

**Real time drought forecasting system
for irrigation
management**

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Real time drought forecasting system for irrigation management

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Abstract

In recent years frequent periods of water scarcity have enhanced the need to use water more carefully, even in European areas traditionally rich of water such as the Po Valley in northern Italy. In dry periods problems of water shortage can be enhanced by conflictual uses of water such as irrigation, industrial and power production (hydroelectric and thermoelectric). Further, over the last decade the social perspective about this issue is increasing due to possible impacts of climate change and global warming scenarios which come out from the fourth IPCC Report. The increased frequency of drought periods has stimulated the improvement of irrigation and water management.

In this study we show the development and implementation of the real-time drought forecasting system PRE.G.I., an Italian acronym that stands for “Hydro-Meteorological forecast for irrigation management”.

The system is based on ensemble prediction (20 members) at long-range (30 days) with hydrological simulations of water balance to forecast the soil water content over a maize field.

The hydrological model was validated against measurements of latent heat flux acquired by an eddy-covariance station, and soil moisture measured by TDR probes. Reliability of the forecasting system and its benefits were assessed on the growing season of 2012.

Obtained results show how the proposed drought forecasting system is able to have a high reliability of forecast at least for a fortnight as lead time.

1 Introduction

The lack of water has always been one of the most critical factors for people survival around the world. The United Nations have proclaimed the year 2003 as the international year of freshwater and the year 2006 as the international year of deserts

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and desertification, highlighting the importance in prevention, mitigation, and adaption of events related to water supply.

Future climate change scenarios combined with limited water resources require better irrigation management and planning; this has also occurred in areas habitually full of water as the Lombardy region, in the north of Italy.

Recent studies demonstrate that there is not a significant decrease in precipitation amounts, although a reduction of total precipitation in the last twenty years has been observed over Italian country (Salerno et al., 2007). However, a new and more frequent distribution of extreme events has been shown (Maugeri, 2006), as occurred in the most recent drought episodes of the years 2003, 2005 and 2006 in the Lombardy region (Craveri, 2006).

Scientific literature provides some studies focused on the optimization of irrigation management coupling meteorological and hydrological models. Some of main international studies are: the EPIC-PHASE model developed at the center of Toulouse (Cabelguenne et al., 1997), the real-time scheduled irrigations approach in UK proposed by Gowing and Ejeji (2001), the Danish warning system “eWarning” (Jensen and Thysen, 2003), and real-time forecasts for daily evapotranspiration proposed by Cai et al. (2007). In the north of Italy the recurrence of water stress periods has improved the management and coordination of water bodies (lakes, hydroelectric reservoirs, rivers, etc.), together with testing other alternative sources such as water withdrawals from large quarry lakes (Ravazzani et al., 2011a). This activity has foreseen a better management of water distribution by water consortia according to season, different cultivation requests and total available water in lakes and snowpack. For a consortium a prudent policy of water distribution means a wiser and thriffter way of irrigation maximizing the agricultural production. However, these management policies are currently based on sensitivity and experience of managers. A policy of saving the irrigation turn would be helpful if districts were subsequently affected by significant rainfall, but extremely dangerous if no precipitation will occur in the following weeks. It is clear that the complexity of these matters related to water resources should

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be studied with a scientific and engineering approach, in order to be able to predict in advance the occurrence of potentially harmful droughts; this latter it is even one of the main goal of DEWFORA Project (2011) which focus on drought early warning and mitigation in African countries.

5 In this context an adoptable methodology is the one used for real-time flood predictions (Rabuffetti et al., 2008; Ceppi et al., 2013), coupling meteorological forecasts with hydrological simulations.

The application we proposed in this paper provides a useful product to water resource management and to customers involved in agriculture field.

10 The knowledge of Quantitative Precipitation Forecasts (QPFs) for the following weeks combined with the updating of hydrological conditions of the system is fundamental for water distribution management and irrigation purposes. The PRE.G.I. system is based on ensemble forecasts at long-range with hydrological simulations of water balance to forecast the soil moisture at field scale. The studied area is the Muzza Bassa Lodigiana consortium (MBL) in the middle of the Po Valley, near the city of Lodi (Fig. 1a). Hydrological ensemble forecasts are based on 20 meteorological members of the non-hydrostatic WRF-ARW model with one month as lead-time, provided by Epsom Meteo Centre, while the hydrological model used to generate soil moisture simulations is the rainfall-runoff distributed FEST-WB model developed at Polytechnic of Milan (POLIMI).

2 Area of study

The territory of the Muzza Bassa Lodigiana consortium (MBL) covers an area of 740 km². Within the 74 000 ha there are over 150 irrigation basins and thousands of irrigation sub basins with individual fields of landowners (Fig. 1b).

25 The Muzza canal (about 40 km long) derives water from the Adda River at Cassano d'Adda and it flows back into the Adda River close to Castiglione d'Adda. Along the canal there are 38 intakes and many more hydraulic nodes; the entire Muzza network

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is composed by open earth canals. The Muzza is both the largest irrigation canal by capacity and the first artificial canal built in northern Italy.

