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# The use of meteorological analogues to account for LAM QPF uncertainty

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## Abstract

Flood predictions issued employing quantitative precipitation forecasts (QPFs) provided by deterministic models do not account for the uncertainty in the outcomes. A probabilistic approach to QPF seems to be indispensable to obtain different future flow scenarios that allow to manage the flood accounting for the variability of phenomena and the uncertainty associated with an hydrological forecast. A new approach based on a search for past situations (analogues), similar to previous and current day in terms of different meteorological fields over Western Europe and East Atlantic, has been developed to determine an ensemble of hourly quantitative precipitation forecasts for the Reno river basin, a medium-sized catchment in northern Italy. A statistical analysis, performed over an hydro-meteorological archive collecting ECMWF analyses at 12:00 UTC relative to the autumn seasons ranging from 1990 to 2000 and the corresponding precipitation measurements recorded by the raingauges spread over the catchment of interest, has underlined that the combination of geopotential at 500 hPa and vertical velocity at 700 hPa provides a better estimation of precipitation. The analogue-based ensemble prediction has to be considered not alternative but complementary with the deterministic QPF provided by a numerical model, even in view of a joint employment to improve real-time flood forecasting. In the present study, the analogue-based QPFs and the precipitation forecast provided by the Limited Area Model LAMBO have been used as different input to the distributed rainfall-runoff model TOPKAPI, thus generating, respectively, an ensemble of discharge forecasts, which provides a confidence interval for the predicted streamflow, and a deterministic discharge forecast taken as an error affected "measurement" of the future flow, which does not convey any quantification of the forecast uncertainty. To make more informative the hydrological prediction, the ensemble spread could be regarded as a measure of the uncertainty of the deterministic forecast.



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## 1 Introduction

In the field of hydrological prediction for medium-sized watersheds, with short response times to rainfall events, forecasts cannot rely only upon observed precipitation: predicted rainfall is in this case an essential input for hydrological models to increase the lead time up to a minimum critical value that allows the activation of civil protection plans. The classical deterministic approach to rainfall forecasting is through numerical weather prediction (NWP) models, even though only limited area models (LAMs) have a spatial and temporal resolution that can be adequate for hydrological applications. However, the capability of such models to forecast correctly local and intense precipitation is still nowadays limited, even at short time-range, up to 48 h, due primarily to atmospheric instabilities which cause a rapid growth of the observation-analysis errors, tending to affect more adversely the smaller scales typical of medium-sized watersheds. As a consequence, deterministic meteorological models, even the high-resolution ones, cannot provide reliable quantitative rainfall forecasts to be used directly for flood forecasting purposes, further not conveying any quantification of the forecast uncertainty. This issue demands the problem of QPF should be tackled relying upon alternative methodologies based on a probabilistic approach. Using different future precipitation scenarios to force a hydrological model should enable to manage a flood event counting for the variability of phenomena and the uncertainty associated with an hydrological forecast. In this way, the use of uncertainty in hydrological model prediction is related with the problem to integrate meteorological forecast uncertainty into a hydrological model capable to propagate such into hydrological forecast and warning uncertainty.

The need to deal with uncertainties in hydrological model predictions has been widely recognised in recent years, since forecasting should not only offer an estimate of the most probable future state of a system, but also provide an estimate of the range of possible outcomes (Schaake, 2004). Operational real-time flood forecasting systems must be designed and structured in order to reduce forecasting uncertainty and to provide a usable quantification of it (Todini, 2000). Quantifying uncertainty has some potential benefits like to aid the forecaster in making unbiased judgements, to issue warnings and alarm in probabilistic format. Accounting for risks in decision making may increase economic benefits of forecasts (Krzysztofowicz et al., 1993).

In the last twenty years several approaches to probabilistic QPF have been developed (Rodriguez-Iturbe et al., 1987; Hughes and Guttorp, 1994; Foufoula-Georgiou and Krajewski, 1995; Todini, 1999; Molteni et al., 2001; Marsigli et al., 2001; Marsigli et al., 2005), at the same time ensemble forecasting techniques are beginning to be applied to hydrological prediction, offering a general approach to probabilistic prediction able to improve hydrological forecast accuracy (Schaake, 2004). Ensembles are a convenient method of handling uncertainty, since information about forecast uncertainty could be derived from the dispersion of ensemble members.

In the present study, an empirical approach to probabilistic QPF is proposed, based on the analogue method. This technique relies upon the concept of analogy applied in meteorology and exploits the reliable representation of large scale hydrodynamic variables, like geopotential fields, provided by NWP models to derive precipitation forecasts indirectly. In literature, the analogue method has already been employed in several studies and has been demonstrated that it's a valid alternative way to issue precipitation forecasts (Radinovic, 1975; Vislocky and Young, 1989; Cacciamani et al., 1989 and 1991; Roebber and Bosart, 1998; Obled et al., 2002). However, the probabilistic QPF provided by analogues can be considered not only competitive but rather complementary with the deterministic one supplied by NWP models (Djerboua and Obled, 2002).

The implementation of the analogue method presented in this work is based on a search for analogues which similarity, in terms of synoptic circulation pattern over Western Europe and East Atlantic, is assessed by considering different meteorological variables (geopotential height at 500 and 850 hPa, specific humidity at 700 hPa, vertical velocity at 700 hPa and several combinations of them). The method has been developed to achieve an ensemble of hourly quantitative precipitation forecasts for the

Reno river basin, a medium-sized catchment in northern Italy. A statistical analysis has been performed over a eleven-year long archive, collecting hydro-meteorological data for the fall season, to establish which meteorological field provides a better estimation of precipitation, which similarity criteria to adopt and the optimal size of analogous ensemble. Subsequently, the analogue-based QPFs have been used as input to the distributed rainfall-runoff model TOPKAPI (TOPographic Kinematic Approximation and Integration; Todini and Ciarapica, 2002), generating an ensemble of discharge forecasts, which provides a confidence interval about future streamflows. The range of the ensemble values can be used to convey the uncertainty of the deterministic hydrological prediction obtained by feeding the TOPKAPI with the QPF provided by the Limited Area Model LAMBO, taken as a error affected "measurement" of the future flow.

