EFFECTS OF HYDRO-METEOROLOGICAL SOURCES OF UNCERTAINTIES ON DISCHARGE FORECASTS

A. Ceppi[1], G. Ravazzani[1], A. Salandin[2], D. Rabuffetti[2], A. Montani[3], E. Borgonovo[4] & M. Mancini[1]

(1) Dipartimento di Ingegneria Idraulica, Ambientale, Infrastrutture viarie, e Rilevamento, Politecnico di Milano, Italy, e-mail: alessandro.ceppi@mail.polimi.it
(2) Agenzia Regionale per la Protezione dell'Ambiente Piemonte, Italy, e-mail: a.salandin@arpa.piemonte.it
(3) Agenzia Regionale per la Protezione dell'Ambiente Emilia-Romagna, Italy, e-mail: amontani@arpa.emr.it
(4) ELEUSI Research Centre Department of Decision Sciences, Bocconi University, Italy, e-mail: emanuele.borgonovo@unibocconi.it

ABSTRACT

In recent years the interest in the prediction and prevention of natural hazards, related to hydro-meteorological events, has increased the challenge for numerical weather modelling, in particular for limited area models, to improve the Quantitative Precipitation Forecasts for hydrological purposes.
In mountain river basins where snow dynamics can affect both precipitation (snow accumulation) and runoff (snow melting), air temperature uncertainty has to be thoroughly investigated. The analysis focuses on two Piedmont basins, located in the North-West Italy. The aim of this work is to assess the reliability of a real time flood forecasting system, coupling meteorological and hydrological models, analysing the forecasting precipitation and temperature fields at different spatial scales, and in different weather conditions.

1 INTRODUCTION

The number of great natural catastrophes is increasing worldwide, as underlined in the last Munich Re report: since 1980 a total number of 773 natural disasters were mainly caused by meteorological and hydrological events (46% and 28% respectively). This fact, combined with the increased antropization of our territories that makes them less resilient to climatic and hydrological variability especially under prolonged and alternating periods of drought and intense rainfall, has a strong impact on society with potentially high financial losses.

Indeed, coupling meteorological and hydrological models has become one of the most importance challenges in the scientific community during the two last decades; in particular, in recent years we have assisted to a widespread diffusion and use of hydro-meteorological chains by international agencies and research centres. This is also related to an increase in projects regarding flood forecasts like the Mesoscale Alpine Programme (MAP) between 1994 and 2005, the EFAS project in 2003, HEPEX in

2004, the European COST Action 731 (Propagation of Uncertainty in Advanced Meteo-Hydrological Forecast System) between 2005 and 2010, and in 2007 the D-PHASE Project (Demonstration of Probabilistic Hydrological and Atmospheric Simulation of Flood Events); this latter has shown 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 (Zappa et al., 2008, Rotach et al., 2009, Ranzi et al., 2009).

In this study we present an analysis for two different types of precipitation events that occurred during the D-PHASE Operational Period (DOP) over the Toce basin, in order to evaluate certain effects regarding discharge forecasts due to hydro-meteorological sources of uncertainties, and a hindcast occurred in November 2008 over the Toce and Sesia basins analysing the atmospheric forcing errors that can affect river discharge predictions. To better investigate these effects of temperature error on the peak discharge, we introduce a sensitivity analysis which allows us to consider jointly errors in the precipitation and temperature fields, evidencing both their individual effect and their interactions.

Two non-hydrostatic meteorological limited area models are used to force hydrological simulations: one with a coarse spatial resolution, supported by the Ensemble Prediction System (the COSMO-LEPS system based on COSMO model, Marsigli et al., 2005) and the other with a finer grid, but with one deterministic output only (the MOLOCH model, Malguzzi et al., 2006).

The hydrological model used to generate runoff simulations is the distributed FEST-WB (Flash–flood Event–based Spatially–distributed rainfall–runoff Transformation – Water Balance) model, developed at Politecnico di Milano (Mancini, 1990; Montaldo et al., 2007; Rabuffetti et al., 2008; Ravazzani et al., 2007).

