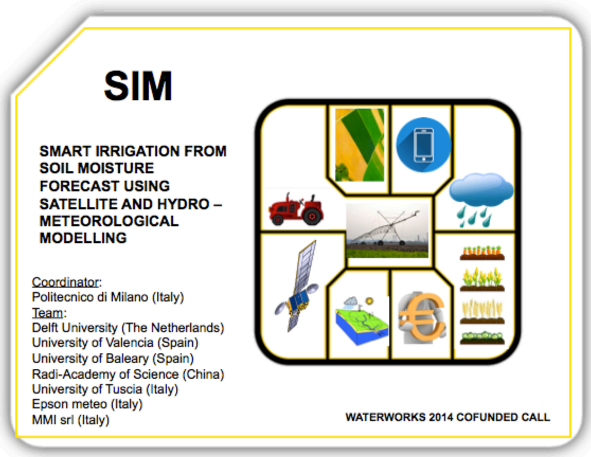

SIM

SMART IRRIGATION FROM SOIL MOISTURE FORECAST USING SATELLITE AND HYDRO –METEOROLOGICAL MODELLING

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Technical report

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SUMMARY

The main project objective is to design and to realize, an operative web-gis system (SIM) for monitoring in real time and forecasting crop water needs supporting precise irrigation allowing to have a parsimonious irrigation without affecting the crop production.

The SIM irrigation strategy allows to keep crop present and forecast soil moisture between two soil moisture thresholds: the higher one relative to soil moisture content for which the percolation flux in the soil starts to be significant (field capacity) and a lower one where the crop begins to suffer for lack of soil water (crop stress). This criterion supports the correct timing of irrigation and the amount of water for each irrigation, allowing to reduce the passages over the field capacity threshold reducing the percolation flux with a saving of irrigation volume, while evapotranspiration remains almost the same. This irrigation strategy allows to increase the irrigation efficiency (ton/mc) and water productivity (€/mc) saving important percentage of water, but also of fertilizer and energy, compared to today's irrigation practices.

The SIM user interface is a web dashboard, developed for the five project case studies: in Northern and Southern Italy, in the Netherlands, in China and in Spain, places that have different climates, water availability, crop types and irrigation systems (sim.polimi.it/dashboards). SIM combines the most recent results of scientific research to compute soil moisture at high spatial and temporal resolution: as the remote sensing data analysis, the soil water balance models, the meteorological forecasts and the economics analysis. System outputs are also organized in performance indicators (water, environment and economic) supporting irrigation strategies of any level of users: farmers who keep soil moisture in an optimum interval, irrigation consortia which manage the water allocation; water authorities which manage reservoirs. This is obtained due to an integrated design based on pixel wise approach, that allows to maintain the same modelling spatial resolution for single cultivated field as well as for the entire region covered by the irrigation consortium or water authority.

RESULTS ACHIEVED

The main SIM project results are herein summarized for each WP.

1.1 WP0 COORDINATION

An intense coordination activity was carried not only among the project partners but also with the stakeholders of each case study, ensuring their collaboration and interest to the activities for parsimonious water use. End-users belong to farmers, irrigation districts and water basin authorities, and have been involved since the early beginning of the project to confirm the specific needs relative to the water use. As example in Figure.1a the meeting May 2016 between POLIMI, RADI and the Heihe water basin authority and in Figure.1b April 2016 & October 2017 - meeting between POLIMI, RADI, MMI srl and the Capitanata Irrigation Consortium, the Guzzetti farm and the Advisory board.

Figure 1. (left) Meeting at the experimental farm of Heie river basin authority (China); right Meetting at Guzzetti farm part of the Capitanata consortium.

In Figure.2 the final SIM project meeting organized at the Ministry of Agriculture in Rome on June 2019 among all partners, ANBI and most of representatives of Italian Irrigation Consortia in June 2019 is shown.

Figure 2. SIM Final meeting at Sala Cavour Ministry of Agriculture, Rome.

1.2 WP1 GROUND MONITORING

A large data base consistent with the modelling activity (hydrologic, meteorological and economic) was set up for the different case study allowing the calibration of model parameters as the validation of model outputs variables. The acquisition of the data was performed for each case study for reanalysis data and also for real-time acquisitions. The data were organized and formatted in similar manner for the all case studies (2 Italians, 1 Dutch, 1 Spanish, 1 Chinese) helping in applying the project tools and testing the defined methodology in the different environments.

In Figure.3 the case studies are shown along with some of the ground monitoring stations for soil moisture and evapotranspiration specifically installed during the project and irrigation methods.

1.2.1 Capitanata irrigation consortium (Southern Italy)

The Sud Fortore district of the Capitanata irrigation consortium (www.consorzio.fg.it) is located in the Puglia region, which is an intensive cultivation area, mainly devoted to wheat, tomatoes and fresh vegetables cultivation with hot summer and warm winters. Farms are usually of 20-ha size but with the presence of very large innovative farms (600 ha). Two large farms, which operate in the mass retail sector, Guzzetti Gianpaolo e Stefano s.s.a. and FUTURAGRI S.C.A.P.A. are already involved in the project proposal.

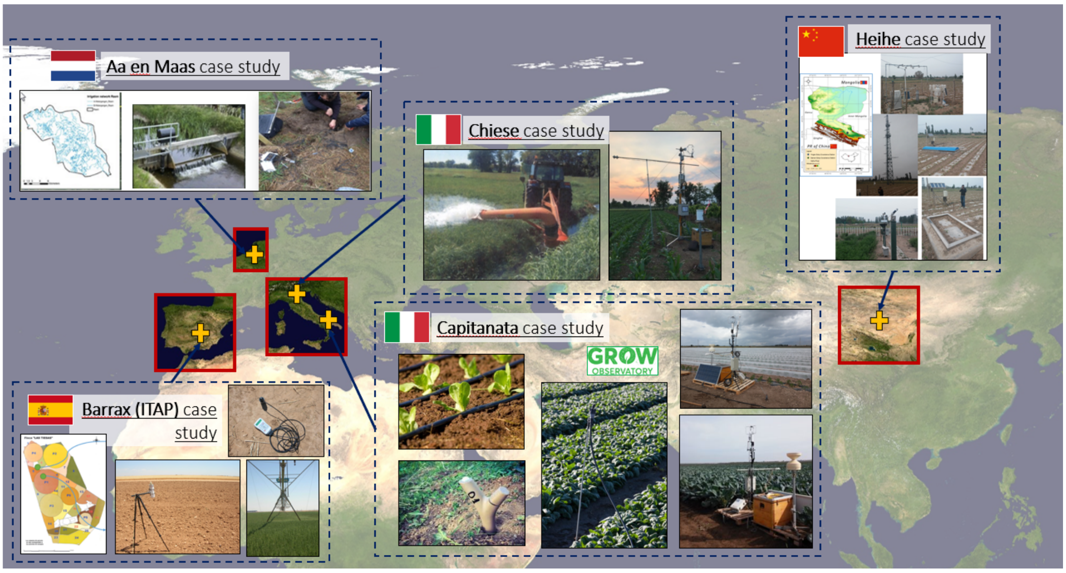


Figure 3. SIM case studies and monitoring local meteorological and soil stations

Irrigation water is supplied by pressurized water network from storage dams' reservoirs. The role of irrigation is crucial with a mean volume of about 600 mm, while the rainfall amount is 150 mm. Meteorological data are available from 22 stations from ARPA-Regione Puglia and from the association Meteonetwork. The stations provide rainfall, air temperature, incoming solar radiation, relative air humidity and wind speed at a temporal resolution of 1 hour from 2013 to 2019, but also in real-time. Two eddy covariance stations are installed for the project to measure evapotranspiration (computed considering all the corrections needed when measuring in the atmospheric boundary layer) and soil moisture. Each year from 2014, the stations are moved to follow different crops cycles on different soil types.

1.2.2 Chiese irrigation consortium (northern Italy)

The Chiese irrigation district (www.consorziodibonificachiese.it), down valley the Lake Idro, covers an area of 20'000 ha and is intensively cultivated with summer crops (i.e. corn, forage) and winter wheat, which cover about 68% and 8% of the agricultural land, respectively. The irrigation practice is based on fixed irrigation turn every between 7 ½ and 8 ½ days which are defined a priori before the beginning of the irrigation season from April to September. The irrigation is provided to each field with a channel network of 1400 km covering an area of 18'000ha and with wells (more than 10'000) covering about 2000 ha. The irrigation is mainly by surface irrigation, with a volume of about 100 mm. ARPA Lombardia and Regione Trentino provide meteorological data together with Meteonetwork for reanalysis and real-time. An eddy-covariance station has been installed between April and September in 2016, 2017 and 2018 in the same maize field.