The paper is structured as follows: a description of the study area and the forecasting tools (analogue method, meteorological model and hydrological model) is presented in Sect. 2. Section 3 describes the results of analogue-based QPFs, while the corresponding discharge simulations are discussed in Sect. 4. Concluding remarks are drawn in Sect. 5.

## 2 Forecasting tools and study area

### 2.1 The analogue method

Studies in past decades evidenced that weather patterns over certain areas and over the entire Northern Hemisphere tend to repeat themselves from time to time (Baur, 1951; Namias, 1951; Lorenz, 1969). Using this property of the atmosphere, in meteorology it has been introduced the concept of analogy, meaning with the terms "analogues" two or more states of the atmosphere, together with its environment, which resemble each other so closely that the differences may be ascribed to errors in observation (Lorenz, 1963). Many authors tried to investigate the possibilities to improve weather forecasts by means of the analogue method, employing the philosophy that



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weather behaves in such a way that the present initial conditions, if found to be similar to a past situation, will evolve in a similar fashion. The method is based on the assumption that the general circulation of the atmosphere is a unique physical mechanism whose course of development is continual and dependent on the given initial conditions. This means that if a good analogous can be found for the current situation, the weather forecast for a given period of time can be obtained by the sequence of meteorological conditions observed in that past event (Radinovic, 1975; Bergen and Harnack, 1982). Lorenz (1969) affirms that, ideally, two states should be considered similar only if the three-dimensional global distribution of wind, pressure, temperature, water vapour and clouds, and the geographical distributions of such environmental factors as sea-surface temperature and snow cover, are similar. Also the states should occur at the same time of the year, so that the distributions of the solar energy striking the atmosphere will be similar. However, it seems unlikely that two states of the atmosphere occurring at different seasons will resemble each other closely, even if they should, they cannot be expected to vary similarly, because the fields of heating are dissimilar. Hence, the analogues research have to be conducted over the times of the year that are within few months respect to the date at hand, excluding as possible analogues any pairs of states which are fairly close together in time, such as those coming from the same year.

Since it should be required at least a few dozen independent variables to describe a hemispheric circulation pattern in its full dimensionality, it has been demonstrated that it's highly improbably to find good analogues over global scale for different level and variables (Toth, 1991). Rather, it is easy to find good analogues over a small area, even if the data-set available for the analogue research is short: this is a sample matter of spatial degrees of freedom involved (Gutzler and Shukla, 1984; Rousteenoja, 1988; Roebber and Bosart, 1998). Searching for the analogy over a small area, which can be more effective when weather patterns are affected strongly by local conditions, does not imply that only small spatial scales are matched (Van den Dool, 1989). The domain size should be larger enough to consider the evolution of the structure of the lower atmosphere over the region of interest, including the movement and intensity change of the weather systems that will affect the weather in the target area. Therefore, the meteorological variables at different observation times, usually every 24 h, have to be involved (Vislocky and Young, 1989; Obled et al., 2002).

Considering that similar general circulation patterns should provide similar local effects, the search for past situations similar to the one at hand should provide hints on what could happen locally. During analogue situations, local variables, such as precipitation over medium-sized catchment, react partly in response to the synoptic situation, but also to more local features (e.g. orography, wind channelling, etc.). Hence, this approach takes into account the spatial distribution of phenomena over the catchment concerned and its potentially specific reactions according to the given meteorological pattern since past observed values used to make forecasts automatically contain the orographic, diabatic and other local influences characterising the area of interest (Rousteenoja, 1988; Obled et al., 2002).

The methodology exploits the reliable representation of large scale hydrodynamic variables by meteorological models to derive precipitation forecasts indirectly. It is bypassed the steps which in a meteorological model allows to go from the hydrodynamic and thermodynamic variables, controlling the general circulation, to the precipitation forecasted at ground.

The developing of the analogue method in time has evidenced its advantages. It can be simply implemented and is capable of quickly generating objective forecasts; furthermore it does not rely upon complex and subtle reasonings inherent in physical/statistical methods (Namias, 1951; Radinovic, 1975; Bergen and Harnack, 1982; Toth, 1989), yielding a real solution to a difficult problem and not introducing any simplification over the physics of the atmosphere (Van den Dool, 1989).

Although the analogue approach appears to be straightforward, it is not without its pitfalls. From the theoretical standpoint, the method has limited possibilities, since the analogue situations one can find are still going to differ from the current one (Namias, 1978). An underlying problem concerns the dependence of the method upon the extent of available historical data (presently from 10 to 100 years), thus it is likely that the predictive abilities of the method are restricted by limited amounts of data. Particularly, in case of rare and intense events the method is less reliable due to the limited historical data in the archive: in fact, the past situations available as potential good analogues will be less numerous and characterised by a lower analogy degree, so causing systematic underestimation and bias.

The approach needs several steps to be applied: first, the building of a historical archive with sufficient hydro-meteorological data which enable to describe a synoptic situation at the ground level as well as in the atmosphere. Next it's necessary to establish which meteorological variable (or a combination of them) is better to characterise a circulation pattern regarding to the observed precipitation: for such aim an analogy criterion and an objective procedure for the forecast verification need. When the method has been optimised in terms of spatial domain for analogue search, size of past situation sample, analogy criterion to be chosen, it's possible to proceed to the extraction of past time series of raingauge measurements.

