Dear Editor,

Thank you very much for taking into account our paper.

In the following table, we answer in detail to every comment given by you and all the reviewers. Thanks to your observations, we have corrected our mistakes, modified some sections and improved the quality of the paper.

Kind regards

The authors

Comments by the editor	Comments by authors
On many issues raised by the reference	We modified and added in the paper the answers
you already state in the replice that	provide and added in the paper the answers
you will add the modifications/details	previously explained to the referees, as you suggested.
that are asked for In reference to	
that are asked for. In reference to	
the issue in the weals but do not	
the issue in the reply, but do not	
state that you will modify the revised	
manuscript accordingly (one of such	
examples is the addition of the steps	
from Eq 1 to Eq. 2): I suggest you to	
always do so (11 the referees, who are	
experts in this research area, cannot	
understand the meaning of a paragraph	
or of a figure, the 'average' reader	
will have even more difficulties).	
One of the main issue is that of the	In Section 2.2 (Pag. 5) we describe the coupling strategy
data employed for calibration and	for the forecasting chain between meteorological and
validation of the hydrological model:	hydrological model, and the available dataset where we
the use of the observations and meteo	explain which parameters were calibrated, which hydro-
forecasts of the 3 years should be	meteorological data were measured and which are the
clarified, as highlighted by all	required information to set up the hydrological model.
referees.	
Reformulate 11. 13-21 of page 15815 to	
clarify how the hydrological is	
initialized (see Ref2's comment).	
Concerning data availability and the	a) In order to set up the hydrological model, it is
use of field measures (often not	necessary (Pag. 5, section 2.2):
available in real-world applications),	
you should also better clarify which	- Land use
model parameters are derived from	- Water retention properties for the soil texture
measures and which have been	(Table 1)
calibrated, see Refl's comment (in	- Soil depth
fact nor the caption nor the text	- Hydraulic conductivity (Ks)
referring to Table 1 state that such	- Soil moisture
values refers to parameters that were	- Type of vegetation (date of sowing and
optimised; and, if a calibration was	harvest)
performed, some details on the	- DEM
optimization procedure must be added).	- Aquifer parameters
	- Scheduled irrigations
	- Observed weather data (at least temperature
	and precipitation)
	Soil texture. Ks and soil moisture values were also
	measured in-situ
	Soil properties (shown in Table 1) for the Livraga silt
	loam soil were calibrated as well as the soil depth which

	was modelled as a single layer. As mentioned in the text (L.12, Pag. 6), eddy-covariance
	 measures to control actual evapotranspiration (E1) fluxes are not necessary for the PREGI target. b) In order to couple the FEST-WB model with the WRF meteorological model, weather forecasts (temperature and precipitation fields) are required.
And it is absolutely fundamental the addition, that you now intend to carry out as specified in your replies, to add a comparison between the simulations obtained with or without the use of the PREGI platform.	As it is shown in the text (Pag. 13), this issue is the main addition we did (Section 3.3). We re-ran two simulations: one assuming that the landowner follows the advice provided by the PREGI platform on when to irrigate, and the other assuming that he follows the currently planned decision criteria. The results show that one out of three irrigations could have been saved!
2) The second important issue is that of skill assessment and, related to that, the better definition and meaning of the thresholds, as raised by Ref2. Ref2 suggests to use Brier Skill Score for assessing the improvement of the proposed approach in respect to an unskilled standard forecast: if you do not have climatological information on the pilot case study, you may use persistence as a standard for reference.	As explained in the previous answers, we cannot use the climatological data, since weather data on our experimental test-site (Livraga) were available for the 3 project years (2010, 2011 and 2012) only, hence this period is not sufficient to be analysed from a climatological point of view. In regard to the persistence score, since a persistence forecast is defined as "a forecast that the current weather condition will persist and that future weather will be the same as the present (e.g., if it is raining today, a forecast predicting rain tonight)" (NOAA), this skill index is usually applied with daily precipitation values and not with cumulated values, such as we carried out for cumulated precipitation forecasts over a period of 1, 2, 3,, 30 days (Pag. 7).
The meaning of the threshold is not well-defined, too: rephrase ll. 1-5 p. 15824, clarifying the period of cumulated rainfall and the meaning of such thresholds; the phrase ' the last two values are quite equivalent' is indeed not clear as highlighted by Ref2.	As better explained in the text (L. 8-19, P10): In regard to the BS score, suppose that the forecast probability to exceed a threshold of cumulated rainfall 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. In this analysis, three thresholds were chosen: 20, 50, 100 mm; these last two values are reasonably similar to half and full irrigation in the Livraga maize field, while the 20 mm threshold corresponds to typical precipitation amounts in that area, which is not usually affected by heavy rainfall in the summer season, as occurred in 2012. It is important to bear in mind that this computation, performed with the entire forecast dataset, is not referred to daily precipitation values, but cumulated precipitation values over a period of 1, 2, 3, 30 days. For instance, the BS score at 7th day as lead time considers the occurrence probability of a cumulated precipitation forecast over a period of 7 days to exceed the threshold of 20, 50 or 100 millimeters (occurred over the same time period of 7 days).
Meaning and interpretation of Fig. 7 must be clarified too (mening of BS in reference to the thresholds).	 a) Fig. 7 (now changed in Figure 5 (Pag. 26)) shows the REPS-WRF model performance with forecasted precipitation, using the Brier Score index for a forecast horizon from 1 to 30 days during the 2012 growing season. b) L.8-15, Pag. 13: Our decision, to show the weather model performance over a period of 1-30 days as lead time, is the result of a preliminary investigation carried out with the landowner of the Livraga field who is the real

	 decision-maker: from his point of view he was more interested in knowing the reliability of a cumulated precipitation forecast over 7 days or 10 days and not whether it is going to rain exactly on the 7th or 10th day from the forecast initialization date. c) L. 7-8, Pag. 13: For the 2012 growing season it is found a good level of the forecast reliability (BS values lower than 0.15) within the first 10 days even for an occurrence probability forecast to exceed the threshold of 20 mm (cumulated in 1, 2, 3,,10 days). Therefore, the Livraga landowner can rely on cumulated precipitation forecasts at least for one week (which the available irrigation time allotment for his field). We are aware, we cannot draw general conclusions with one-year analysis only, in fact, one of the future developments is to extend the study over different sites with other case studies during future growing seasons. However, taking into account the cumulated precipitation forecast over 7 days or 10 days and not whether it is going to rain exactly on the 7th or 10th day, the performance shows a good starting point for a real-time drought forecasting system for irrigation management and answers to landowner's expectations.
I believe, too, that some of the	A revision of the English was done
doubts/concerns of the Referees are due to the English syntax: a final revision of the language is now done for every article in HESS by the Editorial office, but of course if the English is improved and made clearer in the revised manuscript it would greatly help the second revision process (and also the following English editing). I warmly suggest to ask a colleague to revise the manuscript.	

