	450
6 June 2024	350
25 June 2024	400
15 July 2024	450
5 August 2024	600
Total	**2,250**

Recommendations for irrigation derived using the long-term DA forecast were in the same order of magnitude as irrigation quotas actually applied at the farm level following the traditional ICITID method (Table 11). Although not fully comparable due to the large conceptual differences between methods, in general, the ICITID method provided recommendations 35% lower than the MAGDA solution. These differences highlight the importance of accurately simulating the soil moisture dynamics and the climate forcings that control the water balance in the atmosphere-crop-soil continuum. The MAGDA solution may provide a clear advantage against current practices that rest on coarse approaches applied at county and regional scales

Table 11. Comparison of recommendations for irrigation derived from IrriSPHY forced with long-term DA forecasts and the irrigation quotas already applied in the SCDAB pilot site in Romania. Precipitation values, P_{obs} and P_{fcast}, refer to the total rainfall in the testing period. ET_c and IWR values are in m3/ha/day.

Site	Testing period	P_obs	MAGDA method - DA (5-days)			ICITID method	
			P_fcast	ETc	IWR	ETc	IWR
SCDAB	**29 Jun - 3 Jul 2024**	10.5	16.2	108.3	30.1	49.48	20.0
	22 – 26 Jul 2024	3.2	18.3	104.6	44.6	56.23	28.1
	5 – 9 Aug 2024	5.1	10.6	86.8	20.3	52.23	10.7
	7 - 11 Sep 2024	12.1	13.5	30.9	0.0	25.20	10.7
	Average	7.7	14.7	82.7	23.8	45.8	17.4

3.4 Dissemination through Farm Management System

The outcomes of IrriSPHY are displayed into the Farm Management System. In order to maintain simplicity within this dashboard and not overload farmers with information, only the most key values are displayed. These values are:

- Forecasted accumulated **precipitation** within the time window (in mm, mean grid-value).
- Forecasted daily mean **potential crop reference evapotranspiration** within the time window (in mm, mean grid-value).
- Forecasted accumulated **irrigation water requirement** within the time window (in m3/ha, median grid-value). The final advice is the accumulated IWR divided by the length of the forecasted time window, so the advised irrigation value is supposed to be applied daily.

Irrigation advice is computed at the daily scale, but it was decided within the consortium members not to update the dashboard daily, to keep the FMS information simple for farmers. That's why these variables are updated every **2 days**, both for a time window of 2 and 5 days (the latter with less reliability) and obtained from the two types of forecasts received (WRF-DA and WRF-OL).

Table 12 shows a sample of the output data from IrriSPHY. The three listed variables above correspond to the orange highlighted columns in the figure.

Table 12. Example of output data from IrriSPHY.

site_name	fcast_product	fcast_ini	fcast_end	prcp_sum	prcp_obs_sum	et0_mean	etr_mean	iwr_m3/ha_P25	iwr_m3/ha_P50	iwr_m3/ha_P75	fcast_model
SCDAB	magda-fcast-da	2024-06-29	2024-06-30	0.00	0.00	9.22	11.06	82.02	82.47	84.62	2D_da
SCDAB	magda-fcast-ol	2024-06-29	2024-06-30	0.00	0.00	8.62	10.34	75.72	76.12	76.42	2D_ol
SCDAB	magda-fcast-da	2024-06-29	2024-07-03	14.45	10.48	8.99	10.79	77.85	88.50	92.41	5D_da
SCDAB	magda-fcast-ol	2024-06-29	2024-07-03	14.60	10.48	8.59	10.30	71.70	83.37	87.07	5D_ol

Outputs are uploaded to the shared MAGDA SFTP service, each subfolder contains the forecast CSV file launched on the date that is specified on the title of each subfolder. Figure 19 shows the folder structure.

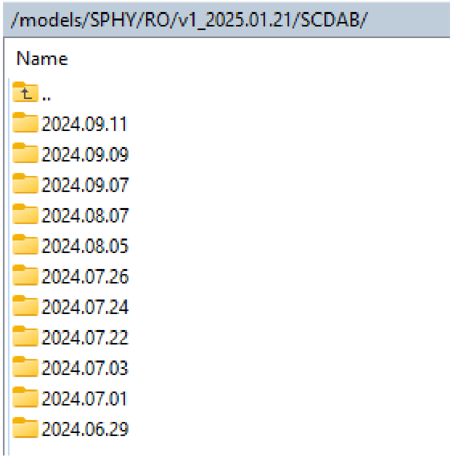

Figure 19. Folder structure on MAGDA SFTP

An example of the irrigation advice disseminated to farmers through the FMS dashboard is shown in Figure 20. The red-highlighted section corresponds to the IrriSPHY part. In the dropdown “Date” the user can select one of the past cases that were selected for this demonstrator. Once the date is selected, the user can select one of the three forecasted variables displayed (light blue squares items with icons). These variables are (from left to right): precipitation, potential crop reference evapotranspiration and irrigation advice. As explained in previous chapters, these variables are provided for two different forecasting windows: 2 and 5 days. The user can choose between the two forecasting windows by selecting the variable either from the first or the second row (number of days specified next to the calendar icon).

The variable selected will be displayed into the grey markers that are shown in the map. Each marker represents the targeted value per pilot site. The data displayed is directly retrieved from the shared SFTP. For the irrigation advice, the value that is displayed on the markers is the one obtained with the WRF-DA forecast, as it accounts better for local conditions. However, the user can get more information when clicking on a marker. In that case, the bar graphs shown below in the screenshot will appear. On these graphs, the user can see both advice obtained from WRF-DA and WRF-OL forecasts (differentiated by colour) for the selected date and past forecasts for the same period of interest.

