Real time flood forecasts coupling meteorological and hydrological models

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Over the last twenty years severe river floods occurred in Europe, causing thousands of deaths and billion Euros in insured financial losses. Experience suggests that appropriate warnings with sufficient lead time can mitigate the consequences of heavy precipitation events and floods. Therefore, meteorological forecasts coupled with hydrological models can be used to decide on an early water-system control action to prevent or reduce problems with floods or droughts.

Main Projects in the last 15 years


Social and financial impact: extreme events and financial losses

Main floods in the last 15 years in Italy and Europe

Italy
- Liguria, Tuscany, Veneto, Campania (2010)
- Messina, Tuscany (2009)
- Piedmont (2008)
- Marche (2006)
- Lombardy (2002)
- Soverato, Calabria (2000)
- Piedmont/Aosta Valley (2000)
- Sarno, Campania (1998)

Europe
- Poland, Czech Republic and Germany (2010)
- Cumbria, United Kingdom (2009)
- Austria, Switzerland, Sheffield, Yorkshire (2007)
- Germany (2006)
- Romania, Moldava, Switzerland, Austria (2005)
- Poland, Czech Republic, Germany, Romania (2002)

Definition of great natural catastrophe: "a region’s ability to help itself is distinctly overtaxed, making supraregional or international assistance necessary."

Geophysical events: Earthquake, volcanic eruption

Meteorological events: Tropical storm, winter storm, severe weather, hail, tornado, local storms

Hydrological events: River flood, flash flood, storm surge, mass movement (landslide)

Climatological events: Heatwave, freeze, wildland fire, drought

--- Ten-year average

Source: Munich Re report, 2010
Figure 10.12. Multi-model mean changes in (a) precipitation (mm day$^{-1}$), (b) soil moisture content (%), (c) runoff (mm day$^{-1}$) and (d) evaporation (mm day$^{-1}$). To indicate consistency in the sign of change, regions are stippled where at least 80% of models agree on the sign of the mean change. Changes are annual means for the SRES A1B scenario for the period 2080 to 2099 relative to 1980 to 1999. Soil moisture and runoff changes are shown at land points with valid data from at least 10 models. Details of the method and results for individual models can be found in the Supplementary Material for this chapter.
Figure 10.18. Changes in extremes based on multi-model simulations from nine global coupled climate models, adapted from Tebaldi et al. (2006). (a) Globally averaged changes in precipitation intensity (defined as the annual total precipitation divided by the number of wet days) for a low (SRES B1), middle (SRES A1B), and high (SRES A2) scenario. (b) Changes in spatial patterns of simulated precipitation intensity between two 20-year means (2000–2009 minus 1980–1999) for the A1B scenario. (c) Globally averaged changes in dry days (defined as the annual maximum number of consecutive dry days). (d) Changes in spatial patterns of simulated dry days between two 20-year means (2000–2009 minus 1980–1999) for the A1B scenario. Solid lines in (a) and (c) are the 10-year smoothed multi-model ensemble means; the envelope indicates the ensemble mean standard deviation. Stippling in (b) and (d) denotes areas where at least five of the nine models concur in determining that the change is statistically significant. Extreme indices are calculated only over land following Frich et al. (2002). Each model’s time series was centred on its 1980 to 1999 average and normalised (rescaled) by its standard deviation computed (after de-trending) over the period 1960 to 2009. The models were then aggregated into an ensemble average, both at the global and at the grid-box level. Thus, changes are given in units of standard deviations.
Aims and tools of the study

Goal

• Assessing the reliability of a real time flood forecasting system, coupling meteorological and hydrological models, analysing the quantitative forecasting precipitation and temperature fields over mountain basins in different weather conditions.

Tools

• Set up an hydro-meteorological chain as an operative real time flood forecasting tool in mountain basins: MAP-D-PHASE Project.