In this work, the implementation of the analogue method is proposed as follows. Based on the research of Cacciamani et al. (1989, 1991) and Obled et al. (2002), it has been considered the geopotential height (Z) at 500 (Z500) and 850 hPa (Z850), the specific humidity (Q) at 700 hPa, the vertical velocity (W) at 700 hPa and several combinations of them to characterise the atmospheric circulation over Western Europe and East Atlantic. The search for similar synoptic patterns has been performed relying upon an archive collecting ECMWF (European Centre for Medium-range Weather Forecasts) analyses of these variables at 12:00 UTC, for the period 1990–2000. The domain area starts from 10° W to 20° E and from to 30° N to 60° N, covered by 3721 model grid points with a grid spacing of 0.5°. According to two similarity criteria, S1 score (Wilks, 1995) and Euclidean Distance (hereafter ED), a certain subset of such analogues is singled out and the corresponding precipitation measurements, recorded for the next 72 h by the raingauges spread over the Reno river basin (Fig. 1), are extracted and treated as the probabilistic precipitation forecasts.

The forecasts obtained via this approach (referred hereafter as scheme A) have been compared with those provided by an alternative implementation of the method (hereafter, scheme B), based on the proposal of Obled et al. (2002). The two approaches can be summarized as follows. In the scheme A, each current day $D_c$ and each past analogue day $D_p$ is characterised by ECMWF analyses at 12:00 UTC of day D and day D-1 and the precipitation forecast is obtained by the next 72 h of historical rain-gauge recordings starting from 13:00 UTC of day $D_p$. In the scheme B, the days $D_c$ and $D_p$ are characterised by ECMWF analyses at 12:00 UTC of day D and corresponding model forecasts at +24, +48 and +72 h. For each of the three different forecast times, the related precipitation forecast is obtained by the 24 h historical raingauge recordings characterising the corresponding past analogue day, up to achieve the 72 h rain-time series.

### 2.2 The meteorological model

The Limited Area Model BOlogna (LAMBO) was the ARPA-SIM operational atmospheric model until 2004, whose rainfall forecasts have been used in this work. It is a grid-point, split-explicit, primitive equation hydrostatic model, based on an early version of the NCEP ETA Model (Mesinger et al., 1988). At ARPA-SIM, the operational suite was based on two consecutive LAMBO runs: the coarser one was at about 40 km of horizontal resolution and 21 vertical levels on terrain following sigma-coordinates. The initial conditions were provided by ECMWF operational analysis, interpolated to LAMBO resolution; the boundary conditions were provided by ECMWF operational forecast, available every 6 h throughout all integration time. The integration region covered approximately the area 4° W–29° E, 33° N–52° N. The higher resolution run had an horizontal resolution of about 20 km and the integration domain covered the Italian peninsula and the Alpine region, with 32 vertical levels again on terrain following sigma-coordinates. Boundary and initial conditions were provided by the coarser run and updated every 3 h. LAMBO was operationally run twice a day, nested on ECMWF operational runs of 00:00 and 12:00 UTC, the forecast length being 72 and 84 h, respectively. Outputs were provided every three hours.

### 2.3 The hydrological model

The hydrological model used to generate simulated discharges is the TOPKAPI (TOPographic Kine-matic APproximation and Integration) model (Todini and Ciarapica, 2002), a physically-based distributed rainfall-runoff model applicable at different spatial scale, ranging from the hillslope one to the catchment one, and in the perspective to the GCMs one, maintaining at increasing scales physically meaningful values for the model parameters. The parameterisation is relatively simple and parsimonious. It couples the kinematic approach with the topography of the catchment and transfers the rainfall-runoff processes into three "structurally-similar" zero-dimensional non-linear reservoir equations. Such equations derive from the integration in space of the non-linear kinematic wave model: the first represents the drainage in the soil, the second represents the overland flow on saturated or impervious soils and the third represents the channel flow.

The parameter values of the model are shown to be scale independent and obtainable from digital elevation maps (DEM), soil maps and vegetation or land-use maps in terms of slopes, soil permeabilities, topology and surface roughness. Land cover, soil properties and channel characteristics are assigned to each grid cell that represents a computational node for the mass and the momentum balances. The flow paths and slopes are evaluated from the DEM, according to a neighbourhood relationship based on the principle of minimum energy.

The evapo-transpiration is taken into account as water loss, subtracted from the soil water balance. This loss can be a known quantity, if available, or it can be calculated using temperature data and other topographic, geographic and climatic information. The snow accumulation and melting (snowmelt) component is driven by a radiation estimate based upon the air temperature measurements.

A detailed description of the model can be found in Liu and Todini (2002).

For the implementation of the model over the Reno river basin, the grid resolution is set to 1000 m×1000 m. The calibration and validation runs have been performed using the hourly meteo-hydrological data-set available from 1990 to 2000. The calibration process did not use a curve fitting process: an initial estimate for the model parameter set was derived using values taken from the literature, then the adjustment of parameters was performed according to a subjective analysis of the discharge simulation results. The simulation runs performed for the present work have been carried out exploiting different techniques to spatially distribute the precipitation data (forecasts and raingauge observations) onto the hydrological model grid. The Thiessen polygon method was applied to interpolate the irregularly distributed surface observations, whereas the rainfall fields predicted by LAMBO were downscaled to each pixel of the hydrological model structure by assigning to the value of the nearest atmospheric model grid point.

### 2.4 The study area

The Reno river basin is the largest in the Emilia-Romagna Region, measuring 4930 km$^2$. It extends about 90 km in the south-north direction, and about 120 km in the east-west direction, with a main river total length of 210 km. Slightly more than half of the area pertains to the mountain basin. The basin is divided into 43 sub-catchments (Fig. 1). The mountainous part crossed by the main river covers 1051 km$^2$ up to Casalecchio Chiusa, where the river reaches a length of 84 km starting from its springs. This upper catchment extends about 55 km in the south-north direction, and about 40 km in the east-west direction. Downstream is a foothill reach about 6 km long of particular hydraulic relevance, since it connects the mountain basin stream regime with the river regime of the leveed watercourse in the valley. Then, the valley reach conducts the waters (enclosed by high dikes) to its natural outlet in the Adriatic Sea, flowing along the plain for 120 km. In the valley reach, the transverse section of the Reno river is up to about 150–180 m wide.

