Journal of Environmental Science and Engineering B 1 (2012) 379-396
Formerly part of Journal of Environmental Science and Engineering, ISSN 1934-8932

An Operational Hydro-Meteorological Chain to Evaluate the Uncertainty in Runoff Forecasting over the Verbano Basin

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Received: August 4, 2011 / Accepted: October 24, 2011 / Published: March 20, 2012.

Abstract: The development and implementation of a real-time flood forecasting system with a hydro-meteorological operational alert procedure during the MAP-D-PHASE Project is described in this paper. This chain includes both probabilistic and deterministic forecasts. The hydrological model used to generate the runoff simulations is the rainfall-runoff distributed FEST-WB model, developed at Politecnico di Milano. The observed data to run the control simulations were supplied by ARPA-Piemonte. The analysis is focused on Maggiore Lake basin, an Alpine basin between North-West of Italy and Southern Switzerland. Two hindcasts during the D-PHASE period are discussed in order to evaluate certain effects regarding discharge forecasts due to hydro-meteorological sources of uncertainties. In particular, in the June convective event it is analysed how the effect of meteorological model spatial resolution can influence the discharge forecasts over mountain basins, while in the November stratiform event how the effect of the initial conditions of soil moisture can modify meteorological warnings. The study shows how the introduction of alert codes appears to be useful for decision makers to give them a spread of forecasted QDFs with the probability of event occurrence, but also how alert warnings issued on the basis of forecasted precipitation only are not always reliable.

Key words: Hydro-meteorological chain, MAP-D-PHASE, quantitative discharge forecasts, ensemble hydrological forecasts.

1. Introduction

Over the last 20 years severe river floods have occurred in Europe, causing thousands of deaths and billion of Euros in insured economic losses [1]. Weather forecasts, combined with hydrological models, can be used to define early water-system control actions to take preventive measures or reduce problems with floods, droughts or water quality [2]. Therefore, coupling meteorological and hydrological models became a great issue and challenge in the scientific community during the last two decades.

To diminish the impact of floods through an early warning system, in 2003 the European Commission started the development of a EFAS (European flood alert system) to provide medium-range flood simulations across Europe [3, 4]. Other international programmes dealing with these topics were HEPEX in 2004, which aimed at fostering the development of probabilistic hydrological forecasting and corresponding decision making tools [5, 6], AMPHORE (Application des Methodologies de Previsions Hydrometeorologiques Orientees aux Risques Environnementaux), a continuation of HYDROPTIMET [7], mainly devoted to the hydro-meteorological modelling study of heavy precipitation episodes resulting in floods event and the optimisation of the existing warning system in the Western Mediterranean Basin [8, 9], RAPHAEL (Runoff and Atmospheric Process for Flood hazard Forecasting and Control) [10], and the European COST Action 731 (propagation of uncertainty in advanced

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meteo-hydrological forecast system) [11, 12].

The idea of a forecasting cascade was also one of the scientific objectives of the MAP (Mesoscale Alpine Programme) between 1994 and 2005. A unique initiative to improve the understanding of the processes involved in orographically induced precipitation events and the improvements of the high-resolution numerical weather prediction [13, 14].

After these encouraging results obtained in the MAP Project and considering that orographic precipitation has often led to disastrous flooding events over the Alps, it was decided to devote the MAP FDP (Forecast Demonstration Project) to show recent improvements in the operational use of an "end-to-end" forecasting system, consisting of atmospheric models, hydrological prediction systems, nowcasting tools and warnings for end users. The project acronym chosen was D-PHASE that stands for Demonstration of Probabilistic Hydrological and Atmospheric Simulation of flood Events in the Alpine region and is a FDP (Forecast Demonstration Project) of the WWRP (World Weather Research Programme of WMO). The MAP FDP has addressed the entire forecasting chain, ranging from limited-area ensemble forecasting, high-resolution atmospheric modelling (km-scale), hydrological modelling and nowcasting to decision making by the end users, i.e., it is foreseen to set up an end-to-end forecasting system. For a complete review see Refs. [15-18].

The use of EPS (ensemble prediction systems), instead of single (deterministic) forecasts for flood warning [19], is increasing among the hydrological community in order to quantify better the uncertainty of flood prediction. From the hydrological perspective using EPS as input to a hydrological model it is an important tool to produce river discharge predictions [20-22] and to assess uncertainty involved in forecasting precipitation [23, 24].

In this study it presents a hindcast for two different types of precipitation events that occurred during the D-PHASE Operational Period (DOP), from 1 June to 30 November 2007, in the Verbano basin in order to evaluate certain effects regarding discharge forecasts due to hydro-meteorological sources of uncertainties.

Two non-hydrostatic meteorological limited area models are used to force the distributed hydrological model (FEST-WB): one with a coarse spatial resolution, supported by the EPS (COSMO-LEPS system based on COSMO model) and the other with a finer grid, but with one deterministic output only (MOLOCH model).

The paper is organized as follows: in both events there is a meteorological introduction of the actual weather scenario, followed by hydrological forecast analyses over the watersheds. In the June convective event, it has been studied how the effect of meteorological model spatial resolution can influence the discharge forecasts over mountain basins (and subbasins), while in the November stratiform event how the effect of the initial conditions of soil moisture can modify meteorological warnings.

2. Area of Study

The subject area is the Verbano basin, also known as Maggiore, a regulated lake at the border between North-West Italy and South Switzerland. The drainage area covers 6,598 km^2: 3,229 km^2 in Italy and 3,369 km^2 in Switzerland. The study focuses on the three main rivers: the Ticino (1,616 km^2), the Toce (1,534 km^2) and the Maggia (926 km^2) (Fig. 1).

Nearly 17% of the total area is above 2,000 m a.s.l. Climate conditions are typically humid, characterized by higher precipitations in autumn, spring and summer with a dry season in winter [25]. Snowfall characterizes precipitation in autumn and winter and snow melting in spring gives a significant contribution to runoff. Climatic characteristics, together with morphology and soil texture, induce frequent flood events (1993, 1994, 1996, 2000 and 2002).

Three threshold levels were defined in the framework of the MAP-D-PHASE project to issue meteorological and hydrological warnings for the three

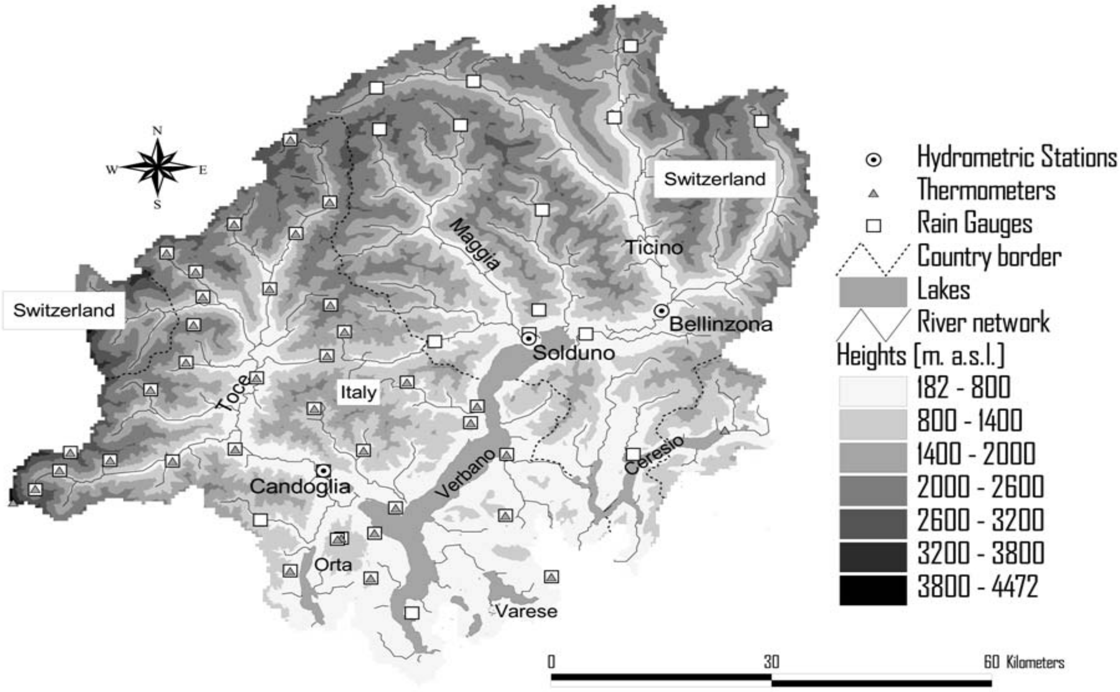


Fig. 1 The Verbano watershed, extracted from the DEM (digital elevation model) showing locations of the rain gauges, thermometers and hydrometric stations.