• Evaluation of the forecasted atmospheric forcing errors: in particular the key role of air temperature that can affect the Quantitative Discharge Forecast (QDF) and the whole hydro-meteorological alert system in the Alpine region.
Uncertainties in hydrological forecasts

Uncertainty in observed measures, missing data, anthropogenic interferences (dams and by-passes for production of electrical energy)

Meteorological data used to force the hydrological model: i.e., we need accurate predictions of precipitation amounts and temperature (especially for snow events)

Initial condition uncertainty

Hydro-Meteorological Chain

Hydrological model uncertainty

Calibration of parameters, uncertainty in the physic conceptualization of the model

Forecast output uncertainty

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
The POLIMI hydro-meteorological chain: the forecasting cascade system

- Weather forecasts are useful to predict possible extreme hydrological events, in order to activate in advance mitigation measures and alert systems, above all over small-medium size mountain basins where lag times are low.

- In the present day, 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 initial hot start is sent daily by ARPA-Piemonte which runs the same hydrological model with weather observations.

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.
Real time flood forecasts coupling meteorological and hydrological models

Hydro-Meteorological observed ground data

"...Everybody believes in experimental data except who collected them ..."

2000-2008 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

Pyranometer
Anemometer
Thermo-hygrometer
Rain gauge

(2000-2008 database (ARPA Piemonte and Meteo Swiss))
Meteorological models: Global & Limited Area Model

"Nobody believes in simulation models except their developers …" G.S. Campbell

Boundary conditions are provided by ECMWF model

Grid resolution: ~ 28 km – 80 km
**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.
Meteorological maps: Cosmo-Leps

Relative Humidity [%]

Precipitation in 3 hours [mm]

Temperature [°C]
Hydrological model

Real time flood forecasts coupling meteorological and hydrological models

Fusione nivale

Neve

Infiltrazione

Drenaggio

Pioggia

ET

Flusso superficiale

Flusso ipodermico
The snow model includes the snow melt and the snow accumulation dynamics.

1) Snow accumulation dynamic

\[
\begin{align*}
\alpha P &= \begin{cases} 
0 & \iff T_a \leq T_{\text{inf}} \\
\frac{T_a - T_{\text{inf}}}{T_{\text{sup}} - T_{\text{inf}}} & \iff T_{\text{inf}} < T_a < T_{\text{sup}} \\
1 & \iff T_a > T_{\text{sup}}
\end{cases} \\
\end{align*}
\]

The partitioning of total precipitation, \( P \), in liquid, \( P_L \), and solid, \( P_s \), phase is a function of air temperature, \( T_a \) (Tarboton et al., 1994).

\( T_{\text{inf}} \) and \( T_{\text{sup}} \) 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)

\[ M_s = C_m(T_a - T_b) \]

\( C_m \) is an empirical coefficient depending on meteorological conditions and geographic location (Salandin et al., 2004).
Vertical thermal gradient: theory

Reference level

Constant vertical thermal gradient: 0.65°C/100 m

Digital Elevation Model

Temperature
Performance of the hydrological FEST-WB model


- Calibration period: 2000-2002
- Validation period: 2003
- Temporal resolution: $\Delta t = 1\text{h}$
- Spatial resolution: $\Delta x = 1\text{km}$

- Atmospheric forcing: observed or forecasted
  a) air temperature
  b) relative humidity
  c) incoming short wave solar radiation
  d) precipitation

The FEST-WB performance related to the exceeding of warning thresholds during 2000-2008 events