2 RESULTS AND DISCUSSION

2.1 THE JUNE 2007 EVENT: EFFECT OF MODEL SPATIAL RESOLUTION

The June event (13-15 June 2007) was the most severe and relevant during the Map-D-Phase period on the Toce basin where 85-95 millimetres fell in only 24 hours (between 14 and 15 June).

The two meteorological models were characterized by an opposite behaviour in terms of forecasted cumulative precipitation between 14-15 June, in comparison with observed mean basin values: in fact, there was an underestimation for the COSMO-LEPS model (- 28%) and an overestimation for the MOLOCH model (+ 20%). Because of this, the COSMO-LEPS issued a meteorological and hydrological yellow warning, vice versa the MOLOCH issued an orange warning (for a complete review about alert thresholds, see Ceppi, 2011).

The maximum observed discharge at Candoglia was 783.2 $m^3 s^{-1}$ on 15 June at 17:00 UTC (however this discharge value exceed the orange warning, it caused no flood damage in the catchment area), while the simulated maximum discharge by the FEST-WB forced with observed hydro-meteorological data was 750 $m^3 s^{-1}$ at 20:00 UTC; despite this delay in reaching the peak (+ 3 hours), the hydrological model achieved a good performance, issuing the correct warning (Figure 1).

The response of the hydrological model was different when implemented with the forecasted meteorological forcings. Although better simulations were obtained with the one day ahead run (i.e. 24-48 hours before the main peak discharge), the median value of the COSMO-LEPS ensemble predictions has shown very poor results with a total underestimation of the peak discharge (- 56 %), which was also forecasted about 10 hours later than the observed time; 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. An opposite result was obtained using the MOLOCH model. In fact, with the one day ahead run, the peak discharge was overestimated by 48 % (1162.3 m^3 s^{-1}), but the magnitude of the event was correctly predicted, issuing an orange warning (Figure 1).

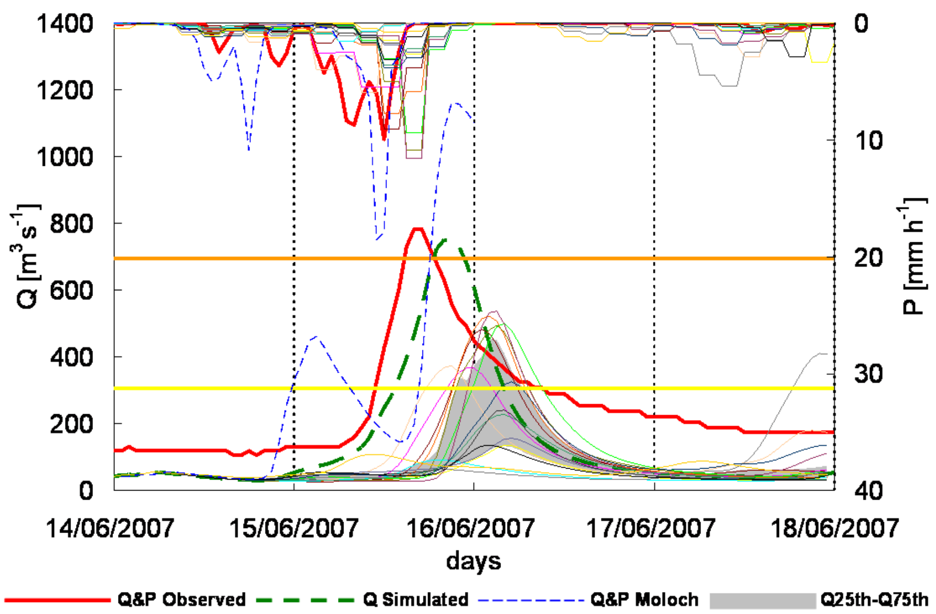


Figure 1. QPFs and QDFs of the FEST-WB model forced with observed meteorological data and with the CLEPS and Moloch model forecast over the Toce basin. The hydrological simulation driven by the two meteorological model was launched on 14 June 2007 00:00 UTC. The discharge value of each ensemble forecast is shown in different colours. The horizontal yellow and orange lines are the warning codes 1 and 2 respectively for the Toce basin.

