

1 Real time drought forecasting system for irrigation 2 management

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4 A. Ceppi¹, G. Ravazzani¹, C. Corbari¹, R. Salerno², S. Meucci³, and M. Mancini¹

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6 ¹Department of Civil and Environmental Engineering (D.I.C.A.), Politecnico di Milano, Italy

7 ²Epson Meteo Centre, Cinisello Balsamo (Mi), Italy

8 ³M.M.I. srl, Milano, Italy

9
10 Correspondence to: A. Ceppi (alessandro.ceppi@polimi.it)

11 12 Abstract

13 In recent years frequent periods of water scarcity have enhanced the need to use water more
14 carefully, even in European areas which traditionally have an abundant supply of water, such as the
15 Po Valley in northern Italy. In dry periods, water shortage problems can be enhanced by conflicting
16 uses of water, such as irrigation, industrial and power production (hydroelectric and thermoelectric).
17 Furthermore, in the last decade the social perspective in relation to this issue is increasing due to the
18 possible impact of climate change and global warming scenarios which emerge from the fifth IPCC
19 Report (IPCC, 2013). Hence, the increased frequency of drought periods has stimulated the
20 improvement of irrigation and water management.

21 In this study we show the development and implementation of the PREGI real-time drought
22 forecasting system; PREGI is an Italian acronym that stands for “Hydro-meteorological forecast for
23 irrigation management”. The system, planned as a tool for irrigation optimization, is based on
24 meteorological ensemble forecasts (20 members) at medium-range (30 days) coupled with
25 hydrological simulations of water balance to forecast the soil water content on a maize field in the
26 Muzza Bassa Lodigiana (MBL) consortium in northern Italy. The hydrological model was validated
27 against measurements of latent heat flux acquired by an eddy-covariance station, and soil moisture
28 measured by TDR (Time Domain Reflectivity) probes; the reliability of this forecasting system and
29 its benefits were assessed in the 2012 growing season. The results obtained show how the proposed
30 drought forecasting system is able to have a high reliability of forecast at least for 7-10 days ahead.

1 **Keywords:** drought forecasts, water management, irrigation scheduling, soil moisture, hydro-
2 meteorological forecasting chain, irrigation water use efficiency (IWUE)

3

4 **1. Introduction**

5

6 A lack of water has always been one of the most critical factors for the survival of populations
7 around the world. The United Nations proclaimed the year 2003 as the international year of
8 freshwater and the year 2006 as the international year of deserts and desertification, highlighting the
9 importance of prevention, mitigation and adaption of events related to water supply. Future climate
10 change scenarios combined with limited water resources require better irrigation management and
11 planning (English et al., 2002, Farrè and Faci, 2008); this has also occurred in areas habitually with
12 an abundant supply of water as the Po Valley in the north of Italy. Considering historical climate
13 data sets, recent studies demonstrate that there is not a significant decrease in the amount of
14 precipitation, although a reduction in the last twenty years has been found over Italy (Salerno et al.,
15 2007). However, a new and more frequent distribution of extreme events has been observed
16 (Maugeri, 2006), as occurred in the most recent drought episodes of the years 2003, 2005 and 2006
17 in the Lombardy region (Craveri, 2006).

18 Scientific literature provides interesting issues focused on the optimization of irrigation management
19 also coupling meteorological and hydrological models. Examples of main international research are:
20 the CROPWAT program by Smith (1992), the EPIC-PHASE model developed at the center of
21 Toulouse (Cabelguenne et al., 1997), the real-time scheduled irrigation approach proposed by
22 Gowing and Ejieji (2001) in United Kingdom, the "eWarning" Danish warning system (Jensen and
23 Thyssen, 2003), real-time forecasts for daily evapotranspiration proposed by Cai et al., (2007) and the
24 Canterbury Irrigation Scheduler (CIS) by Brown et al., 2010. In the north of Italy the recurrence of
25 water stress periods requires an improvement in the management and coordination of water courses
26 (lakes, hydroelectric reservoirs, rivers, etc.), together with testing other alternative sources, such as
27 water withdrawals from large quarry lakes (Ravazzani et al., 2011a). This activity has contributed to
28 the better management of water distribution by water consortia according to season, different
29 cultivation requests and total available water in lakes and snowpack. A prudent water distribution
30 policy means wiser and thriftier methods of irrigation, maximizing agricultural production (Hassanli
31 et al., 2008, Oweis and Hachun, 2008, Geerts and Raes, 2009). However, these management policies
32 are currently based on the sensitivity and experience of consortia managers. A policy of saving
33 irrigation water would be helpful if districts were subsequently affected by significant rainfall, but
34 extremely dangerous if no precipitation occurs in the following weeks.

1 It is clear that the complexity of these matters related to water resources should be studied with a
2 scientific and engineering approach, in order to be able to predict the occurrence of potentially
3 harmful droughts in advance; this issue is also one of the main goals of the DROUGHT R&SPI
4 (www.eu-drought.org) and DEWFORA (www.dewfora.net) projects which focus on drought early
5 warning systems respectively in European and African continents.

6 Scientific literature proposes different methods, more related to statistical approach, for optimizing
7 irrigation scheduling and planning (Kuo and Liu, 2003, Negesh Kumar et al., 2006, Azamathulla et
8 al., 2008, Vico and Porporato, 2010 and 2013), while the application suggested in this paper takes
9 into account actual measures of soil moisture and observed weather data in addition to updated
10 forecasts to provide landowners with a suitable product for real-world farm profit optimization, as
11 well as cost savings for irrigation practices: e.g. water volume, pumping system from ditches, fuel
12 for tractors and labor costs. Our task is to put the scientific know-how into practice as a tool for
13 better irrigation management and planning. In fact, working on the PREGI Project, funded by the
14 Lombardy Region in the years 2010-2012, we discovered how irrigation practices in the Po Valley
15 area are left to very old strategies more related to landowner experiences rather than scientific
16 studies and engineering processes. In this context, an adoptable methodology is the one applied for
17 real-time flood predictions (Rabuffetti et al., 2008 and Ceppi et al., 2013), coupling meteorological
18 forecasts with hydrological simulations. The knowledge of Quantitative Precipitation Forecasts
19 (QPFs) for the following weeks combined with the updating of hydrological conditions makes it
20 possible to obtain a tool for water distribution management in cultivated areas in order to improve
21 irrigation scheduling, minimize irrigation costs and save water; therefore, to comply with this aim,
22 our idea was to create a web application where farmers are able to monitor real-time soil moisture
23 conditions and forecasts.

24 The PREGI system is based on meteorological forecasts at medium-range with hydrological
25 simulations of water balance to forecast the soil moisture at field scale. In particular, three TDR
26 probes were installed to monitor soil moisture conditions, while to produce probabilistic soil
27 moisture forecasts, the non-hydrostatic WRF-ARW (Weather Research and Forecasting –
28 Advanced Research WRF) meteorological model based on 20 ensemble members with one month
29 as forecast horizon provided by Epsom Meteo Centre (EMC), was coupled with the FEST-WB
30 (Flash–flood Event–based Spatially–distributed rainfall–runoff Transformation- Water Balance)
31 distributed hydrological model developed at Politecnico di Milano (POLIMI), and used to generate
32 soil moisture simulations.

33 The area of study is a maize field in the MBL consortium in the Po Valley (northern Italy), used as
34 an experimental test-site for the PREGI tool. A calibration phase was carried out for the 2010 and

1 2011 growing seasons, while a validation was performed in the 2012 season, when it was also
2 possible to couple hydrological simulations with meteorological forecasts in order to obtain soil
3 moisture predictions; the results of this forecasting chain show a high reliability up to 7-10 days as
4 lead time of forecast. Notwithstanding this, during the 2012 season the PREGI system was not fully
5 employed by the landowner of the experimental field, and the decision-making criteria did not
6 follow the indications highlighted in the PREGI platform; in fact, as shown in Sect. 3.3, a better
7 management of water distribution could have been carried out and even one scheduled irrigation
8 could have been saved.

