Real-time hydro-meteorological forecasts: re-analysis of some operational case studies

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Abstract

In the present day, coupling meteorological and hydrological models, it is recognized by scientific community as a necessary way to forecast extreme hydrological phenomena, in order to active useful mitigation measurements and alert systems in advance, above all over mountain basins where lag times are low.

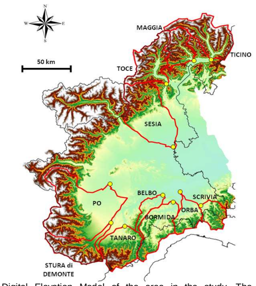
A real-time flood forecasting system is described in this study with a re-analysis of some operational case studies occurred between 2007 and 2008 in the Piedmont Region, North-West of Italy.

We check if hydrological simulations, coupled with weather forecasts are able to predict possible flood occurrences with sufficient lead time, valuing the efficiency of hydro-meteorological chain in case of exceeding warning code.

The goal is to evaluate how the uncertainty of meteorological forecasts influences the performance of hydrological predictions in terms of Quantitative Discharge Forecasts (QDFs) over different catchments. In particular, we investigate how the meteorological forecasts are efficient into hydrological forecasting system at different days in advance, focusing the attention on key role of air temperature which is a crucial factor in determining the partitioning of precipitation in solid (snow) and liquid phase (rainfall) that can affect the river discharge prediction in Autumn season over Piedmont watersheds. Further, we try to understand how the effect of meteorological model spatial resolution and soil moisture initial conditions can influence discharge forecasts and warnings over mountain basins.

Area of study

11 BASINS	Lag time [h]	Area [km²]
Ticino basin (closed at Bellinzona)	9	1537
Maggia basin (closed at Solduno)	6.8	902
Toce basin (closed at Candoglia)	9	1534
Sesia basin (closed at Palestro)	18.8	2606
Po basin (closed at Carignano)	18	3960
Stura basin (closed at Fossano)	9.5	1239
Tanaro basin (closed at Farigliano)	14.8	1457
Belbo basin (closed at Castelnuovo)	15.1	421
Bormida basin (closed at Cassine)	23.2	1523
Orba basin (closed at Casal Cervelli)	14.2	750
Scrivia basin (closed at Serravalle)	10	617



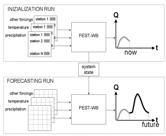
Digital Elevation Model of the area in the study. The boundaries of each basin are shown in red, while watershed gauging stations are illustrated with yellow dots.

The POLIMI hydro-meteorological chain: the forecasting cascade system

Operational real time hydro-meteorological forecast systems are realized by use of one-way coupling, i.e. the meteorological output variables are driven into hydrological models

The Hydro-Meteorological chain → Observations: Weather and Hydro data → Local M^{-al} Modelling → Basin H^{-al} Modelling → Quality Control

ARPA Piemonte, Meteo Swiss | COSMO-LEPS, MOLOCH | FEST-WB | Skill scores, Statistical analysis



- The initial hot start is sent daily by ARPA-Piedmont which runs every day the same hydrological model with weather observations for nowcasting monitoring and as a civil-protection tool.
- The current hydro-meteorological chain includes:
  a) probabilistic forecasts based on ensemble prediction systems with lead time of a few days
  b) short-range forecasts based on high resolution deterministic atmospheric model
- The hydrological model used to generate the runoff simulations is the FEST-WB model, developed at Politecnico di Milano.
- Statistical analyses are used to calculate the skill scores for hydrological applications.

Hydro-Meteorological data

2000-2008 available database (ARPA Piemonte and Meteo Swiss)

- Temperature: 465 thermometers
- Relative Humidity: 186 hygrometers
- Precipitation: 486 rain gauge stations
- Solar Radiation: 92 pyranometers
- Wind Speed: 123 anemometers
- Hydrometer: 132 data @ basin close sections

Atmospheric forcing

Input values for the FEST-WB model may be derived from observed (i.e. measured) data from the hydro-metrological stations of ARPA Piedmont and of MeteoSwiss or from the forecasted data of the COSMO-LEPS and MOLOCH meteorological models. Afterwards, the FEST-WB model calculates different physical processes (snow dynamics, infiltration, water balance, hypodermic and surface propagation etc), and returns different hourly output.