Average annual rainfall measured in the MBL Consortium are between 800 (southern area) and 1000 mm (northern area) with two peaks in spring and autumn. During the summer season most of water supply comes from the irrigation network. The upper-medium part of the basin is irrigated by surface water flowing, while in the bottom part of the basin water is lifted by the Adda and Po rivers through proper pumping systems. Our test-site is located in central area of the basin at Cascina Buona farm, in Livraga town, where meteorological, eddy-covariance stations and TDR probes for evapotranspiration fluxes and soil moisture profile respectively have been installed to measure hydrological processes (Masseroni et al., 2012).

3 Models

The drought cascade forecasting system applied in this study is currently based on hydrological model initialization from meteorological model output, providing soil moisture forecasts at 30 days as lead time and obtaining useful information for irrigation management procedures. Two fundamental meteorological fields are available every two days: temperature and precipitation provided at 12h intervals as driving input into the hydrological model for soil moisture simulations. The hydrological model is initialized with a simulation run forced with observed data, provided by the ARPA Lombardy and Meteonetwork-Epson Meteo Centre meteorological station network to create initial conditions.

In addition to observed and forecasted data, the knowledge of scheduled irrigation dates are fundamental to calculate the irrigation water input over the experimental field of Livraga.

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3.1 Meteorological model

The probabilistic forecast is supplied by a Regional Ensemble Prediction System (REPS), based on the WRF-ARW model, implemented and developed by the Epson Meteo Centre (EMC). The REPS-WRF used in this project has a grid mesh size of 18 km, 36 vertical levels and 20 members; boundary and initial conditions are provided by a global ensemble prediction system (GEPS) based on a modified version of the WRF-ARW applied to the global scale, which has a grid mesh size of 200 km and the same number of vertical levels as REPS, and it uses the same initial conditions in the control runs provided by the 12:00 UTC GFS analysis at 0.5° of horizontal resolution. The forecast has a lead time of 30 days and the output fields are produced every 12 h. Each perturbation of the ensemble is produced by an algorithm developed by EMC based on a special application of Ensemble Transform Kalman Filter (EnTKF) able to allow covariance localization whilst maintaining computational efficiency and removing spurious long-range correlations. The combined system GEPS-REPS is carried out every two days. The REPS-WRF run starts at 00:00 UTC, the same initial time of the hydrological simulation. For a detailed description of WRF model, the reader can refer to Skamarock and Klemp (2008).

3.2 Hydrological model

In this study hydrological simulations are performed using the FEST-WB distributed water balance model, spatially distributed and physically-based, developed entirely at Polytechnic of Milan since 1990. The FEST-WB is a rainfall-runoff model, and the acronym stands for “Flash Flood Event-based Spatially-distributed rainfall-runoff Transformations-Water Balance”.

The FEST-WB calculates the main processes of the hydrological cycle: evapotranspiration, infiltration, surface runoff, flow routing, subsurface flow, snow dynamics and soil water content. The computational domain is discretized with a mesh

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of regular square cells (200 m in this application), in which soil moisture is calculated at daily time intervals.

The model requires observed data of precipitation and air temperature coming from ground stations which are interpolated to a regular grid using the inverse distance weighting technique. For further details about development of the FEST-WB, the reader can refer to Montaldo et al. (2003, 2007), Ravazzani et al. (2007, 2011b), Corbari et al. (2011), and Ravazzani (2013).

As far as concerning soil information, in situ field tests carried out during the PRE.G.I. Project classify the soil texture as silt loam according to the USDA classification; in particular, a content in clay of 19.2 %, in silt of 48.1 %, and in sand of 32.7 % was found in soil analyses.

Different measures of permeability were performed with the Guelph infiltrometer to investigate the hydraulics conductivity which turned out to be of $2.36 \times 10^{-7} \text{ ms}^{-1}$ in the studied field. Table 1 summarizes main soil properties implemented in the FEST-WB model for the maize field in Livraga.

Another important parameter to define in the hydrological model for water volume computation is the soil depth which has been modeled as one single layer with a value of 0.7 m, considering the predominant growing zone of maize roots; consequently the three TDR probes were installed at 10, 35 and 60 cm depth.

As described in Sect. 4, observed and forecasted data of soil moisture are influenced by water irrigation turns and evapotranspiration fluxes which denote main inflows and outflows in water balance during the summer season at Livraga field scale. In particular, each field of the Muzza consortium has its own scheduled irrigation turn following centuries old time tables where planned irrigations are reported. The scheduled turn in the Livraga experimental field is 2 weeks, i.e. the landowner has the possibility to withdraw water from the nearest irrigation ditch every 14 days. Theoretical water concession for the Cascina Nuova farm is 650 L s^{-1} taken from the “Porra Nuova” ditch, but considering that the irrigation efficiency of the Muzza basin is about 45 % out of the theoretical value, the available water discharge is only about 300 L s^{-1} . Since this

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water amount is used to irrigate our experimental field of 8 ha in about 8 h, the irrigation contribution estimated and implemented in the FEST-WB model is 108 mm.

In addition to irrigation contributions, evapotranspiration losses plays a crucial role in the water balance during the summer season in the Po Valley area with cumulated values that could exceed 300 mm in four months (see Figs. 2, 3 and 5).