9

10 **2. Case study, models and methods**

11

12 *2.1 Area of study*

13

14 The territory of the MBL consortium covers an area of 740 km² in which there are more than 150
15 irrigation basins and thousands of irrigation sub-basins which include the private lots of landowners
16 (Fig. 1). Inside the MBL basin, which is composed of open earth canals, the Muzza channel (about
17 40 km long) derives water from the Adda River at Cassano d'Adda and it flows back into the Adda
18 close to Castiglione d'Adda. It is both the largest irrigation canal in terms of capacity and the first
19 artificial canal built in northern Italy: 38 intakes and many more hydraulic nodes are included along
20 the canal.

21 Average annual rainfall measured in the MBL consortium range from 800 (southern area) to 1000
22 mm (northern area) with two peaks in spring and autumn (Ceriani and Carelli, 2000). During the
23 summer season most of the water supply comes from the irrigation network. The upper-medium
24 part of the basin is irrigated by flowing surface water, while in the bottom part of the basin, water is
25 taken and lifted by the Adda and Po rivers through proper pumping systems.

26 The experimental test-site for the PREGI Project is a field located in the middle of the MBL basin at
27 Cascina Nuova farm in the town of Livraga, where meteorological, eddy-covariance stations and
28 TDR probes for evapotranspiration fluxes and soil moisture profile have been respectively installed
29 to measure hydrological processes (Masseroni et al., 2012). Since no measures in other consortium
30 fields were available to calibrate and validate the hydrological model, it was not possible to verify
31 the PREGI forecasting system outside the Livraga experimental site. Notwithstanding this, such a
32 system can be replicated in any geographical area and vegetated field, on condition that soil
33 features, weather, hydrological data and irrigation time allotments are available.

1 2.2 *Meteorological model*

2

3 The probabilistic forecast was provided by the Regional Ensemble Prediction System (REPS),
4 based on the WRF-ARW model, implemented and developed by the EMC. The REPS-WRF used in
5 this project has a grid mesh size of 18 km, 36 vertical levels and 20 members; boundary and initial
6 conditions are provided by a Global Ensemble Prediction System (GEPS) based on a modified
7 version of the WRF-ARW applied at the global scale, which has a grid mesh size of 200 km and the
8 same number of vertical levels as the REPS, and it uses the same initial conditions in the control
9 runs provided by the 12 UTC GFS (Global Forecasting System) analysis at 0.5 degree of horizontal
10 resolution. The forecast has a lead time of 30 days while the temporal resolution is 12 hours. Each
11 perturbation of the ensemble is produced by an algorithm developed by the EMC based on a special
12 application of Ensemble Transform Kalman Filter (EnTKF), able to allow covariance localization
13 whilst maintaining computational efficiency and removing spurious long-range correlations. The
14 REPS-WRF is carried out every two days, since this is the computational time to run the combined
15 system. The REPS-WRF run starts at 00 UTC, the same start time as the hydrological simulation.
16 For a detailed description of the WRF model, please refer to Skamarock and Klemp (2007).

17

18 2.3 *Hydrological model and required data*

19

20 In this study, hydrological simulations are performed using the FEST-WB, a rainfall-runoff
21 spatially distributed and physically-based model, whose development was initiated by the
22 Politecnico di Milano in 1990.

23 The FEST-WB calculates the main processes of the hydrological cycle: evapotranspiration,
24 infiltration, surface runoff, flow routing, subsurface flow, snow dynamics and soil water content.

25 **The model requires observed precipitation and air temperature data from ground stations which are**
26 **both interpolated to a regular grid using the inverse distance weighting technique or forecasted**
27 **weather data.** The spatial domain is discretized with a mesh of regular square cells (200 m in this
28 application), while the temporal resolution of soil moisture simulations and forecasts calculated on a
29 daily time scale; since the Livraga maize field is about 8 ha wide and the landowner schedules his
30 activities on daily/weekly planning, both the spatial and time scale turned out to be appropriate from
31 a computational time point of view.

32 In addition to (observed/forecasted) weather data, the hydrological model needs further information
33 to be set up, such as land use, soil texture, hydraulic conductivity (Ks), type of vegetation (dates of
34 sowing and harvest), DEM (Digital Elevation Model), aquifer parameters and scheduled irrigations.

1 In particular, amounts and methods of water allotments are fundamental to keep updated soil
2 moisture initial conditions. In fact, since irrigation allotments are planned by the MBL consortium,
3 landowners cannot irrigate their fields on days other than the scheduled ones, because each field of
4 the Muzza consortium has its own scheduled irrigation following centuries old time tables where
5 planned water allotments are determined in advance; therefore, this information becomes mandatory
6 in the hydro-meteorological forecasting chain. At the Livraga experimental field this is available
7 every week, i.e. the landowner has the possibility of withdrawing water from the nearest irrigation
8 ditch every 7 days. For instance, the potential water concession for the Cascina Nuova farm is 650 l
9 s⁻¹ taken from the “Porra Nuova” ditch, but considering that the irrigation efficiency of the Muzza
10 basin is about 45% of the theoretical value, the available water discharge is only about 300 l s⁻¹.
11 Since this volume of water is used to irrigate our experimental field of 8 ha in about 8 hours, the
12 estimated irrigation input implemented in the FEST-WB model was assumed to be equal to 108
13 mm.

14 As far as soil information is concerned, in situ field tests carried out during the PREGI Project, have
15 classified the soil texture as silt loam; in particular, a content of: 19.2 % clay, 48.1 %, silt, and
16 32.7% sand was found in soil analyses. Table 1 summarizes the main soil properties for the Livraga
17 maize field: a tuning of these values inside the interval range reported in Maidment (1993) was
18 carried out to calibrate and implement the FEST-WB hydrological model.

19 Another important parameter to define in the hydrological model is soil depth which has been
20 modeled as a single layer with a value of 0.7 m, considering the predominant growing zone of
21 maize roots; consequently the three TDR probes were installed at 10, 35 and 70 cm depth. Finally,
22 different measures of permeability were performed with the Guelph infiltrometer (Eijkelkamp,
23 2008) to investigate the hydraulics conductivity (Ks) which was found to be equal to 2.36E-07 m s⁻¹
24 in the experimental field.

25 As described in the results (Sect. 3), observed and forecasted soil moisture data are influenced by
26 rainfall, irrigation contributions and evapotranspiration fluxes which denote main inflows and
27 outflows in water balance at the Livraga field scale. Evapotranspiration losses plays a crucial role in
28 the water balance during the summer season in the Po Valley area where cumulated values exceed
29 300 mm in four months (see Figs. 2b,-d, -f). Eddy covariance measures were used to control actual
30 evapotranspiration (ET) fluxes and to make a comparison with the ET simulated by the FEST-WB
31 model (see Sect. 3.1 for further details). In case eddy covariance measures are not available, the
32 system target would not in any case be affected, since the main hydrological variable is the soil
33 moisture, and TDR probes are sufficient for monitoring and forecasting purposes. On the contrary,

1 the limits of such a system, in order to be replicated in other areas, are the availability of real time
2 data (weather and soil moisture values), amounts and scheduled irrigation allotments.
3 In the current version of the FEST-WB model, evapotranspiration is computed according to a
4 revised version of the Food and Agricultural Organization (FAO-56) method (Allen et al., 1998).
5 The original approach is based on the use of the Penman-Monteith equation (Monteith, 1965) to
6 calculate a reference evapotranspiration (ET_0) of a surface defined as an “hypothetical crop with an
7 assumed height of 0.12 m, having a surface resistance of 70 s m^{-1} and an albedo of 0.23, closely
8 resembling the evaporation of an extensive surface of green grass of uniform height, actively
9 growing and adequately watered” (Allen et al., 1998). In this paper, due to the availability of only
10 air temperature meteorological forecasts, the Penman-Monteith equation is substituted with a
11 modified Hargreaves and Samani equation (Hargreaves and Samani, 1985) which includes a
12 correction factor for altitude (Ravazzani et al., 2012). In Ravazzani et al., 2012, the reliability of this
13 modified equation to compute ET_0 , has been demonstrated. Subsequently, the crop coefficient (k_c),
14 which embodies all the physiologic characteristics of a specific plant, allows passing from ET_0 to
15 the potential evapotranspiration of a specific crop. Allen et al., 1998 created a database of k_c for a
16 large number of agricultural crops in different climates including maize. Crop coefficient values are
17 assigned by defining the length of phenological phases considering the sowing and reaping dates for
18 each year. For further details about the development and calibration of the FEST-WB, please refer
19 to Montaldo et al., 2003 and 2007, Ravazzani et al., 2007 and 2011b, Corbari et al., 2011, and
20 Ravazzani (2013).