Commente hy Deviewer 4	Commente hy cuthere
Comments by Reviewer 1	Comments by autnors
My main concerns regard the impact of	As written in the text:
the paper. In its current form, the	$\mathbf{r} = \mathbf{r} = \mathbf{r} + $
manuscript provides an apprication of	a) L. 28-33, Pag. 4: The experimental test-site for
budrological models for real time	MDL basis at Cassis Nucces from in the town of
drought forecasting in one location in	MBL basin at Cascina Nuova larm in the town of
Northern Italy with two-year	Liviaga, where meteorological, eduy-covariance stations
calibration and one year validation	moisture profile have been respectively installed to
The impact of the paper would be	moisture prome have been respectively instaned to
greatly enhances should the author	other consortium fields were available to calibrate and
choose i) to discuss the applicability	validate the hydrological model it was not possible to
of the tool beyond the specific case	verify the PREGI forecasting system outside the Livraga
study; ii) to objectively present	experimental site. Notwithstanding this such a system
strengths and weaknesses of the	can be replicated in any geographical area and vegetated
proposed modeling framework when	field on condition that soil features weather.
applied for irrigation management; and	hydrological data and irrigation time allotments are
iii) to quantify the advantage of	available.
employing such a tool. The first two	
points are crucial in defining the	b) L. 12-18, Pag. 6: In addition to these soil
applicability of the proposed	analyses, eddy covariance measures were used to control
framework in routine, 'real world'	actual evapotranspiration (ET) fluxes and to make a
problems - which, as far as I	comparison with the ET simulated by the FEST-WB
understand, is the final goal of the	model (see Sect. 3.1 for further details). In case eddy
project. This discussion should	covariance measures are not available, the system target
include also clearer information on	would not in any case be affected, since the main
data requirements for model running,	hydrological variable is the soil moisture, and TDR
as well as information of the ability	probes are sufficient for monitoring and forecasting
results upon colibration with a more	purposes. On the contrary, the limits of such a system, in
limited (but more common) data	order to be replicated in other areas, are the availability of
availability	real time data (weather and soil moisture values), amounts
availability.	and scheduled irrigation allotments.
	c) Section 3.3 (Pags. 13-14) quantifies the
	advantages that the Livraga landowner could have
	obtained if he had followed the PREGI system, saving
	one irrigation in the 2012 growing season.
The last point, the quantification of	As written in the text (L.8-9, Pag. 11):
benefits, aims at investigating	
whether such tool can really make a	"Unfortunately, in 2010 the PREGI tool with hydro-
difference in water management. The	meteorological forecasts was not yet in service and it was
first step in this direction is	only available for the 2012 vegetation season."
clarifying what role the model	
suggestions played in the investigated	
case: this point is currently not verv	
clear, with an irrigation application	
the day before a major rainfall event.	
but also a hint to the farmer	
employing PREGI in his/her water	
management choices (also, if the	
forecast was used for water	
management, how could that be done	
before model calibration?)	
A more in-depth exploration of the	As above-mentioned, section 3.3 (Pags. 13-14) quantifies
advantages of such a toolbox - which I	the advantages that the Livraga landowner could have
strongly suggest - would require run	obtained if he had followed the PREGI system, saving
two season-long simulations, one	one irrigation in the 2012 growing season.

assuming the farmer follows the PREGI platform suggestions for when to irrigate, the other assuming that the farmer follows the currently employed decision criteria (which could even be as simple as irrigation applications whenever possible). The comparison of total applied water between the two runs will make it possible to assess the benefits of such a system in terms of water savings, the difference in total transpiration (or occurrence of periods with low soil moisture) can be used as a (rough) proxy of yield. A similar analysis could be extended beyond the three-year timeframe, to fully assess the advantages of such a system under a variety of climatic conditions. The model undergoes a calibration based on the data available at the case study site. Nevertheless, no mention is made of which parameters need calibration. This is an	Meteorological forecasts provided by the REPS-WRF were available in the 2012 season only. As written in the conclusions (L.13-16, Pag. 15), one of the future developments is to extend these analyses over different sites with other case studies during future growing seasons. Please, see the above comment to the editor.
important information when considering the applicability of the model beyond the very specific (and data rich) case study (see above).	
The measures of model performance ought to be defined within section 2 (the scope of which should be broadened to 'Methods'), discussing what specific aspect(s) of model performance they allow assessing. In this way, the result section can be focused on just presenting the model performances. The description of data availability (now at the beginning of the result section) should be moved earlier, either by widening the scope of current section 2 or within a new sub- section in section 3, which then should be broadened to 'Methods', as also suggested above).	Results and discussion are described in Section 3, while the measures of model performance were moved in Section 2.6, and the description of data availability in Section 2.2.
The presentation of the PRE.G.I. platform, including Fig. 8 and the description of the website, is unnecessary within the general economy of the paper and could be omitted/moved online as supplementary material.	The presentation of the PRE.G.I. platform was moved in the "Appendix" (Pags. 15-16), while some parts in regard to the website description were omitted.
I suggest broadening the introduction and discussion with reference to other related works (also broadening the reference list - current references mostly refer to works focusing on the	References were broadened with other related works focused on the optimization of irrigation management. L. 8-13, Pag. 3: In particular, we highlighted how scientific literature proposes different methods, more related to statistical approach, for optimizing irrigation scheduling and planning, while the application suggested

same	regi	on in It	taly,	whi	ch is	relevant	in thi	s p	aper take	es into ac	coun	t observed s	soil me	oisture,
but	not	unique	in	the	inte	rnational	weath	ner	data and	updated for	oreca	sts to provid	e lando	owners
aren	a).						with	а	suitable	product	for	real-world	farm	profit
							optim	iza	tion.					

Comments by Reviewer 2	Comments by authors
One of my main concerns is how the model was validated. In figure 7 the authors states that	 The validation of the model is referred to the FEST-WB hydrological model as described in Section 3.1 ("Calibration and validation of the FEST-WB model"). While in Section 3.2 we describe the PREGI performance with three statistical indexes for the 2012 growing season: a) The MAE and MRE for soil moisture forecasts; b) The NS for cumulated precipitation forecasts including the irrigation contribution over a period of 1-30 days as lead time; c) The BS for the RESP-WRF weather forecasts over a period of 1-30 days as lead time; Since the BS is calculated over a period of 1, 2, 3,,30
the rainfall forecasts shows better skills for more extreme precipitation thresholds (100 mm), however this is not completely true if not misleading. As the Brier score is defined, the	cumulated days, 100 mm can be considered as extreme event only if they occur in a few days, but not in 7 or more days. However, as written in the text (L.2 -15, Pag. 13): "In the way in which the BS is defined, the rarer an event, the easier to get a better BS. This is true if we consider
rarer an event it is easier to get a better BS without having any real improvement in the forecast skill.	the frequency of events, which exceed the threshold of 100 mm cumulated in 1, 2, 3,, 30 days, occurred during March-August 2012, and more in general in the summer season in the Po Valley area, in comparison with the cumulated precipitation values (observed/forecasted) of 20 mm which are much more typical from a climatological point of view for this area; however, there is a good level of reliability (BS values lower than 0.15) within the first 10 days even for a threshold of 20 mm cumulated in 10 days. Notwithstanding this, our decision to show the performance over a cumulated period of 1, 2, 3,, 30 days is the result of a preliminary investigation carried out with the landowner of the Livraga field who is the real decision-maker: as mentioned above, from his point of view he was more interested in knowing the reliability of a cumulated precipitation forecast over 7 days or 10 days and not whether it is going to rain exactly on the 7th or 10th day from the forecast initialization date."
In this respect I would recommend the authors to benchmark the model with different metrics that take into account a reference forecast as the climatology or the persistence. Just to name one, this is the case for the Brier Skill Score (BSS, see Mason 2004). In this way, some of the authors' statements need additional justification.	As explained to the editor and referee 1 (see the above comments), we cannot use the climatology as reference, since weather data over our experimental test-site (Livraga) were available for 3 years (2010, 2011 and 2012) only, hence this period is not sufficient to be analysed. Neither the persistence score could have been used, since a persistence forecast is defined as "a forecast that the current weather condition will persist and that future weather will be the same as the present (e.g., if it is raining today, a forecast predicting rain tonight)" (NOAA). In this study, we calculate the BS not with daily values (as it is usually performed), but with cumulated precipitation forecast values over a period of 1-30 days.
Page 15815, lines 16-18: Here is not clear the source of the temperature and precipitation data. Are an output from the WRF or is observed data? Why at every 2 days? And not 1 or 10 days?	As written in the text (L. 22-29, Pag. 6 and L. 3-4, Pag.12): Probabilistic forecasts (temperature and precipitation) were provided by the REPS, based on the WRF-ARW model, implemented and developed by the EMC. The forecast has a lead time of 30 days while the temporal resolution is 12 hours. The REPS-WRF is carried out