In the used version of the FEST-WB model, evapotranspiration is computed according to a revised version of the FAO-56 method (Allen et al., 1998). The original approach is based on the use of the Penman–Monteith equation to compute a reference evapotranspiration (ET_0) of a surface defined as an “hypothetical crop with an assumed height of 0.12 m having a surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evaporation of an extension surface of green grass of uniform height, actively growing and adequately watered” (Allen et al., 1998). In this paper, due to the availability of only air temperature meteorological forecast, the Penman–Monteith equation is substituted with a modified Hargreaves and Samani equation (Hargreaves and Samani, 1985) which includes a correction factor for altitude (Ravazzani et al., 2012). In Ravazzani et al. (2012) the reliability of this modified equation to compute ET_0 , has been demonstrated.

Then, the crop coefficient (k_c), which embodies all the physiologic characteristics of a specific plant, allows passing from ET_0 to the potential evapotranspiration of a specific crop. Allen et al. (1998) created a database of k_c for a large number of agricultural crops in different climates including maize. Crop coefficient values are assigned by defining the length of phenological phases considering the sowing and reaping dates for each year.

3.3 Coupling strategy

The coupling of hydro-meteorological models and the knowledge of irrigation turn let know in advance soil moisture content and expected cumulated precipitation for irrigation management and water control from 1 up to 30 days as forecast horizon.

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In order to value soil moisture conditions, probabilistic forecasts are compared with two thresholds: one is the water surplus equal to the field capacity of the soil and the other is the stress threshold, where below this point the crop begins to suffer a lack of water. According to Baroni et al. (2010) this latter is calculated as follow (Eq. 1):

$$5 \quad \text{RAW} = \rho \cdot \text{TAW} \quad (1)$$

where RAW is the Readily Available Water, TAW is the Total Available Water and ρ is coefficient depending on the crop and climatic parameters which can be assumed equal to 0.5 for maize (Allen et al., 1998) in the Livraga field; hence the Eq. (1) becomes:

$$\text{Stress threshold} = \text{field capacity} - 0.5 \cdot (\text{field capacity} - \text{wilting point}) \quad (2)$$

Since this soil has been characterized as silt loam, the two values are 0.23 and 0.33, respectively for the stress and water surplus threshold.

15 **4 Results and discussion**

4.1 Calibration and validation of the FEST-WB model

The years between 2010 and 2012 were used to calibrate and validate the hydrological model with acquired data at Cascina Nuova field in Livraga where one eddy covariance station and three TDR probes were installed to monitor soil moisture content and evapotranspiration fluxes; unfortunately, some observed data are missing due to storage battery problems in the three-year project.

The following Figs. 2 and 3 show the comparison between measured values (red line) by TDR probes (actually, it is a weighting average of the three measures at 10, 35 and 70 cm depth) and simulated data by the FEST-WB model (blue line) during the two growing seasons of 2010 and 2011, including rainfall irrigation amounts over Livraga maize field.

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Figure 2a shows how soil moisture peaks are well associated with rainfall and irrigation input with a Mean Absolute Error (MAE) of 4% and Mean relative Error (MRE) of +1% with a good agreement between model and simulation data even for the real cumulated evapotranspiration (Fig. 2b). It clearly appears how the first seasonal irrigation (14 June) could have been avoided if soil moisture forecasts were known in advance: in fact, severe rainfall (about 85 mm) occurred between 15 and 20 June with a maximum peak of 45 mm on 15 June (just the day after the irrigation!); only after this event, it was decided to skip the next irrigation turn scheduled on 29 June.

The following season (2011) was less abundant in terms of precipitation amount in northern Italy, but significant rainfall occurred during the first ten days of June with approximately 150 mm fallen over Livraga maize fields; this event induced the landowner to skip the irrigation turn scheduled on 14 June.

Figure 3 shows satisfactory comparisons between observed and simulated values both in terms of soil moisture (MAE equal to 8%) and cumulated evapotranspiration, even if an underestimation (MRE of -8%) is generally present in simulated soil moisture values (Fig. 3a), mainly due to higher rates in evapotranspiration simulation (Fig. 3b).

After two years of calibration, a validation of the FEST-WB model was carried out for the growing season of 2012 at Livraga field where precise observations with TDR probes and eddy covariance measures were compared with model simulations at a spatial resolution of 200 m × 200 m.

The performance of the validation (Fig. 4a) reaches a good match between model and observations with a Mean Absolute Error (MAE) of 7% and MRE of -1%. A slight underestimation of the FEST-WB is generally present except at the beginning of the season; however the hydrological model initialized with observed values by the ARPA (Regional Agency for Environmental Protection) of Lombardy and Meteonetwork-EMC weather stations, was able to simulate soil moisture conditions with a daily error within 10%, in particular during the irrigation period which is usually between June and August.

Even the comparison between observed (red line) and simulated (blue line) data for the real cumulated evapotranspiration (Fig. 4b) shows a good agreement during the growing season of 2012.

Although the model validation was carried out at the end of the growing season, hydro-meteorological forecasts were set up in real-time during the 2012 for the PRE.G.I. Project. Actual soil moisture conditions and forecasts led the landowner to postpone one week later the irrigation turn scheduled on 29 July; this decision let the plant phenological phase be extended till end of August when the maize was finally harvested.