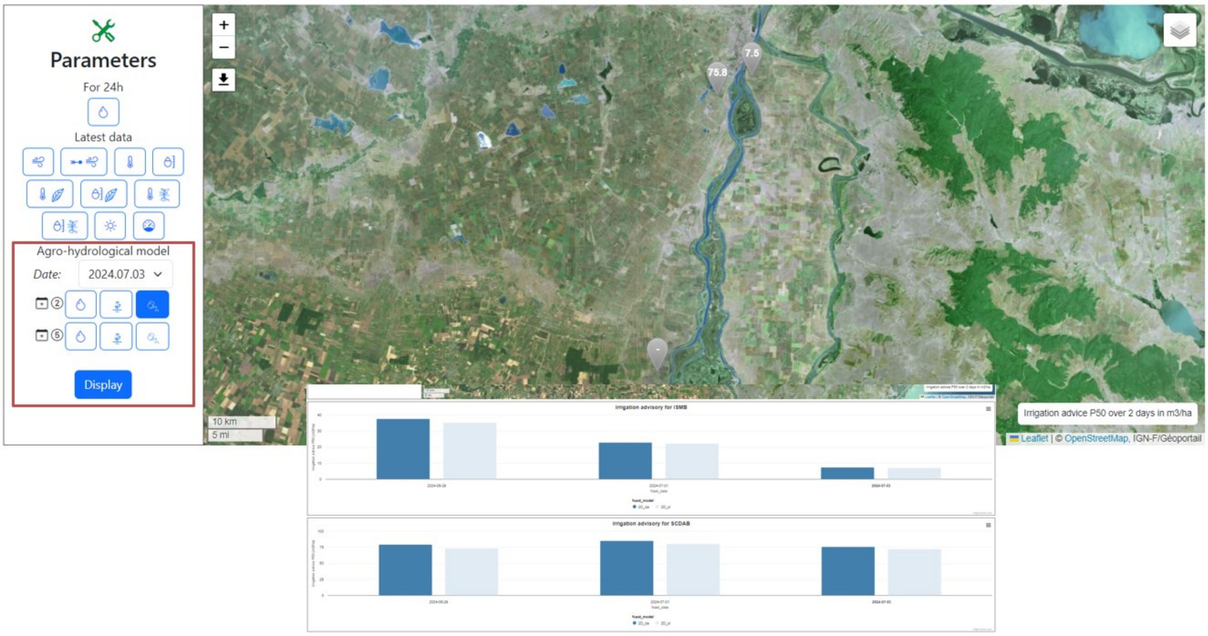

Figure 20. Irrigation advice into MAGDA's Farm Management System dashboard

4 Discussion and conclusion

This exercise successfully demonstrated the potential of an integrated irrigation advisory system that combines advanced weather forecasts, hydrological modelling, and in-situ observations to optimize irrigation management at the farm level. The results obtained from the pilot sites in Romania and Italy highlight the value of considering the soil-moisture dynamics in the root zone, and of assimilating various data sources into the irrigation advisory service to improve its reliability and effectiveness.

One of the key findings is the added value of incorporating weather forecasts with data assimilation compared to forecasts without assimilation. The validation of simulated irrigation water requirements (IWR) demonstrated that using data assimilation led to IWR estimates that were 10–15% higher than those derived from open-loop (non-assimilated) forecasts. This suggests that forecasts with data assimilation better account for localized meteorological conditions in the short term (up to 2-days ahead), leading to improved irrigation recommendations. For medium-term forecasts (up to 5-days ahead), the positive impact of data assimilation is reduced when compared with forecasts without data assimilation. Additionally, the analysis of soil moisture and evapotranspiration revealed that simulations forced with data assimilation were generally closer to observed values, reinforcing the advantage of integrating high-resolution observational data into the forecasting process.

Another key finding of this study underscores the importance of accounting for spatial uncertainties in forecast generation to produce more robust estimates of irrigation needs. Incorporating spatial uncertainty and variability through a spatial-ensemble technique may reduce IWR estimates by approximately 5% compared to single-point forecasts.

The intercomparison and verification of outputs from the irrigation advisory service against in-situ measurements and satellite-based products demonstrated the goodness of the modelling scheme adopted. Although some discrepancies were observed between the satellite-derived and model-simulated evapotranspiration values, the deviations were within expected uncertainty ranges. Similarly, soil moisture comparisons showed that simulations using weather forecasts with data assimilation had slightly better agreement with in-situ measurements than those without assimilation.

This study demonstrates the usefulness of the MAGDA system against BAU practices (only based on in situ measurements), allowing for better irrigation planning by providing timely advice aligned with expected weather conditions, leading to potential water savings as a consequence of anticipation to crop water requirements.

Despite these positive outcomes, some challenges and limitations were identified. First, the lack of long-term observational data at some pilot sites limited the calibration of certain hydrological parameters in the IrriSPHY model. Future efforts should focus on improving site-specific parameter calibration through additional field measurements. Second, more forecasting windows would be required to derive more robust conclusions on the impact of data assimilation.

Finally, ensuring that the irrigation advisories are effectively communicated to farmers via the Farm Management System (FMS) remains crucial for the system's operational success on the long term.

5 References

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