main river basins: a "yellow-attention" level when 60-day return period was exceeded, an "orange-alert" level when 180-day return period was exceeded and "red-alarm" level when 10-year return period was exceeded. Rainfall thresholds were estimated for each basin for six durations, ranging from 3 to 72 hours on the basis of statistics of daily precipitation over the Alps and scaling assumptions with respect to storm duration and area. Flood peak thresholds were estimated on the basis of at-site statistics of runoff peaks or from the rational formula. Of course, in operational forecasting levels are usually higher (with return periods of 10 year and more), but low thresholds were chosen in this project in order to see some action on the maps during the very short demonstration phase. Rainfall and discharge thresholds for the three studied river basins are reported in Table 1 and Table 2, respectively.

Table 1 Rainfall thresholds (in millimetres of rain) of the meteorological warnings for six durations from 3 to 72 hours.

Warning level (WL)	Σ 03 h	Σ 06 h	Σ 12 h	Σ 24 h	Σ 48 h	Σ 72 h
River Toce at Candoglia						
Yellow-attention	10.9	15.5	22.4	31.9	42.3	49.8
Orange-alert	24.6	35.2	50.7	72.4	96.1	113.3
Red-alarm	56.2	80.5	116.0	165.7	220.1	259.4
River Ticino at Bellinzona						
Yellow-attention	15.3	22.0	31.5	44.8	59.6	70.2
Orange-alert	27.4	39.4	56.4	80.4	106.8	125.9
Red-alarm	55.2	79.4	113.8	162.2	215.6	254.1
River Maggia at Solduno						
Yellow-attention	17.0	24.4	34.8	49.2	65.1	76.6
Orange-alert	34.0	48.7	69.4	98.1	129.8	152.7
Red-alarm	73.0	104.7	149.1	210.8	278.9	328.0

Table 2 Flood peak thresholds in ($m^3 \cdot s^{-1}$) for the three river basins investigated.

Warning level (WL)	Toce	Ticino	Maggia
Yellow-attention	306	269	234
Orange-alert	694	584	884
Red-alarm	1588	1320	2959

Available digital cartographic data include: the DEM (digital elevation model) available in raster format at 100 m × 100 m resolution, CORINE land cover maps updated in the year 2000, and pedologic characteristics for soils available in vector format [26, 27]. From these basic thematic layers, basin parameters required for the application of the hydrological model, have been derived at a spatial resolution of 1,000 m × 1,000 m. These include: Curve Number [28], flow direction, slope and aspect, residual and saturated soil moisture, albedo, pore size distribution index, saturated hydraulic conductivity, wilting point, field capacity and soil depth.

3. Hydrologic and Meteorological Data

To calibrate and test the hydrological model FEST-WB meteorological and hydrologic ground measured data were collected by the telemetric monitoring system in Italy and Switzerland. Records of rainfall, air temperature, short wave solar radiation and air relative humidity are available at hourly or sub-hourly time steps. Hydrometric observations at 30 minutes time step are available at Candoglia, Solduno and Bellinzona gauging stations (rivers Toce, Maggia and Ticino respectively, see Fig. 1). All these data were accessible for the time period from 1 January 2000 to 31 December 2003; for a complete review about the FEST-WB hydrological model calibration the reader can refer to Ref. [9].

During the MAP-DPHASE period, ground measured meteorological forcings were used for the hydrological model initialization, before being forced by forecasted meteorological fields to predict river discharge, for more details, see section 4 “Coupling strategy”.

3.1 Meteorological Models

The hydro-meteorological chain includes both probabilistic forecasts based on ensemble prediction systems with a lead time of a few days and short-range forecasts based on a high resolution deterministic atmospheric model, in order to predict the QDF (quantitative discharge forecast). The probabilistic forecast was supplied by COSMO-LEPS model (Consortium for Small-scale Modelling–Limited area Ensemble Prediction System), implemented and developed by A.R.P.A. Emilia-Romagna in the framework of COSMO Consortium [29, 30]. The spatial resolution is 10 km (0.09°), while the temporal resolution is 3 h, with 40 vertical levels, 16 ensemble members, nested on ECMWF EPS (European Centre for Medium Range Forecast-Ensemble Prediction System) and 132 h as lead-time; the run starts every day at 12:00 UTC, while the hydrological simulation begins 12 hours later at 00:00 UTC, so 120 hours of hydrological simulation are available.

The deterministic forecast was supplied by MOLOCH model (MOdello LOCale in “H” coordinate) of I.S.A.C.-C.N.R. in Bologna, Italy [31]. The model chain comprises the hydrostatic model BOLAM and the non-hydrostatic model MOLOCH, nested in BOLAM. The BOLAM model has a horizontal grid spacing of 0.11° in rotated coordinates (about 12 km), with 50 levels and a parameterization (Kain-Fritsch) of moist convection. On the contrary, the MOLOCH model has a horizontal grid spacing of 0.02°, corresponding to about 2.3 km, with 50 levels; moist deep convection is computed explicitly. The forecasting chain is based on the 18:00 UTC, ECMWF analysis/forecasts at 0.25° resolution; BOLAM run starts at 18:00 UTC, MOLOCH is nested at 00:00 UTC, the same time as the hydrological simulation.

The different spatial resolution used by the two weather models over the Maggiore basin is shown in Fig. 2: the COSMO-LEPS model, with a spatial resolution of 10 km, which covers the Toce basin (1,534 km^2) with 15 squares, on the contrary, the high-resolution MOLOCH model, with a spatial grid of 2.3 km, which fills the Toce basin with 317 squares.

3.2 Hydrological Model

Hydrological simulations were performed using the FEST-WB distributed water balance model [9, 32-34].

FEST-WB calculates the main processes of the hydrological cycle: evapotranspiration, infiltration, surface runoff, flow routing, subsurface flow and snow dynamics. The computational domain is discretized with a mesh of regular square cells (1 km in this application), in which water fluxes are calculated at hourly time intervals.

Five main components can be identified in the FEST-WB model:

(1) the flow paths and channel network definition;

(2) the spatialization of site measured meteorological forcings;

(3) the snow pack dynamics;

(4) the runoff calculation;

(5) the overland and subsurface flow routing.

In the first component the flow path network is automatically derived from the digital elevation model using a least-cost path algorithm [35]. It assigns flow from each pixel to one of its eight neighbours, without the necessity to remove pits in the elevation data. For hillslope and channel network definition the model uses the constant minimum support area concept. It consists of selecting a constant critical support area that defines the minimum drainage area required to initiate a channel [36].

In the second component, the spatial interpolation of ground measured meteorological forcings is carried out. The model requires precipitation, air temperature, air relative humidity, and net solar radiation, sum of short wave and long wave components.

The observed data at ground stations are interpolated with a regular grid, using the inverse distance weighting (IDW) technique. In order to facilitate integration with meteorological models, the FEST-WB can also accept spatial gridded meteorological as input.

The third component deals with snow dynamics simulation. The snow module of the FEST-WB includes snow melt and snow accumulation dynamics.