2.2 THE NOVEMBER 2007 EVENT: EFFECT OF SOIL MOISTURE CONDITIONS

After a long dry period that hit the Southern edge of the Alps from the beginning of October, this rainfall was the first relevant meteorological phenomenon that occurred after 50 days of the dry autumn season of 2007. The observed amount of precipitation during this stratiform event (21-24 November) was about 80 mm as a mean value over the Toce basin.

According to the D-PHASE threshold, 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 $m^3 s^{-1}$, which is a very low value, with no alert all.

Due to the dry antecedent soil condition, the FEST-WB hydrological simulations, forced with forecasted meteorological data, performed well, issuing no warning. In fact, looking at the soil moisture field, before the event we find very dry values (near to θ_{res}) generally over the whole Toce basin 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 2007; values near to the saturation (θ_{sat}) were found only along the main river tributaries.

2.3 THE NOVEMBER 2008 EVENT: THE ROLE OF ATMOSPHERIC FORCINGS

In the first five days of November 2008 more than 100 mm fell over the Piedmont watersheds, in particular over the Toce and Sesia basins, where locally more than 200 mm were cumulated in less than 5 days, and a meteorological warning was issued by the regional authority.

The snow line during this event was located at about 1700-2100 m a.s.l. on the Alpine area. This snow threshold was a key factor in estimating correctly the forecasted discharge at basin scale.

A false alarm in discharge forecasts was found on the Toce, where the performance decreases approaching the peak event on 5 November, forecasting an exceeding of the alert code 2, which was not observed instead; this result needs to be investigated in more depth, thus the FEST-WB model was tested for alternative combinations of input variables and the corresponding model output simulations were compared, in order to understand better which was the error forcing.

2.4 SENSITIVITY ANALYSIS AT FINITE CHANGES

Our task was to understand "what it was about the inputs that made the outputs come out as the did (Little 1970, p.B469, in Borgonovo and Peccati 2011): in our case it was the interaction between forecasted temperature and precipitation errors that can affect the peak discharge on a mountain basin during autumn/winter period. Following the approach reported in Borgonovo 2010 and Borgonovo and Peccati 2011, a sensitivity analysis at finite changes has been applied to evaluate different simulation scenarios.

Some notation first. We let:

- P = precipitation field;
- T = temperature field;

(That is, the factors in our case are the entire precipitation and temperature fields, which, in turn, are constituted by the set of all the corresponding measurements.)

- $f(P^0, T^0)$ = the maximum discharge value of our hydrological model simulation forced with both P and T fixed at the observed data;
- $f(P^1, T^1)$ = the maximum discharge value of the ensemble median of our hydrological model simulation forced with both P and T at the values forecasted by the

COSMO-LEPS model.

Then, by the factor separation method extended to factor groups [Sobol' (1993), Borgonovo and Peccati (2011)], one can write:

$$\Delta f = \Delta f_P + \Delta f_T + \Delta f_{P,T} \tag{1}$$

where:

(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 forced with the observed temperature field, and the forecasted precipitation values of the COSMO-LEPS model; this latter simulation referred to as S_1;

(Δf_T) is the difference between the FEST-WB simulation (referred to as S_0), forced with all observed values, and the FEST-WB simulation forced with the observed precipitation field, but with the forecasted temperature values of the COSMO-LEPS model; this latter simulation referred to as S_2;

($\Delta f_{P,T}$) is the difference between the FEST-WB simulation (referred to as S_0), forced with all observed values, and the FEST-WB simulation forced with both the forecasted precipitation and temperature values of the COSMO-LEPS model; this latter simulation referred to as S_3.

The FEST-WB discharge simulation, forced with the observed field values (precipitation, temperature, humidity and solar radiation), is very similar in terms of peak amount to the measured situation (S_0 in Figure 2). Thus, the first two steps of the decomposition involve individual changes in “precipitation” and “temperature” to compare the discharge differences; in particular, we alternated the observed precipitation and temperature fields with the forecasted fields. The humidity and solar radiation field were not changed in this sensitivity analysis instead, and their inputs were always implemented as observed data.