21

22 *2.4 Coupling strategy and warning thresholds*

23

24 The cascade forecasting system applied in this study is currently based on hydrological model
25 initialization from meteorological model output: temperature and precipitation forecasts.

26 Before launching the coupled system, the hydrological model is initialized with observed weather
27 data of the previous day, provided by the ARPA (Regional Agency for Environmental Protection) of
28 the Lombardy region and Meteonetwork-EMC meteorological station network to set up the initial
29 soil moisture conditions. In order to better understand the developed forecasting chain, an example
30 of each step of the operative chain is detailed in Table 2.

31 This coupling of hydro-meteorological models joint to irrigation scheduling knowledge provides
32 advance information on soil moisture content and expected cumulated precipitation for irrigation
33 management and water control from 1 to 30 days as forecast horizon.

1 In order to issue warnings regarding soil moisture forecasts, two thresholds were defined in the
 2 PREGI system: one is the water surplus equal to the field capacity of the soil and the other is the
 3 stress threshold, where below this point the crop begins to suffer because of a lack of water.
 4 According to the FAO-56 definition (Allen, et al., 1998) and also applied in Baroni et al., (2010) the
 5 latter is calculated as follows (1):

$$6 \text{ RAW} = p \cdot \text{TAW} \quad (1)$$

7 where RAW is the Readily Available Water defined as field capacity minus stress threshold, TAW
 8 is the Total Available Water defined as field capacity minus wilting point, and p is a coefficient
 9 depending on the crop and climatic parameters which can be assumed to be equal to 0.5 for maize
 10 (Allen et al., 1998) in the Livraga field. Therefore, the Eq. (1) becomes:

$$11 \text{ field capacity} - \text{stress threshold} = p \cdot (\text{field capacity} - \text{wilting point}) \quad (2)$$

12 Substituting the values of 0.33 and 0.13 respectively for field capacity and wilting point for the
 13 Livraga silt loam soil (see Sect. 2.4), the Eq. (3) becomes:

$$14 \text{ stress threshold} = 0.33 - 0.5 \cdot (0.33 - 0.13) \quad (3)$$

15 Hence, the stress threshold value we are looking for is equal to 0.23. As described in Sect. 3.3, this
 16 stress threshold is a decision criterion in order to plan whether or not to irrigate on the days when
 17 water allotment is available.

18

19 *2.5 Statistical indexes*

20

21 Common skill scores in scientific literature are used to compare soil moisture simulations between
 22 observed and simulated values by the FEST-WB model initialized with observed values and
 23 weather data forecasted by the REPS-WRF model; since the WRF is a probabilistic model with 20
 24 ensemble members, the median value is chosen for analysis clarity. In particular, results described
 25 in Sect. 3.2 include the Mean Relative Error (MRE) calculated as follows Eq. (4):

$$26 \text{ MRE} = \frac{1}{n} \sum_{i=1}^n \left(\frac{F_i - O_i}{O_i} \right) \quad (4)$$

27 where:

28 O_i = observed values

29 F_i = median of forecasted values

30 n = numbers of analyzed events

31 and the NS index (Nash and Sutcliffe, 1970):

$$NS = 1 - \frac{\sum_{i=1}^n (O_i - F_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad (5)$$

2 where:

3 \bar{O} = the average of observed values

4 which shows how well the forecast predicts the observed time series, with best scores close to 1,
 5 and a range between $-\infty$ to 1. In this study, Eq. 5 measures the ratio between the deviations of
 6 forecasted median values by the FEST-WB hydrological model initialized by 20 ensembles of the
 7 REPS-WRF model with observed values and the deviation between the observed mean and
 8 observed values.

9 Another skill score used in this study is the Brier Score (BS) which is essentially the mean-squared
 10 error of the probability forecasts, considering that the observation is $o=1$ if the event occurs, and
 11 $o=0$ if the event does not occur. The score averages the squared differences between pairs of
 12 forecast probabilities and the subsequent observations (Wilks, 2006). Equation (6) for the BS score
 13 is:

$$BS = \frac{1}{n} \sum_{k=1}^n (F_k - O_k)^2 \quad (6)$$

15 where

16 N = number of forecasting instances

17 F_k = the probability that an event was forecasted

18 O_k = the actual outcome of the event at instance k (0 if it doesn't happen and 1 if it happens)

19 For instance, suppose that the forecast probability to exceed a threshold of cumulated rainfall is
 20 70% and then this event occurs, the BS score is equal to 0.09; vice versa if it does not occur the BS
 21 score is 0.49; therefore, best scores are close to 0. In this analysis, three thresholds were chosen: 20,
 22 50, 100 mm; these last two values are reasonably similar to half and full irrigation in the Livraga
 23 maize field, while the 20 mm threshold corresponds to typical precipitation amounts in that area,
 24 which is not usually affected by heavy rainfall in the summer season, as occurred in 2012. It is
 25 important to bear in mind that this computation, performed with the entire forecast dataset, is not
 26 referred to daily precipitation values, but cumulated precipitation values over a period of 1, 2,
 27 3,...,30 days. For instance, the BS score at 7th day as lead time considers the occurrence probability
 28 of a cumulated precipitation forecast over a period of 7 days to exceed the threshold of 20, 50 or
 29 100 millimeters (occurred over the same time period of 7 days).

30

1 **3. Results and discussion**

2

3 **3.1 Calibration and validation of the FEST-WB model using observed data**

4

5 The 2010-2012 period was used to calibrate and validate the hydrological model with data acquired
6 at Cascina Nuova field in Livraga, where one eddy covariance station and three TDR probes were
7 installed to monitor evapotranspiration fluxes and soil moisture content. Figs. 2 shows the
8 comparison between values measured (red line) by TDR probes (in reality, it is a weighted average
9 of the three measures at a depth of 10, 35 and 70 cm) and data simulated (blue line) by the FEST-
10 WB model during the three growing seasons of 2010, 2011 and 2012, including rainfall (light blue
11 bars) and irrigation (orange bars) amounts in the Livraga maize field.

12 As far as the 2010 season is concerned, Fig. 2a shows how soil moisture data are well associated
13 with rainfall and irrigation inputs with a MAE of 4% and MRE of +1%; a good match between
14 observed and modelled simulation data is also shown in Fig. 2b for the actual cumulated
15 evapotranspiration. In addition, Figure 2a shows how the first seasonal irrigation (14 June 2010)
16 could have been avoided if soil moisture and precipitation forecasts were known in advance; in fact,
17 severe rainfall (about 85 mm) occurred between 15 and 20 June with a maximum peak of 45 mm on
18 15 June (the day after the irrigation!). Unfortunately, in that year the PREGI tool with hydro-
19 meteorological forecasts was not yet in service and it was only available for the 2012 vegetation
20 season.

21 In regard to the 2011 season, satisfactory results are found between observed and simulated values
22 both in terms of soil moisture (MAE equal to 8%, Fig. 2c) and cumulated evapotranspiration (Fig.
23 2d), even if an underestimation is generally present (MRE of -8%) in simulated soil moisture
24 values, mainly due to higher rates in evapotranspiration.