In the FEST-WB model the partitioning of total precipitation, P, in liquid, P_l, and solid, P_s, phase is a function of air temperature, T_a [37]:

$$P_l = \alpha_P P \quad (1)$$

$$P_s = (1 - \alpha_P) P \quad (2)$$

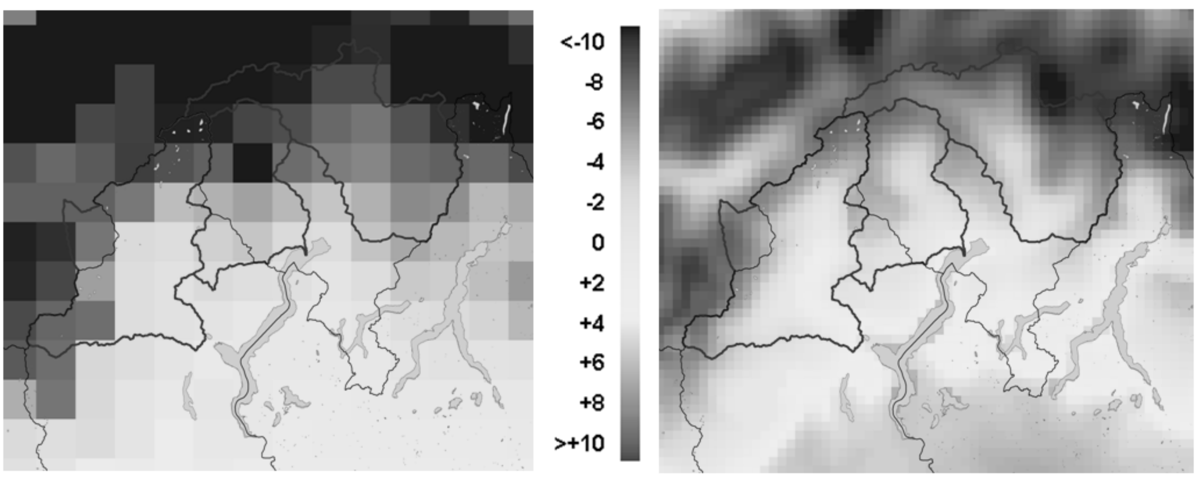


Fig. 2 Different spatial resolutions used by the two weather models over the Verbano basin: COSMO-LEPS, 10 km (left) and the MOLOCH model, 2.3 km (right). A temperature field on 27 November 2007 is shown in Celsius degrees.

where α_P is calculated as follows:

$$\alpha_p = \begin{cases} 0 & if \quad T_a \le T_{low} \\ 1 & if \quad T_a \ge T_{up} \\ \dfrac{T_a - T_{low}}{T_{up} - T_{low}} & if \quad T_{low} < T_a < T_{up} \end{cases} \quad (3)$$

where T_{low} and T_{sup} are air temperatures below or above which precipitation falls as snow or rain, respectively [38].

The snow melt simulation is based on the degree day concept [39]. The melting rate in m·s^{-1}, M_s, is proportional to the difference between air temperature and a predefined threshold temperature, T_b:

$$M_s = \begin{cases} C_m (T_a - T_b) & if \quad T_a > T_b \\ 0 & if \quad T_a \le T_b \end{cases} \quad (4)$$

where C_m (m·°C^{-1}·s^{-1}) is an empirical coefficient, depending on meteorological conditions and geographic location; generally C_m coefficient ranges from 4.8×10^{-8} to 6.9×10^{-8} m·°C^{-1}·s^{-1}.

The predefined temperature T_b fixes a threshold beyond which snow starts melting, and its value is usually assumed to be equal to 0 °C; T_b and C_m are calibrated values of the model.

The terrain covered by snow is supposed to be frozen and hence the melted water is prevented from infiltrating the soil. Conversely, the liquid fraction of snow water equivalent, R_s, the sum of melted water and liquid precipitation, is supposed to flow cell by cell through the snow pack with a linear reservoir routing scheme [40] with a celerity of 1.67×10^{-3} m·s^{-1} [41]. When R_s reaches a cell not covered by snow, it is added to the liquid precipitation of that cell, becoming part of the infiltrable water.

In the fourth component, the runoff is computed for each elementary cell, according to a modified SCS-CN method extended for continuous simulation [33].

The potential maximum retention, S, is updated cell by cell at the beginning of rainfall as a linear function of the degree of saturation, ε

$$S = S_1 (1 - \varepsilon) \quad (5)$$

where S_1 is the maximum value of S when the soil is dry (AMC 1) and ε is obtained using following formula:

$$\varepsilon = \frac{\theta_t - \theta_{res}}{\theta_{sat} - \theta_{res}} \quad (6)$$

where θ_t is explained in Eq. (7), θ_{sat} is the saturation soil moisture, while θ_{res} is related to the residual soil humidity. The dynamic of the soil moisture θ, for a cell not covered by snow, is calculated using the following water balance equation:

$$\frac{\partial \theta}{\partial t} = \frac{1}{Z}\left(P_l - R - D - ET\right) \quad (7)$$

where R is surface runoff flux, D is drainage flux, ET is evapotranspiration rate and Z is soil depth. Soil moisture in cells covered by snow is assumed not to vary over time.

The actual evapotranspiration, ET, is computed as a fraction of the potential rate calibrated by a function that, in turn, depends on soil moisture content [42]. Potential evapotranspiration is calculated with a radiation-based equation [43].

The fifth component performs the runoff routing throughout the hillslope and river network. The surface flow routing, calculated for the cells that are not covered by snow, is based on the Muskingum-Cunge method in its non-linear form with time variable celerity [32]. Subsurface flow routing, similar to the method implemented for routing in the snow pack, is calculated with a linear reservoir routing scheme [40] with a celerity calculated as a function of soil saturated conductivity.

The FEST-WB model can save state variables on the file system at regular time intervals, permitting the restart of a simulation from a previous condition. This feature is used where a long simulation has to be carried out at a different time, or to initialize the model before carrying out a forecast run.

4. Coupling Strategy

The hydro-meteorological chain was launched automatically once a day during the DOP. The hydrological model was initialized with a simulation run forced with observed ground measured data. In order to limit the frequency and the amount of data transfer, the initialization run was directly launched by ARPA Regione Piemonte which collected data coming from the monitoring network. Only the updated state variables of the hydrological model were subsequently transferred to Politecnico di Milano to perform forecasting run.

Meteorological data were received automatically every day from two weather services: ARPA Emilia-Romagna and ISAC-CNR in GRIB1 format. The meteorological variables used from COSMO-LEPS were: NSWRS (net short wave radiation solar), NLWRS (net long wave radiation solar), DPT (dew point temperature), TCDC (Total ClouD Cover), APCP (Amount PreCiPitation) and TPT2 (TemPeraTure at 2 m). Conversely, SPFH (SPeciFic Humidity), TCDC (Total ClouD Cover), GRAD (Global RadiAtioN), APCP (Amount PreCiPitation), TPT2 (TemPeraTure at 2 m) and PRES (local atmospheric PRESsure) were implemented from MOLOCH model.

Discharge forecasts at hourly time step were obtained by forcing meteorological forecasts in the hydrological model. Meteorological forecasted fields were downscaled to hydrological model spatial resolution, using the simple nearest neighbour re-sampling method.

The statistical analysis which describes the capability of our simulation outcomes includes common methods frequently found in literature [44].

The Box-Whisker plot is a graphic representation which is useful for visualizing groups of numerical data through “the five-number summary”. It sums up the smallest observation (sample minimum), the lower quartile (Q25), the median, the upper quartile (Q75) and the largest observation (sample maximum).

The graphs reported in Figs. 3-5 showed the median (white line), the mean (white rhombus), the 25th and 75th percentile (boxes), the minimum and maximum value of the ensembles (bars-whisker). The results shown in section 5, if the observed discharge value is outside or inside the lower and upper box, it see an under/overestimation or a good performance respectively for the maximum forecasted discharge of the 16 CLEPS ensembles during the events we analysed.