4.2 The PRE.G.I. performance

One of the main goals of the PRE.G.I. Project was indeed to couple weather and hydrological models to give soil moisture forecasts as a support decision system in irrigation management over the Livraga maize field. The hydro-meteorological chain was set up using the REPS-WRF output provided by the EMC into the FEST-WB hydrological model developed by the POLIMI. Soil moisture comparisons were carried out between observed and simulated values by FEST-WB initialized with observed and forecasted by the REPS-WRF model weather data; since the WRF is a probabilistic model with 20 ensemble members, the median value was chosen for analysis clearness.

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. Since the weather model has a forecast horizon of 30 days, the statistical analysis has been done 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 from the initialization date as lead time. The statistical analysis in this paper was done using common skill score known in literature (Wilks, 2006; Jolliffe, 2003).

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values:

$$E_{ns} = 1 - \frac{\sum_{i=1}^n (O_i - F_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad (4)$$

The reason to consider the sum of rainfall and irrigation cumulated in different days of forecast horizon, and not the forecasted amount in 24 h for a single day, answers the aims of the Pre.G.I project: in fact, for irrigation management it is more important to know if a wet or dry period is coming on in the next 7 or 14 days, which usually coincide with days of irrigation turnation in the MBL fields, rather than if a precipitation event will exactly occur on 14th or 15th day of forecast. However, in the following picture (Fig. 7) the REPS-WRF model performance is analyzed only with forecasted precipitation, excluding irrigation contribution.

The comparison is done using the Brier Score index, which is essentially the mean-squared error of the probability forecasts, considering that the observation is $o = 1$ if the event occurs and $o = 0$ if the event does not occur. The score averages the squared differences between pairs of forecast probabilities and the subsequent observations (Wilks, 2006). Equation (5) for the BS score is:

$$\text{Brier Score: } BS = \frac{1}{n} \sum_{k=1}^n (F_k - O_k)^2 \quad (5)$$

where n = number of forecasting instances, F_k = the probability that an event was forecasted, O_k = the actual outcome of the event at instance k (0 if it does not happen and 1 if it happens).

For instance, suppose that the forecast probability to exceed a cumulated rainfall threshold is 70 % and then this event occurs, the BS score is equal to 0.09; vice versa if it does not occur the BS score is 0.49; therefore best scores are close to 0.

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evaluated. Soil moisture simulations by the FEST-WB hydrological model initialized with observed data by the ARPA of Lombardy and Meteonetwork-EMC station network are shown in green line and the forecasted data by the 20 ensembles of the REPS-WRF meteorological model in colored lines. In Fig. 9 we do not report all the 20 ensembles, but only the 25th percentile, the median, the 75th percentile and the mean of ensemble forecasts (respectively grey, blue, black and yellow lines). The average value of soil moisture measured with TDR probes in Livraga test-bed is shown in red line for the entire forecast horizon; as described in Sect. 3, the area below the stress threshold (0.23) is highlighted in red, while the one above the field capacity point (0.33) is shown in orange.

The next picture (Fig. 10) shows the cumulated inflows (as sum of rainfall and planned irrigations) for the entire horizon. The two irrigations scheduled on 29 June and 14 July 2012 raised significantly soil moisture values in the following days above the water surplus threshold as shown in Fig. 10.

The comparison between the REPS-WRF model forecast and the observed value at Livraga rain gauge (leaving out the two scheduled contributions coming from irrigations which are known a priori) shows a good agreement during the central phase of the maize growing season.

5 Conclusions

The aim of the PRE.G.I. Project is to realize an integrated system coupling meteorological and hydrological models to monitor and forecast soil water contents in the Muzza consortium (MBL) in order to manage irrigation water in a wiser way. The test-bed of the project was the maize field at Livraga, about 50 km south-eastern Milan in northern Italy. The hydro-meteorological chain to produce ensemble soil moisture forecasts is based on 20 meteorological members of the non-hydrostatic WRF-ARW model with 30 days as lead-time, provided by the Epson Meteo Centre, while the

hydrological model used to generate soil moisture simulations is the rainfall-runoff distributed FEST-WB model, developed at the Polytechnic of Milano.

According to crop water consumption determined by the soil type and the degree of saturation, a continuous control and forecast of soil water content up to 30 days as lead time has been carried out during the entire growing season of 2012.

Considering that one of main targets of the project is to predict long dry periods that could affect the agricultural production, we focus the attention on cumulated precipitation forecasts for several days over the MBL basin in comparison with a precipitation forecast for one single day.

This developed tool for irrigation management has a higher reliability in comparison with flood forecasting systems, because it is characterized by slower and persistent weather dynamics over larger areas. One can consider, for instance, the large difference in hydrological processes between rainfall events with intensities which can reach up to 100 mm h^{-1} over areas of a few tens of km^2 (flood events) and events with evapotranspiration rates of about 7–8 mm per day over areas of a few thousand of km^2 (drought events).

Results show how combing meteorological and hydrological models it was possible to have reliable precipitation and soil moisture forecasts up to 10 and 20 days respectively, with a mean relative error less than 10 %; this helped famers in the water management at the Cascina Nuova field during the PRE.G.I. activities.

Benefits of this project are both direct and indirect: the first regard the monitoring and forecasting the soil water content according to the current state of soil moisture value and water crop requirements in order to reduce plant stress and maximize the production, while the latter regard the optimization of water irrigations pursuing the best quantitative distribution, in particular periods of water scarcity, in order to minimize production losses caused by water stress due to lack or insufficient watering.