<table>
<thead>
<tr>
<th>basin</th>
<th>warning threshold</th>
<th>number of events</th>
<th>mean relative error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toce</td>
<td>alert code</td>
<td>4</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>alarm code</td>
<td>1</td>
<td>0.13</td>
</tr>
<tr>
<td>Po</td>
<td>alert code</td>
<td>3</td>
<td>-0.50</td>
</tr>
<tr>
<td></td>
<td>alarm code</td>
<td>1</td>
<td>-0.61</td>
</tr>
<tr>
<td>Stura</td>
<td>alert code</td>
<td>3</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>alarm code</td>
<td>2</td>
<td>0.13</td>
</tr>
<tr>
<td>Sesia</td>
<td>alert code</td>
<td>8</td>
<td>-0.31</td>
</tr>
<tr>
<td></td>
<td>alarm code</td>
<td>2</td>
<td>-0.14</td>
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<tr>
<td>Ticino</td>
<td>alert code</td>
<td>10</td>
<td>-0.04</td>
</tr>
<tr>
<td></td>
<td>alarm code</td>
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<td>0.17</td>
</tr>
<tr>
<td>Scrivia</td>
<td>alert code</td>
<td>3</td>
<td>-0.39</td>
</tr>
<tr>
<td>Tanaro</td>
<td>alert code</td>
<td>2</td>
<td>-0.41</td>
</tr>
<tr>
<td>Orba</td>
<td>alert code</td>
<td>5</td>
<td>-0.21</td>
</tr>
</tbody>
</table>

$\text{Mean Relative Error} = \frac{1}{n} \sum_{i=1}^{n} \frac{Q_{\text{sim}}^{\text{max}} - Q_{\text{obs}}^{\text{max}}}{Q_{\text{obs}}^{\text{max}}}$

Rabuffetti et al., 2008
Effects of meteorological data spatial aggregation

Mean absolute error = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{Q_{\text{sim} \neq \Delta x} - Q_{\Delta x=1\,km}}{Q_{\Delta x=1\,km}} \right|

![Graph showing the mean absolute error for different spatial aggregations.](chart.png)

- \Delta x = 50 \text{ km}
- \Delta x = 25 \text{ km}
- \Delta x = 10 \text{ km}
- \Delta x = 7 \text{ km}
- \Delta x = 4 \text{ km}
- \Delta x = 2 \text{ km}
MAP-D-PHASE Project

- A Forecast Demonstration Project (FDP) of the WWRP (World Weather Research Programme of WMO). It aims at demonstrating some of the many achievements of the Mesoscale Alpine Programme (MAP), in particular the ability of forecasting heavy precipitation and related flooding events in the Alpine region.

- The MAP FDP addresses the entire forecasting chain ranging from limited-area ensemble forecasting, high-resolution atmospheric modelling, hydrological modelling and nowcasting to decision making by the end users, by setting up an **end-to-end forecasting system**.

- The **D-PHASE Operations Period (DOP)** has been from **1 June to 30 November 2007**, but it is still working!


Source: Ravazzani, G., Ceppi, A., Rabuffetti, D., Mancini, M. 2009; dphase_fest: hydrological model FEST run by Politecnico di Milano for the MAP D-PHASE project. World Data Center for Climate. [doi: 10.1594/WDCC/dphase_fest]

Analyzed watersheds by POLIMI: the **Toce, Maggia, Ticino**

**D-PHASE hydro-meteorological warning codes**

- No data
- No alert
- 6 times a year
- Twice a year
- Every 10 years
How does the POLIMI forecasting cascade system work?