Another similar index to understand an under/overestimation of the forecasted discharge “Q” is the QDF (quantitative discharge forecast) error. The formula used is the following:

$$QDF_{error} = \frac{Q_{fct}^{\max} - Q_{obs}^{\max}}{Q_{obs}^{\max}} \tag{8}$$

where:

$Q_{fct}^{\max}$ = forecasted peak discharge;

$Q_{obs}^{\max}$ = observed peak discharge;

Best score = 0.

5. Simulation Results over the Three River Basins

5.1 The June 2007 Event: Effect of Model Spatial Resolution

The June event (13-15 June 2007) was the most severe and relevant during the DOP on the Maggiore Lake basin. The synoptic analysis over Europe on 15 June 2007 showed a “cold drop” located South-West of the British Isles, triggering moist flow from the Mediterranean Sea towards the Alps and the Po Valley, causing convective cells with associated thunderstorms on the Lake Maggiore basin 95-110 millimetres fell in three days (13, 14, 15 June) over the three basins (Table 3), about 85-95 of them in only 24 hours between 14 and 15 June.

This amount of rainfall yielded the following measured peak discharges: 783.2 $m^3 \cdot s^{-1}$ observed at Candoglia (orange warning), 941.7 $m^3 \cdot s^{-1}$ at Solduno (orange warning) and 761.5 $m^3 \cdot s^{-1}$ at Bellinzona (orange warning); however, these discharge values caused no flood damage in the catchment areas.

Table 3 Observed rainfall over the Lake Maggiore basins between 13-15 June 2007.

Day	Toce	Ticino	Maggia
13 June 2007	4.9	7.4	6.9
14 June 2007	16.3	24.6	20.6
15 June 2007	68.2	72.7	82.1
Total precipitation (mm)	89.4	104.7	109.6

Before analysing the results, it is important to highlight that since the precipitation forecast of the CLEPS and MOLOCH models over the three Maggiore Lake basins showed some under/overestimation errors during the event, better results in hydrological forecasts were obtained with the meteorological run initialized on the 14 June (i.e. 24-48 hours before the main peak discharge on 15 June) as is shown in the Bow-Whisker plots for all three basins (Figs. 3-5). Thus, all the tables and figures shown regarding this June 2007 event, and related to the simulations driven by observed and meteorological model data, refer to the hydrological simulation launched on 14 June 2007.

5.1.1 River Toce at Candoglia

Over the Toce basin the two meteorological models were characterized by an opposite behaviour in terms of forecasted cumulative precipitation between 14-15 June, in comparison with the observed mean basin values: in fact, there was an underestimation for the COSMO-LEPS model and an overestimation for the MOLOCH model (Table 4).

Because of this, the COSMO-LEPS issued a meteorological and hydrological yellow warning, vice versa the MOLOCH issued an orange warning (Table 5).

The maximum observed discharge at Candoglia was 783.2 $m^3 \cdot s^{-1}$ (orange warning) on 15 June at 17:00 UTC, while the simulated maximum discharge by the FEST-WB forced with observed hydro-meteorological data was 750 $m^3 \cdot s^{-1}$ at 20:00 UTC (Fig. 6); despite this delay in reaching the peak (Table 6), the hydrological model achieved a good performance (Table 7), issuing the correct warning.

The response of the hydrological model was

Table 4 Relative errors of cumulated precipitation between 14 and 15 June for the ensemble median of the CLEPS and for the deterministic run of the MOLOCH model in comparison with the observed mean basin values over the three catchments. The CLEPS forecast was initialized on 13 June 2007 12:00 UTC, while the MOLOCH was initialized on 14 June 2007 00:00 UTC.

River basin	June 2007 event	
	CLEPS median	MOLOCH
Toce	-28%	+20%
Ticino	-30%	-56%
Maggia	-25%	-24%

Table 5 Meteorological and hydrological warnings issued by the COSMO-LEPS and the MOLOCH model between 14 and 17 June over the three basins. The hydrological simulation run started on 14 June 2007 00:00 UTC and finished on 18 June 2007 00:00 UTC.

	River basin	June 2007 event	
		CLEPS median	MOLOCH
Meteorological warning	Toce	yellow	orange
	Ticino	yellow	green
	Maggia	yellow	yellow
Hydrological warning	Toce	yellow	orange
	Ticino	orange	orange
	Maggia	orange	orange

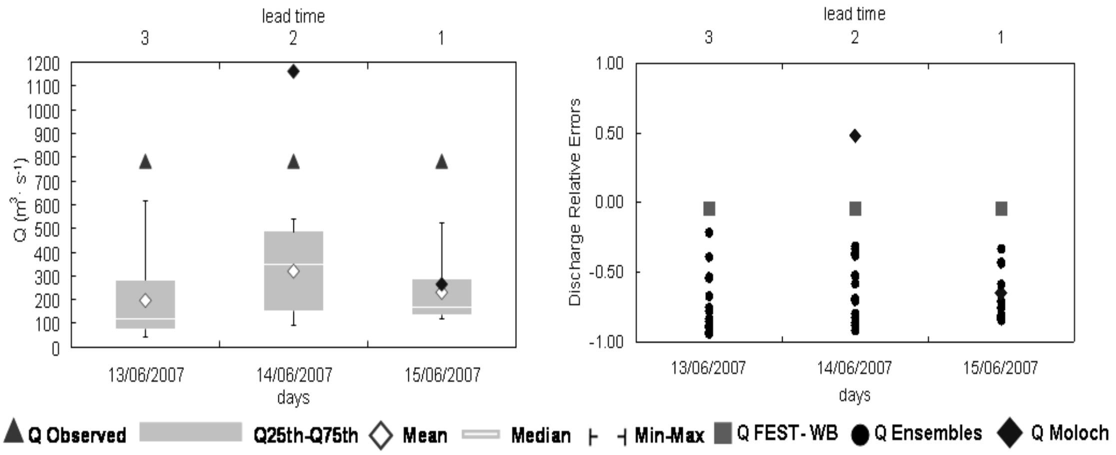


Fig. 3 The Box-Whisper plot (left) and the QDF error (right) for the forecasted peak discharge for 15 June on the Toce basin, obtained with the FEST-WB model simulation forced with observed meteorological data (squares) and with the COSMO-LEPS (boxes and whiskers) and MOLOCH (rhombus) model runs, started on 13, 14 and 15 June 2007.

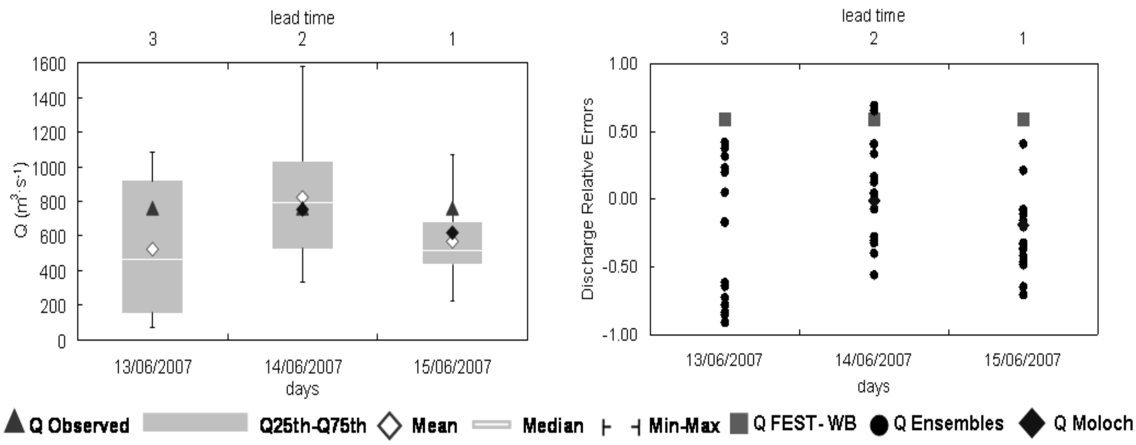


Fig. 4 The Box-Whisper plot (left) and the QDF error (right) for the forecasted peak discharge on 15 June for the Ticino basin, obtained with the FEST-WB model simulation forced with observed meteorological data (squares) and with COSMO-LEPS (boxes and black whiskers) and MOLOCH (rhombus) model runs, started on 13, 14 and 15 June 2007.