One of future developments could be to extend these analyses over different sites with other case studies during future growing seasons. This opportunity is extremely useful in contexts of plural use of water resource. In fact, the joint knowledge of

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observed and forecasted soil moisture contents allows understanding real water crop demands in different season periods, avoiding the waste of irrigation water as occurred in the growing season of 2010.

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References

- Allen, R., Pereira, L., Raes, D., and Smith, M.: Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements, Food and Agriculture Organization of the United Nations (FAO) Irrigation and Drainage Paper No. 56, Rome, FAO, 300 pp., 1998.
- Baroni, G., Facchi, A., Gandolfi, C., Ortuani, B., Horeschi, D., and van Dam, J. C.: Uncertainty in the determination of soil hydraulic parameters and its influence on the performance of two hydrological models of different complexity, *Hydrol. Earth Syst. Sci.*, 14, 251–270, doi:10.5194/hess-14-251-2010, 2010.
- Cabelguenne, M., Debaeke, Ph., Puech, J., and Bosc, N.: Real time irrigation management using the EPIC – PHASE model and weather forecasts, *Agr. Water Manage.*, 32, 227–238, 1997.
- Cai, J., Liu, Y., Lei, T., and Pereira, L. S.: Estimating reference evapotranspiration with the FAO Penman – Monteith equation using daily weather forecast messages, *Agr. Forest Meteorol.*, 145, 22–35, 2007.
- Ceppi, A., Ravazzani, G., Salandin, A., Rabuffetti, D., Montani, A., Borgonovo, E., and Mancini, M.: Effects of temperature on flood forecasting: analysis of an operative case study in Alpine basins, *Nat. Hazards Earth Syst. Sci.*, 13, 1051–1062, doi:10.5194/nhess-13-1051-2013, 2013.
- Corbari, C., Ravazzani, G., and Mancini, M.: A distributed thermodynamic model for energy and mass balance computation: FEST-EWB, *Hydrol. Process.*, 25, 1443–1452, 2011.

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Craveri, L.: Siccità nel clima lombardo. L'esperienza del 2003, in Regione Lombardia. ERSF e Agriteam (ac. di) in L'acqua, una risorsa per il sistema agricolo lombardo, 27–30, 2006 (in Italian).

DEWFORA Project: available at: <http://www.dewfora.net>, last access: October 2013, 2011.

Gowing, J. W. and Ejieji, C. J.: Real-time scheduling of supplemental irrigation for potatoes using a decision model and short term weather forecasts. *Agr. Water Manage.*, 47, 137–153, 2001.

Hargreaves, G. H. and Samani, Z. A.: Reference crop evapotranspiration from temperature, *Appl. Eng. Agric.*, 1, 96–99, 1985.

Jensen, A. L. and Thyssen, I.: Agricultural information and decision support by SMS, EFITA 2003 Conference, 5–9 July 2003, Debrecen–Budapest, Hungary, 286–292, 2003.

Jolliffe, I. T. and Stephenson, D. B.: *Forecast Verification: a Practitioner's Guide in Atmospheric Science*, John Wiley and Sons, New York, 2003.

Maidment, D. R.: *Handbook of Hydrology*, McGraw-Hill, New York, 1993.

Masseroni, D., Ravazzani, G., Corbari, C., and Mancini, M.: Turbulence integral length and footprint dimension with reference to experimental data measured over maize cultivation in Po Valley, Italy, *Atmosfera*, 25, 183–198, 2012.

Maugeri, M.: Variabilità e cambiamenti climatici nel corso degli ultimi due secoli: evidenze osservative e problemi aperti. ERSF e Agriteam (ac. di) in L'acqua, una risorsa per il sistema agricolo lombardo, 17–23, 2006 (in Italian).

Montaldo, N., Toninelli, V., Albertson, J. D., Mancini, M., and Troch, P. A.: The effect of background hydrometeorological conditions on the sensitivity of evapotranspiration to model parameters: analysis with measurements from an Italian alpine catchment, *Hydrol. Earth Syst. Sci.*, 7, 848–861, doi:10.5194/hess-7-848-2003, 2003.

Montaldo, N., Ravazzani, G., and Mancini, M.: On the prediction of the Toce alpine basin floods with distributed hydrologic models, *Hydrol. Process.*, 21, 608–621, 2007.

Rabuffetti, D., Ravazzani, G., Corbari, C., and Mancini, M.: Verification of operational Quantitative Discharge Forecast (QDF) for a regional warning system – the AMPHORE case studies in the upper Po River, *Nat. Hazards Earth Syst. Sci.*, 8, 161–173, doi:10.5194/nhess-8-161-2008, 2008.

Ravazzani, G.: MOSAICO, a library for raster based hydrological applications, *Comput. Geosci.*, 51, 1–6, 2013.

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Ravazzani, G., Mancini, M., Giudici, I., and Amadio, P.: Effects of soil moisture parameterization on a real-time flood forecasting system based on rainfall thresholds, in: Quantification and Reduction of Predictive Uncertainty for Sustainable Water Resource Management, Proc. Symposium HS 2004 at IUGG 2007, Perugia, 2–13 July 2007, IAHS Publ., 313, 407–416, 2007.