1.2.3 Water board aa en maas (the Netherlands)

Aa en Maas Waterboard is the regional water authority responsible for water management and sanitation in an area within Noord-Brabant. The Raam subdistrict is one of the most irrigated areas with a relative water stress. Main crops are corn (50% of the area), potatoes, beets and cereals (26%). Both surface and groundwater irrigations are applied. 2600 wells (>10 m3/h) are allowed.

Meteorological data are available from Dutch organizations such as Royal Dutch Meteorological Institute for 2001-2015, but also in real time. For the 2010-16 period, 11 stations provide hourly discharge and water level data and 12 monitoring wells the groundwater level. 15 soil moisture sensors at different depths in a monitored field are available.

1.2.4 Barrax - Itap (Spain)

Las Tiesas experimental farm in Barrax area, managed by ITAP, is characterized by an alternation of irrigated and dry cultivated area (e.g. corn, barley, sunflower and onions). Barrax is a traditional ESA test site for experimental campaigns for satellite data calibration. The climate is semiarid with extreme temperatures in summer. Average rainfall is 325 mm/yr, against average reference ET of

1280 mm/yr. 92% of irrigation water comes from groundwater. The irrigation systems are mainly sprinklers. Meteorological data are available from two stations in the area from 2013 to 2019 for the past analysis and in real time. Soil moisture is measured in a single field from 2011 through 2017.

1.2.5 Heihe water board (china)

The Heihe River basin is an inland river in the arid region of northwest China, with an area of 1.4×105 km2. The upstream area is mountainous; while the downstream area is mainly desert. The midstream area is featuring irrigated artificial oases with a mean rainfall of 125 mm/yr. Irrigation water is mainly from the river through irrigation canals, while groundwater depletion is increasing due to insufficient supply from the river. Flooding irrigation is the main method. The meteorological data were derived from the Weather Research and Forecasting model with spatial and temporal resolutions of 5 km and 1 hour for 2012. Soil moisture and ET data are available at field scales for various landscapes in 21 eddy covariance sites in May-September, 2012. The irrigated croplands in the midstream area are mainly barley, spring wheat, maize, alfalfa, cotton.

1.3 WP2 SATELLITE DATA FOR HYDROLOGICAL MODELS

A data set of satellite images have been created for historical analysis for all the case studies and for the real-time activities in the two Italian and the Spanish case studies. In particular:

- emissivity data from Landsat-7 (L7) Enhanced Thematic Mapper Plus 60 m (ETM+), Landsat-8 (L8) Thermal InfraRed Sensor 100 m (TIRS), Sentinel-3 (S3) Sea and Land Surface Temperature Radiometer 1 km (SLSTR), 1 km of MODIS were acquired and then used as input of different Land Surface Temperature retrieval algorithms at the native resolution but also to improve and setting up downscaling models of the satellite LST data from the coarse spatial and temporal resolution (Δx=1000 m, Δt about 1 day) to the farm field need (Δx 10 m, Δt = 1 hour).
- reflectance data from MODIS, LANDSAT-8 and SENTINEL-2 were acquired for vegetation surface parametrization (NDVI, LAI, FV, albedo).

1.3.1 Algorithms for hydrological data retrieval from satellite data

Land Surface Temperature has been retrieved at the original satellite spatial scale using Single Channel (SC) and Split Window (SW) algorithms. Then downscaling techniques have been applied to increase the resolution using three methodologies. **1)** Nearest Neighbor Temperature Sharpening (NNTS) (Skokovic 2017) based on a variant of the Temperature Sharpening (TsHARP) and takes into account similar pixel properties and its distance, both over a sliding N×N area over LST image using relationships of NDVI and Normalized Difference Water Index data. **2)** STARFM (Spatial and Temporal Adaptive Reflectance Fusion Model) allows to generated Top of Atmosphere radiance at high resolution using a synthetic TIR channels at high spatial resolution from a multi-spectral image with an adaptive radiance model on the analysis of synthetic 100-m daily **3)** The DisTrad method is based on a relation between NDVI and LST, to be applied to the NDVI fine-resolution data to obtain an LST equivalent. Furthermore, to account for in-pixel heterogeneity, an estimation error is also taken into account (Kustas et al.,).

Vegetation parameters and albedo: The Fractional Vegetation Cover (FVC) can be estimated from NDVI, by setting two reference values for bare areas (0.15) and green vegetation (0.9). FVC is then used to obtain surface emissivity and Leaf Area Index (LAI). Albedo (α) is calculated as the integration of at-surface reflectance across the shortwave spectrum.

1.3.2 Satellite real-time data

These are downloaded automatically from NASA and ESA websites and are usually available 12-24 hours after scene acquisition. L8 and S2 provide Visible Near-InfraRed (VNIR), while L7, L8 and S3 provide TIR. As VNIR data do not have dramatic changes from one day to another, a 16-days composite image is obtained for albedo, FVC and LAI. All the images are atmospherically corrected with 6S or Sen2Corr software to estimate the Bottom of Atmosphere (BOA) reflectance. In the case of TIR data, a high revisit time is required: SLSTR data is used to obtain LST twice per day but at spatial resolution of 1 km. Thus, a sharpening process is performed to carry the SLSTR resolution to 30m. Finally, two additional ancillary data are required for the atmospheric correction:

the Aerosol Optical Depth (AOD) and total atmospheric water vapor (w). AOD and w are used on TIRS, ETM+ and SLSTR images but not on MSI as Sen2Cor does not require any inputs for BOA extraction.

1.3.3 The Capitanata case study

Time series for 2011-2019 have been obtained and near-real time Landsat-7/8 and Sentinel-2/3 series are available until 2019. The reliability of LST estimates is analysed by comparison with ground measurements. The angular coefficient of the linear regression is □1, with a high R2 (0.8-0.9) and a low mean error (0.09°C). The accuracy of albedo is evaluated against the EC station net radiometer: Bias (almost zero) and RMSE (0.038) are close to negligible.

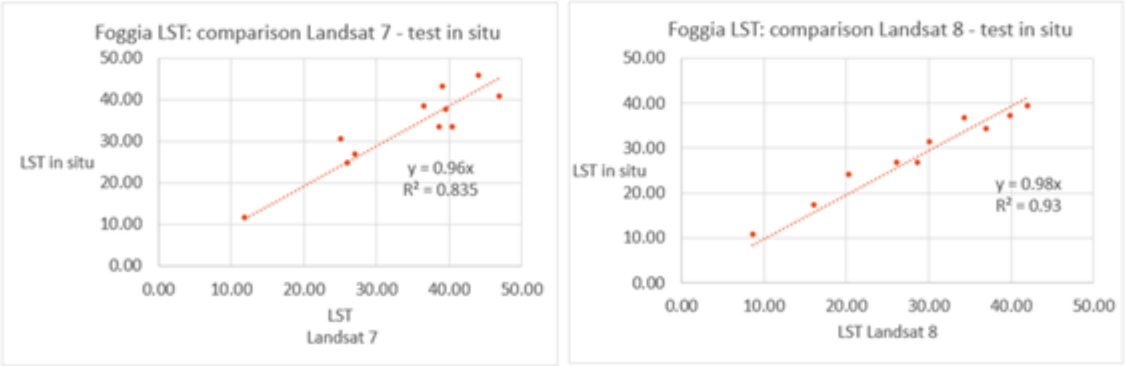


Figure 4. Comparison between ground and satellite LST for Capitanata for validation

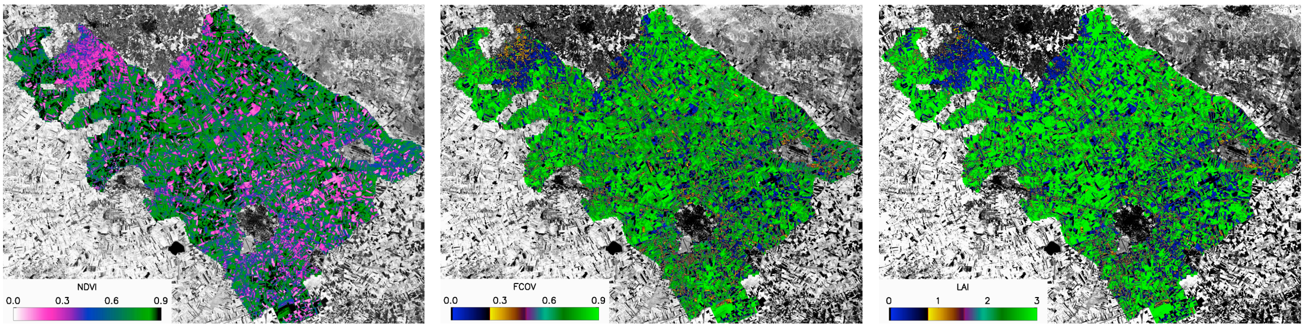


Figure 5. From left to right: NDVI, fCover and LAI estimated from Sentinel-2 data on June 02, 2019

1.3.4 The Chiese case study

Daily, 1-km resolution LST data from MODIS (MOD11A1) are used. The DisTrad downscaling algorithm is adopted to obtain 250-m data. The area is characterized by homogeneous maize cultivated areas, showing low variability between the original and the downscaled data. The main differences are found in the upper mountain area (1.7 °C) where low-resolution LST overestimates the high resolution images. In summer, high differences are also present in the plain area (1.2°C), with cities and irrigated fields. LAI maps were retrieved from the MODIS LAI products (MOD15A2), generated over an 8-day compositing period with a spatial resolution of 1 km. Albedo maps were retrieved from the MODIS white-sky product over an 8-day compositing period at 5 km.