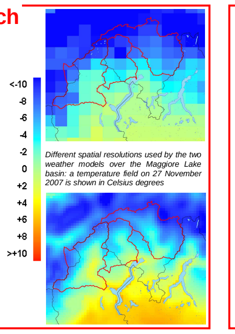
Meteorological models: Cosmo-Leps and Moloch

COSMO-LEPS Model (Marsigli et al., 2005)

- **Spatial Resolution:** 10.0 km (0.09°)
- **Temporal Resolution:** 3 h
- **Vertical levels:** 40 (non-hydrostatic)
- **Ensemble members: 16** nested on ECMWF EPS
- **Forecast range:** +132 h
- **Run starting at:** 12:00 UTC
- **Owner:** ARPA Emilia-Romagna

MOLOCH Model (Malguzzi et al., 2006)

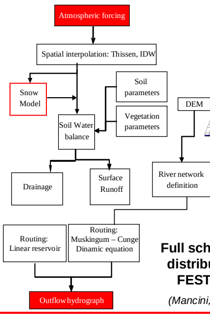
- **Spatial Resolution:** 2.3 km (0.02°)
- **Temporal Resolution:** 1 h
- **Vertical levels:** 50 (non-hydrostatic)
- **Deterministic model**, nested on BOLAM, nested on ECMWF
- **Forecast range:** +48 h
- **Run starting at:** 00:00 UTC
- **Owner:** ISAC-CNR

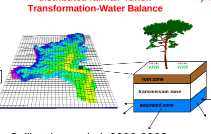


Different spatial resolutions used by the two weather models over the Maggiore Lake basin: a temperature field on 27 November 2007 is shown in Celsius degrees

PoliMi - Distributed Hydrological Model: FEST-WB

Flash–flood Event–based Spatially–distributed rainfall–runoff Transformation-Water Balance





Calibration period: 2000-2002

Validation period: 2003

Temporal resolution: Δt = 1h

Spatial resolution: Δx = 1km

Full scheme of the rainfall-runoff distributed hydrological model FEST-WB, physically based

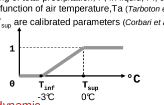
(Mancini,1990 → Ravazzani et al., 2010)

The snow model includes the snow melt and the snow accumulation dynamics

1) snow accumulation dynamic

$$\begin{cases} P_L = \alpha P \\ P_S = (1-\alpha)P \end{cases} \qquad \alpha = \begin{cases} 0 & \Leftrightarrow T_a \le T_{inf} \\ \frac{T_a - T_{inf}}{T_{sup} - T_{inf}} & \Leftrightarrow T_{inf} < T_a < T_{sup} \\ 1 & \Leftrightarrow T_a \ge T_{sup} \end{cases}$$

The partitioning of total precipitation, P, in liquid, Pl, and solid, Ps, phase is a function of air temperature,Ta (*Tarboton et al., 1994*). T_{inf} and T_{sup} are calibrated parameters (*Corbari et al., 2009*).



2) snow melt dynamic

The snow melt simulation is based on the degree day concept (*Martinec et al., 1960*)

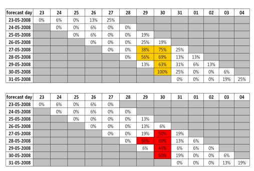
C_m is an empirical coefficient depending on meteorological conditions and geographic location

$$M_s = C_m(T_a - T_b)$$

The melt rate in ms^{-1}, M_s, is proportional to the difference between air temperature T_a and a predefined threshold temperature, T_b *(Salandin et al., 2004)*

The May 2008 event: working in real time

The probability of exceeding the alert code 2 (top) and alarm code 3 (bottom). Discharge forecasts are based on the FEST-WB simulation, forced with CLEPS meteorological data. The probability tables are reported as in the EFAS Project (Younis et al., 2008).

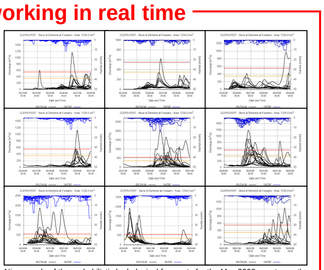


Alert code 2

Probability of exceeding

Alarm code 3

Stura basin ↑ Flood — 26-30 May 2008: stratiform event



Nine panels of the probabilistic hydrological forecasts for the May 2008 event over the Stura di Demonte basin. Forecasts are updated every day from 23 to 31 May. The black lines show the ensemble QDFs, and the blue lines show the ensemble QPFs; alert code 2 is shown by the horizontal orange line and alarm code 3 by the red horizontal line.