The altitude of 44% of the area is below 50 m, 51% is characterised by an altitude from 50 m up to 900 m, and the remaining 5 % is between 900 and 1825 m.



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The concentration time of the watershed is about 8–10 h at the Casalecchio Chiusa river section and about 25 h when the flow propagates through the plain up to the outlet. In this work, the observed and simulated discharges are evaluated at Casalecchio Chiusa, the closure section of the mountainous basin (hereafter with “Reno river basin” we refer only to this upper zone of the entire watershed). In the operational practice, a flood event at such river section is defined when the water level, recorded by the gauge station, reaches or overcomes the value of 0.8 m, corresponding to the warning threshold. The pre-alarm level is set to 1.6 m.

## 3 Analogue-based QPFs

A statistical analysis has been performed in terms of mean error (hereafter ME) and root mean-squared error (hereafter RMSE) over the hourly analogue-based QPFs provided for the fall season (4 September–29 November) of each year within the period 1990–2000, searching for the relative analogue subset on the remaining years. These measures are useful for comparing two or more solutions that have been adopted to make the same prediction, despite that they do not provide a means to say if each one is reliable enough to be used (Carter and Keislar, 2000).

The results obtained for the analysed eleven years are shown in Figs. 2 and 3, where each solution for the analogue-based precipitation forecast is identified by the initials of the meteorological variables employed to characterise the synoptic pattern and to define the analogues. In detail, with Z we mean the forecast based on the analogues of geopotential height at 500, with ZZ the combination of the previous variable with the same field at 850 hPa, with W the vertical velocity at 700 hPa, with Q the specific humidity at 700 hPa; the suffix “red” means a domain area reduced (0° E–20° E; 40° N–50° N) over which the analogy is investigated, while the initials “rnd” indicates random selected analogues. In Fig. 2 it is also displayed the mean value of hourly rainfall, averaged over the period 1990–2000, as reference to the error magnitude.

The analysis shows that the analogue precipitation estimates are unbiased and the

RMSE values are quite similar for both analogy criteria if Z500 is considered. Rather, if Z500 is not considered the analogue precipitation forecasts exhibit a bias with a trend when sorted by ED, while no trend and bias are observed when analogues are selected by S1. Furthermore, the smallest values of RMSE are due principally to the best prediction of no-rainy events when the analogy criterion is the ED. This result does not occur if analogues are selected by S1. Finally, it's evident a daily cycle with peaks corresponding to the most rainy hours.

The verification of these probability forecasts over the eleven years has been carried out using the Ranked Probability Score (Epstein, 1969; Murphy, 1971), particularly exploited as evaluation criterion to determine which meteorological field provides a better estimation of precipitation, the relevance of the two similarity criteria and the optimal size of the analogue ensemble. This measure considers a number of categories (J) over which the probabilistic forecast is distributed. For a perfect forecast the RPS is equal to 0, forecasts that are less than perfect receive score that are positive number, up to the worst possible score that is J-1: therefore, the closer the forecast to 0, the more useful the forecast. The number of classes and the class boundaries should be suitably defined counting for the climatology and extension of the area involved, as well as the accumulation period of the precipitation.

Depending on the regime of precipitation over the Reno river basin, ten classes of hourly rainfall have been defined, whose details are shown in Table 1. The statistical study has been performed considering three forecast range (+0-24 h; +24–48 h; +48–72 h). The result in terms of RPS for the entire period (1990-2000) is conveyed by the mean value of RPS obtained by averaging the RPS values, calculated for each autumn season, corresponding to the hourly forecasts issued by a certain analogue subset for each raingauge and event.

From the computation results achieved for the first forecast range period (displayed in Fig. 4, with the RPS values multiplied by 100) different facets concerning the scheme optimisation have been evaluated. Regarding the sensitivity of the analogy criterion, in the case of S1 score it's rather indifferent about the choice of which predictor variables



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provide the better forecast. On the other hand, the ED tends to prefer analogues sorted involving Z500 and the analogue ensembles selected not considering Z500 are characterised by higher RPS values, near to the random subset. About the optimal size of the analogue ensemble, for both similarity criteria and schemes, slight differences are observed reducing the number of analogues from 50 to 30, whereas the ten-member sample shows higher RPS values. It is preferable to choose the fifty-element subset as it includes more variability. As regards which meteorological variable provides a better estimation of precipitation, by consensus of both the analogy criteria, the best forecast (lower values of RPS) is the one that considers both Z at 500 hPa and W at 700 hPa (and also together with Q at 700 hPa). The scheme comparison reveals slightly lower values for the method B, even if the differences can be regarded as negligible since the RPS value (being multiplied by 100) can range from 0 to 900 in this analysis.

For the next forecast ranges (the +24–48 h and +48–72 h periods) the conclusions are substantially equivalent to the aforementioned ones, in addition it results a performance decay more evident in the scheme A with respect to the scheme B. The decreasing of forecast accuracy is strongly marked between the first and the second lead-time period, while in the third period the performances of different solutions are comparable with those of random selected analogues.

A further test has been carried out to assess the influence of the domain size, extending the area over which the analogy is investigated (20° W–30° E; 30° N–60° N, covered by 6161 model grid points): the obtained results (not shown) do not reveal remarkable differences with respect to the scheme A. Furthermore, the statistical study in terms of RPS has been repeated by considering the daily analogue-based QPFs (seven classes of rainfall have been defined, whose details are shown in Table 2), confirming the aforementioned outcomes regarding the hourly forecasts about different facets of the scheme optimisation (results not shown). By a visual analysis of temporal forecasting sequences of daily precipitation, it results that the deterministic forecast provided by the meteorological model LAMBO predict better the no-rainy events with respect to analogue-based QPFs, but tend to underestimate the rainfall amount in case



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of intense events.