Then in the next sentence the authors state that the hydro model is initialized with observed data. Are referring to the same data from the previous statement? I do think that the entire paragraph need to be	every two days, since this is the computational time to run the combined system and, in fact, the data set includes 90 forecast instances out of about 180 days between 27 February and 31 August 2012. As written in the text (Section 2.2, Pag. 5), the FEST-WB hydrological model can be fed with observed weather data (used for hydrological simulations and for creating the initial soil moisture conditions), and with forecasted data by the REPS-WRF model (to generate soil moisture forecasts)
rephrased, please try to be more specific here.	
Page 15815, lines 22-24: "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." This is a general statement or the authors want to refer to the information used in the analysis? This sentence seems to be disconnected, please rephrase.	As written in the text (L.30-34, Pag. 5): "In particular, amounts and methods of water allotments are fundamental to keep updated soil moisture initial conditions. In fact, since irrigation allotments are planned by the MBL consortium, landowners cannot irrigate their fields on days other than the scheduled ones; therefore, this information becomes mandatory in this hydro- meteorological forecasting chain."
Page 15819 eq (2): For me it is not clear how eq(1) becomes eq(2) and how the stress threshold is defined. A clearer link between the two equations is necessary. Please explain in more detail the meaning of RAW and TAW and their link with the stress and water surplus threshold. Page 15819 lines 12-13: the values of 0.23 and 0.33 are intended to be incorporated in eq(2)? I can't follow the construction of this thresholds.	This was better detailed in the text (L.25-34, Pag. 8 and L. 1-4, Pag. 9).
Page 15820 line 4: It's hard to see the contribution of the precipitation and irrigation separately. I suggest to use a stacked bar with two colors (one for each contribution) in the figures 2, 3 and 4 and enlarge the axis fonts -specially the horizontal axis- as it is difficult to read them in the printed version.	This suggestion was accepted and this figure was modified (Pag.23).
Page 15820 paragraph between lines 9- 13: Is this paragraph referring to Figure 3? If yes, I would recommend to swap this paragraph with the next in order to present the Figure first.	This paragraph was changed (L.10-13, Pag. 11).
Section 4.2. I feel that this section could be reorganized and addressed in a better way. For instance, some results of the performance metrics are presented first than the metric is defined. This is the case of MAE and MRE that are already depicted in the previous section 4.1. Also MAE values are presented but this metric is not	Statistical indexes, which are used in this analysis, are moved in Section 2.6 (Pags. 9-10) separately, while the PREGI performance is described in Section 3.1

defined at all in the text. The Nash- Sutcliffe index is used (lines 16-20 page 15822) before the equation is defined (eq-4). Also the acronym related with this index should be homogenized (NS or ENS, or are different things?). I suggest to present first the performance metrics used. Sections 2 and 3 can be merged as a section named as data and methodology where all the metrics can be defined. Or preferably this metrics can be defined separately in an appendix.	
Page 15824 line 2: It's not clear to me why the thresholds of 50 and 100 mm are equivalent? Please explain or rephrase.	As we explained in Section 2.4 (L.26-31, Pag. 7), the estimated irrigation input implemented in the FEST-WB model was assumed to be equal to 108 mm, hence 100 mm as threshold is reasonably similar to full irrigation water allotment, while 50 mm (as threshold) can be thought as half irrigation water allotment in the Livraga maize field.
Figure 7. In my opinion this is one of the weakest points of the paper. The authors states that the greater skill is observed for the forecasts of the extreme events. These results obtained in such a short period are only an artifact of the methodology used to assess the skill.	Although this index was performed in the 2012 growing season only, it takes into account 90 forecast instances from 27 February to 31 August. In regard to " <i>the greater skill for the threshold of 100 mm</i> ", see the above comments.
I would recommend the authors to assess the skill of these forecasts by using other metrics that take into account reference forecasts like the climatology as a benchmark.	Please, refer to the above-comments to the editor and referee 1.
Page 15824 lines 19-21: This sentence is a little bit cryptic. Please consider rephrasing it.	This paragraph was re-written (L.31-34, Pag. 15 and 1-6, Pag. 16).
Page 15824 lines 22-26. After reading this sentence, I'm not 100% sure if I understand how the probabilities were computed. The number of ensemble members exceeding the threshold is a daily value or it is accumulated over 30 days? Please explain. Figure 8: What are the meaning of the yellow circle and the 60% value? Please add a clarification in the caption.	As shown in Figure 9, the picture shows 60% probability (i.e. 12 ensembles out of 20) of exceeding the surplus threshold in at least one of the subsequent 30 days with the forecast simulation started on 31 August 2012. Therefore, the value displayed on the colored dot means the higher daily probability value over a period of 30 days. (L.31-34, Pag. 15 and 1-6, Pag. 16).

differences between the forecast and	
observations. Also it can be helpful	
to see in the plots the 25 and /5th	
percentile as in figure 9.	
Page 15825 lines 15-18: The authors	
state that "The comparison between the	
REPS-WRF model forecast and the	
observed value at Livraga rain gauge	
(leaving out the two scheduled	
contributions coming from irrigation	
which are known a priori) shows a good	
agreement during the central phase of	
the maize growing season." How the	
authors drawn this conclusion? Is hard	
to see it from figure 10 as the	
magnitude of the irrigation is too	
nigh. Please consider to rearaw Fig 10	
With only the accumulated rainfall.	
the good agrooment? To this measured	
cine good agreement: is this measured	
somenow of is only a graphical	
elements that sustain this conclusion	
erements that sustain this conclusion,	
as this is one of the key questions.	
Page 15826 lines 10-16: This paragraph	Parts of the conclusions were re-written (L. 28-34, Pag.
is a quite general statement that is	14 and L.1-5, Pag. 15) and that statement omitted, as you
not supported in the paper. Moreover,	suggested.
I can't agree that the system	
presented in this paper "has a higher	
reliability in comparison with flood	
forecasting systems", at least I can't	
found any evidence of that in the	
paper. Please consider deleting or	
rephrasing this paragraph as in the	
present form is not completely	
accurate.	