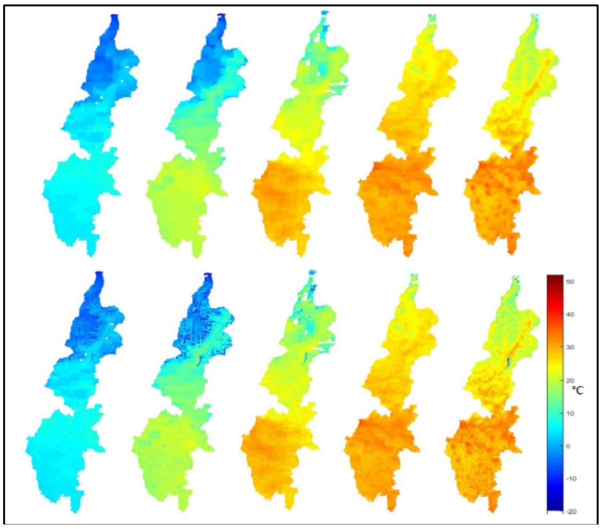


Figure 6. Example of LST images at 1km (upper) and 250 m (lower) for 01/01/05, 13/03/05, 07/05/05, 17/07/05, 05/08/05 for Chiese

1.3.5 The Barrax case study

Satellite LST estimates are compared with ground radiometric measurements performed in 2012-16: RMSE is 1.4 K with a +1.1 K bias (Algorithm–Data). Validation of resampled LST estimated with SLSTR was also conducted during 2018-19. One validation test site is on a large pivot field of approximately 1x1 km and another is in a small grass field of 90x90 m. Results show that the downscaling process improves the accuracy of LST on small fields, but not on large fields. Decreases of bias (4 K) and standard deviation (1 K) were observed. Near-real time L7/8 and S3 data are available for 2019, resampled to 30 m. NDVI, FVC and LAI have been estimated with a moderate resolution sensor, obtaining, on average, 2 images per day, with L7/8 and S2 platforms. Real-time composite images (16 days) are obtained for every Landsat and Sentinel-2 pass. Combining all satellites, revisit time over Barrax is reduced to 3-4 days, with 30 m spatial resolution.

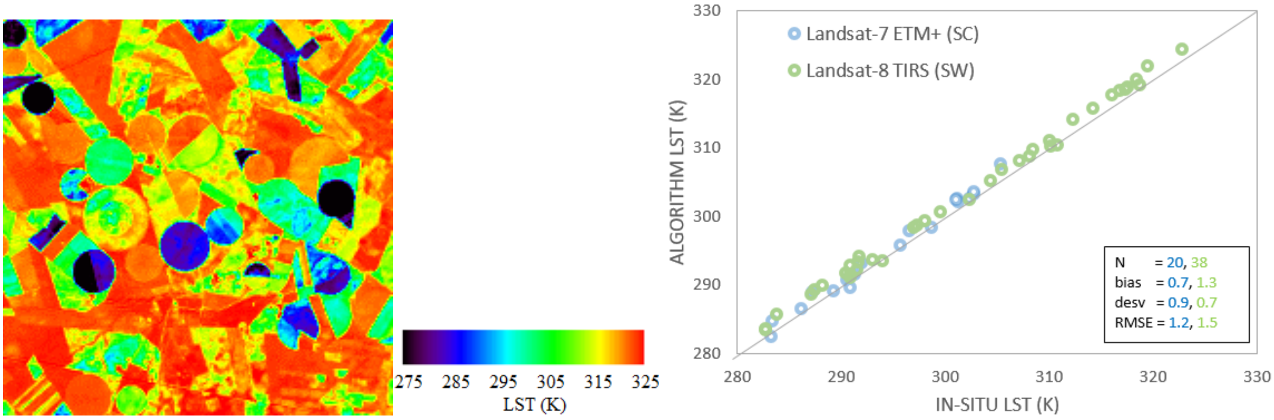


Figure 7. Comparison between ground and satellite LST for Barrax site

1.3.6 The Aa & Maas case study

The LST data is provided by MODIS' MOD11A1 product. Only clear images (without clouds) in the irrigation period (May to September) have been selected (37 images). The highest temperature variability is found between the urban and forest areas. The NDVI data used in this study comes from the MOD13Q1 product, provided every 16 days at 250 m spatial resolution. As could be expected, the NDVI increases at the start of the irrigation season (May to August), reaching its higher values in the months of July-August, with values approaching 1. The employed MODIS albedo product is MCD43A3, which provides 500 m data describing both hemispherical (black-sky albedo) and bi-hemispherical (white-sky albedo) reflectances.

1.3.7 The Heihe Case Study

LST data are obtained from MOD11A1 LST and using two downscaling procedures (Distrad and STARFM) from the MOD11A1 product (1 km) to 30m. Their errors against the L7 data are computed. All methods overestimate the L7 LST: STARFM has a higher mean RMSE (15.3 K) than MODIS (7.1 K) and DisTrad (7.8 K). NDVI data from MODIS vegetation index product (MOD13A2, 1-km/16-day) was used to calculate FVC and LAI.

1.4 WP3 HYDROLOGICAL MODELLING OF WATER-ENERGY FLUXES

The FEST-EWB model has been calibrated and validated over all the case studies using the historical ground soil moisture and evapotranspiration data from WP1 and satellite LST at basin scale (WP1 e WP2). FEST-EWB model with its energy-water balance scheme allows to compute continuously in time and distributed in space soil moisture and evapotranspiration (ET) fluxes thanks to a double link with satellite-derived data as input parameters (e.g. LAI) and as variables for model states update as the land surface temperature (LST) (Corbari et al.,2011; Corbari & Mancini, 2014) instead of using dedicated ground measurements. ETMonitor model is forced by meteorological data and several biophysical parameters (LAI, fractional vegetation cover) and surface soil water status (soil moisture) derived from multi-source remote sensing data (from optical to microwave sensors), is applied on the Chinese and Northern Italy case studies.

1.4.1 The Capitanata case study

FEST-EWB is run for the period between 2014 and 2016 at the temporal resolution of 1 hour and at the spatial resolution of 30 m. The calibration of soil hydraulic and vegetation parameters is performed through the comparison between RET estimates from FEST-EWB run in different parameters configurations and LANDSAT LST: before calibration highly underestimates observed satellite values, with a mean absolute difference pixel by pixel of 5 °C; while after the calibration procedure it is equal to 2.5 °C. The model is then validated between 2017 and 2018 with a mean absolute difference pixel by pixel of 3.5 °C. FEST-EWB model is then validated by comparing the simulated energy and water fluxes (LE, SM, H, Rn) with the observed ones measured with the eddy covariance stations (5 crop seasons). Low errors are obtained: LE with a coefficient of determination equal to 0.8 and a RMSE of 35 W m-2, while for H with R2 of 0.7 and RMSE of 37 W m-2, soil moisture is correctly reproduced with a RMSE of 0.03.