Ravazzani, G., Giudici, I., Schmidt, C., and Mancini, M.: Evaluating the potential of quarry lakes for supplemental irrigation, *J. Irrig. Drain. Engin.*, 137, 564–571, 2011a.

Ravazzani, G., Rametta, D., and Mancini, M.: Macroscopic Cellular Automata for groundwater modelling: a first approach, *Environ. Modell. Softw.*, 26, 634–643, 2011b.

Ravazzani, G., Corbari, C., Morella, S., Gianoli, P., and Mancini, M.: Modified Hargreaves–Samani equation for the assessment of reference evapotranspiration in Alpine river basins, *J. Irrig. Drain. Engin.*, 138, 592–599, 2012.

Salerno, R., Giuliacci, M., and Bertolani, L.: Climate change in Italy: an assessment of data and reanalysis models, in: Mountains: witnesses of global changes—research in the Himalaya and Karakoram, edited by: Baudo, R., Tartari, G., and Vuillermoz, E., Elsevier B.V., 10, 123–132, 2007.

Skamarock, W. C. and Klemp, J. B.: A time-split nonhydrostatic atmospheric model for research and NWP applications, *J. Comput. Phys.*, 227, 3465–3485, doi:10.1016/j.jcp.2007.01.037, 2008.

Zappa, M., Rotach, M. W., Arpagaus, M., Dorninger, M., Hegg, C., Montani, A., Ranzi, R., Ament, F., Germann, U., Grossi, G., Jaun, S., Rossa, A., Vogt, S., Walser, A., Wehrhan, J., and Wunram, C.: MAP D-PHASE: real-time demonstration of hydrological ensemble prediction systems, *Atmos. Sci. Lett.*, 2, 80–87, 2008.

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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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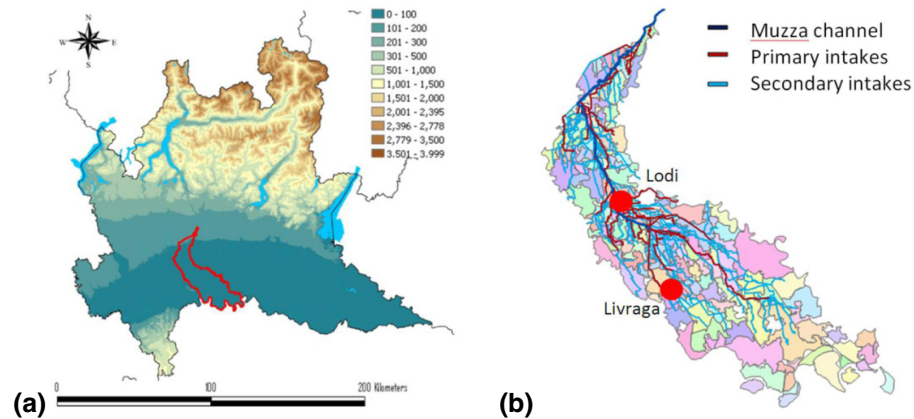


Fig. 1. The Lombardy region in the North of Italy **(a)** and the Muzza basin with its irrigation sub basins **(b)**.

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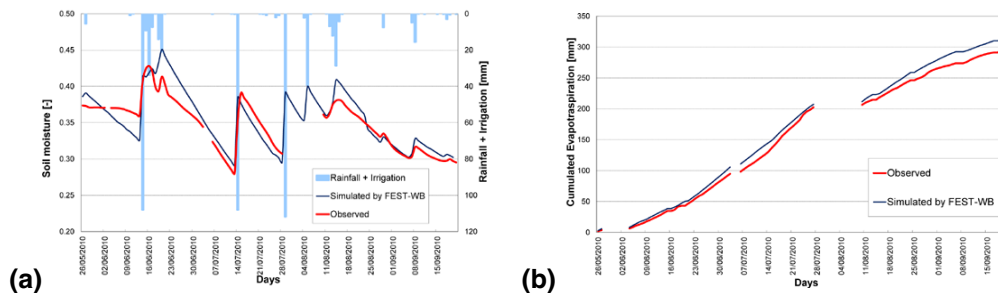


Fig. 2. Comparison between observed (red line) and simulated (blue line) soil moisture values by the FEST-WB model at Livraga maize field for the growing season of 2010; precipitation and irrigation amounts are shown in light blue histograms (a). Comparison between observed (red line) and simulated (blue line) real cumulated evapotranspiration values (b).

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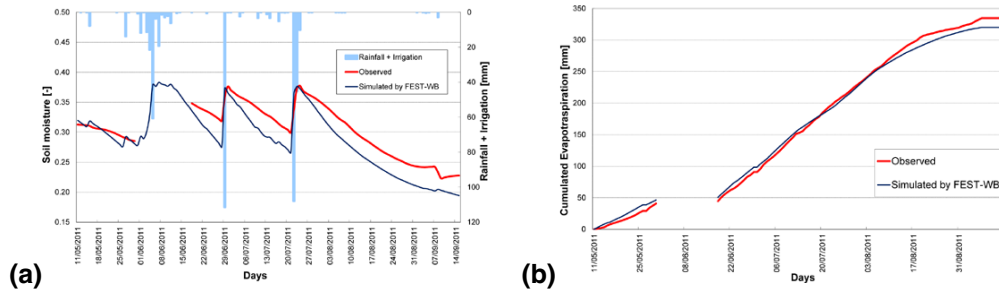


Fig. 3. Comparison between observed (red line) and simulated (blue line) soil moisture values by the FEST-WB model at Livraga maize field for the growing season of 2011; precipitation and irrigation amounts are shown in light blue histograms **(a)**. Comparison between observed (red line) and simulated (blue line) real cumulated evapotranspiration values **(b)**.