Comments by Reviewer 3	Comments by authors
The topic of the paper is interesting and challenging, but I think a proper validation of the procedure is still missing. Only one growing season (2012) was considered to evaluate the reliability and the benefits of the forecasting chain, but the reliability assessment would definitely need more than a year of experiment and the benefits should be more clearly investigated by comparing two situations, one supported by the forecasting system and one without this system. Results are not well documented and not clearly explained.	Following your suggestions, we added the Section 3.3, where we quantify the advantages of the PREGI system in the 2012 growing season. Unfortunately, meteorological forecasts provided by the REPS-WRF were available in the 2012 season only, and it was not possible to test in other seasons. As written in the conclusions (L. 13-16, Pag. 15), one of the future developments is to extend these analyses over different sites with other case studies during future growing seasons.
The potentials of the forecasting system for other case studies is not discussed, nor are its limits.	 As answered to referee 1 and written in the text: a) (L.28-31 Pag. 4 and L.1-2 Pag. 5) The experimental test-site for the PREGI Project is a field located in the middle of the MBL basin at Cascina Nuova farm in the town of Livraga, where meteorological, eddy-covariance stations and TDR probes for evapotranspiration fluxes and soil moisture profile have been respectively installed to measure hydrological processes Since no measures in other consortium fields were available to calibrate and validate the hydrological model, it was not possible to verify the PREGI forecasting system outside the Livraga experimental site. Notwithstanding this, such a system can be replicated in any geographical area and vegetated field, on condition that soil features, weather, hydrological data and irrigation time allotments are available. b) (L.12-18, Pag. 6) In addition to these soil analyses, eddy covariance measures were used to control actual evapotranspiration (ET) fluxes and to make a comparison with the ET simulated by the FEST-WB model (see Sect. 3.1 for further details). In case eddy covariance measures are not available, the system target would not in any case be affected, since the main hydrological variable is the soil moisture, and TDR probes are sufficient for monitoring and forecasting purposes. On the contrary, the limits of such a system, in order to be replicated in other areas, are the availability of real time data (weather and soil moisture values), amounts and scheduled irrigation allotments.
validation purposes is missing. Part of it is included in chapter 3 but should be moved in my opinion to chapter 2.	This suggestion is accepted and Section 2.2 (Pags. 5-6) describes also the available dataset in order to set up hydrological simulations.

Page 4 - line 6-7 - meteorological fields are available every two days? or every 12 hours (twice a day)?	Please, see our comments to referee 2.
Page 5 line 5-6 - 200 m spatial resolution and daily time scale, you should discuss the suitability of this space and time scale for the goal of your analysis	As written in the text (L.13-17, Pag. 7): "The spatial domain is discretized with a mesh of regular square cells (200 m in this application), while the temporal resolution of soil moisture simulations and forecasts calculated on a daily time scale; since the Livraga maize field is about 8 ha wide and the landowner schedules his activities on daily/weekly planning, both the spatial and time scale turned out to be appropriate from a computational time point of view."
Page 6 line 33 - deduction of eq. 2 is not clear.	The deduction of equations used in Section 2.5 was clarified (L.25-34, Pag. 8 and L. 1-4, Pag. 9).
Results and discussion- Figures and numbers provided only refer to the Livraga site, while it would be interesting to see how the hydrological model performs on the whole simulated domain (Livraga experimental filed?)	As written in the text (L.31-33, Pag. 4): "Since no measures in other consortium fields were available to calibrate and validate the hydrological model, it was not possible to verify the PREGI forecasting system outside the Livraga experimental site."
References - Two papers by Ravazzani et al. (2011) are actually listed, they shoud be probably cited as 2011a and 2011b.	References were corrected.
Wilks (2006) is not listed, nor is Joliffe (2003) which should probably be substituted in the text by Joliffe and Stephenson (2003).	

Comments by T. Caloiero	Comments by authors
Pag. 15812 Line 8 The fourth IPCC	This reference was changed, as you suggested.
Report has been cited, but the fifth IPCC Report has been published even though only as "Summary for Policymakers". I suggest to cite the fifth IPCC Report (2013) and insert the following reference in the reference list: IPCC, 2013: Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, GK. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.	
Pag. 15814 Lines 10-20 In the introduction the aims of the paper are not clearly stated, so, I recommend rewriting the paragraph from lines 10 to 20.	Parts of the introduction were re-written to better clarify the aims of the paper (L.8-25, Pag.3).
Pag. 15817 Lines 3-5 In these lines the authors refer to some precipitation and temperature gauges, avoiding details about their location. I suggest to localize these gauges in Fig. 1a. Figure 1 I suggest to localize the precipitation and temperature gauges in Fig. 1a and to insert a bar scale in Fig. 1b.	Figure 1 (Pag. 22) was changed as you suggested.
Formulae Results of some indices are described before the equation are defined, I suggest to define the formulae and then to describe the results of the application of these formulae (e.g. Nash-Sutcliffe)	Statistical indexes were moved in section 2.6 (Pags.9-10).

Real time drought forecasting system for irrigation management

3

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

5

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11

12 Abstract

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

In this study we show the development and implementation of the PREGI real-time drought forecasting system; PREGI is an Italian acronym that stands for "Hydro-meteorological forecast for irrigation management".

The system is based on ensemble predictions (20 members) at medium-range (30 days) coupled

with hydrological simulations of water balance to forecast the soil water content on a maize field in

the Muzza Bassa Lodigiana (MBL) consortium in northern Italy.

The hydrological model was validated against measurements of latent heat flux acquired by an
eddy-covariance station, and soil moisture measured by TDR (Time Domain Reflectivity) probes;
the reliability of this forecasting system and its benefits were assessed in the 2012 growing season.

30 The results obtained show how the proposed drought forecasting system is able to have a high

31 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

A lack of water has always been one of the most critical factors for the survival of populations
around the world. The United Nations proclaimed the year 2003 as the international year of
freshwater and the year 2006 as the international year of deserts and desertification, highlighting the
importance of prevention, mitigation and adaption of events related to water supply.

10 Future climate change scenarios combined with limited water resources require better irrigation

management and planning (English et al., 2002, Farrè and Faci, 2008); this has also occurred in
areas habitually with an abundant supply of water as the Po Valley in the north of Italy.

Considering historical climate data sets, recent studies demonstrate that there is not a significant decrease in the amount of precipitation, although a reduction in the last twenty years has been found over Italy (Salerno et al., 2007). However, a new and more frequent distribution of extreme events has been observed (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 interesting issues focused on the optimization of irrigation management also coupling meteorological and hydrological models. Examples of main international research are: the CROPWAT program by Smith (1992), the EPIC-PHASE model developed at the center of Toulouse (Cabelguenne et al., 1997), the real-time scheduled irrigation approach proposed by Gowing and Ejieji (2001) in United Kingdom, the "eWarning" Danish warning system (Jensen and Thysen, 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.

25 In the north of Italy the recurrence of water stress periods requires an improvement in the 26 management and coordination of water courses (lakes, hydroelectric reservoirs, rivers, etc.), together 27 with testing other alternative sources, such as water withdrawals from large quarry lakes (Ravazzani 28 et al., 2011a). This activity has contributed to the better management of water distribution by water consortia according to season, different cultivation requests and total available water in lakes and 29 snowpack. A prudent water distribution policy means wiser and thriftier methods of irrigation, 30 maximizing agricultural production (Hassanli et al., 2008, Oweis and Hachun, 2008, Geerts and 31 Raes, 2009). However, these management policies are currently based on the sensitivity and 32 experience of consortia managers. A policy of saving irrigation water would be helpful if districts 33

were subsequently affected by significant rainfall, but extremely dangerous if no precipitation
 occurs in the following weeks.