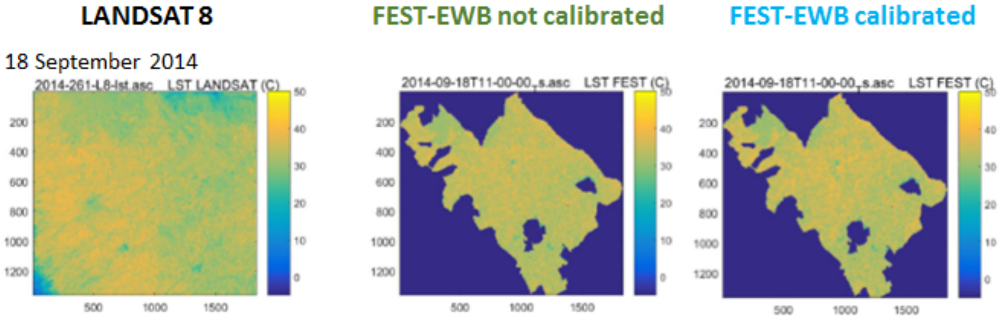


Figure 8. FEST-EWB calibration again satellite LST for the Capitanata case study

1.4.2 The Chiese case study

FEST-EWB is run for the period between 2005 and 2016 at the temporal resolution of 1 hour and at the spatial resolution of 250 m (2005 to 2010 for calibration, 2011 to 2016 for validation). FEST-EWB before calibration underestimates observed satellite values, with a mean absolute difference pixel by pixel of 5.2 °C; while after the calibration procedure it is equal to 3.4 °C. FEST-EWB model is then validated by comparing the simulated energy and water fluxes (LE, SM, H, Rn) with the observed ones at the eddy covariance station during 2016, 2017 and 2018 in the vegetation period of maize. Good reproductions are obtained for the surface sensible and latent heat fluxes with a RMSE of 40 W m-2, and of 24.7 W m-2, respectively. Soil moisture is correctly reproduced with a RMSE of 0.03.

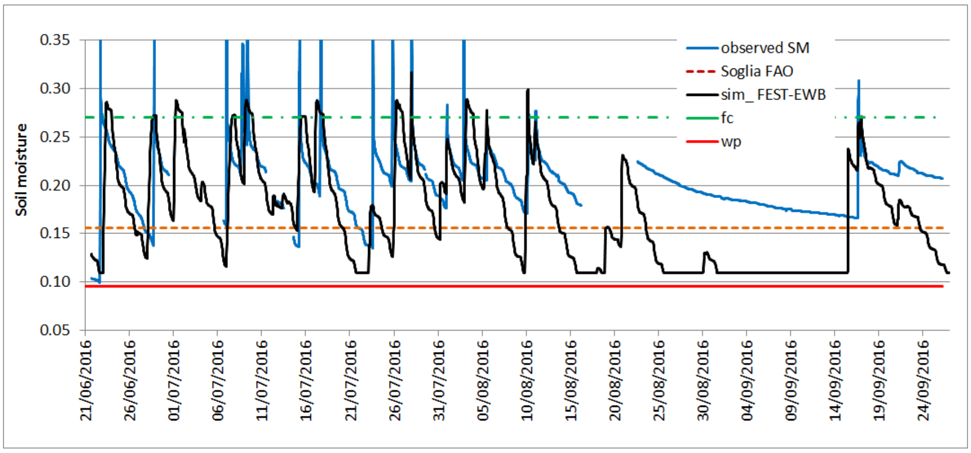


Figure 9. FEST-EWB model validation at field scale against ground soil moisture data in the Chiese case study

1.4.3 The Barrax case study

FEST-EWB is run in a continuous mode at a temporal resolution of 10 minutes and at the spatial resolution of 4 m. FEST-EWB before calibration generally overestimates observed values, while after the calibration a reasonable agreement is reached with RMSD that goes from 4.6 °C to 2.1 °C. The MAD for sensible heat flux in the four stations from FEST-EWB is between some 10 and 60 Wm^{-2}, while for TSEB it is between 5 and 40 Wm^{-2}. Good agreements are obtained for the latent heat flux showing even lower MAD values, under 15 W m^{-2}.

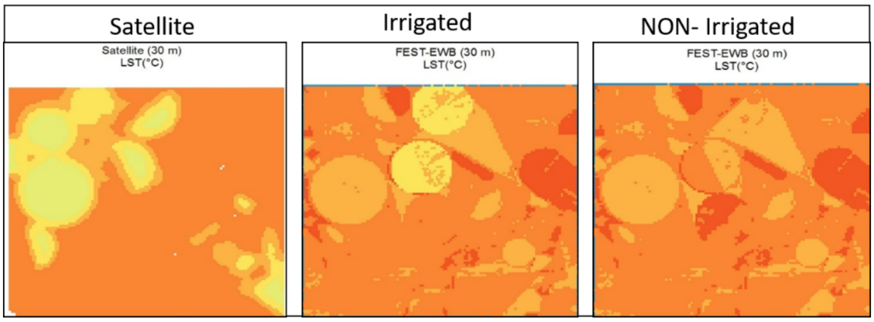


Figure 10. LST from LANDSAT and Fest-ewb Model with and without irrigation 02/09/2015

1.4.4 The Aa & Maas case study

The FEST-EWB model was calibrated and validated against remotely sensed land surface temperature maps, ground soil moisture data and also groundwater level. Available data have been split into a calibration period from 2011 to 2013, and a validation period from 2014 to 2016. From observed data analysis it is clear that withdrawals have a very small influence on the water table dynamic. By comparing withdrawals volumes to precipitation volumes, we realize that these latter are more than hundred times greater than the formers, that explains why we did not observe significant variation of the water table due to only extracted water for irrigation. Water table fluctuation seems well correlated to precipitation rate. With the not calibrated parameters it is possible to see how: temperature differences are between 2°C and 6.5°C, with average of about 3.8; after calibration average bias reduces to about 2 °C.

1.4.5 The Heihe Case Study

FEST-EWB model is calibrated against LST for 2012, with a mean final error of 2.5 °C. Then, along with ETMonitor model, FEST-EWB estimate daily ET are compared with the eddy covariance (EC) observations for grasslands, forests, croplands, and wetlands separately, showing good agreement of ET estimates

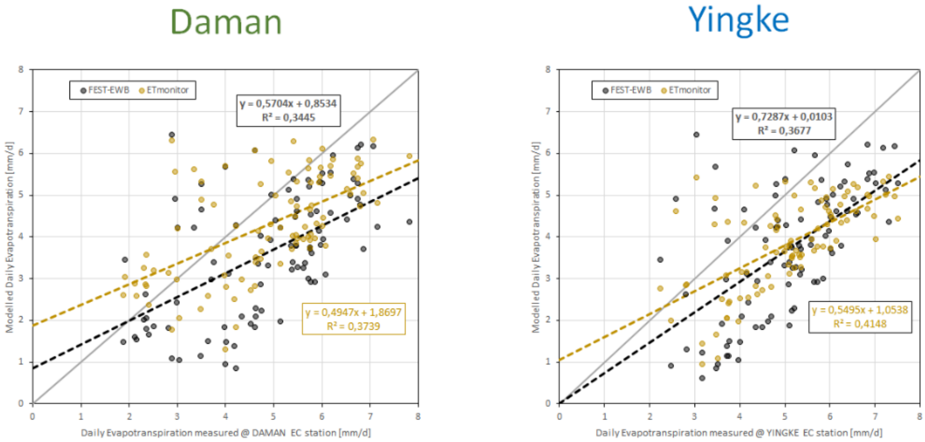


Figure 11. Evapotranspiration comparison between FEST-EWB and ETMonitor models for the Heihe case study

1.4.6 Impacts on functioning of Irrigation systems

SIM parsimonious water use as also positive impacts on the existing irrigation aqueducts reducing flow peak and relative failure in the distribution network as shown for the Capitanata (side Figure), where on demand drip irrigations holds. Impact on temporal water distribution is also investigated: for the Barrax test site where sprinkler irrigation is supported by large pivot the very large irrigation pivot is investigated and for the Aa en Maas where the role of water table irrigation is analysed respect to the sprinkler irrigation.