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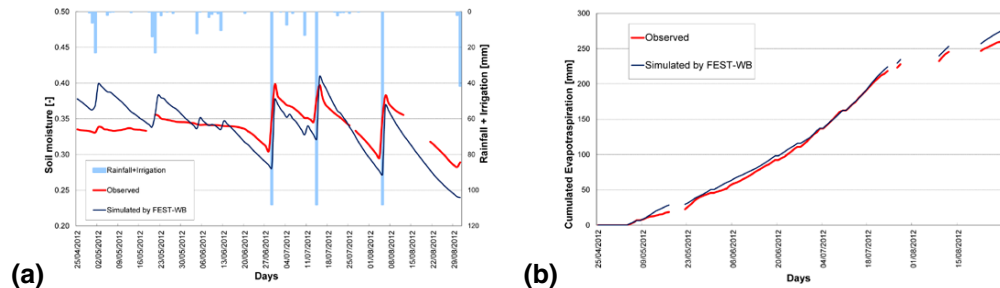


Fig. 4. Comparison between observed (red line) and simulated (blue line) soil moisture values by the FEST-WB model at Livraga maize field for the growing season of 2012; precipitation and irrigation amounts are shown in light blue histograms (a). Comparison between observed (red line) and simulated (blue line) real cumulated evapotranspiration values (b).

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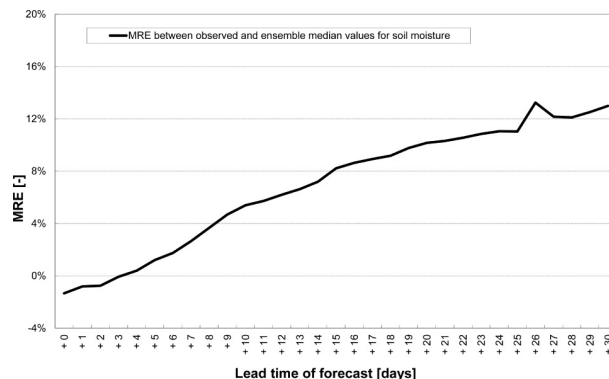


Fig. 5. The Mean Relative Error for soil moisture between observed data and the median of the all FEST-WB simulations forced with the 20 ensemble of REPS-WRF model at different lead time for the growing season 2012.

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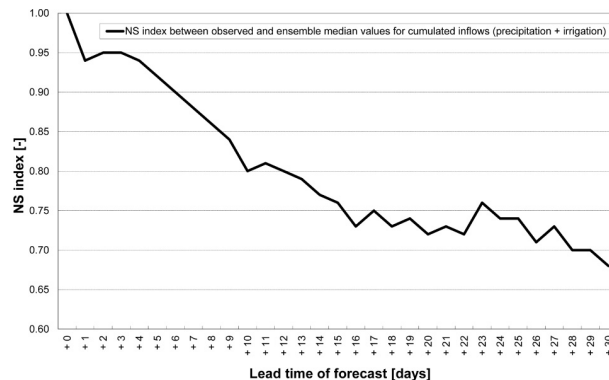


Fig. 6. The NS index for rainfall and irrigation amounts between observed data and the median of 20 ensemble of the REPS-WRF model at different lead time for the growing season 2012.

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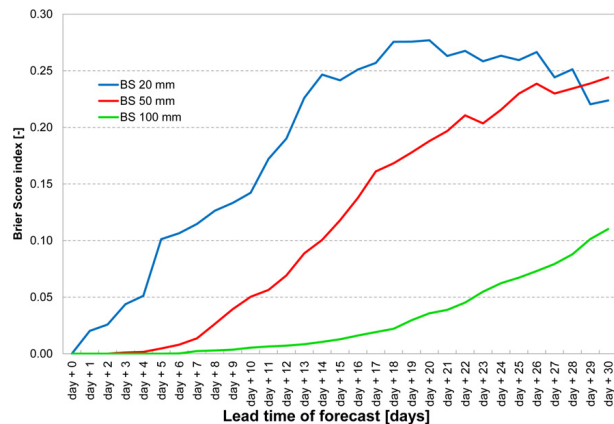


Fig. 7. Brier score index for three cumulated rainfall thresholds: 20 mm (blue line), 50 mm (red line) and 100 mm (green line).

