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Impact of precipitation forecast uncertainties and initial soil moisture conditions on a probabilistic flood forecasting chain

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A R T I C L E   I N F O

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SUMMARY

One of the main difficulties that flood forecasters are faced with is evaluating how errors and uncertainties in forecasted precipitation propagate into streamflow forecast. These errors, must be combined with the effects of different initial soil moisture conditions that generally have a significant impact on the final results of a flood forecast. This is further complicated by the fact that a probabilistic approach is needed, especially when small and medium size basins are considered (the variability of the streamflow scenarios is in fact strongly influenced by the aforementioned factors). Moreover, the ensemble size is a degree of freedom when a precipitation downscaling algorithm is part of the forecast chain. In fact, a change of ensemble size could lead to different final results once the other inputs and parameters are fixed. In this work, a series of synthetic experiments have been designed and implemented to test an operational probabilistic flood forecast system in order to augment the knowledge of how streamflow forecasts can be affected by errors and uncertainties associated with the three aforementioned elements: forecasted rainfall, soil moisture initial conditions, and ensemble size.

1. Introduction

A reliable operational flood forecasting system is important if streamflow, possible flooding and its effects are to be predicted with sufficient lead time to allow for appropriate actions. This is a particularly challenging task in the case of small to medium sized basins with drainage areas of order of magnitude from 10 to 10,000 km^2 or less (Siccardi et al., 2005). In this context, two main issues arise: (i) the need to base the flood prediction system on rainfall forecast (because of the fast response time of these catchments), and (ii) the need to follow a probabilistic approach (because of the inconsistencies between meteorological modeling and hydrologic response, Ferraris et al., 2002).

Such forecasting systems, as a basic option, use an atmospheric model and a hydrological prediction system. When dealing with small catchments however, a downscaling module is necessary to account for uncertainties and inconsistencies in the rainfall predicted by meteorological models (Mascaro et al., 2010; Siccardi et al., 2005).

Each component of the system is affected by uncertainty and these uncertainties propagate and amplify from the beginning of the chain (the atmospheric models) to the discharge or its transformation into river level and eventually the corresponding flood scenarios.

Many works have been devoted to dealing with errors and uncertainties related to: (i) precipitation estimation (e.g. Germann et al., 2009), (ii) hydrological model parameterization (e.g. Carpenter and Georgakakos, 2006; Vrugt et al., 2006), (iii) soil moisture initial conditions (e.g. Brocca et al., 2011; Tramblay et al., 2012), and (iv) forecasted rainfall (e.g. Siccardi et al., 2005). Zappa et al. (2011) analyzed the superposition of different sources of uncertainties. Mascaro et al. (2010) analyzed how ensemble precipitation errors affect streamflow simulations using a multifractal rainfall downscaling model coupled with a distributed hydrological model. However, most of these works analyzed a particular source of uncertainty, with no reference to the multi-catchment approach or to the influence of sample size on the results of probabilistic chains. In addition, the errors related to the quantitative use of expert precipitation forecasts were never discussed.

In this work, a probabilistic chain used operationally for flood forecasts on small and medium-sized basins in Liguria, Italy is considered (Silvestro et al., 2011, 2012) and several synthetic experimental suites have been designed and implemented in order to provide answers to practical and operational questions. That is,

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how errors in the forecasted rainfall propagate and affects the final results of the flood forecasting chain and how these effects change and combine with the soil moisture initial conditions. Further, since we considered a probabilistic system, an analysis of the effects related to the ensemble size is also done.

For simplicity, the uncertainties related to the hydrological model parameters (Beven and Binley, 1992; Liu et al., 2005; Zappa et al., 2011) have been neglected. These parameters can have considerable effects on flood simulations, but they are generally negligible with respect to those related to the rainfall forecasts and initial wetting conditions (Mascaro et al., 2010; Zappa et al., 2011) especially when dealing with small basins. In small basins, errors on precipitation localization or bad estimation of rainfall amounts at small spatial–temporal scales can lead to huge errors in flood forecasts. Moreover, in the case presented in this paper, the considered hydrological model is quite consolidated in the test region and the suitability of the operational parameters set is constantly verified comparing simulations with the streamflow observations.

There are three main peculiarities of the flood forecast chain under consideration: (i) the forecasted precipitation is quantitatively predicted by an expert forecaster and not by a Numerical Weather Prediction System (NPWS), (ii) the expert forecast is downscaled in order to properly account for the uncertainties on small catchments, and (iii) the forecast is carried out following two different approaches depending on the dimension of the basins: single-site and multi-catchment (Siccardi et al., 2005).