Goal: think to be in real time…

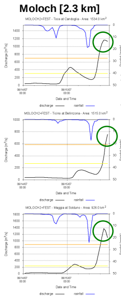
- Evaluate the efficiency of hydro-meteorological chain in case of exceeding a warning code
- How many days in advance is my operative system reliable?

In this case study we show that probabilistic forecasts could be considered truly significant for taking precautionary measures with sufficient lead times (some days before the peak discharge on 30 May).

13-15 June 2007: convective event

Moloch [2.3 km] — **Effect of model spatial resolution** — **Cosmo-Leps [10 km]**

Ranzi et al., 2009; Ceppi et al., 2009



Toce basin

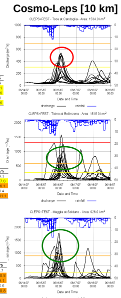
Days	Observed	Simulated Fest	Moloch2	Ensemble Min	Max	Mean	Median	St. Dev.	Q25	Q75
14/06/2007	132.1	55.4	328.4	55.4	55.5	55.4	55.4	0.0	55.4	55.4
15/06/2007	783.2	750.7	1162.3	63.5	437.0	219.5	153.0	138.8	103.4	369.1
16/06/2007	448.0	605.8		57.4	537.1	288.4	259.9	176.1	136.0	486.6
17/06/2007	221.3	54.2		41.2	410.9	95.7	63.1	92.3	51.6	94.0
Max Discharge (m3/s)	783.2	750.7	1162.3	92.5	537.1	319.9	347.0	162.7	151.8	486.6

Ticino basin

Days	Observed	Simulated Fest	Moloch2	Ensemble Min	Max	Mean	Median	St. Dev.	Q25	Q75
14/06/2007	124.5	39.1	39.2	39.1	65.1	40.9	39.2	6.5	39.2	39.3
15/06/2007	761.5	1210.4	753.9	41.4	1289.1	344.2	223.7	338.6	97.7	507.8
16/06/2007	440.5	1037.1		95.3	1580.1	705.7	629.2	368.1	466.8	866.1
17/06/2007	154.3	59.1		48.6	1073.1	154.1	70.7	254.5	59.5	83.4
Max Discharge	761.5	1210.4	753.9	335.9	1580.1	823.8	793.9	347.8	529.2	1031.1

Maggia basin

Days	Observed	Simulated Fest	Moloch2	Ensemble Min	Max	Mean	Median	St. Dev.	Q25	Q75
14/06/2007	11.2	24.3	63.5	38.4	102.6	42.7	38.5	16.0	38.5	38.7
15/06/2007	941.7	956.4	1366.1	110.7	1737.1	841.1	830.7	464.7	540.5	1240.8
16/06/2007	446.4	325.6		28.3	1775.9	733.4	623.0	499.4	436.0	979.1
17/06/2007	[illegible]	[illegible]		14.1	1182.4	[illegible]	51.7	306.5	19.9	196.6
Max Discharge (m3/s)	941.7	956.4	1366.1	110.7	1775.9	917.0	988.5	448.5	617.1	1240.8



Errors in meteorological forecasts can be a consequence of the different spatial resolution between the two meteorological models: thus, forecasting hydro-meteorological systems should be supported by both the two models, i.e. probabilistic and deterministic.

21-24 November 2007: stratiform event

Effects of soil moisture conditions

Meteorological ALERT

COSMO-LEPS [probability of exceeding yellow code]

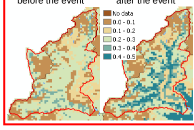
forecast day	21	22	23	24	25	26
21-11-2007	0%	100%	25%	25%		
22-11-2007		81%	62%	0%	0%	
23-11-2007			43%	25%	0%	0%

MOLOCH forecast [millimeters of rain]

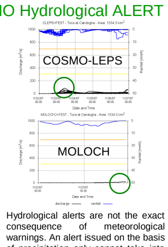
forecast day	21	22	23	24
21-11-2007	11.7	48.7		
22-11-2007		37.3	52.9	
23-11-2007			41.5	9.0