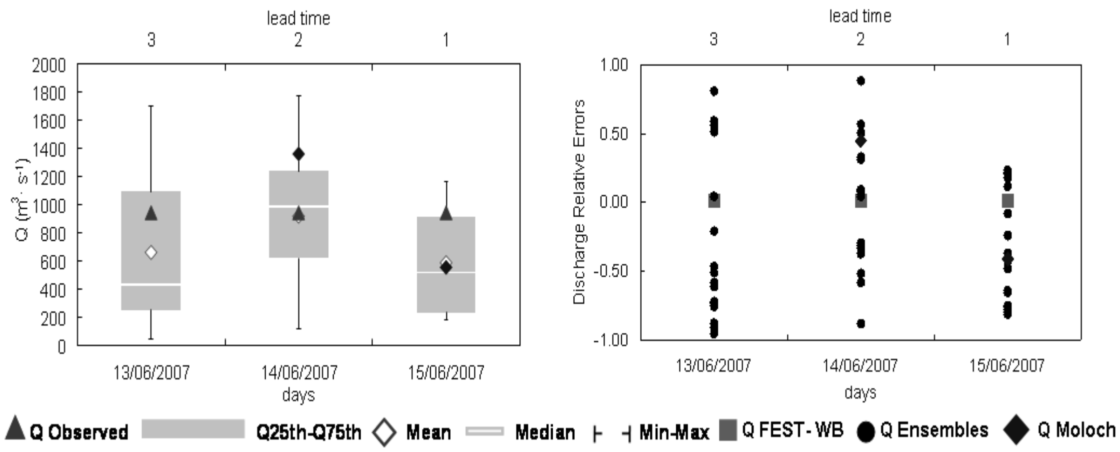


Fig. 5 Box-Whisper plot (left) and QDF error (right) for the forecasted peak discharge on 15 June for the Maggia basin, obtained with the FEST-WB model simulation forced with observed meteorological data (squares) and with COSMO-LEPS (boxes and black whiskers) and MOLOCH (rhombus) model runs, initialized on 13, 14 and 15 June 2007.

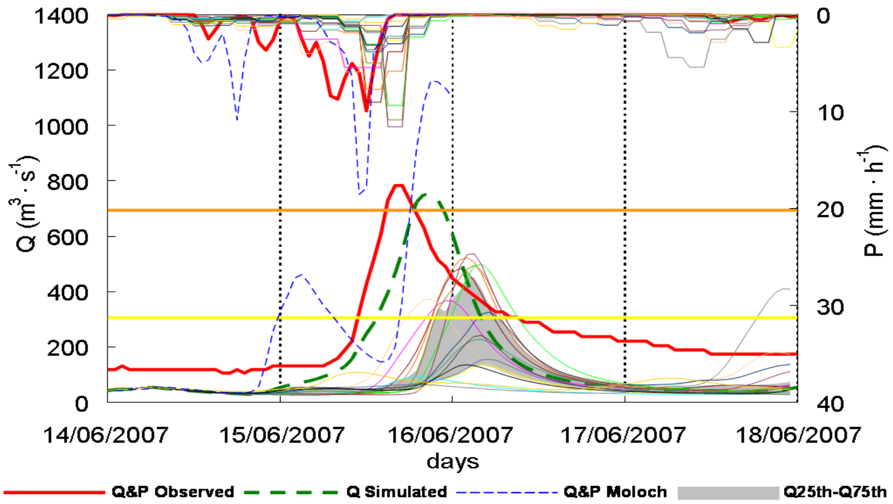


Fig. 6 QPFs and QDFs of the FEST-WB model forced with observed meteorological data and with the CLEPS and MOLOCH model forecast over the Toce basin. The hydrological simulation driven by the two meteorological model was launched on 14 June 2007 00:00 UTC. The discharge value of each ensemble forecast is shown with different coloured lines.

Table 6 Time lag errors of peak discharges on 15 June for the FEST-WB hydrological simulation driven by observed meteorological forcings over the three basins, time lag errors of peak discharges between 14 and 17 June for the ensemble median of the CLEPS, and for the deterministic run of the MOLOCH model. Hydrological simulations started on 14 June 2007 00:00 UTC and finished on 18 June 2007 00:00 UTC.

Peak discharge time lag errors (hour)	June 2007 event		
	FEST-WB	CLEPS median	MOLOCH
Toce	+3 h	+10 h	+3 h
Ticino	+2 h	+10 h	+4 h
Maggia	+1 h	+7 h	+4 h

Table 7 Relative errors in peak discharges between 14 and 17 June for the FEST-WB hydrological simulation driven by observed meteorological forcings over the three basins and for the ensemble median of the CLEPS and for the deterministic run of the MOLOCH model. Hydrological simulations started on 14 June 2007 and finished on 18 June 2007 00:00 UTC.

Peak discharge relative errors	June 2007 event		
	FEST-WB	CLEPS median	MOLOCH
Toce	-4%	-56%	+48%
Ticino	+59%	+4%	-1%
Maggia	+2%	+5%	+45%

different when implemented with the forecasted meteorological forcings. Although better simulations (Fig. 3) were obtained with the one day ahead run (i.e. 24-48 hours before the main peak discharge), the COSMO-LEPS ensemble predictions have shown very poor results with a total underestimation of the peak discharge (Table 7), which was forecasted about 10 hours later (Table 6) than the observed time (Fig. 6); furthermore all 16 members of the COSMO-LEPS model were affected by errors in terms of timing and amount of rainfall over the Toce river basin for this event.

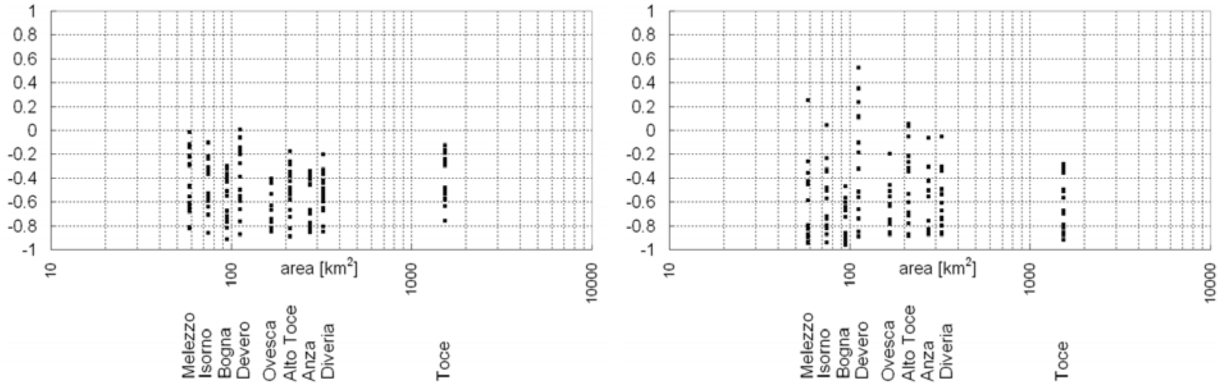
The performance was even worse for the forecast initialized two days before the peak event and for the run started on the same day, as shown in Fig. 3.

An opposite result was obtained using the MOLOCH model. In fact, with the one day ahead run, the peak discharge was overestimated (1,162.3 $m^3 \cdot s^{-1}$), but the magnitude of the event was correctly predicted, issuing an orange warning (Fig. 6).