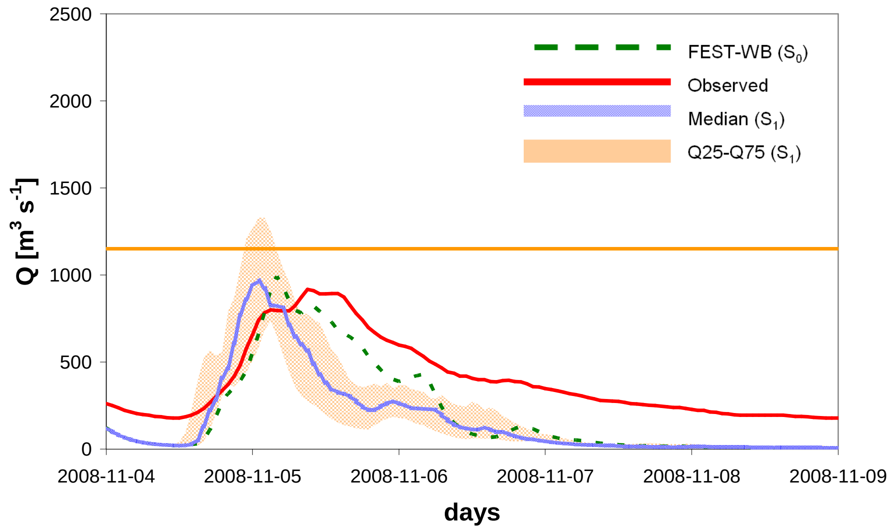


Figure 2: QDF of the FEST-WB simulation (S_1) forced with observed temperature field and forecasted precipitation by the COSMO-LEPS model (blue line). The red line shows the observed discharge at Candoglia and the green dashed line shows the simulated discharge by the FEST-WB (S_0), forced with observed data; the hydrological simulation was started on 4 November 2008 over the Toce basin. The horizontal orange line shows the alert code 2 for the Toce basin.

Figure 2 shows that no big differences exist between the two simulations S_0 and S_1: i.e. putting the COSMO-LEPS precipitation field as input in the FEST-WB model and maintaining the other observed meteorological data (air temperature, relative humidity and solar radiation) the discharge difference (Δf_P) between the ensemble median (blue line) and the FEST-WB (green dashed line) is only 26 $m^3 s^{-1}$.

On the contrary for the simulation S_2 shown in Figure 3 the ensemble median Q_{max} shows a remarkable difference of 686 $m^3 s^{-1}$ in comparison with S_0.

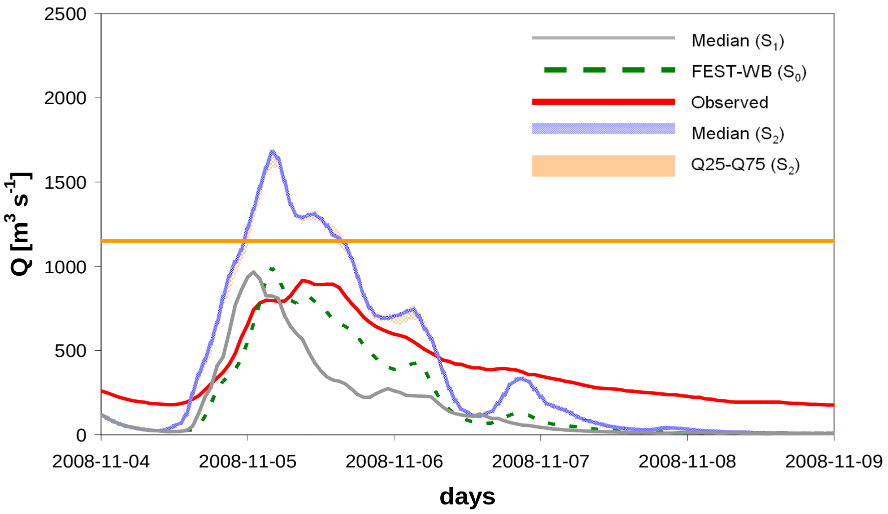


Figure 3: QDF of the FEST-WB simulation (S_2) forced with observed precipitation field and forecasted temperatures by the COSMO-LEPS model (blue line). The red line shows the observed discharge at Candoglia and the green dashed line shows the simulated discharge on the FEST-WB, forced with observed data (S_0). The grey line illustrates the ensemble median of the simulation S_1 as a comparison with the new simulation (S_2). The hydrological simulation was initialized on 4 November 2008 over the Toce basin. The horizontal orange line shows the alert code 2 for the Toce basin.