Soil Moisture

20 November 2007: before the event — 25 November 2007: after the event



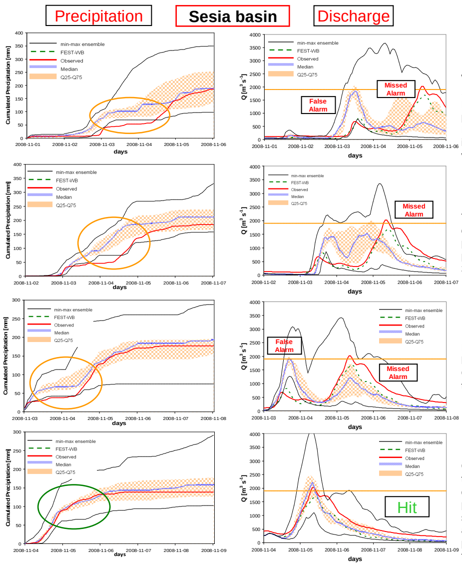
NO Hydrological ALERT



Hydrological alerts are not the exact consequence of meteorological warnings. An alert issued on the basis of precipitation only cannot take into account the actual state of the river basin (in this example, dry antecedent soil moisture conditions), which is crucial in defining transformation into runoff. Therefore it is necessary to use a hydrological rainfall-runoff simulation and a coupling strategy.

The role of atmospheric forcing: precipitation

Precipitation — Sesia basin — Discharge



1-5 November 2008: stratiform event

1 November output run: 96-120 h before the main peak flow

With the simulation runs started on 1, 2, 3, November the COSMO-LEPS model predicted higher precipitation values for the 3 and 4 November, i.e. 24 hours in advance in comparison with the observed values on 4 and 5 November.

2 November output run: 72-96 h before the main peak flow

These errors led to an overestimation of discharge values predicted by the CLEPS model with possible "false alarms" expected for 3 November.

3 November output run: 48-72 h before the main peak flow

No significant improvements in hydrological forecasts forced with CLEPS data have been found during these first three days of simulation.

4 November output run: 24-48 h before the main peak flow

Only 24-48 hours beforehand (lead time 1), with the simulation started on 4 November 2008, the forecasted precipitation for 5 November were similar in terms of timing and amount to the observed values, producing matching in discharge forecasts "hit event".

The reliability of the hydro-meteorological chain: brief summary

Stura basin (May 2008 event)

BS for alarm code	0.77	0.14	0.25	0.32
BS for alert code	0.56	0.02	0.10	0.10
hours before the main peak	96-120	72-96	48-72	24-48

Sesia basin (November 2008 event)

BS for alert code	0.77	0.47	0.47	0.14
hours before the main peak	96-120	72-96	48-72	24-48

Hit

Toce basin (November 2008 event)

BS for alert code	0.31	0.25	0.31	0.88
hours before the main peak	96-120	72-96	48-72	24-48

Stura basin (November 2008 event)

BS for alert code	0.25	0.06	0.39	0.56
hours before the main peak	96-120	72-96	48-72	24-48

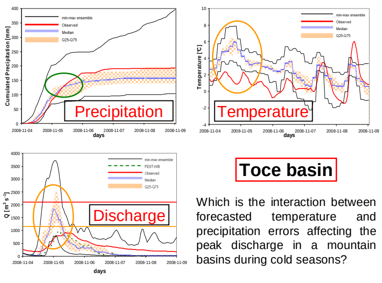
Why does not this reliability subsist over Toce and Stura basins?

False Alarm — ?

Brier Score

$$BS = \frac{1}{n}\sum_{k=1}^{n}(y_k - o_k)^2$$

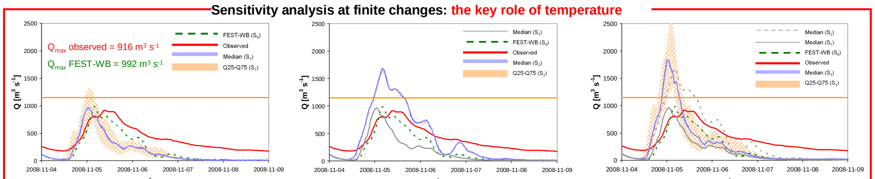
The role of atmospheric forcing: temperature



Toce basin

Which is the interaction between forecasted temperature and precipitation errors during the peak discharge in a mountain basins during cold seasons?