5.1.2 Impact at Subbasin Scale

The COSMO-LEPS forecast precipitation error was also investigated over the Toce subbasins to understand if the underestimation persists even at smaller scales. As can be seen in the QPF and QDF plots (Fig. 7), the underestimation in forecasting is generally confirmed in most of the Toce subbasins: in particular, the worst results were achieved for the Bogna and Ovesca subbasins and a better outcome was instead obtained for the Devero, where there was appeared to be an overestimation for some ensemble members in the peak flow.

If considering the ensembles median of the cumulated precipitation (red dashed line), there is an underestimation of about 40 mm (*ΔP*) in the Bogna subbasin (Fig. 8), in comparison with the subbasin mean rainfall (dark solid line); this produced an underestimation of the forecasted ensemble median



(a) QPF error (b) QDF error

Fig. 7 Semi-log plot for the QPF error between 14 and 15 June by the CLEPS model on the Toce basin and its subbasins. The CLEPS forecast was initialized on 13 June 2007 12:00 UTC (a). Semi-log plot for the QDF error of FEST-WB model driven by the CLEPS forecast on 15 June over the Toce basin and its subbasins; the hydrological simulation driven by the CLEPS forecast was launched on 14 June 2007 00:00 UTC and finished on 18 June 2007 00:00 UTC (b). Black dot show the ensemble QPF errors.

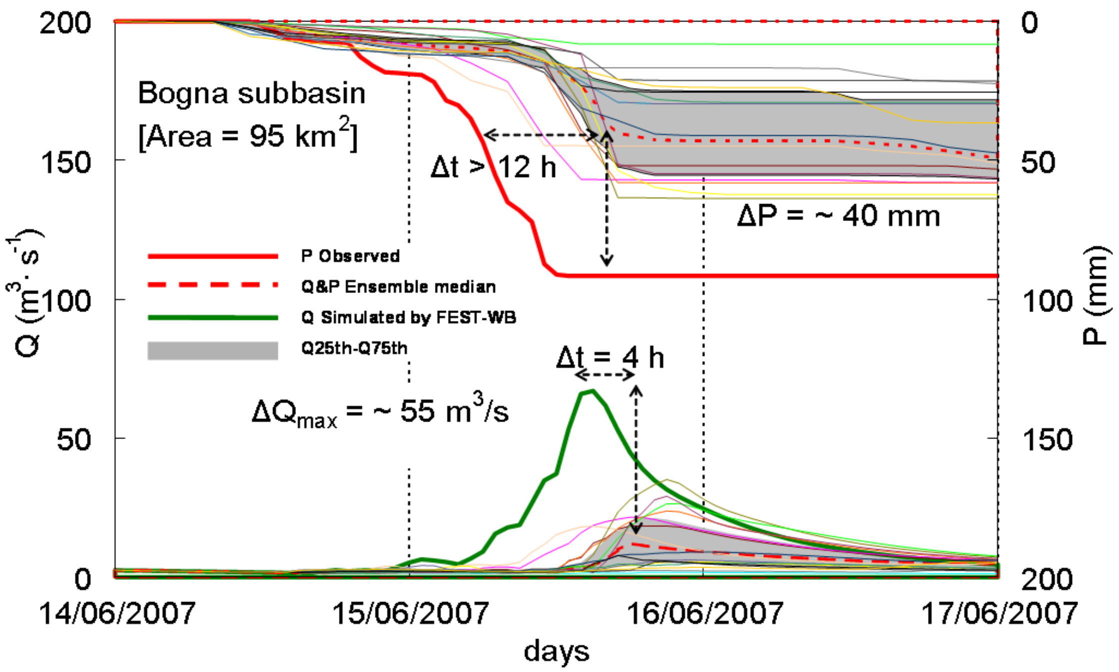


Fig. 8 QPFs and QDFs of FEST-WB and CLEPS models over the Bogna subbasin. The CLEPS forecast started on 13 June 2007 12:00 UTC, while the hydrological simulation driven by the CLEPS forecast was launched on 14 June 2007 00:00 UTC and finished on 18 June 2007 00:00 UTC.

discharge (dark dashed line), compared to the discharge simulated by the FEST-WB model (light solid line) of about 55 $m^3 \cdot s^{-1}$, as ΔQ_{max}. In terms of the hydrograph's water volume, about 2.55 × 10^6 m^3 of water less than the simulated amount was forecasted over this small watershed (~ 100 km^2) in three days.

Due to unknown measured discharge values at subbasin scale, discharge simulations obtained with the FEST-WB model, driven by observed data, were used as a reference.

This underestimation obtained in the QPF and in the QDF was strongly pronounced in almost all the Toce subbasins, except over the Devero, where better results were found. As shown in Fig. 9, there are only 12 mm of difference (ΔP) between the median of cumulated precipitation, compared with the subbasin mean rainfall value; this involves a ΔQ_{max} of only 13 $m^3 \cdot s^{-1}$ between the value forecasted by CLEPS and the value simulated by the FEST-WB model. In this case, in terms of the hydrograph's water volume, this underestimation is much less than the one obtained for the Bogna subbasin, in fact, about 0.68 × 10^6 m^3 of water less than the simulated amount was forecasted over the Devero subbasin.

5.1.3 River Ticino at Bellinzona

Moving now our attention to the Ticino basin, the COSMO-LEPS and MOLOCH models significantly underestimated the cumulative precipitation (Table 6). The maximum observed discharge at Bellinzona was 761.5 $m^3 \cdot s^{-1}$ (orange warning), while the simulated maximum discharge by FEST-WB driven by observed hydro-meteorological data was 1,210.4 $m^3 \cdot s^{-1}$ (Fig. 10).

The relevant overestimation by the hydrological FEST-WB model, when it was forced with a meteorological forecast, was compensated by a precipitation underestimation of the COSMO-LEPS and MOLOCH models. This led to small errors in peak discharge prediction (Table 6 and Fig. 4) and to the correct issuing of the hydrological warning level (Table 5).

5.1.4 River Maggia at Solduno

Last analyses for this convective summer event were carried out on the Maggia, the smallest of the three catchments. As well as for the other two basins, the two

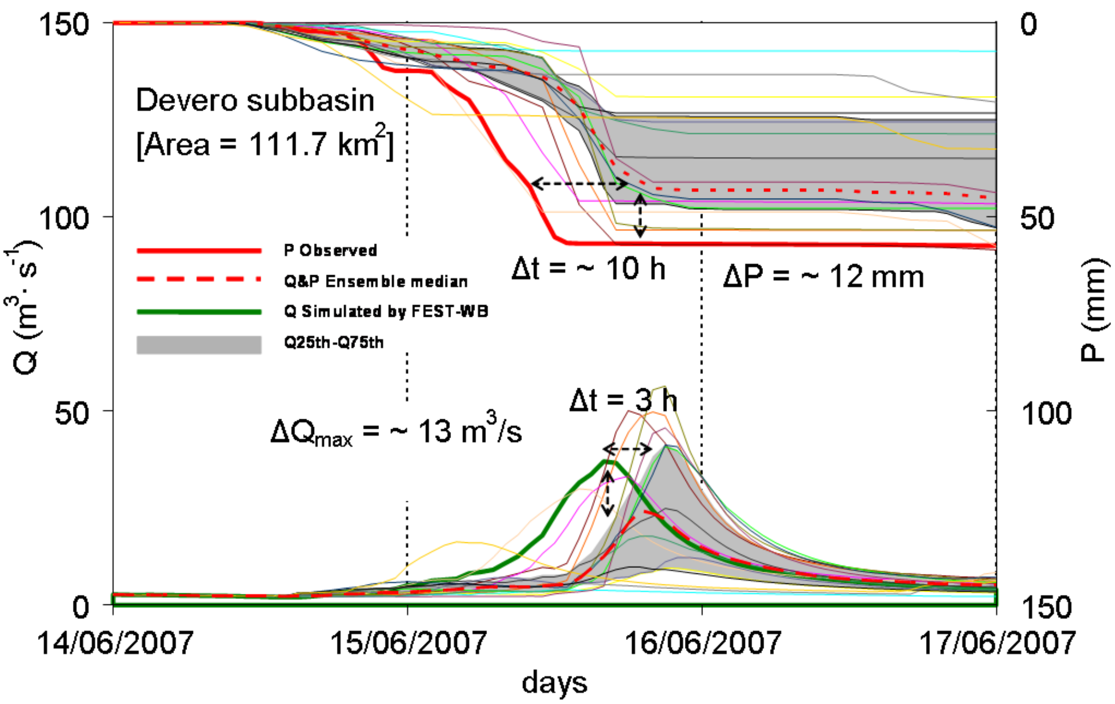


Fig. 9 QPFs and QDFs of FEST-WB and CLEPS models over the Devero subbasin. The CLEPS forecast started on 13 June 2007 12:00 UTC, while the hydrological simulation driven by the CLEPS forecast was launched on 14 June 2007 00:00 UTC and finished on 18 June 2007 00:00 UTC.