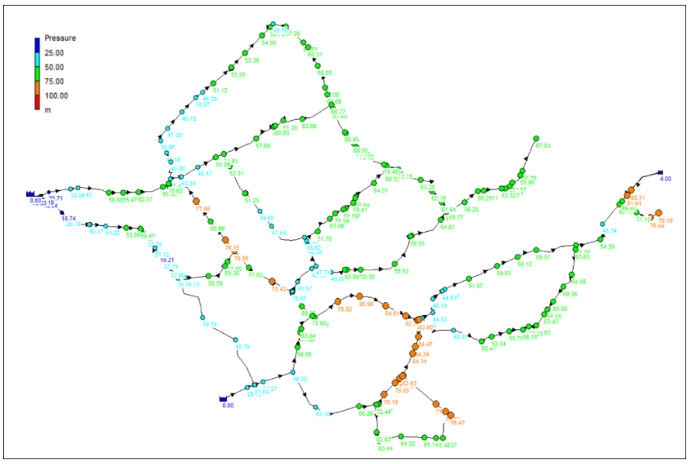
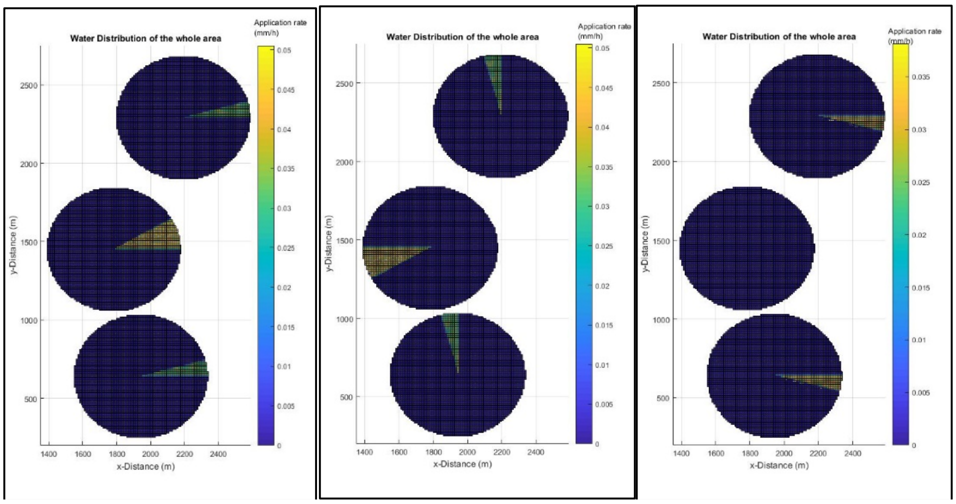


Figure 12. Pressure distribution for a peak discharge in the Capitanata aqueduct using EPANET hydraulic software



Hour = 01:00 Hour = 07:00 Hour = 23:00

Figure 13. Simulated water distribution patterns of center pivots in the Barrax case study

1.5 WP4 METEOROLOGICAL FORECAST

The forecast meteorological schemes is based on a multi models approach in their ensemble and deterministic mode. The different meteorological models are: 1) the deterministic MOLOCH model by the Italian ISAC-CNR at about 1.5 km as spatial grid resolution, 1 hour as temporal resolution with 45 hours as lead time, 2) the deterministic BOLAM model by the ISAC-CNR as well at about

11 km as spatial grid resolution, 1 hour as temporal resolution with 72 hours as lead time, 3) The deterministic ECMWF model supplied by the University of Balearic Islands at about 9 km as spatial grid resolution, 6 hours as temporal resolution with 240 hours as lead time, 4) The unperturbed ECMWF (control) run with 50 ensembles supplied by the University of Balearic Islands as well at about 18 km as spatial grid resolution, 6 hours as temporal resolution with 240 hours as lead time, 5) The deterministic WRF model by the University of Balearic Islands at about 3 km as spatial grid resolution, 1 hour as temporal resolution with 96 hours as lead time, 6) the multi-model WRF by Epson Meteo Centre at about 5 km as spatial grid resolution, 1 hour as temporal resolution with 72 hours as lead time.

The models scores are evaluated at consortium scale and at experimental farms scale. As for the deterministic runs, the skill of the ensemble forecasting is lower for Chiese than for Capitanata.

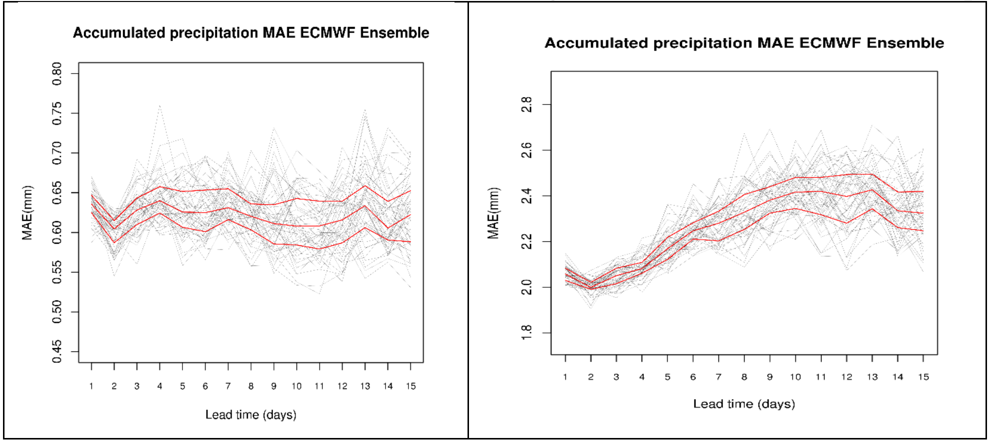


Figure 14. ECMWF ensamble forecast daily precipitation MAE for Capitanata (left) and Chiese (right) at consortium scale

The models have been verified also at the farm scales in the two Italian case studies. For Capitanata, a general bias is found in the ECMWF solar radiation forecasts, where a general underestimation in the whole time horizon is shown. This is due to temporal resolution of the weather model which is 6 hours, and it is not able to accurately cover the daylight radiation. For the Chiese farm (2016 to 2018), Remarkable to note, it is the precipitation performance by Bolam and Moloch models over the two growing season 2017 and 2018: high values of Mean Absolute Error denote a bad quality performance by the two weather models. This is mainly due to an error prediction of summer thunderstorms which are very localized in this area, close to Pre-Alps around the city of Brescia.

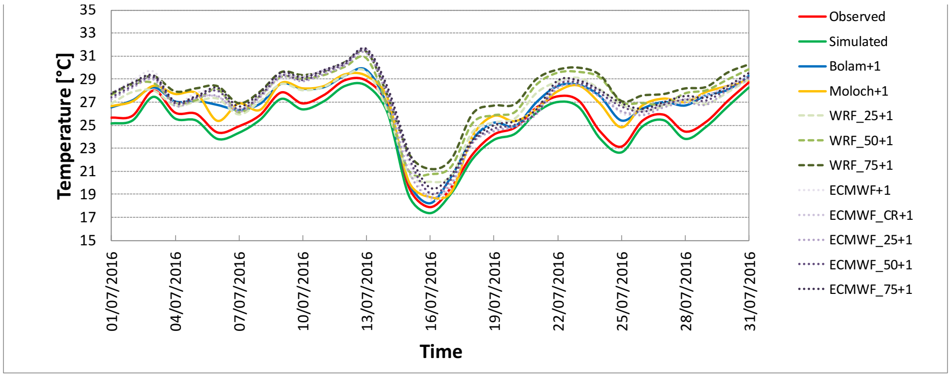


Figure 15. Daily air temperature for the growing season 2016 over Capitanata Farm1: observed data are shown in red, simulated data in green, the forecast mean of all available models in blue and its standard deviation in dashed blue lines

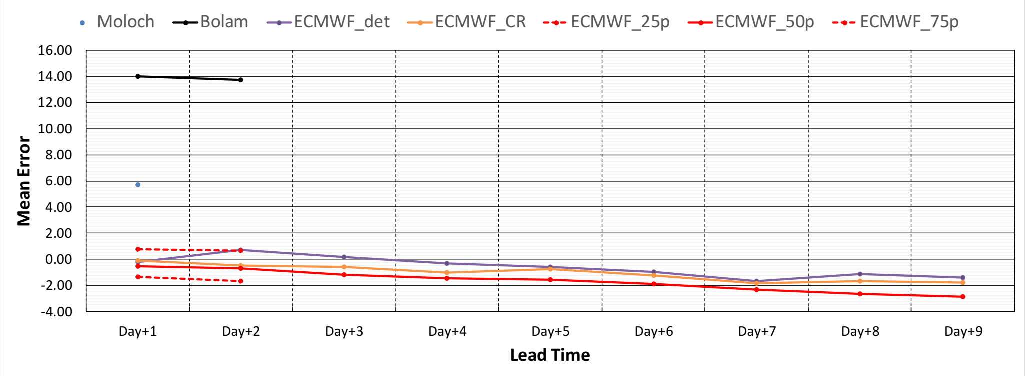


Figure 16. Mean Error for precipitation at different lead times of forecast for the Chiese farm.

1.6 WP5 SOIL MOISTURE AND EVAPOTRANSPIRATION REAL TIME FORECAST FOR IRRIGATION WATER NEEDS

This include the definition of the SIM irrigation strategy and the forecast of irrigation water needs, comparing the simulated soil moisture from the soil water balance models with the soil moisture threshold values of field capacity and crop stress for given soil and crop type.