The simulation S_2 shown in Figure 3 is the keystone in our analysis and it answers our proposed objectives. The discharge overestimation (ensemble median value of 1678.4 m^3s^{-1}), exceeding alert code 2 can only be attributed to an error of the CLEPS forecasted temperature (about 3°C higher than the observed temperature), because it was the only changed variable in this new simulation scenario.

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.

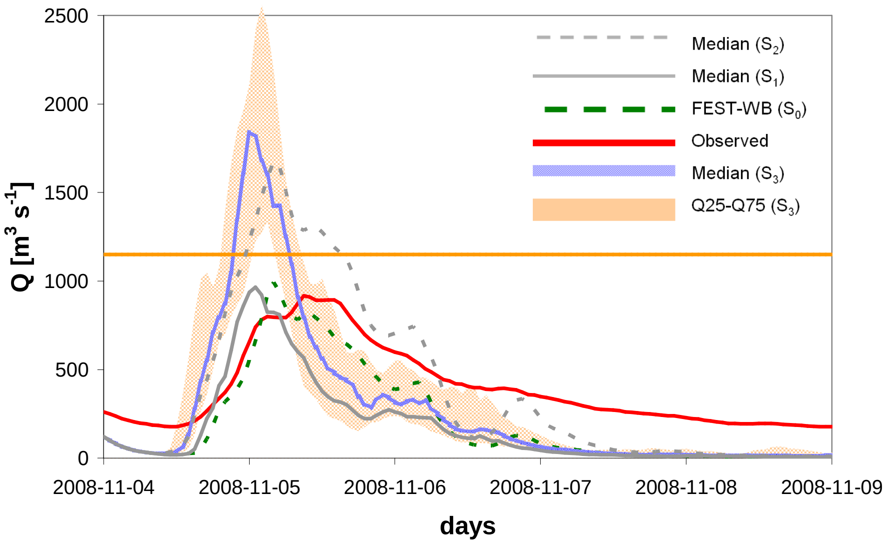


Figure 4: QDF of the FEST-WB simulation (S_3) forced with both forecasted precipitation and temperature fields by the COSMO-LEPS model (blue line). The red line shows the observed discharge at Candoglia and the green dashed line shows the simulated discharge on the FEST-WB (S_0), forced with observed data. The grey line shows the ensemble median of the S_1 simulation, the grey dashed line illustrates the S_2 simulation; the hydrological simulation was initialized on 4 November 2008 over the Toce basin. The horizontal orange line shows the alert code 2 for the Toce basin.

Figure 4 shows an increase in the peak discharge: the ensemble median reaches a value of 1841 m^3s^{-1} (grey dashed line), with a difference of about 849 m^3s^{-1} (Δf) in comparison with the FEST-WB simulation (S_0), forced with all observed fields. By eq. (1), the interaction effect ($\Delta f_{P,T}$) is equal to +189 m^3s^{-1} showing that the forecasted discharge error cannot be explained only by individual effects; instead interactions play a relevant role.

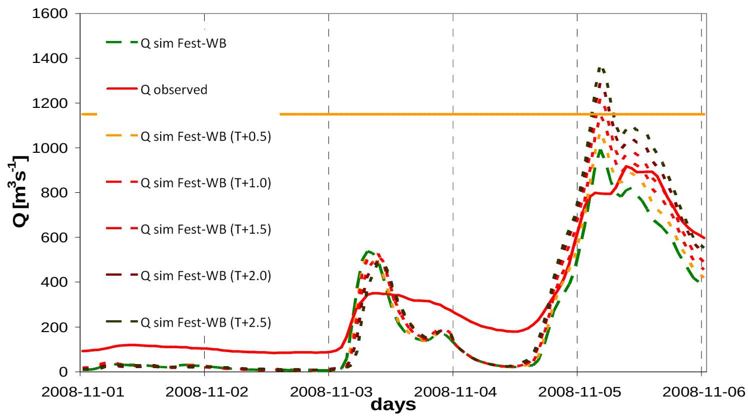
This term is significant, signalling the response of the hydrological model is structurally non-additive. Thus, the overall change is not the superimposition of individual effects. The positive sign of Δf_{PT} indicates that this interaction tends to amplify the effect of temperature while it opposes to the effect of precipitation.