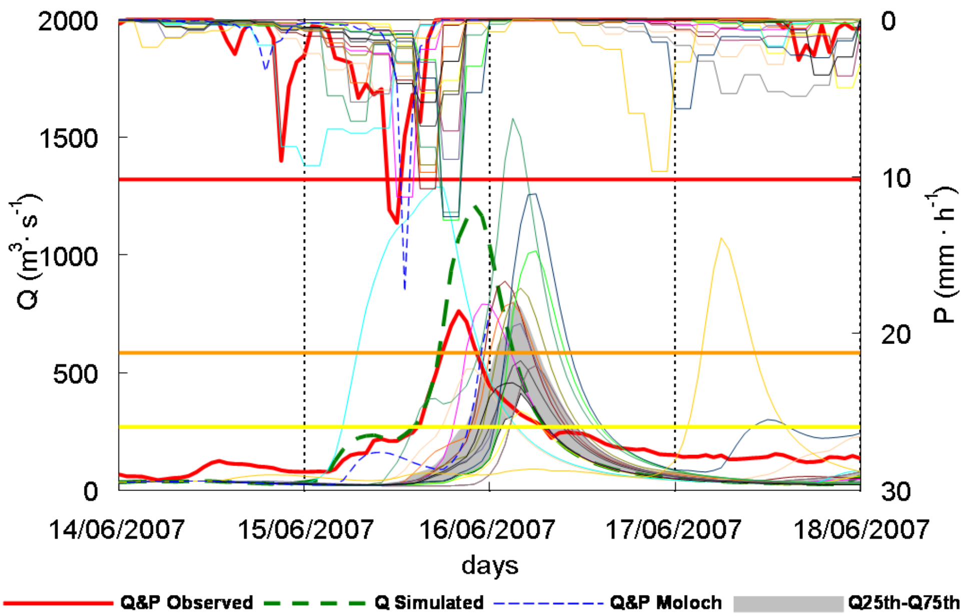


Fig. 10 QPFs and QDFs of the FEST-WB model forced with observed meteorological data, and with the CLEPS and MOLOCH model forecast over the Ticino basin. The hydrological simulation driven by the two meteorological model was launched on 14 June 2007 00:00 UTC and finished on 18 June 2007 00:00 UTC.

meteorological models have demonstrated a better hydrological simulation 24-48 hours before the observed peak (Fig. 5).

The FEST-WB simulation shows a very good performance (956.4 $m^3 \cdot s^{-1}$), in accordance with the observed discharge value (941.7 $m^3 \cdot s^{-1}$), both in terms of time (Table 7) and peak flow (Table 6). Although cumulative precipitation was underestimated by both weather models, thanks to an overestimation in precipitation rate, especially in the MOLOCH model (Fig. 11), the hydrological forecasts correctly showed that the orange warning has been exceed (Table 5).

In this first experiment carried out in 2007, it is found that an overestimation or underestimation of

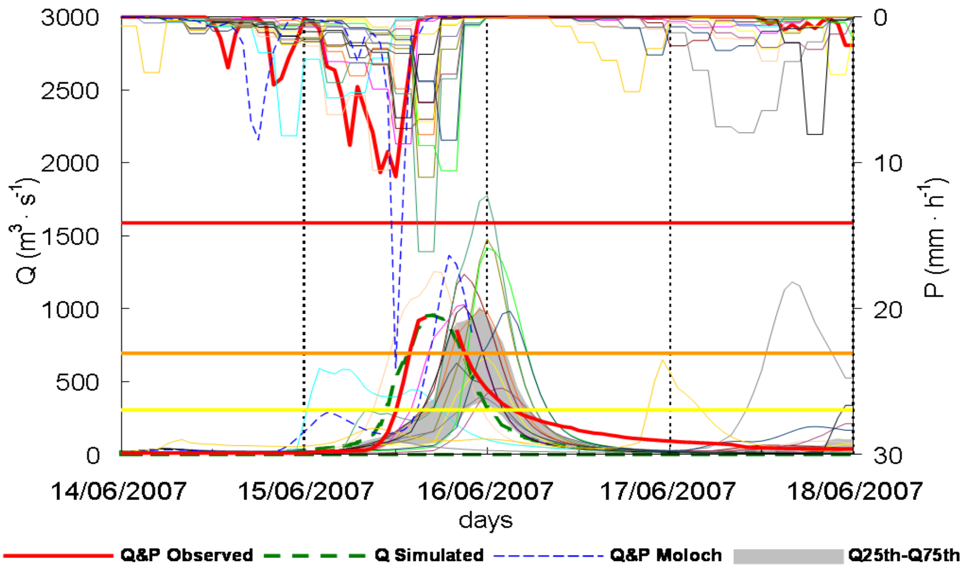


Fig. 11 QPFs and QDFs of the FEST-WB model forced with observed meteorological data, and with the CLEPS and MOLOCH model forecast over the Maggia basin. The hydrological simulation driven by the two meteorological model was launched on 14 June 2007 00:00 UTC and finished on 18 June 2007 00:00 UTC.

weather models can be enhanced or smoothed out by hydrological model performance. Errors in meteorological forecasts can be a consequence of the different spatial resolution between the two meteorological models with markedly different orographies as shown in Fig. 2 in Section 3.1. But, another aspect to be considered is that both forecasts are fed into a hydrological model on 00:00 UTC as "initialization time". This means that the hydrological forecast is based on a 12-hour forecast by CLEPS and at the same hour-forecast by MOLOCH.

Especially for short lead times and small catchments, forecast error is in general a function of lead time (the longer the lead time, the more uncertain the forecast). This is probably not as important for the 3- and 2-day forecasts, but it could be for the 1-day forecasts. High-resolution models (like MOLOCH) are mainly targeted for the short-range where more spatial detail is required, while the lower-resolution models such as COSMO-LEPS is mainly targeted for ranges from one day onwards. It is known that it may not be recommended to directly compare the forecast qualities for such different lead times of meteorological forecasts, but the idea it is not to put one model against the other, but to show that forecasting hydro-meteorological systems should be supported by both the two models, i.e. probabilistic and deterministic.

5.2 The November 2007 Event: Effect of Soil Moisture Conditions

The November event over the Maggiore Lake basin was a stratiform event with light but continuous precipitation over the area, but with very small peak stream-flows in all three main basins. The weather analysis over Europe on 23 November shows a typical autumnal pattern with an upper level trough, coming from the Atlantic Ocean, moving eastward, trigging humid air from the South toward the Southern edge of Italian and Swiss Alps.

After the long dry period that hit the Southern edge of the Alps from the beginning of October, this precipitation was the first relevant meteorological phenomenon that occurred after 50 days of the dry autumn season of 2007.