1.6.1 SIM irrigation strategy

The SIM strategy irrigation decision criteria in order to plan whether or not to irrigate is based on the comparison in real time between the present and forecasted soil moisture with two soil moisture thresholds: the higher one relative to soil moisture content for which the percolation flux in the soil starts to be significant (field capacity) and a lower one where the crop begins to soffer for lack of soil water (fao crop stress) . This criterion will determine the correct timing of irrigation and the amount of water, allowing to reduce the passages over the field capacity threshold reducing the percolation flux with a saving of irrigation volume without affecting evapotranspiration and so that the crop production

A number of water indicators are computed to summarize the results and to compare the observed irrigations with the SIM strategy at irrigation district scale and at field scale. The used indicators are: Water use efficiency: [kg/m3] WUE=yield/ET, Irrigation water use efficiency: [kg/m3] IWUE=yield/irrigation, Percolation deficit: P_er D=((P+I)-P_er)/(P+I).

In the following SIM strategy are reported for the two Italian case study

Water indicator are also able to catch this SIM strategy behavior as showed in the following figure.

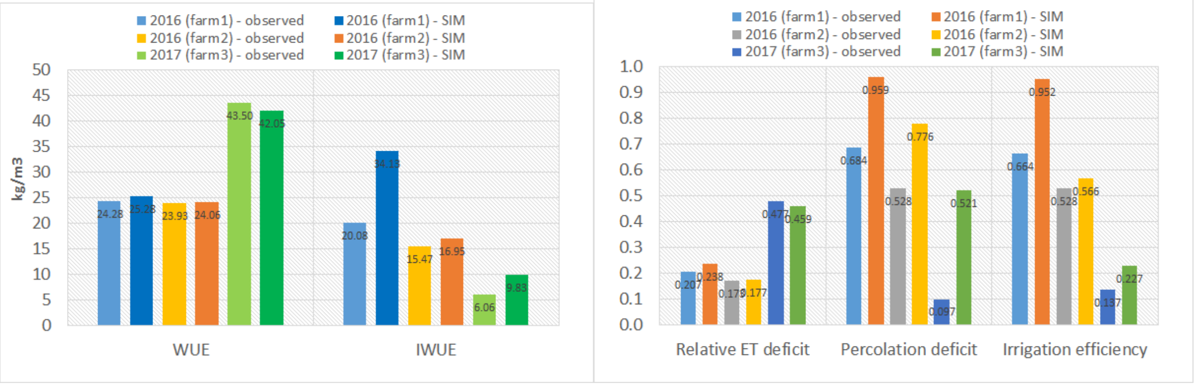


Figure 17. Water indicator for different farm fields. Water Use Efficiency is also known as Physical Water productivity

SIM irrigation strategy has been simulated for Capitanata tomatoes fields in 2016 and 2017, and in 2017-2018 and it is compared for the same fields with the observed irrigations (WP3), that is applied with drip on demand irrigation. The SIM strategy has shown a significative irrigation water saving (see following table) also in this area where a traditional careful use of water is assessed.

		Irrigation (mm)	Number of irrigations	Rainfall cum (mm)
Farm 1 (2016)	**Observed**	**547.9**	**27**	**145**
	SIM	**322.3**	**15**	
Farm 2 (2016)	**Observed**	**646.6**	**43**	**150**
	SIM	**590**	**90**	
Farm 3 (2017)	**Observed**	**1000**	43	28
	SIM	850	25	

In the following Figure cumulative water balance fluxes on the irrigation season are compared for a tomatoes field showing that most of the saving water belongs to the percolation fluxes while effective evapotranspiration it is not affected from the SIM strategy showing similar values between simulations and observations without affect crop production. ,

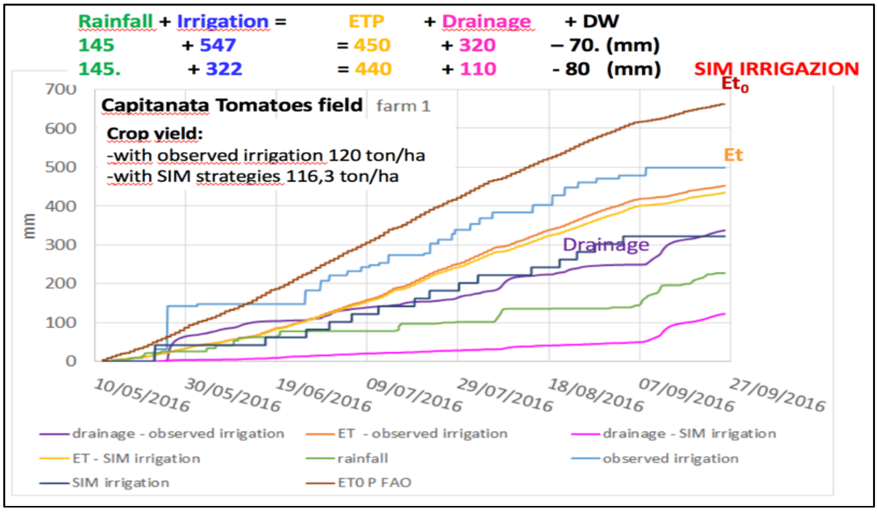


Figure 18. Soil water balance components (mm) for observed irrigation and SIM strategy simulations.

1.1.1.1. The Chiese case study

		Irrigation (mm)	Number of irrigations	Rainfall cum (mm)
2016	**Observed**	**1426**	**11**	**269**
	SIM	**301**	**5**	
2017	**Observed**	**1480**	**17**	**223**
	SIM	**488**	**10**	
2018	**Observed**	**1750**	**13**	**515**
	SIM	**200**	**5**	

The same analysis has been done for the Chiese maize fields where scheduled flooding irrigation is used. Here it is possible to observe a larger water saving as shown on the side table. In the following Figure cumulative water balance fluxes on the irrigation season are compared for a maize field showing more significant water saving than in the Capitanata case study.

The water indicators show an increase in the water use efficiency (even if less in respect to the Capitanata Consortium) and an increase of the percolations deficit.

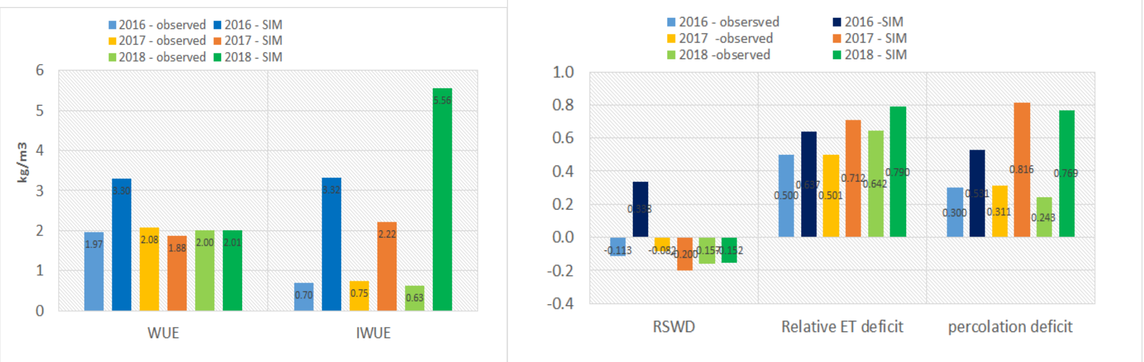


Figure 19. Water indicators of the SIM strategy in the Chiese case study. Water Use Efficiency is also known as Physical water productivity

Also in this case most of the saving water belongs to the percolation fluxes And crop production is not affected although evapotranspiration change from potential to effective one .