In order to have some reference levels for the analogue-based QPFs, a comparison has been carried out for the 2000 autumn season with poor-man forecasting methods (climatology and persistence), considering the fifty-member analogue subset. In case of hourly rainfall forecast, the obtained results in terms of RPS (displayed in Fig. 5 for the scheme A) point out that the best analogue-based solution (i.e. by consensus of both schemes, the analogues of ZW selected with ED) provides a higher forecast skill with respect to the climatology up to the 48th forecast hours, whereas its performance decays during the last time range resembling the climatological forecast. On the other hand, the scores of the worst analogue-based solution (i.e. by consensus of both schemes, the analogues of WQ selected with ED) demonstrate the importance of a suitable selection about the meteorological variable(s) exploited to investigate the analogy and the usefulness of a scheme optimisation process to avoid poor forecast accuracy in the analogue method. The subset of random selected analogues shows scores rather similar to the climatology: this result is quite reasonable since such past situations are sorted by chance from the available historical data-base, which constitutes the known climatology over the target area. If daily rainfall forecasts (provided by the scheme A) are considered, it is evident the lowest forecast skill characterising the persistence with respect to the climatology and the random analogue sample (Fig. 6), confirming the results obtained by Obled et al. (2002). The performances of the these latter two methods are similar to one of the worst analogue-based solutions (i.e. analogues of ZW selected with ED).

## 4 Discharge forecasts driven by analogue-based rainfall predictions and by LAMBO

The hourly analogue-based QPFs can be used as inputs to the TOPKAPI model, thus generating an ensemble of discharge forecasts. A test has been carried out for the autumn 2000. A statistical analysis has been performed in terms of RPS on the analogue-driven streamflow predictions issued for the river section of Casalecchio Chiusa. The RPS values are computed considering the discharge obtained by feeding the hydrological model with observed rainfall as the observation, making the assumption of a perfect hydrological model forecast. In this way, the attention is focused on the hydrological effects of errors in the QPFs, since the dominant effect influencing the reliability and accuracy of the hydrological prediction is related to the forecast skill of QPFs used as input to the TOPKAPI model.

The statistical study has been performed considering three forecast range (+0–24 h; +24–48 h; +48–72 h). For each one, the result is conveyed by the mean value of RPS obtained by averaging the RPS values corresponding to the hourly discharge forecasts provided by each analogue-based QPF scenario for every event of autumn 2000. A high number of classes (23) has been defined (Table 3) in order to appreciate a wider range of streamflow values, enabling to evaluate the forecast skill in detail (a further test carried out relying upon only eleven classes does not substantially modify the outcomes discussed afterward).

Conditionally to the outcomes provided by the verification of QPFs, the hydrological simulations have been forced with the fifty-member analogue subset. The results (Fig. 7) confirm that discharge forecasts driven by QPFs corresponding to analogues selected considering Z500 are better than those obtained not involving Z500. In particular, by consensus of both schemes and analogy criteria, the solution of geopotential at 500 hPa combined with vertical velocity at 700 hPa provides a better estimation of future flows, although the remaining solutions involving Z500 show differences which can be regarded as negligible since, in this case, the RPS value (multiplied by 100) can range from 0 to 2200 (depending on the number of classes defined). Within the first 24 forecast hours, the performances of discharge simulations based on the two analogue schemes are substantially equivalent. The performance decay with lead-time increasing is evident, and more pronounced for the scheme A, limiting the reliability of the discharge forecast for an operational use by civil protection authorities. However, this drawback can be partially overcome exploiting the scheme B beyond the first 24 forecast hours.

The impact of the analogy criterion on the selection of the best solution is clear only for ED, whereas the performance of the different solutions are rather similar with S1 (Fig. 7b). The ED criterion penalises the discharge forecasts based on analogues selected not involving Z500, whose RPS values are comparable with the ones provided by the random analogue subset (Fig. 7a), demonstrating the poor accuracy of such streamflow predictions.

The attained results resemble those corresponding to the QPFs, but the differences among solutions are attenuated. This facet can be explained considering that the intermittence of the rainfall signal is dampened by the non-linearity in rainfall-runoff processes, playing a fundamental role the dynamics of the overall soil filling and depletion mechanisms and the flood routing.

Also the deterministic QPFs provided by the meteorological model LAMBO (run at 12:00 UTC) for the autumn 2000 have been used as input to the TOPKAPI, evaluating the relevant discharge forecasts in terms of RPS. Even if such measure is conceived for probabilistic forecasts, it has been applied to the LAMBO-driven hydrological runs in order to give a term of comparison about the reliability and accuracy of predictions based on the analogue method. The scores related to LAMBO result worse than the best solution of the analogue method (i.e. the fifty-member analogue subset of ZW, selected by ED) performed by both the schemes A and B (Fig. 8). For every forecast range, it is evident the less forecast skill (higher RPS values) of LAMBO-driven simulations, but the deterministic nature of such forecasts have to be considered in evaluating the result.

The statistical study performed on the autumn 2000 has allowed to evaluate in general the performance of the analogue-based discharge forecasts; in the following, a detailed analysis of three case studies, corresponding to the most important flood events occurred during the autumn 2000 at the Casalecchio Chiusa river section, is proposed. In particular, the case studies investigated are: the 6–7 November 2000 event, characterized by a maximum water level of 2.20 m (corresponding to a discharge value of about 1200 $m^3$/s), which represents the 3rd critic case in terms of flood event magnitude over a historical archive collecting 90 events from 1981 to 2004; the 20–21 November 2000 event, with a maximum water level of 1.55 m (corresponding to a discharge value of about 580 $m^3$/s), is the 20th critic case; finally, the 3–4 November 2000 event corresponds to the 31st critic case, being recorded a maximum water level of 1.39 m (corresponding to a discharge value of about 450 $m^3$/s). The relevant discharge forecasts forced with the QPFs provided by analogues of the geopotential field at 500 hPa and the vertical velocity at 700 hPa, selected by ED, are illustrated in Figs. 9–11, for different forecast lead-times, by means of "spaghetti-like" plots as well as expressed in terms of a percentile confidence interval. The observed discharge, obtained by applying the rating curve available for the Casalecchio Chiusa river section to the corresponding water level gauge recordings, is also displayed in order to convey the performance of the TOPKAPI in reproducing the Reno river streamflow.