For the sake of brevity, it is focused the attention over the Toce basin, where a more detailed physiographic characterization is available. The observed amount of precipitation during this stratiform event (21-24 November) was about 80 mm as a mean basin value (Table 8).

Figs. 12 and 13 show the millimetres of precipitation forecasted by the MOLOCH model (Fig. 12) and the expected probability in exceeding the meteorological yellow code by the CLEPS model (Fig. 13) with the weather forecasts initialized on 21, 22 and 23 November 2007.

According to the D-PHASE threshold (Tables 1 and 2), the CLEPS and MOLOCH models issued a meteorological warning (yellow code) expected on 22 and 23 November, but the measured peak discharge on 23 November at the Candoglia gauging station was only 57.8 $m^3 \cdot s^{-1}$, which is a very low value, with no alert all!

As it has been seen for the June event, there is not always a univocal relationship between meteorological and hydrological warnings. In this event, due to the dry antecedent soil condition, the FEST-WB hydrological simulations, forced with forecasted meteorological

Table 8 Observed precipitation during the 21-24 November event.

Day	Observed precipitation (mm)
21 November 2007	6.7
22 November 2007	30.6
23 November 2007	34.7
24 November 2007	9.4
Total Precipitation (mm)	81.5

MOLOCH forecast [millimeters of rain]

forecast day	21	22	23	24
21-11-2007	11.7	48.7		
22-11-2007		37.3	52.9	
23-11-2007			41.5	9.0

Fig. 12 Millimetres of forecasted rain by the MOLOCH model. The hydrological runs were initialized on 21, 22 and 23 November.

COSMO-LEPS [probability of exceeding yellow code]

forecast day	21	22	23	24	25	26
21-11-2007	0%	100%	25%	25%		
22-11-2007		81%	62%	0%	0%	
23-11-2007			43%	25%	0%	0%

Fig. 13 Probability of exceeding yellow code with the CLEPS forecast. The hydrological runs were initialized on 21, 22 and 23 November.

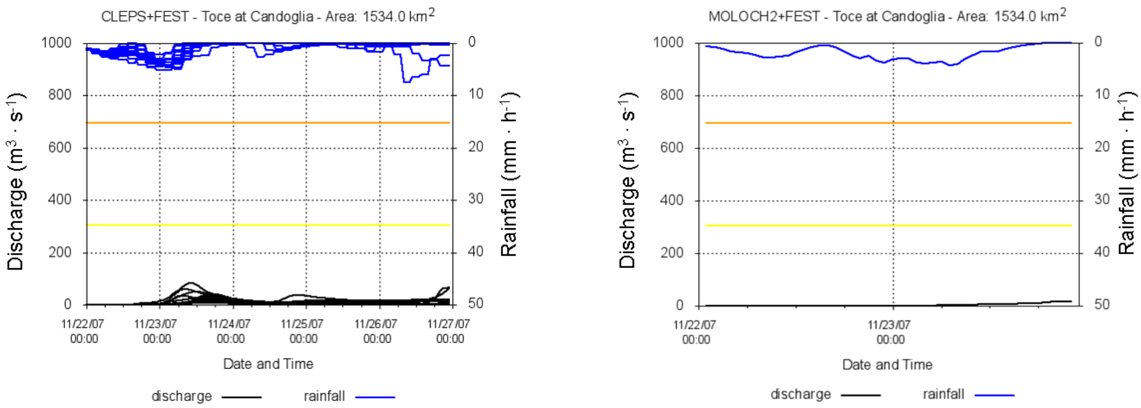


Fig. 14 Forecasted discharge by the FEST-WB model forced with COSMO-LEPS (left) and MOLOCH (right) data; the hydrological run was started on 22 November.

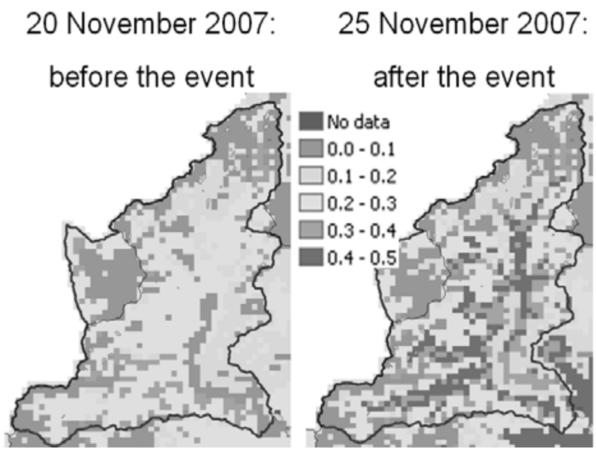


Fig. 15 Soil moisture field before (left) and after (right) the 21-24 November event.

data, performed well, issuing no warning. As shown in Fig. 14, both the CLEPS and MOLOCH forecast are very far from the yellow threshold.

Looking at the soil moisture field, very dry values near to θ_{res} (Eq. (6)) before the event generally over the Toce basin (Fig. 15-left) are found, and even at the end of the rainfall with the soil not totally saturated, as proof of the drought period that hit North-West Italy during the autumn of 2007; values near to the saturation θ_{sat} are found only along the main river tributaries (Fig. 15-right).

6. Conclusions

This study, part of the project MAP-D-PHASE, evaluated a forecasting operational chain based on a distributed hydrological model, coupled with two weather output: one deterministic of the MOLOCH model and one with an ensemble prediction system of the COSMO-LEPS.

These experiments were carried out for two events during the D-PHASE period: a convective event in June and a stratiform event in the autumn over the three main basins of Lake Maggiore: the Toce, Ticino and Maggia.

The results obtained show how alert warnings issued on the basis of forecasted precipitation are not always reliable. In fact, an underestimation of the warning level was observed in the June event due to an underestimation of cumulative precipitation. To the contrary an overestimation of the meteorological warning level was observed in the November event.

But, hydrological alerts are not the exact consequence of meteorological warnings, above all in mountain watersheds where many uncertainties must be considered in hydrological forecasts. Furthermore, an alert issued on the basis of precipitation only cannot take into account the actual state of the river basin, which is crucial in defining transformation into runoff. Therefore, it is necessary to use a hydrological rainfall-runoff simulation and a coupling strategy between meteorological and hydrological models.

When forced with meteorological ground observed data, the FEST-WB performance, in terms of error in simulated peak discharge, was different in the three river basins, with an error ranging from -4% at Solduno to 59% at Bellinzona during the June event. Despite this, the magnitude of the flood event, defined by the warning level, was always correctly simulated. When coupled with the meteorological models, some errors are enhanced, while other are compensated, with a general degradation in the performance of the hydrological model.

As far as the peak discharge time lag is concerned (Table 7), the MOLOCH model predicted much better the peak flow arrival, in comparison with the CLEPS', which is subject to a systematic delay for June event and to an advance bias in November's.

The study highlights how it is important in hydrological simulations to use both probabilistic meteorological models with a coarser resolution and deterministic ones with a high spatial resolution, developing what it is now called a multi-model approach [45-47], which gives more information, since it comes from different meteorological models.

However, in this case study, it is not the aim to provide general trends, but to show the results relative to the main cases study investigated during the D-PHASE Project. In fact, generalized conclusions can be only drawn after a large number of cases.

Acknowledgments

The authors are grateful to ARPA Regione Piemonte (Italy), ARPA Regione Lombardia (Italy), Ufficio Federale dell'Ambiente UFAM Berna (Switzerland) and the Federal Office of Meteorology and Climatology Meteoswiss (Switzerland) for providing the ground measured data. The authors would like to thank also ARPA Regione Emilia-Romagna (Italy) for its contribute in providing COSMO-LEPS model data, ISAC-CNR (Italy) for MOLOCH model data, and EPSON METEO Centre (Italy) for the substantial grant received in these years of Ph.D. research project. This work was partially supported by PRE.G.I. Project and Dote Ricerca Applicata, are funded by Regione Lombardia.

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