2.5 EFFECTS OF TEMPERATURE ON THE PEAK DISCHARGE

Once we had evaluated that the false alarm in discharge forecast over the Toce basin prevalently depends on by temperature errors, we quantified this overestimation in terms of peak discharge over the Toce and Sesia basins. The strategy we adopted was the following: new synthetic temperature fields were created, rising all observed temperature station data in the subject area by 0.5, 1.0, 1.5, 2.0, and 2.5 Celsius degrees.

Because the 1-5 November 2008 event was characterized by a snow line above 1700-2100 m a.s.l over mountain basins, this means rising the snow line about 100 m at a time.

With an increase in temperature from 0.5°C up to 2.5°C over the Toce basin the snow line was risen approximately 500 m, with a difference of nearly 30% in terms of water runoff for the 5 November peak, because the drainage area becomes greater. On the contrary, over the Sesia basin with a completely different ipsographic curve the rise of the snowfall line does not substantially imply any differences in discharge error: whether the 0°C line is at about 1900 m or at about 2500 m a.s.l., the precipitation remains in liquid form in almost the entire basin and in fact the evaluated error variation was only 5%. In Figure 5, five different discharge simulations are shown for the corresponding five selected temperature increases over the Toce and Sesia catchments.



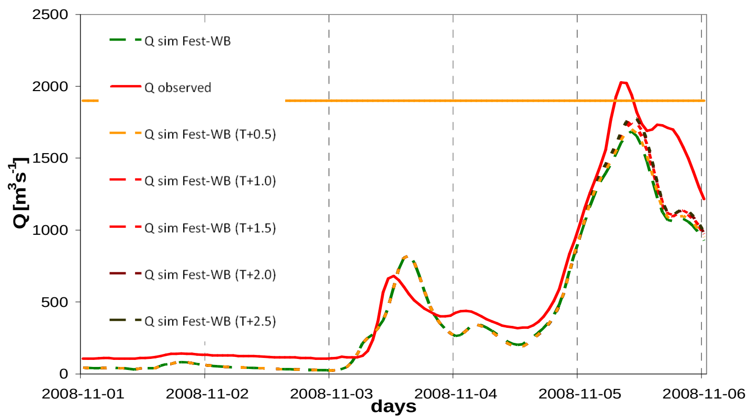


Figure 5: Discharge simulations over the Toce (upper) and Sesia (bottom) basin, with the modified temperature field as input into the FEST-WB model initialized on the 1 November 2008. The measured discharge at Candoglia and Palestro are highlighted

in red, the FEST-WB simulations forced with observed data are shown by the green lines, while coloured dashed lines refer to discharge simulation by the FEST-WB model forced with increased temperature at 0.5°C intervals. In this case we launched the simulation on 1 November to show the entire simulation for the event. The horizontal orange line shows the alert code 2 for the Toce (upper) and Sesia (bottom) basins.

3 CONCLUSION

In this study we develop a hydro-meteorological chain as an operating tool to assess the reliability of a real time flood forecasting system, coupling meteorological and hydrological models, analysing the quantitative precipitation and temperature fields in different weather conditions over two mountain basins of the Piedmont Region. The aim was to evaluate how Quantitative Precipitation Forecasts (QPFs) influence the performance of hydrological predictions in terms of Quantitative Discharge Forecasts (QDFs) at different spatial scales (the June 2007 event), and how initial conditions of soil moisture are relevant before a meteorological event (the November 2007 event).

Further, we analysed an event that occurred in November 2008 to better understand the role of atmospheric forcing (precipitation and temperature) conditioned by a significant snow line. Through a sensitivity analysis we calculated the effects of interactions that can modify the discharge prediction. We quantified how the QDF is influenced by temperature errors and is related to the basin’s ipsographic curve, and therefore to the percentage of the area that contributes with the most liquid water (rain) in the watershed. This forecast error can have a big impact on hydrological forecasts which are generally quite reliable at 24-48 hours before the main peak discharge.

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