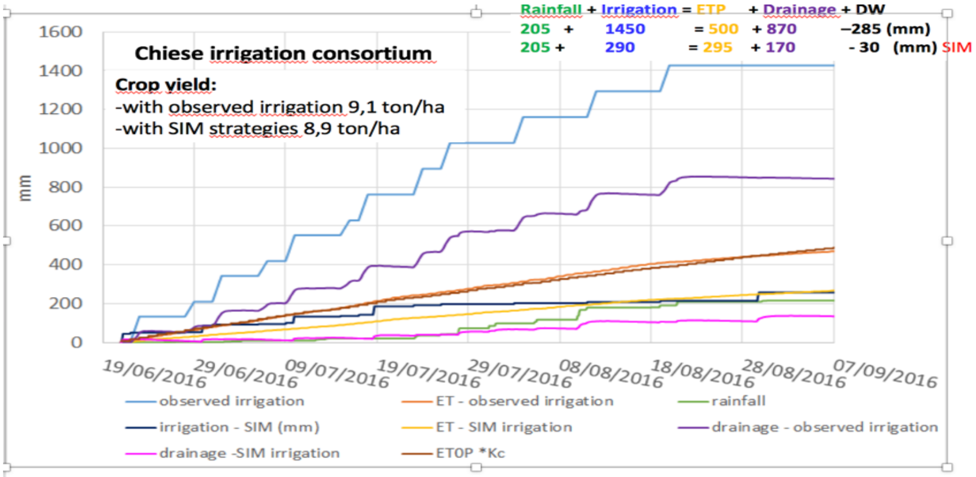


Figure 20. Comparison of soil water balance components (mm) for present observed irrigation and SIM strategy simulations

1.6.2 THE HYDRO-METEOROLOGICAL FORECAST

The forecasted soil moisture and relative irrigation water need is computed coupling FEST-EWB hydrological model (WP3) for all meteorological forcing provided by the forecast meteorological models (WP4). The hydrological model is initialized any day with the observed weather data of the day before at 6 a.m. The hydrological model is than run using the meteorological forecast data provided for the day ahead from any meteorological model.

For the Capitanata farms in the growing season of 2016 and 2017 reanalysis show a good agreement with the local observed data. Indeed, performances are more reliable for the lead time day +1 and, in particular, for first days as forecast horizon. Soil moisture forecasts shows a mean error of -0.05, up to day +3 and subsequently it increase to -0.10 for the day +9 of the ECMWF forecast model.

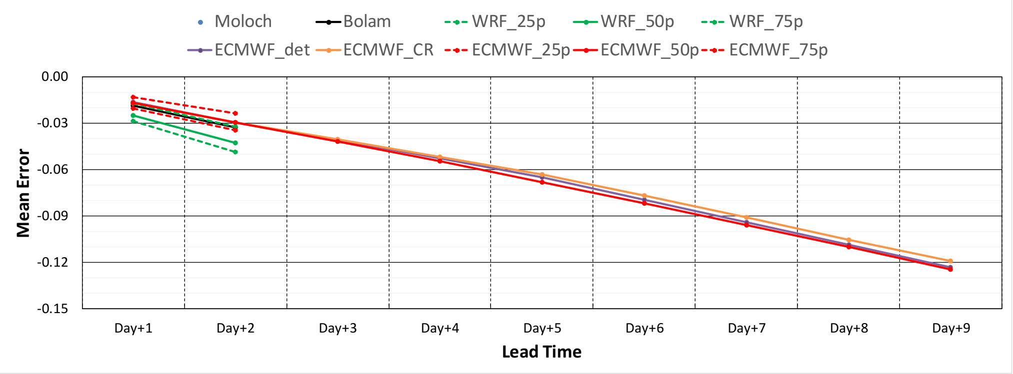


Figure 21. he Mean Error for soil moisture at different lead times of forecast for the Capitanata field case study farm 1 for 2016

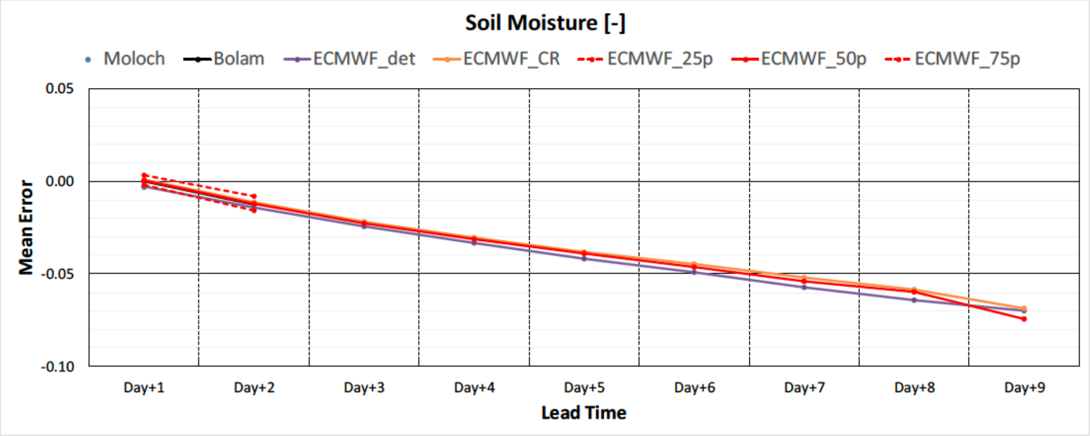


Figure 22. The Mean Error for soil moisture at different lead times of forecast for the Chiese field case study assessed in the 2016, 2017 and 2018 maize growing seasons

For the Chiese Consortium farm, the proposed analysis method has been carried out for the growing season 2016, 2017 and 2018. General results are similar to those highlighted for the Capitanata basin with a good agreement.

1.7 WP6 ECONOMIC AND ENVIRONMENTAL ANALYSIS

The economic impact of the SIM irrigation strategy is evaluated in terms of farm profitability and productivity based on the production costs, including costs for water use . This has been done by assessing different economic indicators using the European Farm Accountancy Data Network (FADN) and local farm data for the period 2011-2016, both for the Capitanata and Chiese Irrigation Consortia. Three indicators related to water productivity in agriculture are proposed in the analysis: (i) p*hysical water productivity (PWP) as* the ratio between the crop yield achieved (Y_a in Kg per hectare) and the quantity of water used, expressed in m^3 per hectare; (ii) *economic water productivity* (EWP) as the ration of gross margin, (i.e. the monetary value of the achieved yield Ya after having subtracted the variable costs of production, in € per hectare over water used; and (iii) *economic water productivity ratio* (EWPR) as the ratio between the costs of irrigation water used and the total variable production costs. Due to data and resource availability (it should be noted that the group of agriculture economists has contributed to the project with its own funds and without being funded by the Project, as reported in the final report) the analysis has been performed only on the Italian case studies.

The Capitanata consortium case study

For the Capitanata Consortium the indices are computed only for processing tomatoes, which is as the most water-demanding crop in the area (see Table I. below). The physical water productivity (PWP) ranges between 11.95 and 27.13 kg/m^3, as recorded in 2015 and 2016, respectively. Economic water productivity (EWP) ranges between 0.65 and 1.88 €/m^3 , as computed for 2015 and 2011, respectively. Average water used has been subject to considerable variations during the period under consideration (most probably due to climatic conditions).

Table I. Water use indicators for processing tomato in the Capitanata consortium area, FADN data 2011-2016

			AWU	AWEXP	PWP	EWP	EWPR
Year	Average temp. (°C)	Cumulative precipitation (mm)	m^3/ha	€/ha	kg/m^3	€/m^3	€/€
2011	25.3	133.6	4,848	831	24.77	1.88	19%
2013	23.4	90.6	7,090	1,063	16.44	1.07	32%
2014	21.1	214.6	8,420	1,369	12.44	0.75	37%
2015	23.9	113.3	3,630	1,688	11.95	0.65	44%
2016	22.3	150.4	5,918	560	27.13	1.64	15%
Mean	23.4	423.0	4,848	882	19.40	1.10	21%
Std.Dev	0.56	78.87	1,567	443	8.00	0.45	21%
C.V	3.27	18.64	30%	50%	40%	39%	60%

The same indicators have been then computed under the hypothesis that farmers were adopting the SIM irrigation strategy, and under the (strong) assumption that only the quantity of water used for irrigation was modified (all other input and output factors included in the production function remaining constant)

By comparing the results, it is found that the implementation of the SIM-project strategy determines water savings (up to 31% of water within the FADN sample farms) and, consequently, an increase in the PWP by 44% (within the FADN dataset) and in the EWP by 45% within the same group of farms . Similar results are obtained for the experimental farms of the Project. . Evidently, such economic gains would increase in case of increases in the water costs e.g. caused by switching to water tariffs based on the effective consumption (volumetric contribution) or by the expected increased water competition due to increased water demand and resource scarcity.