**POLIMI CPU server:**
- 2 processors Intel Xeon (8 total cores)
- RAM: 8Gb
- Hard-disk: 1 Tb

Real time flood forecasts coupling meteorological and hydrological models

**00:00 UTC**
- Initial conditions arrive @ PoliMi

**01:00 UTC**
- FEST-WB simulation runs in PoliMi

**02:00 UTC**
- FEST-WB simulation runs in PoliMi

**04:00 UTC**
- Uploading CLEPS data on VP

**06:00 UTC**
- Moloch data arrive @ PoliMi

**07:00 UTC**
- Moloch data arrive @ PoliMi

**08:00 UTC**
- FEST-WB simulation runs in PoliMi

**09:00 UTC**
- Uploading Moloch data on VP

**12:00 UTC**
- Cosmo-Leps model initialization

**18:00 UTC**
- Uploading Moloch data on VP

**20:00 UTC**
- Cosmo-Leps data arrive @ PoliMi

**00:00 UTC**
- FEST-WB model runs in ARPA Piemonte with observed weather data to produce initial conditions

**01:00 UTC**
- Moloch model initialization

**02:00 UTC**
- Moloch data arrive @ PoliMi
Today hydrological forecasts

NO ALERT
The May 2008 event: working in real time

### Stura basin

**Goal**

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

**Alert code 2**

**Probability of exceeding**

**Alarm code 3**

26-30 May 2008: stratiform event

**Flood**

**Stura basin**
The reliability of discharge forecast according to lead time

**Goal**

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

**Stura basin**

26-30 May 2008: stratiform event

**Brier Score**

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

- \( N \) = number of forecasting instances
- \( y_k \) = the probability that an event was forecasted
- \( o_k \) = the actual outcome of the event at instance \( k \) (0 if it doesn't happen and 1 if it happens)
- Best score = 0

The BS is essentially the mean-squared error of the probability forecasts, considering that the observation is \( o=1 \) if the event occurs and \( o=0 \) if the event does not occur. The score averages the squared differences between pairs of forecast probabilities and the subsequent observations (Wilks, 2006).
26-30 May 2008: stratiform event

Stura basin

P cumulated [mm]

Rain gauge stations

<table>
<thead>
<tr>
<th>27/5 – 28/5 – 29/5 – 30/5 –Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>CASTELMAGNO – CASTELMAGNO</td>
</tr>
<tr>
<td>13.6</td>
</tr>
<tr>
<td>S. GIACOMO DEMONTE – DEMONTE</td>
</tr>
<tr>
<td>20.2</td>
</tr>
<tr>
<td>DEMONTE – DEMONTE</td>
</tr>
<tr>
<td>12.6</td>
</tr>
<tr>
<td>BELLINO – BELLINO</td>
</tr>
<tr>
<td>38.8</td>
</tr>
<tr>
<td>ACCEGLIO COLLET – ACCEGLIO</td>
</tr>
<tr>
<td>44.0</td>
</tr>
<tr>
<td>NERAISSA – VINADIO</td>
</tr>
<tr>
<td>28.2</td>
</tr>
<tr>
<td>CANOSIO – CANOSIO</td>
</tr>
<tr>
<td>33.3</td>
</tr>
<tr>
<td>PIAN DELLE BARACCE – SAMPEYRE</td>
</tr>
<tr>
<td>18.8</td>
</tr>
<tr>
<td>PONTECHIANALE – PONTECHIANALE</td>
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<td>24.4</td>
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<table>
<thead>
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<th></th>
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<tr>
<td>0</td>
<td>50</td>
<td>100</td>
<td>150</td>
<td>200</td>
<td>250</td>
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</tbody>
</table>

Stura basin

28May

29May

Forecasted Precipitation [mm]
(Re-analyses of some occurred events during 2007-2008)

- 13-15 June 2007: convective event
  Toce, Maggia, Ticino
  the effect of model spatial resolution

- 21-24 November 2007: stratiform event
  Toce, Maggia, Ticino
  the effect of soil moisture conditions
  the reliability of the hydro-meteorological chain

- 1-5 November 2008: stratiform event
  Sesia, Toce, Stura
  the role of atmospheric forcing
  (precipitation and temperature)
13-15 June 2007: convective event

Synoptic analysis over Europe: 15 June

<table>
<thead>
<tr>
<th>Day</th>
<th>Toce</th>
<th>Ticino</th>
<th>Maggia</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 June</td>
<td>4.9</td>
<td>7.4</td>
<td>6.9</td>
</tr>
<tr>
<td>14 June</td>
<td>16.3</td>
<td>24.6</td>
<td>20.6</td>
</tr>
<tr>
<td>15 June</td>
<td>68.2</td>
<td>72.7</td>
<td>82.1</td>
</tr>
<tr>
<td>Total Precipitation [mm]</td>
<td>89.4</td>
<td>104.7</td>
<td>109.6</td>
</tr>
</tbody>
</table>