25 After two years of calibration (2010 and 2011), the validation of the FEST-WB model is carried out
26 for the 2012 growing season at the Livraga field. The performance of the validation (Fig. 2e) shows
27 a good match between model and observations with a MAE of 7% and MRE of -1%. A slight
28 underestimation of the FEST-WB is generally present except at the beginning of the season;
29 however, the hydrological model initialized with observed values by the Lombardy ARPA and
30 Meteonetwork-EMC weather stations, was able to simulate soil moisture conditions with a daily
31 error within 10%, in particular during the irrigation period between June and August. Even the
32 comparison between observed (red line) and simulated (blue line) data for the real cumulated
33 evapotranspiration (Fig. 2f) indicates a good correspondence during the 2012 growing season.

3.2 Evaluation of the PREGI performance coupling meteorological and hydrological forecasts

Indeed, one of the main goals of the PREGI Project was to couple weather and hydrological models to provide soil moisture forecasts as a support decision system for the irrigation optimization in the 2012 season on the Livraga maize field. The hydro-meteorological chain was set up using the REPS-WRF output provided by the EMC in the FEST-WB hydrological model developed by the POLIMI. The REPS-WRF model output was available every 2 days, and therefore the data set includes 90 days of simulations between 27 February and 31 August 2012. Since the weather model has a forecast horizon of 30 days, in order to value the forecasting chain, the statistical analysis has been carried out starting from “day+0”, i.e. the forecast at the same day of the initialization date run, up to “day +30”. For instance, a skill score value for the “day+10” considers all forecast performances at 10 days (as the lead time) from the initialization date. The statistical analysis in this paper was performed using common skill scores known in literature (Wilks 2006, Jolliffe and Stephenson 2003).

As Figures 3 and 4 show, the forecast reliability tends to diminish by increasing the forecast horizon. However, a good performance is achieved up to 10-15 days for soil moisture forecasts (Fig. 3) and up to the first week for cumulated rainfall forecasts by the REPS-WRF model (Fig. 4).

In particular, Fig. 3 shows the MRE between observed and simulated values by the FEST-WB initialized with the REPS-WRF model output. The MRE is around $\pm 2\%$ in the first six days of the forecast horizon, while an overestimation in the FEST-WB simulations initialized with the REPS-WRF weather forecasts is shown in the remaining period (+8% at “day+15”). Even at “day+20” the MRE still remains around +10%, indicating a good forecast reliability by the REPS-WRF model in the 2012 season we analyzed.

The NS index shown in Fig. 4 highlights the high performance of the meteorological forecast in the first days of the forecast horizon (NS index greater than 0.90) with a progressive decrease after “day+10”; however, a good forecast reliability is shown even up to 10th-15th day after the initialization date of the weather model with NS values between 0.80 and 0.75. The reason for calculating the forecast performance of the rainfall plus irrigation accumulated in a moving forecast horizon, and not the forecasted amount on a specific day, satisfies one of the aims of the PREGI project: in fact, from an irrigation management point of view, it is more important to know whether the next 7 or 14 days, which usually coincide with water irrigation allotments in the MBL fields, will be wet or dry, rather than precipitation event occur precisely on the 14th or 15th day of the forecast. On the contrary, Fig. 5 shows the REPS-WRF model performance with forecasted precipitation only, excluding the contribution of irrigation, using the Brier Score index for a forecast

1 horizon from 1 to 30 days during the 2012 growing season. As it is shown in Fig. 5, the forecast
2 performance is better for the threshold of 100 mm cumulated over a moving period from 1 to 30
3 days, worsening as the lead time increases. On the contrary, the forecast reliability has a different
4 trend for thresholds greater than 50, and above all 20 mm, with higher Brier Score values in the first
5 days of lead time and a subsequent worsening in the following period. In fact, in the way in which
6 the BS is defined, the rarer an event, the easier to get a better BS. This is true if we consider the
7 frequency of events, which exceed the threshold of 100 mm cumulated in 1, 2, 3,..., 30 days,
8 occurred during March-August 2012, and more in general in the summer season in the Po Valley
9 area, in comparison with the cumulated precipitation values (observed/forecasted) of 20 mm which
10 are much more typical from a climatological point of view for this area; however, there is a good
11 level of reliability (BS values lower than 0.15) within the first 10 days even for a threshold of 20
12 mm cumulated in 10 days. Notwithstanding this, our decision to show the performance over a
13 cumulated period of 1, 2, 3,..., 30 days is the result of a preliminary investigation carried out with
14 the landowner of the Livraga field who is the real decision-maker: as mentioned above, from his
15 point of view he was more interested in knowing the reliability of a cumulated precipitation forecast
16 over 7 days or 10 days and not whether it is going to rain exactly on the 7th or 10th day from the
17 forecast initialization date. Therefore, considering the available 2012 data set only, this skill
18 analysis with the BS index (as for the NS) was performed with forecast values cumulated over a
19 period of more days (1, 2, 3,...,30) rather than 24-hour values.

20

21 3.3 *To follow or not to follow the PREGI system*

22

23 Although the model validation was only performed after the 2012 growing season, hydro-
24 meteorological simulations were set up in real-time at the beginning of the 2012 season when the
25 PREGI system issued soil moisture, evapotranspiration and precipitation forecasts every two days,
26 providing the landowner with useful information concerning soil conditions for irrigation
27 scheduling. As described in Sect 2.4, the initial conditions of the hydrological model were updated
28 daily taking into account observed weather data and irrigation water amounts which were planned
29 during the entire season more on the basis of the landowner' experience than the PREGI system.
30 Three irrigations were planned during the vegetation season 2012: 29 June, 14 July and 6 August;
31 the latter was supposed to be the previous week, on 29 July, but the observed soil moisture values
32 and forecasts convinced the landowner to follow the PREGI application and to postpone it for one
33 week. This advice led to an extension of the growing season until the end of August when a riper
34 maize was harvested two weeks after the originally scheduled date; however, had the PREGI

1 system been fully followed by the landowner, one out of three irrigations would have been even
2 saved. In fact, to demonstrate the benefits of such a forecasting system, we re-ran two simulations,
3 one assuming that the landowner follows the advice provided by the PREGI platform on when to
4 irrigate, and the other assuming that he follows the currently planned decision criteria; as shown in
5 Figure 6 (where for the sake of clarity we show only the mean, median, the 25th and 75th percentile
6 of ensemble forecasts), one out of three irrigations could have been saved! In particular, the
7 irrigation scheduled for 29 June (Fig. 6b) could have been avoided (Fig. 6a), since none of the 20
8 ensembles would have forecasted a soil moisture value below the stress threshold. According to the
9 forecast shown in Fig. 6c, even the irrigation occurred on 14 July (Fig. 6d) could have been avoided
10 and postponed for one week (Fig. 6f) when it was really necessary, because soil moisture forecasts,
11 issued on 20 July, gave a probability of 35% (i.e. 7 ensemble members out 20) to exceed the stress
12 value if the landowner had not irrigated on the 22nd (Fig. 6e).
13 In the same way during August, the landowner could have postponed the planned irrigation for 6
14 August (Fig. 6h) for one week (Fig. 6j), since no members of the ensemble forecast issued a
15 warning (Fig. 6g) for the next 7 days (which is important to bear in mind for the available irrigation
16 time allotment). In fact, if no irrigation occurred in the following 7 days, the forecast issue on 11
17 August would forecast a probability of 50% to exceed the stress threshold on 17 August (Fig. 6i).
18 This comparison between the two scenarios, with or without the PREGI system, made it possible to
19 assess the benefits of this system in terms of water savings. Figure 7 shows, in fact, how the soil
20 moisture conditions with only two simulated irrigations, instead of three, would have remained
21 within the range of the two surplus and stress thresholds. On the contrary, the three irrigations that
22 actually took place raised the soil water content even further above the surplus threshold for a good
23 part of the 2012 season.