- It is clear that the complexity of these matters related to water resources should be studied with a
 scientific and engineering approach, in order to be able to predict the occurrence of potentially
 harmful droughts in advance; this issue is also one of the main goals of the DROUGHT R&SPI
 (www.eu-drought.org) and DEWFORA (www.dewfora.net) projects which focus on drought early
 warning systems respectively in European and African countries.
 Scientific literature proposes different methods, more related to statistical approach, for optimizing
- 9 irrigation scheduling and planning (Kuo and Liu, 2003, Negesh Kumar et al., 2006, Azamathulla et

al., 2008, Vico and Porporato, 2010 and 2013), while the application suggested in this paper takes

11 into account observed soil moisture, weather data and updated forecasts to provide landowners with

12 a suitable product for real-world farm profit optimization, as well as cost savings for irrigation

13 practices: e.g. water volume, pumping system from ditches, fuel for tractors and labor costs.

14 Our task is to put the scientific know-how into practice as a tool for better irrigation management

and planning. In fact, working on the PREGI Project, funded by the Lombardy Region in the years

16 2010-2012, we discovered how irrigation practices in the Po Valley area are left to very old

strategies more related to landowner experiences rather than scientific studies and engineering
processes.

In this context, an adoptable methodology is the one applied for real-time flood predictions (Rabuffetti et al., 2008 and Ceppi at al., 2013), coupling meteorological forecasts with hydrological simulations. Thus, our idea was to create a web application where farmers are able to monitor realtime soil moisture conditions and forecasts. The knowledge of Quantitative Precipitation Forecasts (QPFs) for the following weeks combined with the updating of hydrological conditions makes it possible to obtain a tool for water distribution management in cultivated areas in order to improve irrigation scheduling, minimize irrigation costs and save water.

The PREGI system is based on meteorological forecasts at medium-range with hydrological 26 simulations of water balance to forecast the soil moisture at field scale. In particular, three TDR 27 28 probes were installed to monitor soil moisture conditions, while to produce probabilistic soil moisture forecasts, the non-hydrostatic WRF-ARW (Weather Research and Forecasting -29 30 Advanced Research WRF) meteorological model based on 20 ensemble members with one month as forecast horizon provided by Epson Meteo Centre (EMC), was coupled with the FEST-WB 31 (Flash-flood Event-based Spatially-distributed rainfall-runoff Transformation- Water Balance) 32 distributed hydrological model developed at Politecnico di Milano (POLIMI), and used to generate 33 34 soil moisture simulations.

1	The area of study is a maize field in the MBL consortium in the Po Valley (northern Italy), used as
2	an experimental test-site for the PREGI tool.

- A calibration phase was carried out during the 2010 and 2011 growing seasons, while a validation
- 4 was performed in the 2012 season, when it was also possible to couple hydrological simulations
- with meteorological forecasts in order to obtain soil moisture predictions; the results of this
 forecasting chain show a high reliability up to 7-10 days as lead time of forecast. Notwithstanding
 - 7 this, during the 2012 season the PREGI system was not fully employed by the landowner of the
- 8 experimental field, and the decision-making criteria did not follow the indications highlighted in the
- 9 PREGI platform; in fact, as shown in Sect. 3.3, a better management of water distribution could
- 10 have been carried out and even one scheduled irrigation could have been saved.
- 11
- 12 **2.** Models and methods
- 13

14 2.1 Area of study

15

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

Average annual rainfall measured in the MBL consortium range from 800 (southern area) to 1000

24 mm (northern area) with two peaks in spring and autumn (Ceriani and Carelli, 2000).

25 During the summer season most of the water supply comes from the irrigation network. The upper-

26 medium part of the basin is irrigated by flowing surface water, while in the bottom part of the basin,

27 water is taken and lifted by the Adda and Po rivers through proper pumping systems.

28 The experimental test-site for the PREGI Project is a field located in the middle of the MBL basin at

29 Cascina Nuova farm in the town of Livraga, where meteorological, eddy-covariance stations and

30 TDR probes for evapotranspiration fluxes and soil moisture profile have been respectively installed

to measure hydrological processes (Masseroni et al., 2012). Since no measures in other consortium

- 32 fields were available to calibrate and validate the hydrological model, it was not possible to verify
- the PREGI forecasting system outside the Livraga experimental site. Notwithstanding this, such a

1	system can be replicated in any geographical area and vegetated field, on condition that soil
2	features, weather, hydrological data and irrigation time allotments are available.
3	
4	2.2 Coupling strategy and available dataset
5	
6	The cascade forecasting system applied in this study is currently based on hydrological model
7	initialization from meteorological model output: temperature and precipitation forecasts.
8	Before launching the coupled system, the hydrological model is initialized with observed weather
9	data of the previous day, provided by the ARPA (Regional Agency for Environmental Protection) of
10	the Lombardy region and Meteonetwork-EMC meteorological station network to set up the initial
11	soil moisture conditions.
12	An example of each step of the operative chain is detailed below, in order to better understand this
13	forecasting chain:
14	- At 00:00 UTC on e.g. 20 June 2012 the Regional Ensemble Prediction System (REPS)-
15	WRF model was launched by the EMC;
16	- At 12:00 UTC on 22 June 2012 the REPS-WRF model outputs were uploaded on the
17	POLIMI server;
18	- At 13:00 UTC on 22 June 2012: observed weather data of the previous day provided by the
19	Lombardy ARPA and Meteonetwork-EMC meteorological station network were available
20	on the POLIMI server;
21	- At 13:30 UTC on 22 June 2012 the FEST-WB model was launched with observed weather
22	data of the previous day to produce initial conditions;
23	- At 14:00 UTC on 22 June 2012, once initial conditions were obtained, the FEST-WB model
24	is initialized with the REPS-WRF probabilistic forecasts to produce soil moistures forecasts;
25	- At 16:00 UTC on 22 June 2012, soil moisture forecasts were uploaded on the google map
26	platform purposely developed.
27	In addition to the above-mentioned weather (observed/forecasted) data, the system requires
28	information to set up the hydrological model, such as land use, soil texture, hydraulic conductivity
29	(Ks), type of vegetation (dates of sowing and harvest), DEM (Digital Elevation Model), aquifer
30	parameters and scheduled irrigations. In particular, amounts and methods of water allotments are
31	fundamental to keep updated soil moisture initial conditions. In fact, since irrigation allotments are
32	planned by the MBL consortium, landowners cannot irrigate their fields on days other than the
33	scheduled ones; therefore, this information becomes mandatory in this hydro-meteorological
34	forecasting chain.
	5

As far as soil information is concerned, in situ field tests carried out during the PREGI Project, have 1 classified the soil texture as silt loam; in particular, a content of: 19.2 % clay, 48.1 %, silt, and 2 32.7% sand was found in soil analyses. Table 1 summarizes the main soil properties for the Livraga 3 maize field: a tuning of these values inside the interval range reported in Maidment (1993) was 4 carried out to calibrate and implement the FEST-WB hydrological model. 5 Another important parameter to define in the hydrological model is soil depth which has been 6 7 modeled as a 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 70 cm depth. Finally, 8 different measures of permeability were performed with the Guelph infiltrometer (Eijkekalmp, 9 2008) to investigate the hydraulics conductivity (Ks) which was found to be equal to 2.36E-07 m s⁻¹ 10 in the experimental field. 11 In addition to these soil analyses, eddy covariance measures were used to control actual 12 13 evapotranspiration (ET) fluxes and to make a comparison with the ET simulated by the FEST-WB model (see Sect. 3.1 for further details). In case eddy covariance measures are not available, the 14 15 system target would not in any case be affected, since the main hydrological variable is the soil moisture, and TDR probes are sufficient for monitoring and forecasting purposes. On the contrary, 16 17 the limits of such a system, in order to be replicated in other areas, are the availability of real time 18 data (weather and soil moisture values), amounts and scheduled irrigation allotments.