For the 6–7 November 2000 event, the forecast skill of the ensemble provided by the scheme A is very limited for the predictions issued 2 and 3 days in advance. The order of magnitude of the event is well enough anticipated (even if too enhanced) three days before only by one member (Fig. 9a), but this signal is missed in next forecast range (Fig. 9b). Only the forecast issued 24 h in advance is sufficiently satisfactory, as several members predict a noteworthy streamflow increase, in particular one member resembles closely the calculated discharge (Fig. 9c). The deterministic run driven by LAMBO heavily underestimates the event at every forecast range. The performance of the hydrological prediction forced with the QPFs provided by the scheme B is substantially equivalent to that of the scheme A for the first 24 h (Fig. 9f), whereas an improvement of accuracy is evident in the ensembles corresponding to the next forecast ranges (Fig. 9d–e).

In the second event analysed, the observed discharge is characterised by two peaks, not well reproduced by the calculated streamflow which provides a more flat signal. The first 24-h forecasts based on analogues and LAMBO are able to detect only the first peak flow (Fig. 10c–f), afterward generally predicting a streamflow decreasing (Fig.

10a–b). For the next lead-times, only the ensembles of the scheme B provide a sufficiently informative prediction (Fig. 10d–e).

Regarding the 3–4 November 2003 event, the analogue ensemble of the scheme A encompasses quite well the observed and calculated discharges during the first forecast range (Fig. 11c), but the variability within the ensemble decreases in the next forecast ranges, missing the flood peak (Fig. 11a–b). Rather, the prediction provided by the scheme B shows an ensemble spread still meaningful with the lead-time increasing (Fig. 11d–f). The streamflow prediction based on LAMBO underestimates the event when issued one day in advance, whereas it fails through and through for longer lead-times.

For the three case studies proposed, a confidence interval expressed by the quantiles corresponding to the non-exceedance probabilities of 5% and 95% is indicated, with the aim to convey as wider as possible the information content of the ensemble. Unfortunately, such confidence interval is not able to fully encompass the observed or calculated discharge at every forecast range, the reliability of the interval decaying with the increase of lead-time and entity of the event (Figs. 9–11). Within a theoretical framework, using confidence intervals should be a more correct approach to assess uncertainty about a discharge forecast and should help stakeholders to easily interpret results, nevertheless it could be misleading during extreme events since the total spread of the forecast may not be conveyed. It could happen that for an extreme event only few forecast scenarios could be able to anticipate the order of magnitude of the peak flow, owing to the limited historical archive, thus a confidence interval based on quantiles should miss a useful information. Rather, in case of not-extreme events the confidence interval should be more suitable.

Finally, by a different point of view, the spread of the ensemble, which usually encompasses the hydrological simulation driven by the LAMBO QPF, can be regarded as a measure useful to quantify the uncertainty of the deterministic forecast.

## 5 Conclusions

In the present work it has been investigated a methodology providing probabilistic quantitative precipitation forecasts (QPFs) based on analogues, which can be considered as complementary, and not alternative, to the classical deterministic approach represented by a NWP model, even in view of a joint employment to improve real-time flood forecasting. The capability of meteorological models, even the high-resolution ones, to supply reliable and precise rainfall forecast to be used directly for flood forecasting purposes is still nowadays limited, since large uncertainties, a large fraction of these arising as the atmosphere is a chaotic system subject to intrinsic predictability limitations, affect the model outputs.

The study aims to quantify the hydrological forecast uncertainty at each step of the forecast process accounting for the uncertainty inherent in a precipitation forecast, which propagated into the hydrological model can provide a more informative hydrological prediction, useful to be communicated to, and applied by stakeholders (i.e. end users such as representatives from civil protection authorities).

To fulfil this issue, an analogue-based method to QPF has been applied. The underlying assumption in this forecasting method is that similar circulation patterns should provide similar local effects, e.g. on variables such as precipitation. In this way, the analogy has not to be directly investigated on the variable of interest but on meteorological parameters that characterise the synoptic situations, like geopotential height, specific humidity and vertical velocity. Practically, the analogue methodology exploits the reliable representation of large scale hydrodynamic variables by meteorological models to derive precipitation forecasts indirectly.

The implementation of the analogue method in this work proceeded, firstly, with the aim to define which meteorological variables, conditioning the weather conditions over the Reno river basin in the following hours, should be considered to derive a better estimation of precipitation. A statistical analysis, performed in terms of Ranked Probability Score over an archive collecting hydro-meteorological data for the autumn seasons of the period 1990–2000, has shown that the QPFs related to analogues selected in terms of geopotential at 500 hPa and vertical velocity at 700 hPa, and sorted by the Euclidean distance similarity criterion up to build a fifty-member subset, provide the best performance. A further analysis pointed out that the analogue-based approach performs much better than poor-man forecasting methods up to 48 h in advance.

Afterwards, in order to extrapolate flood forecasts, these fifty analogue-based rainfall scenarios have been used as different input to the distributed rainfall-runoff model TOPKAPI, thus generating an ensemble of discharge forecasts, which provides a confidence interval for the predicted streamflow. The discharge predictions based on analogues include quite well the observed/calculated discharge for the first 24 forecast hours, showing a decay of performance with the lead-time increase. This drawback can be partially reduced updating the search for analogues every 24 h by means of the meteorological variable forecast provided by a numerical model. However, the analogue method does not appear to be suitable for provide by itself a useful information about the future streamflow because the large spread among members makes difficult to issue real-time flood warnings. This large spread, similar in size to the entire climatological variability, is due principally to the limitation in historical data availability. Owing to this shortcoming, the method is less reliable particularly in case of rare and intense events since past situations available as potential good analogues will be less numerous and characterised by a lower analogy degree, so causing systematic underestimation and bias.