Radar rainfall accumulation over Maggiore Lake basin: 14-15 June

Basin mean rainfall (mm) over Toce, Ticino and Maggia basins
Real time flood forecasts coupling meteorological and hydrological models

Effects of model spatial resolution on forecasted rainfall

“What benefit do I get from a 10 km model? It often rains in Busalla when it’s sunny in Genoa!” R. Rosso (2007)

13-15 June 2007: convective event

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

**Moloch [2.3 km]**

**Ticino basin**

**Maggia basin**

**Cosmo-Leps [10 km]**
Toce basin

Real time flood forecasts coupling meteorological and hydrological models
Toce subbasins

Real time flood forecasts coupling meteorological and hydrological models
21-23 November 2007 event: **stratiform event**

Effect of soil moisture conditions

Radar rainfall accumulation over Maggiore Lake basin: 22-23 November

<table>
<thead>
<tr>
<th>Day</th>
<th>Toce</th>
<th>Ticino</th>
<th>Maggia</th>
</tr>
</thead>
<tbody>
<tr>
<td>21 November 2007</td>
<td>6.7</td>
<td>3.3</td>
<td>7.1</td>
</tr>
<tr>
<td>22 November 2007</td>
<td>30.6</td>
<td>27.6</td>
<td>37.0</td>
</tr>
<tr>
<td>23 November 2007</td>
<td>34.7</td>
<td>37.0</td>
<td>42.3</td>
</tr>
<tr>
<td><strong>Total Precipitation [mm]</strong></td>
<td><strong>72.1</strong></td>
<td><strong>67.9</strong></td>
<td><strong>86.4</strong></td>
</tr>
</tbody>
</table>
Effects of soil moisture conditions

**Meteorological ALERT**

<table>
<thead>
<tr>
<th>COSMO-LEPS [probability of exceeding yellow code]</th>
<th>21</th>
<th>22</th>
<th>23</th>
<th>24</th>
<th>25</th>
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<td>forecast day</td>
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<td>22</td>
<td>23</td>
<td>24</td>
<td>25</td>
<td>26</td>
</tr>
<tr>
<td>21-11-2007</td>
<td>0%</td>
<td>100%</td>
<td>25%</td>
<td>25%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22-11-2007</td>
<td>81%</td>
<td>62%</td>
<td>0%</td>
<td>0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23-11-2007</td>
<td>43%</td>
<td>25%</td>
<td>0%</td>
<td>0%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**MOLOCH forecast [millimeters of rain]**

<table>
<thead>
<tr>
<th>forecast day</th>
<th>21</th>
<th>22</th>
<th>23</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>21-11-2007</td>
<td>11.7</td>
<td>48.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22-11-2007</td>
<td>37.3</td>
<td>52.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23-11-2007</td>
<td>41.5</td>
<td>9.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

20 November 2007:  
before the event

25 November 2007:  
after the event

**Soil Moisture**

Real time flood forecasts coupling meteorological and hydrological models
1-5 November 2008: stratiform event

Cumulated Precipitation [mm]

<table>
<thead>
<tr>
<th>Days</th>
<th>Toce</th>
<th>Ticino</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 November 2008</td>
<td>6.5</td>
<td>4.4</td>
</tr>
<tr>
<td>2 November 2008</td>
<td>7.2</td>
<td>0.0</td>
</tr>
<tr>
<td>3 November 2008</td>
<td>52.2</td>
<td>31.8</td>
</tr>
<tr>
<td>4 November 2008</td>
<td>79.0</td>
<td>22.7</td>
</tr>
<tr>
<td>5 November 2008</td>
<td>95.4</td>
<td>48.1</td>
</tr>
</tbody>
</table>

South-East winds

Real time flood forecasts coupling meteorological and hydrological models
The role of atmospheric forcing: precipitation