24

25 **4. Conclusions**

26

27 The aim of the PREGI Project is to realize an integrated system by coupling meteorological and
28 hydrological models to monitor and forecast soil water content in order to manage irrigation water
29 more wisely. The test-bed of the project was the maize field at Livraga in the MBL consortium,
30 about 50 km south-eastern Milan in northern Italy. The hydro-meteorological chain to produce
31 ensemble soil moisture forecasts is based on 20 meteorological members of the non-hydrostatic
32 WRF-ARW model with a 30 days lead-time, provided by the Epsilon Meteo Centre, while the
33 hydrological model used to generate soil moisture simulations is the FEST-WB rainfall-runoff
34 distributed model, developed by the Politecnico di Milano. This contribution made by ensemble

1 forecasts provides probabilistic information with different forecast scenarios to be below or above
2 stress/surplus thresholds. Furthermore, according to crop water consumption determined by the soil
3 type and the degree of saturation, a continuous **monitoring** of soil water content was carried out
4 during the entire 2012 growing season with three TDR probes installed.

5 The results show how it was possible by combining meteorological and hydrological models to
6 have reliable soil moisture forecasts for up to 10 and 14 days respectively, with a mean relative
7 error of less than 10%. Although the PREGI system showed a good level of performance during the
8 2012 season, decision criteria for when to irrigate were left more to the farmer's experience rather
9 than the hydro-meteorological forecasts. However, thanks to the PREGI system, we highlighted
10 how one of the three irrigations could have been avoided, if the landowner had followed the results
11 generated by our application. Thus, the benefits of this project are both direct and indirect: the direct
12 benefits regard the monitoring and forecasting of soil water content according to the current state of
13 soil moisture values and water crop requirements, while the indirect benefits regard the optimization
14 of water irrigations pursuing the best quantitative distribution, in particular periods of water
15 scarcity, in order to minimize production losses caused by water stress due insufficient watering,
16 avoiding the waste of irrigation water as occurred in the 2010 growing season, when the PREGI
17 system was unfortunately not yet in service.

18 One of the future developments is to extend these analyses over different sites with other case
19 studies during future growing seasons. However, a limit for replicating this system in other areas
20 will be that of obtaining real-time data (weather and soil moisture information), amounts and
21 scheduled irrigation dates, which are usually not easy to acquire in real time.

22

23 **Acknowledgements**

24

25 This work was supported by the PRE.G.I. Project (PREvisione e Gestione Irrigua) and Dote Ricerca
26 Applicata, both funded by the Lombardy Region. The authors are grateful to the MBL consortium
27 (E. Fanfani, M. Chiesa and G. Meazza) for their support in digital cartographic maps and irrigation
28 information for the area we studied, and to the Livraga landowner (E. Grecchi) for giving us the
29 possibility of using his maize field as an experimental test-site for three years. Last but not least, the
30 authors thank the Lombardy Region ARPA and the Meteonetwork Association for the provision in
31 weather data.

32

33

1 **Appendix**

2

3 During the 2012 growing season, real-time simulation data were uploaded on a google maps
4 platform and stored in a database specifically created for the project. An example of the web
5 application realized for the PREGI Project is shown in Fig. 8 with a colored “traffic-light” dot on
6 the google map view of the Cascina Nuova farm. The value displayed on the colored dot means the
7 higher daily probability value over a period of 30 days. The dot can be red or orange if stress and
8 surplus thresholds respectively exceed 33% of ensemble forecasts (i.e. at least 7 ensembles out of
9 20), following the method already used in the MAP D-PHASE Project reported in Zappa, et al.,
10 2008; if both thresholds are exceeded, a display priority has been given to the stress threshold.
11 Otherwise, if none of these two thresholds are exceeded, no alert is forecasted, and a green dot
12 appears on the map; in this way the Livraga landowner has a tool to control real time warnings
13 regarding soil moisture forecasts for his maize field. An example of simulations uploaded on the
14 web platform during the 2012 season, when the performance of the PREGI system was evaluated, is
15 shown in Figure 9. Soil moisture simulations by the FEST-WB hydrological model initialized with
16 observed data by the Lombardy ARPA and Meteonetwork-EMC station network are shown with a
17 green line and the forecasted data by the 20 ensembles of the REPS-WRF meteorological model
18 with colored lines. In this picture, it is evident how the two irrigations planned for 29 June and 14
19 July 2012 significantly raised the soil moisture values above the water surplus threshold over the
20 following days. For reason of clarity, in Figure 9 we do not show all 20 ensembles, but only the 25th
21 percentile, the median, the 75th percentile and the mean of ensemble forecasts (respectively grey,
22 blue, black and yellow lines); however, all the 20 ensemble members can be selected in the web
23 application. The average soil moisture value measured with TDR probes in the Livraga test-bed is
24 shown with a red line for the entire forecast horizon; as described in Sect. 2.4, the area below the
25 stress threshold (0.23) is highlighted in red, while the one above the field capacity point (0.33) is
26 shown in orange.

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Table 1: Water-retention properties classified for a silt loam soil type (Maidment, 1993).

Total porosity (ϕ)	Residual water content (θ_r)	Pore size distribution (λ)	Wilting point	Field capacity	Bubbling pressure (h_b)
0.501	0.015	0.234	0.133	0.330	0.2076

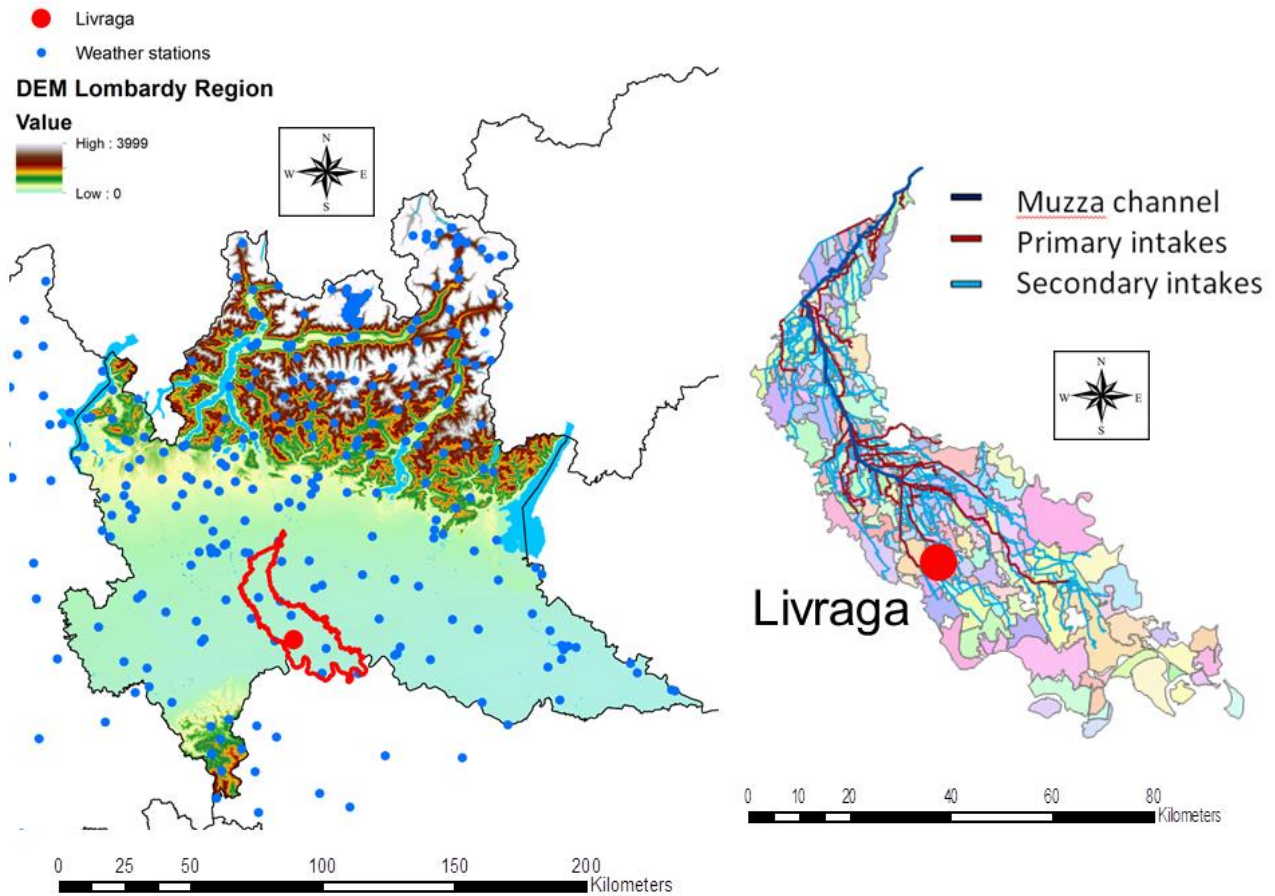
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Table 2: Description of the forecasting chain coupling the meteorological and hydrological model. The action time is reported in UTC (Coordinated Universal Time), while the time delay after the first step of the operative chain is reported in hours and minutes (hh:mm).