Nonetheless, the forecast spread conveyed by the analogue-based ensemble can be associated to the deterministic simulation driven by the meteorological model QPF, taken as an error affected “measurement” of the future flow, and used to quantify the hydrological forecast uncertainty. The discharge forecast forced with LAMBO QPFs, generally included within the range of ensemble values, tends to heavily underestimate the observed/calculated streamflow in case of intense rainfall events, but the prediction of no-rainy events is better detected.

For the next future developments, a more effective approach to convey a quantification of uncertainty about the discharge forecast should be a correction scheme typical of a Kalman filtering approach in scalar form (Jazwinski, 1970; Gelb, 1974; Berger, 1980). Applying this approach, each member of the analogue ensemble, considered as our "a priori best guess", is optimally combined, in a Bayesian sense, with the discharge forecast based on the LAM model to obtain a new "a posteriori" ensemble of discharge forecasts characterised by the removal of the bias of the forecast error and by a significant reduction in the overall uncertainty.

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**Table 1.** Classification of hourly rainfall for the computation of RPS.

| class | rainfall amount (mm/h) |
|---|---|
| 1 | 0 |
| 2 | 0–0.4 |
| 3 | 0.4–1 |
| 4 | 1–3 |
| 5 | 3–6 |
| 6 | 6–15 |
| 7 | 15–30 |
| 8 | 30–50 |
| 9 | 50–75 |
| 10 | >75 |



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**Table 2.** Classification of daily rainfall for the computation of RPS.

| class | rainfall amount (mm/24 h) |
|---|---|
| 1 | 0 |
| 2 | 0–1 |
| 3 | 1–5 |
| 4 | 5–10 |
| 5 | 10–25 |
| 6 | 25–50 |
| 7 | >50 |



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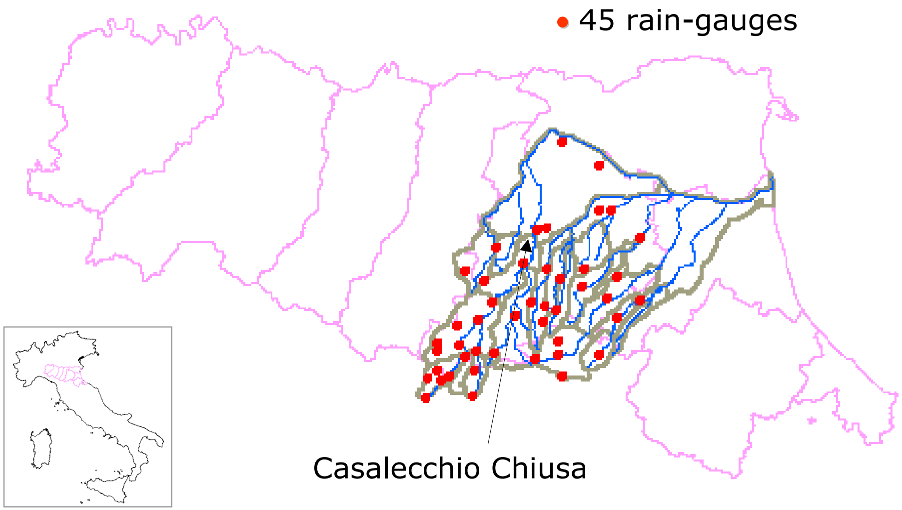


**Fig. 1.** The Reno river catchment area and its sub-catchments, localised in the Emilia-Romagna Region, northern Italy. Dots denote the 45 raingauges present in the basin.

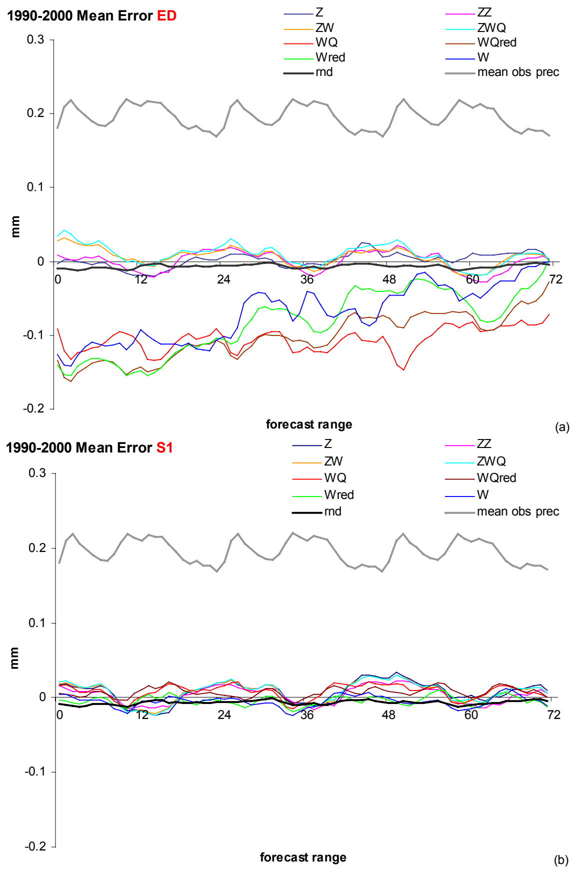


**Fig. 2.** Hourly mean error of the 72 h of analogue-based precipitation forecast covering the fall seasons 1990–2000, for different meteorological variables and combination of them, selected by ED **(a)** and S1 **(b)**.