19

20 2.3 Meteorological model

21

22 The probabilistic forecast was provided by the REPS, based on the WRF-ARW model, implemented and developed by the EMC. The REPS-WRF used in this project has a grid mesh size 23 24 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 25 26 applied at the global scale, which has a grid mesh size of 200 km and the same number of vertical levels as the REPS, and it uses the same initial conditions in the control runs provided by the 12 27 28 UTC GFS (Global Forecasting System) analysis at 0.5 degree of horizontal resolution. The forecast has a lead time of 30 days while the temporal resolution is 12 hours. Each perturbation of the 29 30 ensemble is produced by an algorithm developed by the EMC based on a special application of Ensemble Transform Kalman Filter (EnTKF), able to allow covariance localization whilst 31 maintaining computational efficiency and removing spurious long-range correlations. The REPS-32 WRF is carried out every two days, since this is the computational time to run the combined system. 33

The REPS-WRF run starts at 00 UTC, the same start time as the hydrological simulation. For a
 detailed description of the WRF model, please refer to Skamarock and Klemp (2007).

3

4 2.4 Hydrological model

5

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

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

11 The model requires observed precipitation and air temperature data from ground stations which are

12 both interpolated to a regular grid using the inverse distance weighting technique.

The spatial domain is discretized with a mesh of regular square cells (200 m in this application), while the temporal resolution of soil moisture simulations and forecasts calculated on a daily time scale; since the Livraga maize field is about 8 ha wide and the landowner schedules his activities on daily/weekly planning, both the spatial and time scale turned out to be appropriate from a computational time point of view. For further details about the development and calibration of the FEST-WB, please refer to Montaldo et al., 2003 and 2007, Ravazzani et al., 2007 and 2011b, Corbari et al., 2011, and Ravazzani (2013).

As described in the results (Sect. 3), during the 2010-2012 summer seasons, observed and 20 forecasted soil moisture data are influenced by rainfall, irrigations and evapotranspiration fluxes 21 22 which denote main inflows and outflows in water balance at the Livraga field scale. In particular, each field of the Muzza consortium has its own scheduled irrigation following centuries old time 23 24 tables where planned water allotments are determined in advance; at the Livraga experimental field this is available every week, i.e. the landowner has the possibility of withdrawing water from the 25 nearest irrigation ditch every 7 days. For instance, the potential water concession for the Cascina 26 Nuova farm is 650 l s⁻¹ taken from the "Porra Nuova" ditch, but considering that the irrigation 27 efficiency of the Muzza basin is about 45% of the theoretical value, the available water discharge is 28 only about 300 1 s⁻¹. Since this volume of water is used to irrigate our experimental field of 8 ha in 29 30 about 8 hours, the estimated irrigation input implemented in the FEST-WB model was assumed to be equal to 108 mm. 31

In addition to irrigation contributions, evapotranspiration losses plays a crucial role in the water balance during the summer season in the Po Valley area where cumulated values exceed 300 mm in four months (see Figs. 2b,-d, -f). In the current version of the FEST-WB model, evapotranspiration

is computed according to a revised version of the Food and Agricultural Organization (FAO-56) 1 method (Allen et al., 1998). The original approach is based on the use of the Penman-Monteith 2 equation (Monteith, 1965) to calculate a reference evapotranspiration (ET₀) of a surface defined as 3 an "hypothetical crop with an assumed height of 0.12 m, having a surface resistance of 70 s m⁻¹ and 4 an albedo of 0.23, closely resembling the evaporation of an extensive surface of green grass of 5 uniform height, actively growing and adequately watered" (Allen et al., 1998). In this paper, due to 6 7 the availability of only air temperature meteorological forecasts, the Penman-Monteith equation is substituted with a modified Hargreaves and Samani equation (Hargreaves and Samani, 1985) which 8 9 includes a correction factor for altitude (Ravazzani et al., 2012). In Ravazzani et al., 2012, the reliability of this modified equation to compute ET₀, has been demonstrated. 10

Subsequently, 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.

16

17 2.5 Warning thresholds

18

19 The coupling of hydro-meteorological models and irrigation scheduling knowledge provides 20 advance information on soil moisture content and expected cumulated precipitation for irrigation 21 management and water control from 1 to 30 days as forecast horizon.

In order to issue warnings regarding soil moisture forecasts, two thresholds were defined in the PREGI system: 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 because of a lack of water. According to the FAO-56 definition (Allen, et al., 1998) and also applied in Baroni et al., (2010) the latter is calculated as follows (1):

27	$RAW = p \cdot TAW$	(1)
28	where RAW is the Readily Available Water defined as field capacity minus stress threshold,	<mark>l'AW</mark>
29	is the Total Available Water defined as field capacity minus wilting point, and p is a coeff	cient
30	depending on the crop and climatic parameters which can be assumed to be equal to 0.5 for	naize
31	(Allen et al., 1998) in the Livraga field. Therefore, the Eq. (1) becomes:	
32	field capacity – stress threshold = $p \cdot (filed capacity – wilting point)$	(2)

33 Substituting the values of 0.33 and 0.13 respectively for field capacity and wilting point for the

34 Livraga silt loam soil (see Sect. 2.4), the Eq. (3) becomes:

stress threshold = $0.33 - 0.5 \cdot (0.33 - 0.13)$ 1 (3)Hence, the stress threshold value we are looking for is equal to 0.23. 2 As described in Sect. 3.3, this stress threshold is a decision criterion in order to plan whether or not 3 to irrigate on the days when water allotment is available. 4 5 6 2.6 Statistical indexes 7 Common skill scores in scientific literature are used to compare soil moisture simulations between 8 9 observed and simulated values by the FEST-WB model initialized with observed values and weather data forecasted by the REPS-WRF model; since the WRF is a probabilistic model with 20 10 ensemble members, the median value is chosen for analysis clarity. 11 12 In particular, results described in Sect. 3.2 include the Mean Relative Error (MRE) calculated as follows Eq. (4): 13 $MRE = \frac{1}{n} \sum_{i=1}^{n} \left(\frac{F_i - O_i}{O_i} \right)$ (4)14 and the NS index (Nash and Sutcliffe, 1970) which shows how well the forecast predicts the 15 16 observed time series, with best scores close to 1, and a range between $-\infty$ to 1. In this study, Eq. 5 17 measures the ratio between the deviations of forecasted median values by the FEST-WB hydrological model initialized by 20 ensembles of the REPS-WRF model with observed values and 18 19 the deviation between the observed mean and observed values: $NS = 1 - \frac{\sum_{i=1}^{n} (O_i - F_i)^2}{\sum_{i=1}^{n} (O_i - \overline{O})^2}$ 20 (5)