Day and Time [UTC]	Time delay after the start of the chain [hh:mm]	Action
Day 1 at 00:00	-	The REPS-WRF model is launched by the EMC
Day 3 at 12:00	60:00	The REPS-WRF model outputs are uploaded on the POLIMI server
Day 3 at 13:00	61:00	Observed weather data of the previous day provided by the Lombardy ARPA and Meteonetwork-EMC meteorological station network are available on the POLIMI server
Day 3 at 13:30	61:30	The FEST-WB model is launched with observed weather data of the previous day to produce initial conditions
Day 3 at 14:00	62:00	Once initial conditions are obtained, the FEST-WB model is now initialized with the REPS-WRF probabilistic forecasts to produce soil moistures forecasts
Day 3 at 16:00	64:00	Soil moisture forecasts are uploaded on the google map platform purposely developed

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3 Fig. 1: The Lombardy region in the North of Italy (left) and the MBL consortium with its irrigation
4 sub-basins (right). The Livraga test-site is shown with a red dot, while the available rain gauge
5 stations of the Lombardy ARPA and Meteonetwork-EMC network used as input into the FEST-WB
6 hydrological model are shown with blue dots.

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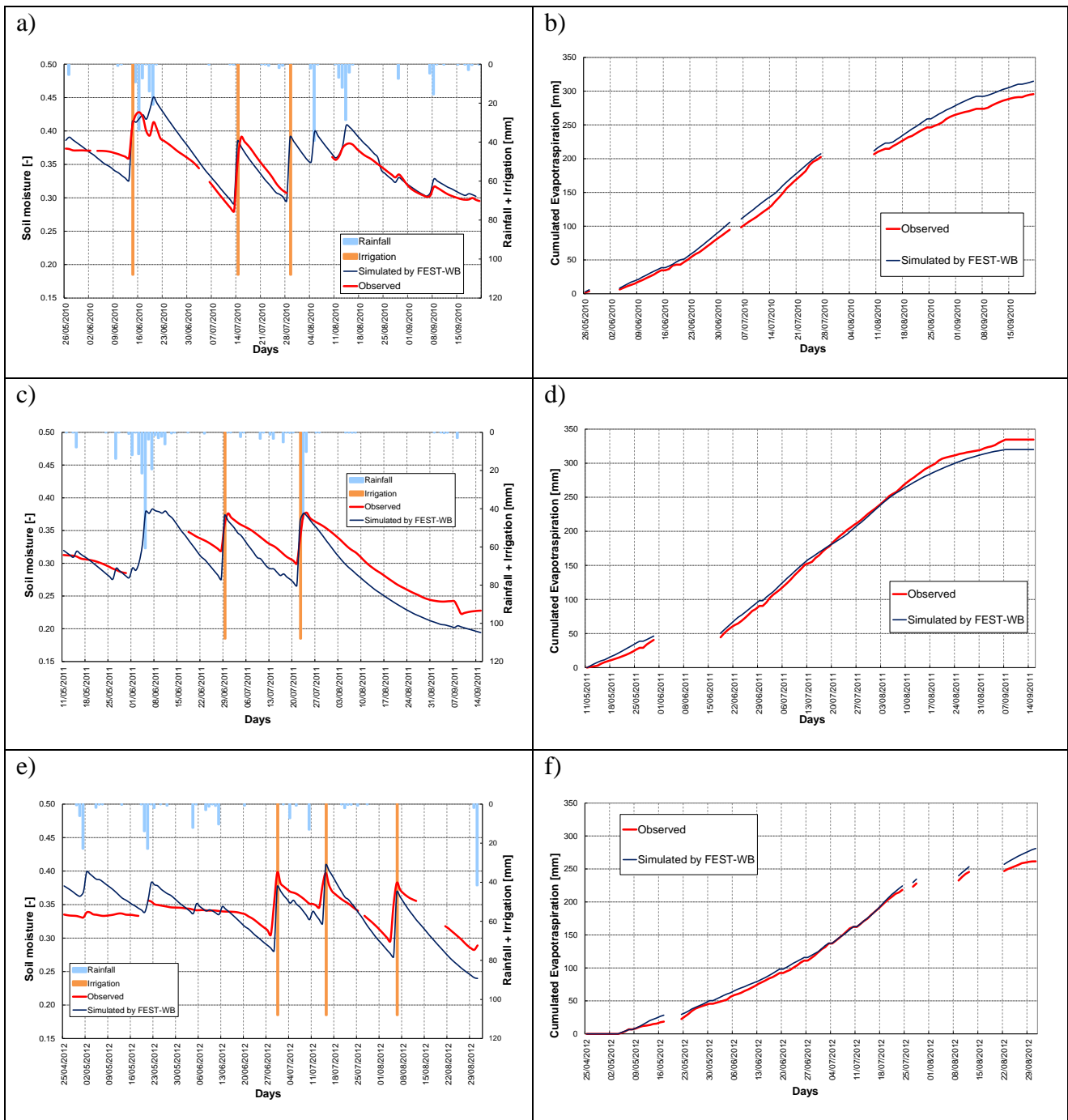
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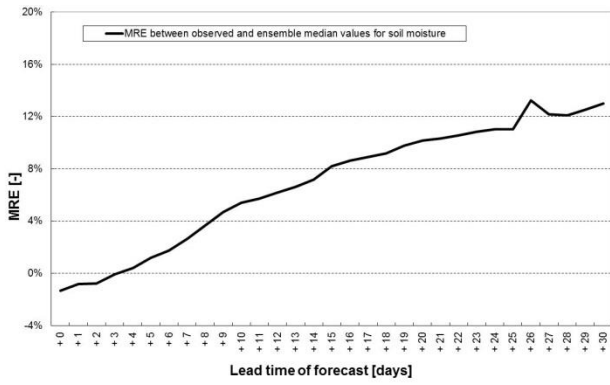
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3 Fig. 2: The left graphs (a, c, e) show the comparison between observed (red line) and simulated
 4 (blue line) soil moisture values by the FEST-WB model at the Livraga maize field for the 2010,
 5 2011 and 2012 growing season; precipitation (blue bars) and irrigation (orange bars) amounts are
 6 shown in light blue histograms. The right graphs (b, d, f) show the comparison between observed
 7 (red line) and simulated (blue line) actual cumulated evapotranspiration values by the FEST-WB
 8 model. Unfortunately, some observed data are missing due to storage battery problems in the three-
 9 year project.