The forecasted rainfall is stochastically downscaled with an algorithm based on Rebora et al. (2006) in order to generate an ensemble of rainfall fields of fine spatial–temporal scales [1 km - 0.5 h]. As a consequence, we seek to investigate the following issues: (a) how errors in the precipitation forecast affect the rainfall ensemble (b) how these errors propagate into the streamflow ensemble and finally, (c) how these errors are amplified or reduced by the different soil moisture initial conditions.

The manuscript is organized as follows: Section 2 describes the context and the flood forecasting chain, Section 3 shows the design of the experiments while in Section 4 the results are reported, and finally the paper concludes in Section 5 with the discussion and conclusions.

2. Case study

2.1. The expert quantitative precipitation forecast (EQPF)

As described in Silvestro et al. (2011) the precipitation forecast for the Liguria Region is provided by a number of Numerical Weather Prediction Models (NWPM) and interpreted by expert meteorologists (see Table 1). The Liguria Region, Italy is divided into five alert sub-regions that are considered homogenous from the hydrological response point of view, and also from their meteo-climatic characteristics (Fig. 1). Each alert sub-region has an area of the order of 10^3 km^2 and contains a number (around 20) of modeled small sized basins (O(Area) 10-10^2 km^2) on a complex topography with steep valleys and concentration times ranging from 1 to 6 h. Few basins in this Region have larger areas and concentration times (O(Area) 10^2-10^3 km^2). A high percentage of the territory is covered by forests or by lawns with shrubs (about 70%) and the main urban areas and towns are established along the coast, often at the mouth of creeks and rivers.

Table 1
NWPM used by the meteorologists of HMFC to carry out the expert quantitative precipitation forecast.

Model Name	Spatial resolution (km)	Type
ECMWF	30	Global scale
COSMO-LAMI	7	Mesoscale
BOLAM	10	Mesoscale
MOLOCH	2	Regional scale

The experts of the Hydro-Meteorological Functional Centre of Liguria Region (HMFC) merge the output of the different meteorological models (the so called “poor man ensemble” e.g. Arribas et al., 2005) with their own experience and provide quantitative precipitation forecasts for the alert sub-regions over predefined time windows. For each alert sub-region, a different quantitative precipitation forecast is made.

We briefly report how the rainfall forecasts are specifically made and used operationally for feeding the flood forecast chain (for further details see Silvestro et al., 2011).

Basically, three quantities are provided for a given rainfall event:

1. The maximum average precipitation in a time window of 12 h for each homogeneous sub-region (named P_{12}). In order to define this quantity, a certain number of meteorological models (Table 1) are analyzed in order to identify the 12 h time window when the maximum precipitation amount is expected. The starting time of the time window is identified as t_{12}. The 12 h window is chosen since it is the typical length of an extreme rainfall event in the area.
2. Once the P_{12} is defined, the meteorologist estimates the rainfall amount (Pb) that is expected between the reference starting time of the forecast (t_0) and the start of the 12 h window (t_{12}) associated with the maximum volume. The time window where Pb is estimated is then $\tau_b = t_{12} - t_0$. This is done for each sub-region. The reference start time (t_0) is the time at which the meteorologist starts his forecast and this is usually 00:00 h on the day he makes the prediction.
3. The third parameter is the maximum precipitation amount forecasted in a time window of 3 h and on areas of approximately 10^2 km^2 (named P_3), that is, on boxes of 10×10 km^2. This number gives an idea of the local intensity of the forecasted event; high values mean possibly critical situations for basins with areas in the range of 10^1–10^2 km^2. It also indicates how much the precipitation volume, defined by P_{12}, tends to be concentrated in localized areas. Generally, a P_3 value is given for each sub-region, but it can also be estimated as a single P_3 value for the entire regional territory. Meteorologists are confident to issue quantitative precipitation forecast up to spatial–temporal scale of 10^2 km^2 – 3 h, which is coherent with the scale of dimension and time of concentration of most of the modeled basins.

Given that P_{12} and P_3 are estimated on different reference areas, the value of P_3 can be larger than P_{12}. In fact, the condition that must be verified is on the total volumes:

$$P_3 \times A_3 \leq P_{12} \times A_{12} \quad (1)$$

where A_3 is the 10^2 km^2 box and A_{12} the area of the homogeneous region.

An automatic software calculates the P_3 and P_{12} values for each model of Table 1 and merges them but the forecasters can decide to modify these values based on their confidence with the used NWPM and their subjective assessment of the occurring event.

2.2. The flood forecasting chain operational at the HMFC (FFC)

The EQPF is used as the input for the operational probabilistic hydro-meteorological forecasting chain (Siccardi et al., 2005;