- 21 For both indexes the key is the following:
- 22
- 23 $O_i = \text{observed values}$
- 24 F_i = median of forecasted values
- 25 \overline{O} = the average of observed values
- 26 n =numbers of analyzed events
- 27
- Another skill score used in this study is the Brier Score (BS) 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

- 1 forecast probabilities and the subsequent observations (Wilks, 2006). Equation (6) for the BS score
- 2 is:

3
$$BS = \frac{1}{n} \sum_{k=1}^{n} (F_k - O_k)^2$$
(

- 4 where
- 5 N = number of forecasting instances
- F_k = the probability that an event was forecasted
- 7 O_k = the actual outcome of the event at instance k (0 if it doesn't happen and 1 if it happens)
- 8 For instance, suppose that the forecast probability to exceed a threshold of cumulated rainfall is
- 9 70% and then this event occurs, the BS score is equal to 0.09; vice versa if it does not occur the BS
 10 score is 0.49; therefore, best scores are close to 0.
- 11 In this analysis, three thresholds were chosen: 20, 50, 100 mm; these last two values are reasonably
- 12 similar to half and full irrigation in the Livraga maize field, while the 20 mm threshold corresponds
- 13 to typical precipitation amounts in that area, which is not usually affected by heavy rainfall in the
- 14 summer season, as occurred in 2012.
- 15 It is important to bear in mind that this computation, performed with the entire forecast dataset, is
- 16 not referred to daily precipitation values, but cumulated precipitation values over a period of 1, 2,
- 17 3,..,30 days. For instance, the BS score at 7th day as lead time considers the occurrence probability
- 18 of a cumulated precipitation forecast over a period of 7 days to exceed the threshold of 20, 50 or
- 19 100 millimeters (occurred over the same time period of 7 days).
- 20

21 **3. Results and discussion**

22

23 3.1 Calibration and validation of the FEST-WB model

24

The 2010-2012 period was used to calibrate and validate the hydrological model with data acquired at Cascina Nuova field in Livraga, where one eddy covariance station and three TDR probes were installed to monitor evapotranspiration fluxes and soil moisture content.

Figs. 2 shows the comparison between values measured (red line) by TDR probes (in reality, it is a

29 weighted average of the three measures at a depth of 10, 35 and 70 cm) and data simulated (blue

30 line) by the FEST-WB model during the three growing seasons of 2010, 2011 and 2012, including

31 rainfall (light blue bars) and irrigation (orange bars) amounts in the Livraga maize field.

As far as the 2010 season is concerned, Fig. 2a shows how soil moisture data are well associated with rainfall and irrigation inputs with a MAE of 4% and MRE of +1%; a good match between observed and modelled simulation data is also shown in Fig. 2b for the actual cumulated evapotranspiration.

5 In addition, Figure 2a shows how the first seasonal irrigation (14 June 2010) could have been

6 avoided if soil moisture and precipitation forecasts were known in advance; in fact, severe rainfall

7 (about 85 mm) occurred between 15 and 20 June with a maximum peak of 45 mm on 15 June (the

8 day after the irrigation!). Unfortunately, in that year the PREGI tool with hydro-meteorological

9 forecasts was not yet in service and it was only available for the 2012 vegetation season.

10 In regard to the 2011 season, satisfactory results are found between observed and simulated values

11 both in terms of soil moisture (MAE equal to 8%, Fig. 2c) and cumulated evapotranspiration (Fig.

12 2d), even if an underestimation is generally present (MRE of -8%) in simulated soil moisture

13 values, mainly due to higher rates in evapotranspiration.

After two years of calibration (2010 and 2011), the validation of the FEST-WB model is carried out 14 15 for the 2012 growing season at the Livraga field. The performance of the validation (Fig. 2e) shows a good match between model and observations with a MAE of 7% and MRE of -1%. A slight 16 underestimation of the FEST-WB is generally present except at the beginning of the season; 17 however, the hydrological model initialized with observed values by the Lombardy ARPA and 18 Meteonetwork-EMC weather stations, was able to simulate soil moisture conditions with a daily 19 error within 10%, in particular during the irrigation period between June and August. Even the 20 comparison between observed (red line) and simulated (blue line) data for the real cumulated 21 evapotranspiration (Fig. 2f) indicates a good correspondence during the 2012growing season. 22

Although the model validation is only performed after the 2012 growing season, hydrometeorological forecasts were set up in real-time at the beginning of the 2012 season. Thanks to the PREGI tool we implemented, updated soil moisture conditions and forecasts led the landowner to postpone the irrigation scheduled on 29 July for one week; this decision allowed the vegetation season to be extended to the end of August when the maize was finally harvested. However, as described in Sect. 3.3, had the PREGI system been fully followed by the landowner, one out of three irrigations would have been even saved.

30

31 *3.2 The PREGI performance*

32

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 season 2012 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 3 days of simulations between 27 February and 31 August 2012. Since the weather model has a 4 forecast horizon of 30 days, in order to value the forecasting chain, the statistical analysis has been 5 carried out starting from "day+0", i.e. the forecast at the same day of the initialization date run, up 6 7 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 8 9 performed using common skill scores known in literature (Wilks 2006, Jolliffe and Stephenson 10 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

19 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 10^{th} -15th day after the initialization date of the weather model with NS values between 0.80 and 0.75.

24 The reason for calculating the forecast performance of the rainfall plus irrigation accumulated in a

25 moving forecast horizon, and not the forecasted amount on a specific day, satisfies one of the aims

26 of the PREGI project: in fact, from an irrigation management point of view, it is more important to

27 know whether the next 7 or 14 days, which usually coincide with water irrigation allotments in the

28 MBL fields, will be wet or dry, rather than precipitation event occur precisely on the 14th or 15th day

29 of the forecast. On the contrary, Fig. 5 shows the REPS-WRF model performance with forecasted

30 precipitation only, excluding the contribution of irrigation, using the Brier Score index for a forecast

31 horizon from 1 to 30 days during the 2012 growing season.

32 As it is shown in Fig. 5, the forecast performance is better for the threshold of 100 mm cumulated

33 over a moving period from 1 to 30 days, worsening as the lead time increases. On the contrary, the

34 forecast reliability has a different trend for thresholds greater than 50, and above all 20 mm, with

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

16

17 3.3 To follow or not to follow the PREGI system

18

During the 2012 growing season, the PREGI system issued soil moisture, evapotranspiration and 19 precipitation forecasts every two days, providing the landowner with useful information concerning 20 soil conditions for irrigation scheduling. As described in Sect 2.2, the initial conditions of the 21 22 hydrological model were updated daily taking into account observed weather data and irrigation water amounts which were planned during the entire season more on the basis of the landowner' 23 experience than the PREGI system. Three irrigations were planned during the vegetation season 24 2012: 29 June, 14 July and 6 August; as mentioned in Sect. 3.1, the latter was supposed to be the 25 previous week, on 29 July, but the observed soil moisture values and forecasts convinced the 26 landowner to follow the PREGI application and to postpone it for one week. This advice led to an 27 extension of the growing season until the end of August when a riper maize was harvested two 28 29 weeks after the originally scheduled date. Consequently, in order to demonstrate the benefits of such a forecasting system, we re-ran two 30 31 simulations, one assuming that the landowner follows the advice provided by the PREGI platform