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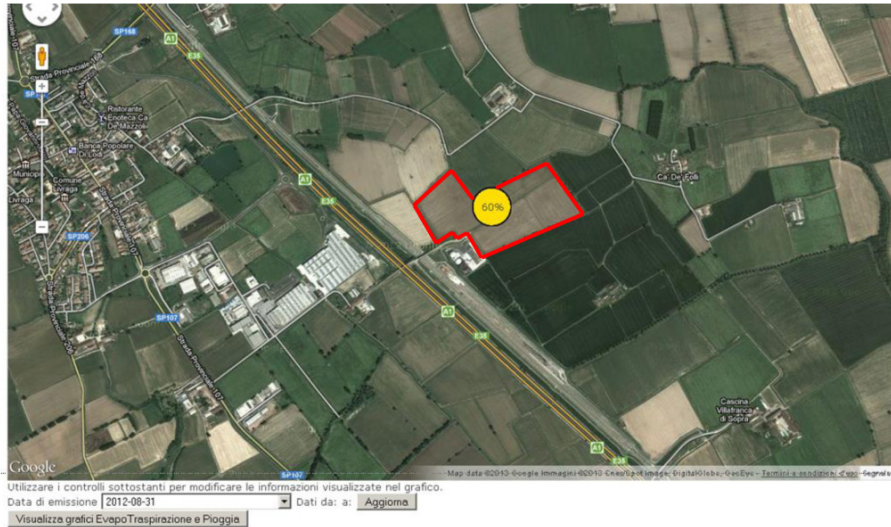


Fig. 8. View of the google map platform of the PRE.G.I. Project. Red contours bound the Cascina Nuova field in Livraga.

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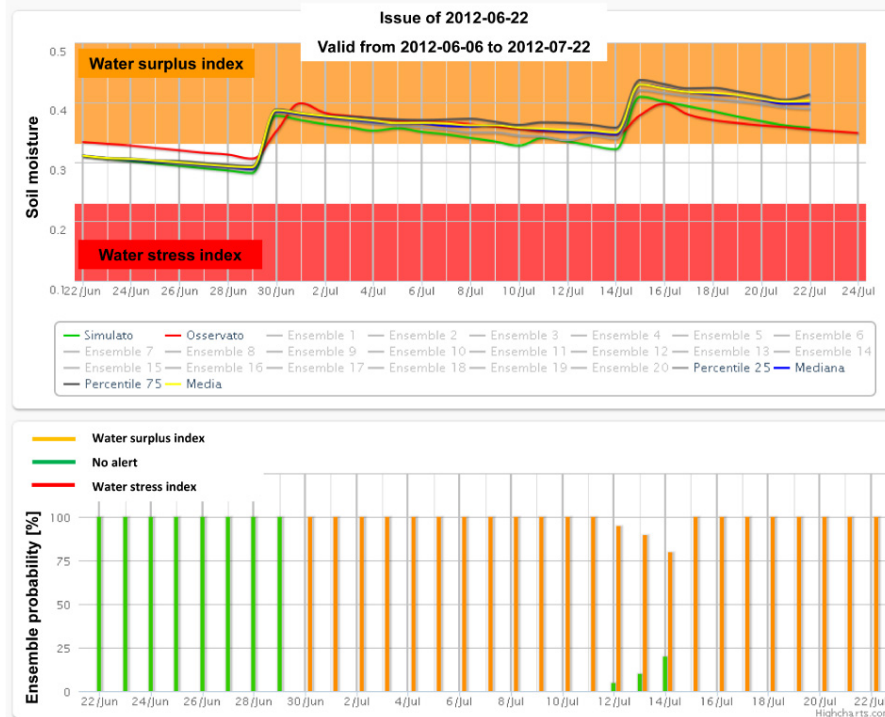


Fig. 9. Soil moisture reanalysis forecast initialized on 22 June 2012 valid until 22 July 2012. Red line shows the average value of soil moisture measured with three TDR probes, green line shows the simulated soil moisture using the FEST-WB model initialized with observed data, and grey, blue, black and yellow lines show the forecasted soil moisture value by the FEST-WB model initialized with the REPS-WRF meteorological model respectively for the 25 %, 50 %, 75 % percentile and the mean.

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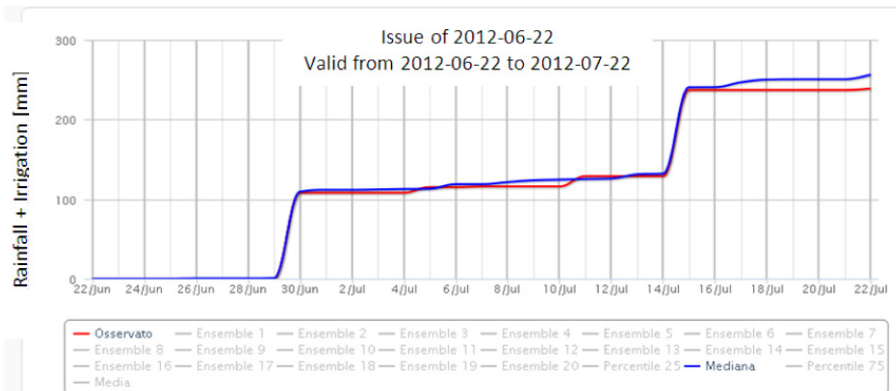


Fig. 10. Analysis of the cumulated rainfall forecasts initialized on 22 June 2012 valid until 22 July 2012. Red line shows the observed precipitation and irrigation inflows at Livraga and the blue line the median of ensemble forecasts of the REPS-WRF meteorological model.

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