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3 Fig. 3: The Mean Relative Error for soil moisture between the observed data and the median of all
4 the FEST-WB simulations initialized with the 20 ensembles of the REPS-WRF model for the 2012
5 growing season over a period of more lead time days.

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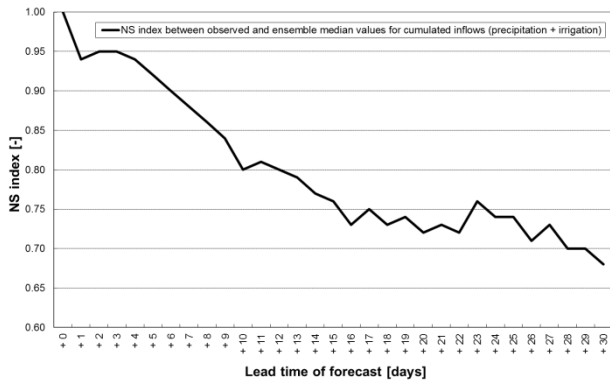
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3 Fig. 4: The NS index for rainfall and irrigation amounts between the observed data and the median
4 of 20 ensembles of the REPS-WRF model for the 2012 growing season over a period of more lead
5 time days.

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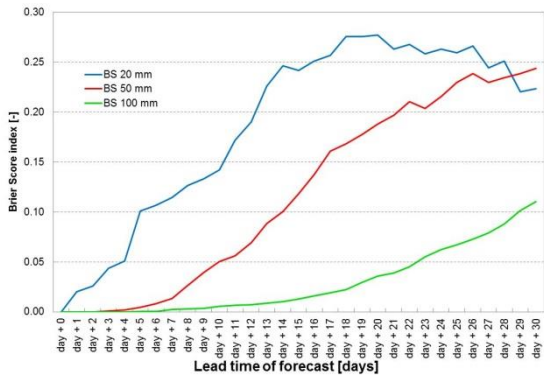
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3 Fig. 5: Brier score index for the three thresholds of cumulated rainfall: 20 mm (blue line), 50 mm
4 (red line) and 100 mm (green line) for the 2012 growing season over a period of more lead time
5 days.

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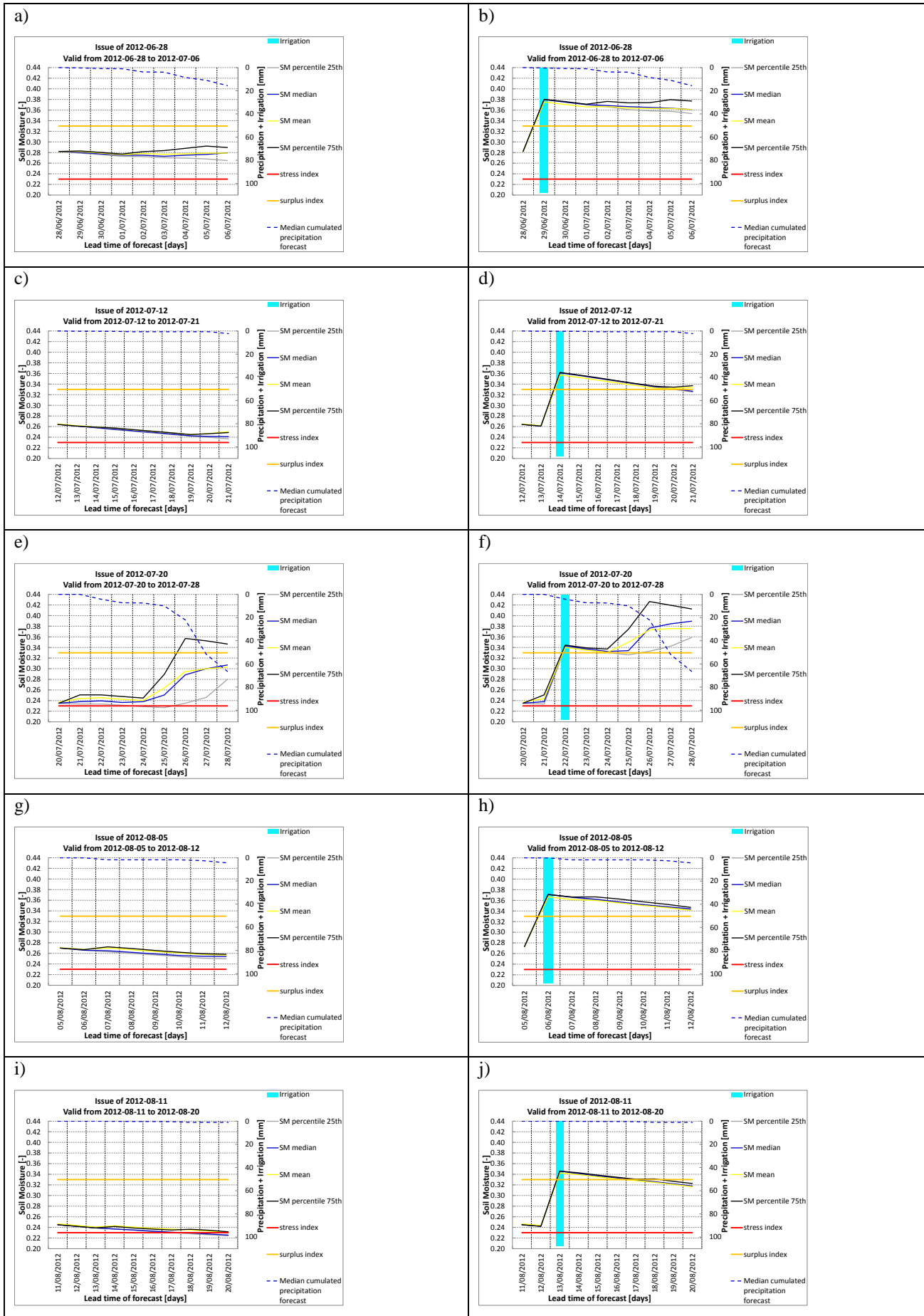
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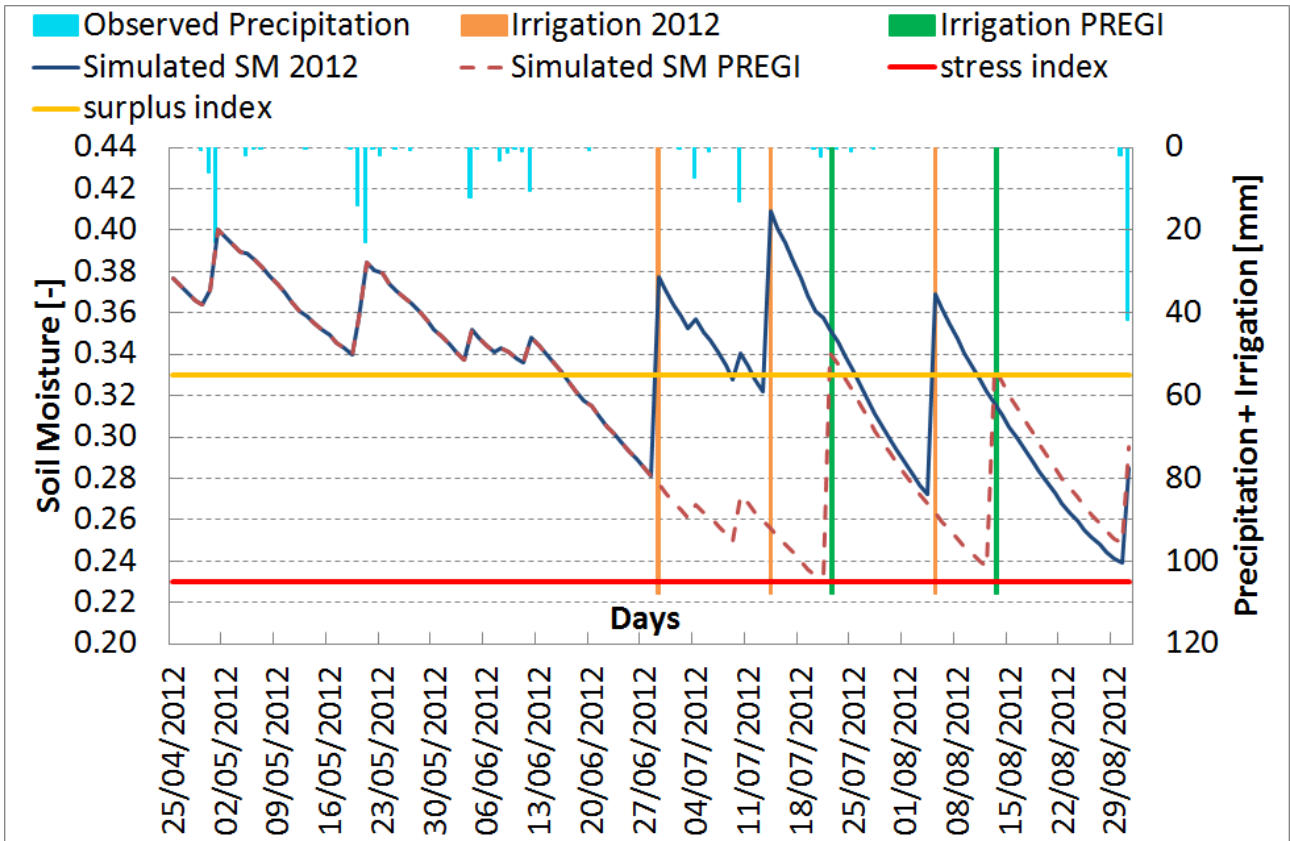
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1 Figure 6: Soil moisture forecasts issued on 28 June (a-b), 12 July (c-d), 20 July (e-f), 5 August (g-h)
2 and 11 August (i-j) without planning irrigations (left) and with including irrigation amounts in
3 simulations (right). For the sake of clarity, only the mean (yellow line), the median (solid blue line),
4 the 25th and 75th percentile (respectively grey and black lines) are shown; the median of forecasted
5 precipitation is shown with a dashed blue line while the scheduled irrigations are shown with light
6 blue bars.