32 on when to irrigate, and the other assuming that he follows the currently planned decision criteria;

as shown in Figures 6 and 7 (where for the sake of clarity we show only the mean, median, the 25th

and 75th percentile of ensemble forecasts), one out of three irrigations could have been saved! In

particular, the irrigation scheduled for 29 June (Fig. 6b) could have been avoided (Fig. 6a), since 1 none of the 20 ensembles would have forecasted a soil moisture value below the stress threshold, 2 and even the irrigation scheduled for 14 July (Fig. 6d) could have been avoided (Fig. 6c) and 3 postponed for one week (Fig. 6f) when soil moisture forecasts issued on 20 July forecasted a 4 probability of 35% (i.e. 7 ensemble members out 20) to exceed the stress value if the landowner had 5 not irrigated on the 22nd (Fig. 6e). 6 In the same way during August, the landowner could have postponed the planned irrigation for 6 7 August (Fig. 7b) for one week (Fig. 7d), since no members of the ensemble forecast issued a 8 9 warning (Fig. 7a) for the next 7 days (which is important to bear in mind for the available irrigation 10 time allotment). In fact, if no irrigation occurred in the following 7 days, the forecast issue on 11 11 August would forecast a probability of 50% to exceed the stress threshold on 17 August (Fig. 7c). This comparison between the two scenarios, with or without the PREGI system, made it possible to 12 13 assess the benefits of this system in terms of water savings. Figure 8 shows how the soil moisture conditions with only two simulated irrigations, instead of three, would have remained within the 14 15 range of the two surplus and stress thresholds. On the contrary, the three irrigations that actually took place raised the soil water content even further above the surplus threshold for a good part of 16 17 the 2012 season.

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19 **4.** Conclusions

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21 The aim of the PREGI Project is to realize an integrated system by coupling meteorological and hydrological models to monitor and forecast soil water content in order to manage irrigation water 22 23 more wisely. The test-bed of the project was the maize field at Livraga in the MBL consortium, about 50 km south-eastern Milan in northern Italy. The hydro-meteorological chain to produce 24 ensemble soil moisture forecasts is based on 20 meteorological members of the non-hydrostatic 25 WRF-ARW model with a 30 days lead-time, provided by the Epson Meteo Centre, while the 26 hydrological model used to generate soil moisture simulations is the FEST-WB rainfall-runoff 27 28 distributed model, developed by the Politecnico di Milano. This contribution made by ensemble forecasts provides probabilistic information with different forecast scenarios to be below or above 29 30 stress/surplus thresholds. Furthermore, according to crop water consumption determined by the soil type and the degree of saturation, a continuous control of soil water content was carried out during 31 32 the entire 2012 growing season with three TDR probes installed. 33 The results show how it was possible by combing meteorological and hydrological models to have

- reliable soil moisture forecasts for up to 10 and 14 days respectively, with a mean relative error of
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less than 10%. Although the PREGI system showed a good level of performance during the 2012 1 season, decision criteria for when to irrigate were left more to the farmer's experience rather than 2 the hydro-meteorological forecasts. However, thanks to the PREGI system, we highlighted how one 3 of the three irrigations could have been avoided, if the landowner had followed the results generated 4 by our application. 5 Thus, the benefits of this project are both direct and indirect: the direct benefits regard the 6 7 monitoring and forecasting of soil water content according to the current state of soil moisture values and water crop requirements, while the indirect benefits regard the optimization of water 8 9 irrigations pursuing the best quantitative distribution, in particular periods of water scarcity, in order to minimize production losses caused by water stress due insufficient watering, avoiding the waste 10 11 of irrigation water as occurred in the 2010 growing season, when the PREGI system was unfortunately not yet in service. 12 13 One of the future developments is to extend these analyses over different sites with other case studies during future growing seasons. However, a limit for replicating this system in other areas 14 15 will be that of obtaining real-time data (weather and soil moisture information), amounts and scheduled irrigation dates, which are usually not easy to acquire in real time. 16 17 Acknowledgements 18

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28 Appendix

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During the 2012 growing season, real-time simulation data were uploaded on a google maps platform and stored in a database specifically created for the project. An example of the web application realized for the PREGI Project is shown in Fig. 9 with a colored "traffic-light" dot on the google map view of the Cascina Nuova farm. The value displayed on the colored dot means the higher daily probability value over a period of 30 days. The dot can be red or orange if stress and

1	surplus thresholds respectively exceed 33% of ensemble forecasts (i.e. at least 7 ensembles out of
2	20), following the method already used in the MAP D-PHASE Project reported in Zappa, et al.,
3	2008; if both thresholds are exceeded, a display priority has been given to the stress threshold.
4	Otherwise, if none of these two thresholds are exceeded, no alert is forecasted, and a green dot
5	appears on the map; in this way the Livraga landowner has a tool to control real time warnings
6	regarding soil moisture forecasts for his maize field.
7	An example of simulations uploaded on the web platform during 2012 the season (Fig. 10), when
8	the performance of the PREGI system was evaluated, is shown in Figure 10.
9	Soil moisture simulations by the FEST-WB hydrological model initialized with observed data by
10	the Lombardy ARPA and Meteonetwork-EMC station network are shown with a green line and the
11	forecasted data by the 20 ensembles of the REPS-WRF meteorological model with colored lines. In
12	this picture, it is evident how the two irrigations planned for 29 June and 14 July 2012 significantly
13	raised the soil moisture values above the water surplus threshold over the following days.
14	For reason of clarity, in Figure 10 we do not show all 20 ensembles, but only the 25 th percentile, the
15	median, the 75 th percentile and the mean of ensemble forecasts (respectively grey, blue, black and
16	yellow lines); however, all the 20 ensemble members can be selected in the web application. The
17	average soil moisture value measured with TDR probes in the Livraga test-bed is shown with a red
18	line for the entire forecast horizon; as described in Sect. 2.5, the area below the stress threshold
19	(0.23) is highlighted in red, while the one above the field capacity point (0.33) is shown in orange.
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-	Total porosity	Residual water content	Pore size distribution	Wilting point	Field capacity	Bubbling pressure
	(φ) 0.501	$(\boldsymbol{\theta}_{r})$	(λ) 0.224	0 122	0.220	(h _b)
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2 Table 1: Water-retention properties classified for a silt loam soil type (Maidment, 1993).



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

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



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



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

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







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



Figure 7: Soil moisture forecasts issued on 5 August (a-b) and 11 August (c-d) without planning
irrigations (left) and with including irrigation amounts in simulations (right). For the sake of clarity
only the mean (yellow line), the median (solid blue line), the 25th and 75th percentile (respectively
grey and black lines) are shown; the median of forecasted precipitation is shown with a dashed blue
line while the scheduled irrigations are shown with light blue bars.







Fig. 9: View of the google map platform of the PREGI Project. The Cascina Nuova field in Livraga
is outlined in red. This example shows 60% probability (i.e. 12 ensembles out of 20) of exceeding
the surplus threshold in at least one of the subsequent 30 days with the forecast simulation started
on 31 August 2012.

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Fig. 10: Soil moisture re-analysis forecast initialized on 22-06-2012 valid until 22-07-2012. The red line shows the average value of soil moisture measured with three TDR probes; the green line shows the simulated soil moisture using the FEST-WB model initialized with observed data, and the 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^{th} , 50^{th} , 75^{th} percentile and the mean.