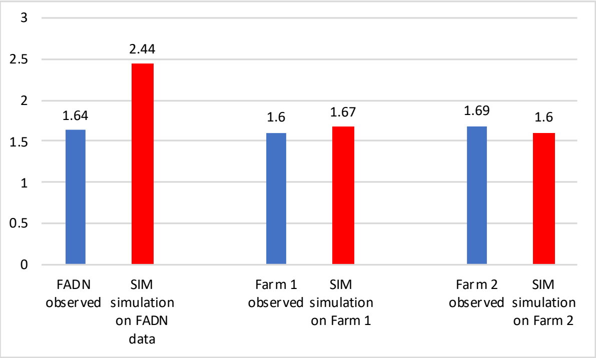


Figure 23. Economic Water Productivity (observed and simulated data) – processing tomato , Capitanata consortium, year 2016

The Chiese consortium case study

Similarly, the economic analysis has been implemented for the Chiese Consortium case study area. The indicators have been computed for maize, which is the most grown crop in the area (as well as the most water-demanding) . By comparing the observed data with those obtained through the simulations conducted using the SIM approach, it is found that the implementation of the SIM strategy can reduce the amount of water used, on average, by 11%within the FADN dataset. and by 40% for the Project experimental Farm 3. Consequently: PWP increase by 9% (within the FADN farms) and 41% for Farm 3; EWP increases by 10% (within the FADN dataset) and 41% for the experimental Farm 3. Such increases are relatively smaller than those shown for the Capitanata Consortium since in the latter water costs constitute a smaller share of production costs with respect to the former. This is due to the different water tariff system (based on the ‘unique contribution’ in the Chiese Consortium (i.e. not depending on the water consumption) and on the ‘volumetric contribution’ in the Capitanata one (i.e. depending on the volume of water consumed).

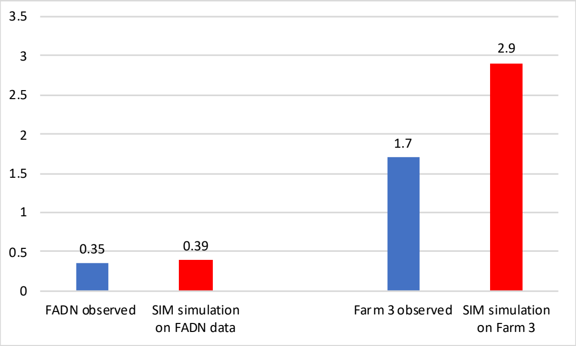


Figure 24. Economic Water Productivity (observed and simulated data) – Maize crop, Chiese Consortium, year 2016

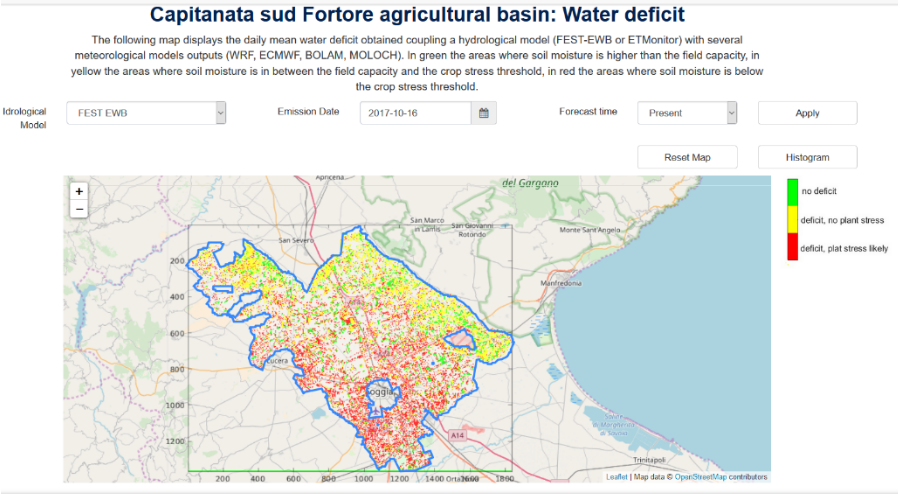
Overall, analytical results show a reduction in the amount of water used in the crop production process as effect of the implementation of SIM strategy. They also indicate economic gains with different impacts in the two case studies proportionally to the different share of water costs over the total production costs. Such economic gains would therefore increase consequently to the hypothesized water costs increases (e.g. due to switching to the ‘volumetric contribution’ water tariff system). The expected trends of increasing water price due to the enhanced water demand and resource scarcity cam also contribute to increase the gains associated with the implementation of the parsimonious water use through SIM.

Last, at consortium level, the implementation of the SIM strategy could determine a reduction in the payments from the farmers (due to the reduced water consumption) which do represent an important source of revenue for the consortia, which are in charge of the maintenance of the whole water distribution and irrigation system. This reduction would be particularly true in areas, like the Chiese Consortium, where water pricing is not based on the effective water consumption. However, water revenues reduction could potentially be compensated through an expansion of the irrigated area, as well as by gains in terms of “behaviour” and compliance with policies aimed at promoting water savings.

1.8 WP7 PRODUCT IMPLEMENTATION

The SIM dashboards are implemented for all the five case studies. The operative web system monitors and forecasts in real time the water content in the soil root layer and compares it with plant stress and soil field capacity water content thresholds, combining hydrological and meteorological modelling (WP5) together with ground (WP1) and satellite (WP2) data. Real-time simulation data are daily uploaded on the specifically developed web dashboard for each case studies (www.sim.polimi.it/dashboards). These dashboards are available in English and in the local language over possible (Italian, Spanish and Ducth).

The dashboards are designed for different level of users: irrigation consortia/water basin authorities and farmers providing different details of information. The results are shown on Openstreet Map platform and graphs, and stored in a database specifically created for the project. For example, for the Capitanata irrigation consortium the following map displays the daily mean water deficit (ammount of soil water needed to reach the field capacity threshold values) obtained coupling a hydrological model (FEST-EWB) with several meteorological models outputs (WRF, ECMWF, BOLAM, MOLOCH). In green the areas where soil moisture is higher than the field capacity also due to the local irrigation, in yellow the areas where soil moisture is in between the field capacity and the crop stress threshold, in red the areas where soil moisture is below the crop stress threshold. Similar results are available at local scale, with the monitoring and forecast of field soil moisture, in between the crop stress thresholds.


Capitanata sud Fortore agricultural basin: Water deficit

The following map displays the daily mean water deficit obtained coupling a hydrological model (FEST-EWB or ETMonitor) with several meteorological models outputs (WRF, ECMWF, BOLAM, MOLOCH). In green the areas where soil moisture is higher than the field capacity, in yellow the areas where soil moisture is in between the field capacity and the crop stress threshold, in red the areas where soil moisture is below the crop stress threshold.

Idrological Model: FEST EWB
Emission Date: 2017-10-16
Forecast time: Present

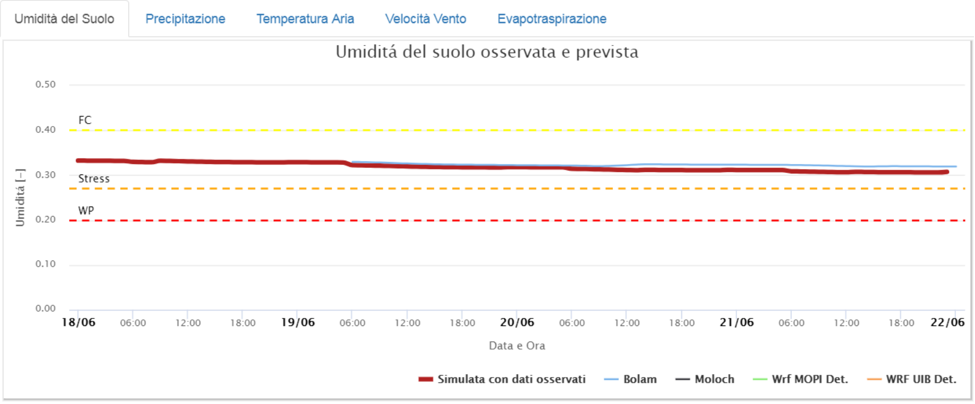


Figure 25.	Dashboard output: soil moisture between field capacity and crop stress thresholds

CONCLUSIONS

The SIM system provides pixel wise present and forecast irrigation water need for any type of soils and crops for farmers irrigation consortia and water authorities at high spatial resolution. It combines remote sensing data, irrigation data, numerical soil water balance models, meteorological forecasts and the economics analysis. SIM is innovative also respect to same similar tools for: assessing the irrigation water need respect to a soil moisture and not respect to potential evapotranspiration deficit; uses remote sensing data as soil moisture sensors and for parametrize crop area and relative fraction cover; it is independent from farmer use. A web-gis dashboard is the user interface, that have been implemented for the five test areas. This one allows to support an irrigation strategy (SIM strategy), that provides a parsimonious use of the water. Using a precise irrigation SIM strategy keeps the soil moisture in the crop root zone between field capacity and crop stress reducing the soil percolation flux and with a saving of irrigation volume, while effective evapotranspiration and crop yield remains almost the same.