Sensitivity analysis at finite changes: the key role of temperature



$$\Delta f = \Delta f_P + \Delta f_T + \Delta f_{P,T}$$

Finite changes sensitivity indices (Borgonovo, 2010)

Δf_P median(Q_{max}|P) – Q_{max} FEST-WB = -26 m^3 s^{-1}

The first term (Δf_P) is the difference between the FEST-WB simulation (referred to as S_0), forced with all observed values and the FEST-WB simulation, using the observed temperature field and the forecasted precipitation values of the COSMO-LEPS model.

Δf_T median(Q_{max}|T) – Q_{max} FEST-WB = +686 m^3 s^{-1}

Then we inverted the input factors: we re-ran the simulation with the observed precipitation values, but this time using the forecasted temperatures of the COSMO-LEPS model; this new simulation is called S_2. The discharge overestimation can only be attributed to an error of the CLEPS forecasted temperature, because it was the only changed variable in this new simulation scenario.

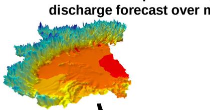
Δf median(Q_{max}|P and T) – Q_{max} FEST-WB = +849 m^3 s^{-1}

$\Delta f_{P,T}$ marginal effects of interaction = +189 m^3 s^{-1}

Finally, we considered both the forecasted temperature and precipitation fields by the CLEPS model in order to understand the simultaneous interaction of effects of the inputted changes; the latter simulation is referred to as S_3.

Effects of temperature on the peak discharge: quantification of errors

Which is the acceptable temperature error in the discharge forecast over mountain basins?

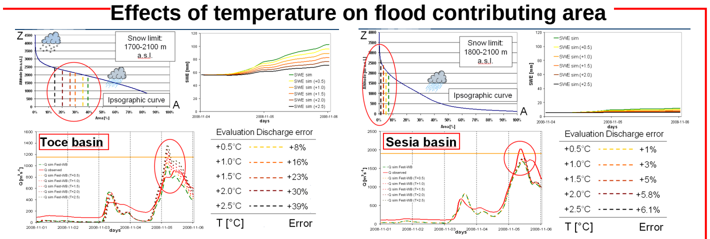


Set the precipitation input using the observed precipitation field (raingauges)

I calculated the discharge differences, changing the temperature input only, keeping the other hydro-meteorological variables unchanged (observed precipitation and initial conditions)

Quantify discharge errors

Effects of temperature on flood contributing area



Toce basin — Evaluation Discharge error

T [°C]	Error
+0.5°C	+8%
+1.0°C	+16%
+1.5°C	+23%
+2.0°C	+30%
+2.5°C	+39%

Sesia basin — Evaluation Discharge error

T [°C]	Error
+0.5°C	+1%
+1.0°C	+3%
+1.5°C	+5%
+2.0°C	+5.8%
+2.5°C	+6.1%

We correlate the increase in temperature to the ipsographic curve of each individual basin, which defines the contributing area in snow melt dynamics, to better investigate what happens over the Toce and Sesia basins respectively. The dashed coloured lines correlate the percentage of contributing area in runoff with different snow lines, related to our "synthetic" increase in temperature fields (from 0.5°C up to 2.5°C). Rising the 0°C line over the Toce catchment, the snowfall line also increases, and the drainage area becomes greater. If we consider this in terms of discharge simulations, a temperature increase, with a consequence higher snow line, results in more liquid water reaching the basin gauging station quicker. On the contrary, with a totally different ipsographic curve over the Sesia basin even a rising of the temperatures and therefore the snow line, no relevant differences are shown in peak discharges.

Conclusions

The hydro-meteorological chain is a very useful tool to predict in real time (generally with 24-48 hours before the main peak discharge) possible river floods in advance over mountain basins, where lag times are generally lower.

The use of ensemble prediction system (EPS) is very powerful, but due to the coarser resolution of the model, a determinist model support with an higher grid resolution is suggested above all during convective events: i.e. to set up a multi-model prediction system approach.

Precipitation is not the only atmospheric forcing to be considered. The quantitative discharge forecast (QDF) is influenced by temperature errors and it is related to the basin ipsographic curve, therefore to the percentage of area that contributes with more liquid water (rain) over watershed.

Main References

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