Discharge

+96-120 h

+48-72 h

Missed Alarm

False Alarm

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

Sesia basin

Brier Score

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

• n = number of forecasting instances
• y_k = the probability that an event was forecasted
• o_k = the actual outcome of the event at instance k (0 if it doesn't happen and 1 if it happens)
• Best score = 0

The BS is essentially the mean-squared error of the probability forecasts, considering that the observation is o=1 if the event occurs and o=0 if the event does not occur. The score averages the squared differences between pairs of forecast probabilities and the subsequent observations (Wilks, 2006).
The role of atmospheric forcing: precipitation

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

Sesia basin

Discharge

Precipitation

Missed Alarm

Real time flood forecasts coupling meteorological and hydrological models
The role of atmospheric forcing: precipitation

Real time flood forecasts coupling meteorological and hydrological models

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

Sesia basin

Precipitation

Discharge

+48-72 h

+0-24 h

Lead Time

0.47

BS for alert code

min-max ensemble

FEST-WB

Observed

Median

Q25-Q75

False Alarm

Missed Alarm
The role of atmospheric forcing: precipitation

Discharge

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

Sesia basin

Precipitation

Cumulated Precipitation [mm]

Hit
The reliability of the hydro-meteorological chain: brief summary

<table>
<thead>
<tr>
<th>Basin</th>
<th>BS for alarm code</th>
<th>BS for alert code</th>
<th>Hours before the main peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stura basin</td>
<td>0.77</td>
<td>0.14</td>
<td>25</td>
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<tr>
<td>May event</td>
<td>0.56</td>
<td>0.02</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>96-120</td>
<td>72-96</td>
<td>24-48</td>
</tr>
<tr>
<td>Sesia basin</td>
<td>0.77</td>
<td>0.47</td>
<td>25</td>
</tr>
<tr>
<td>November event</td>
<td>0.77</td>
<td>0.47</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>96-120</td>
<td>72-96</td>
<td>24-48</td>
</tr>
<tr>
<td>Toce basin</td>
<td>0.31</td>
<td>0.25</td>
<td>25</td>
</tr>
<tr>
<td>November event</td>
<td>0.31</td>
<td>0.25</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>96-120</td>
<td>72-96</td>
<td>24-48</td>
</tr>
<tr>
<td>Stura basin</td>
<td>0.25</td>
<td>0.06</td>
<td>25</td>
</tr>
<tr>
<td>November event</td>
<td>0.25</td>
<td>0.06</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>96-120</td>
<td>72-96</td>
<td>24-48</td>
</tr>
</tbody>
</table>

Why does not this reliability subsist over Toce (and Stura) basins?
The role of atmospheric forcing: temperature

Which is the interaction between forecasted temperature and precipitation errors affecting the peak discharge in a mountain basin during Autumn/Winter period?
Sensitivity analysis at finite changes: the key role of temperature

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

Source: Borgonovo, 2010

Finite changes sensitivity indices

- \( \Delta f \) median(\( Q_{\text{max}} \mid P \) and \( T \)) – \( Q_{\text{max}} \) FEST-WB = +849 m\(^3\) s\(^{-1}\)
- \( \Delta f_P \) median(\( Q_{\text{max}} \mid P \)) – \( Q_{\text{max}} \) FEST-WB = -26 m\(^3\) s\(^{-1}\)
- \( \Delta f_T \) median(\( Q_{\text{max}} \mid T \)) – \( Q_{\text{max}} \) FEST-WB = +686 m\(^3\) s\(^{-1}\)
- \( \Delta f_{P,T} \) marginal effects of interaction = +189 m\(^3\) s\(^{-1}\)

\( Q_{\text{max}} \) observed = 916 m\(^3\) s\(^{-1}\)

\( Q_{\text{max}} \) FEST-WB = 992 m\(^3\) s\(^{-1}\)

median(\( Q_{\text{max}} \mid P \)) = 966 m\(^3\) s\(^{-1}\)

median(\( Q_{\text{max}} \mid T \)) = 1678 m\(^3\) s\(^{-1}\)

median(\( Q_{\text{max}} \mid P \) and \( T \)) = 1841 m\(^3\) s\(^{-1}\)
Which is the acceptable temperature error in the discharge forecast over mountain basins?