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3 Figure 7: Comparison between simulated soil moisture by the FEST-WB model assuming that the
4 landowner had followed his decision criteria (blue line) with three actual irrigations (orange bars) in
5 2012, and if the farmer had followed the PREGI system (dashed brown line) with two hypothetical
6 irrigations (green bars); the observed rainfall is shown with light blue bars.

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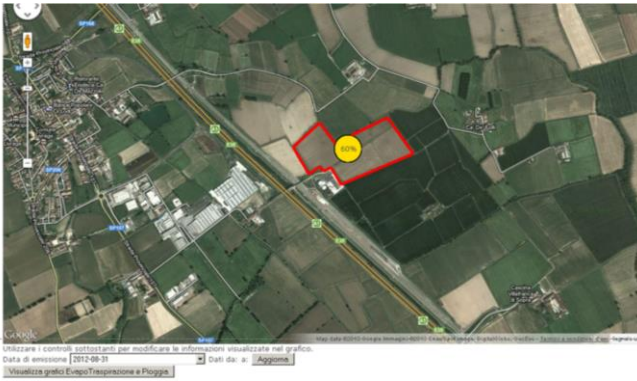
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3 Fig. 8: View of the google map platform of the PREGI Project. The Cascina Nuova field in Livraga
4 is outlined in red. This example shows 60% probability (i.e. 12 ensembles out of 20) of exceeding
5 the surplus threshold in at least one of the subsequent 30 days with the forecast simulation started
6 on 31 August 2012.

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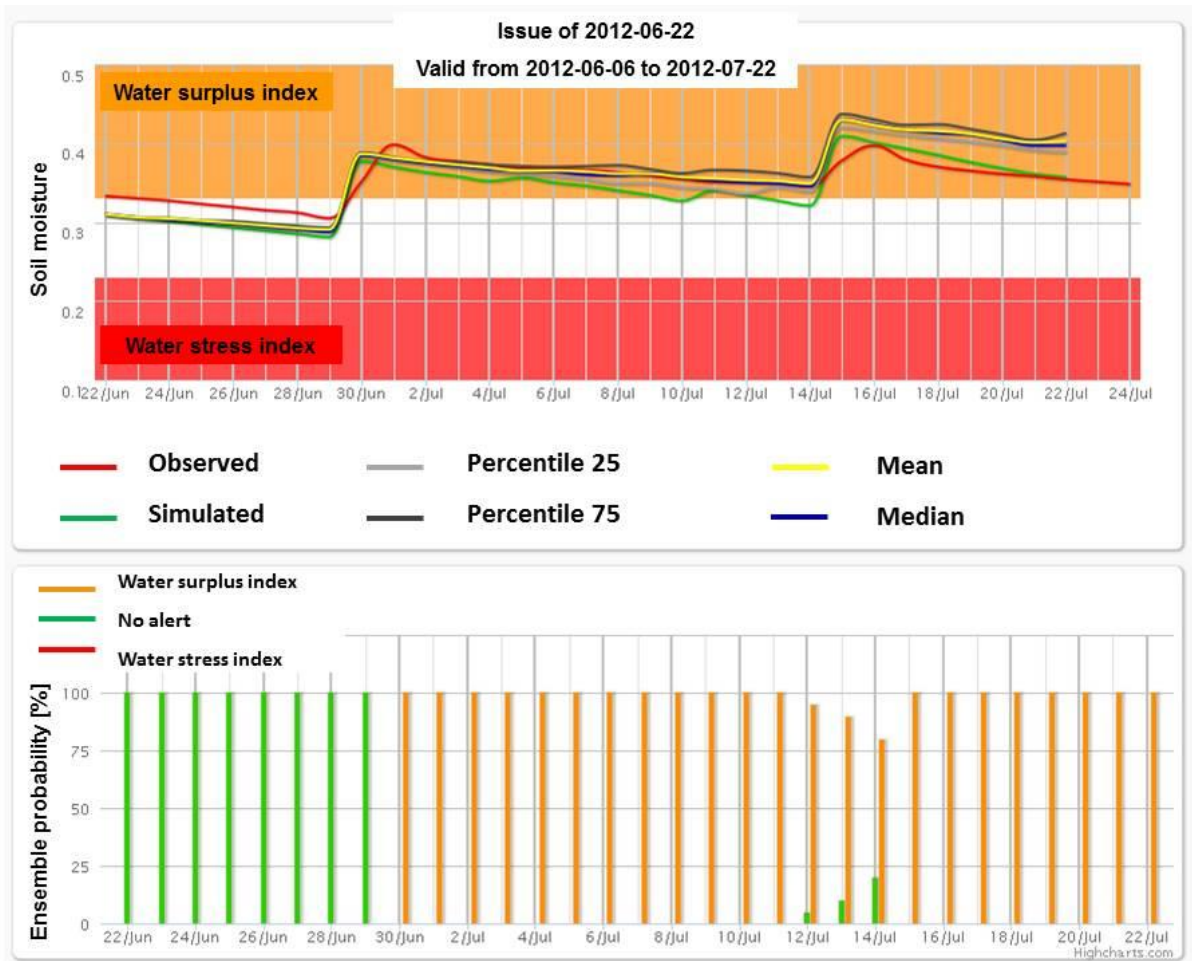
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3 Fig. 9: Soil moisture re-analysis forecast initialized on 22-06-2012 valid until 22-07-2012. The red
4 line shows the average value of soil moisture measured with three TDR probes; the green line
5 shows the simulated soil moisture using the FEST-WB model initialized with observed data, and
6 the grey, blue, black and yellow lines show the forecasted soil moisture value by the FEST-WB
7 model initialized with the REPS-WRF meteorological model respectively for the 25th, 50th, 75th
8 percentile and the mean.

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