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

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

Quantify discharge errors.
Effects of temperature on flood contributing area: Toce basin

Rainfall is crucial for flooding, especially when integrated with snowmelt. The Toce basin is depicted with a contour map showing the snow limit from 1700-2100 m a.s.l. The Ipsographic curve illustrates the percentage area at different altitudes.

The graph on the right shows the evaluation of discharge error for different temperature increments in the Toce basin. The error increments are as follows:

- +0.5°C: +8%
- +1.0°C: +16%
- +1.5°C: +23%
- +2.0°C: +30%
- +2.5°C: +39%

These results highlight the significant impact of temperature on flood discharge, with higher temperatures leading to increased flood contributions.
Effects of temperature on flood contributing area: **Sesia basin**

**Snow limit:**
1800-2100 m a.s.l.

**Ipsographic curve**

**Evaluation Discharge error**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>+0.5°C</td>
<td>+1%</td>
</tr>
<tr>
<td>+1.0°C</td>
<td>+3%</td>
</tr>
<tr>
<td>+1.5°C</td>
<td>+5%</td>
</tr>
<tr>
<td>+2.0°C</td>
<td>+5.8%</td>
</tr>
<tr>
<td>+2.5°C</td>
<td>+6.1%</td>
</tr>
</tbody>
</table>
Real-time flood forecasts coupling meteorological and hydrological models

**16 September 2010 output run:**
36-48 h before the main peak flow

**Last flood in Milan urban area:** the river Seveso...

**Seveso basin**

**Area:** 195 km$^2$

Forecast Reliability: 37.5%

**Discharge**

**Precipitation**

**Cumulated Precipitation [mm]**

**CLEPS-FEST**
- Ensemble 25-75
- Emean
- E median
- P observed
- Q sim Fest-WB
- alarm code
- Ensembles
Last flood in Milan urban area: the river Seveso…

16-17 September 2010 output run:
0-48 h before the main peak flow

WRF spatial resolution = 4 km

Real time flood forecasts coupling meteorological and hydrological models

POLITECNICO DI MILANO
Conclusions

1) 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.

2) 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.

3) Hydrological alerts are not the exact consequence of meteorological warnings, above all in mountain watersheds where many uncertainties must be considered in hydrological forecasts. 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.

4) 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.
POLIMI- Multi model prediction system

Meteorological models

- Cosmo-Leps: 7 km, 3 hours, 1 run daily at 12:00 UTC, 16 ensembles (forecast range +132 h)

- Moloch: 2.3 km, 1 hour, 1 run daily at 03:00 UTC, deterministic (forecast range +45 h)

- Bolam: 11 km, 1 hour, 1 run daily at 00:00 UTC, deterministic (forecast range +72 h)

- GFS: 55 km, 3 hour, 1 run daily at 00:00 UTC, deterministic (forecast range +144 h)

- WRF: 4 km, 1 hour, 1 run daily at 00:00 UTC, deterministic (forecast range +48 h)

Hydrological model

- FEST-EWB (2010)
Pre.G.I. Project: Previsione meteo idrologica per la Gestione Irrigua
(Provincial meteorological and hydrological forecast for irrigation management)

May 2010-May 2012 – Funded by Regione Lombardia

Develop a support decision system based on weather prediction at long range (30 days) with hydrological simulation of water balance to forecast the soil water content in every parcels over Consorzio Muzza Lodigiana basins, in order to use irrigation water in a wiser and thriftier way.
• Thanks to ARPA Emilia-Romagna (A. Montani) for its contribute in providing COSMO-LEPS model data.

Thanks for your attention

alessandro.ceppi@mail.polimi.it