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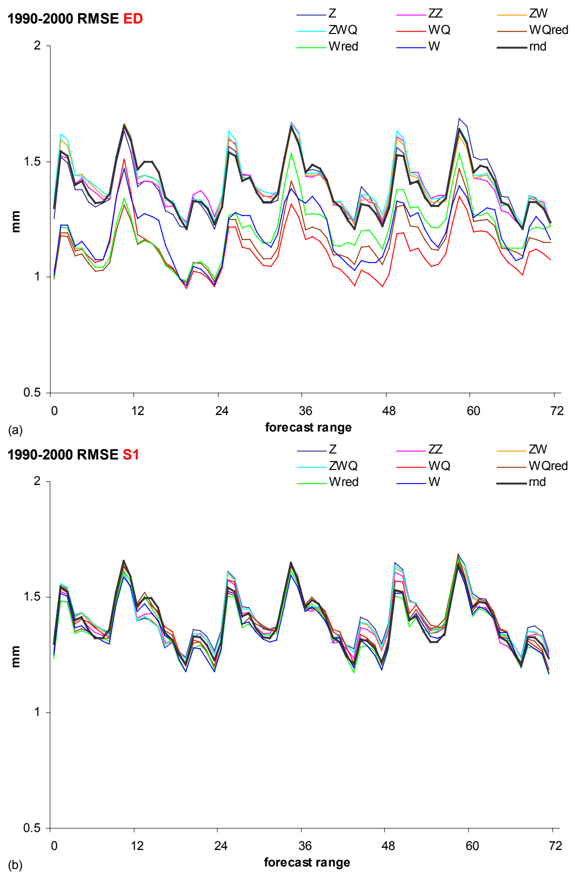


**Fig. 3.** Hourly root mean squared error of the 72 h of analogue-based precipitation forecast covering the fall seasons 1990–2000, for different meteorological variables and combination of them, selected by ED **(a)** and S1 **(b)**.

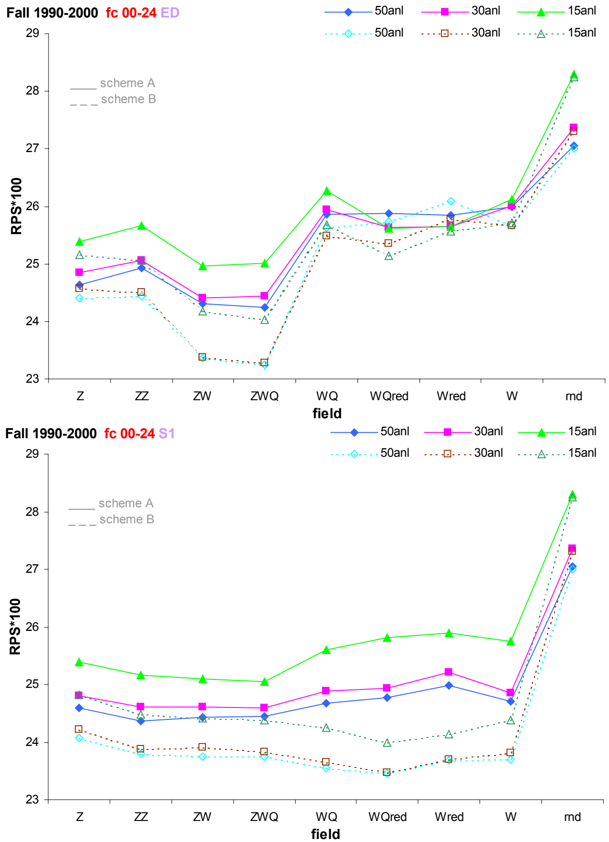


**Fig. 4.** Comparison in terms of RPS on the optimal analogue subset size, performed with the first 24 h of precipitation forecast provided for the schemes A and B by analogues corresponding to different meteorological variables, and combination of them, selected by ED **(a)** and S1 **(b)**.

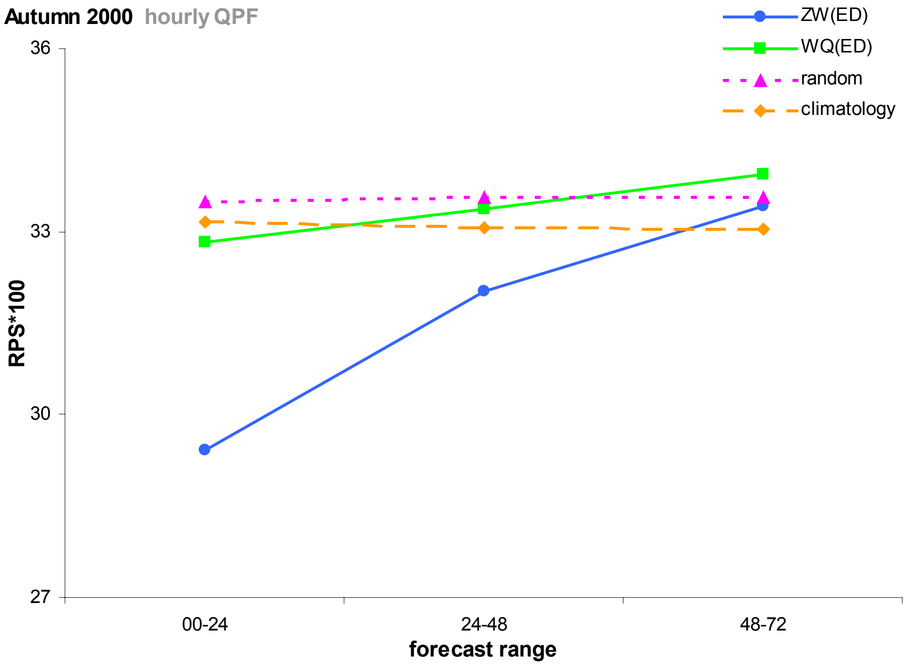


**Fig. 5.** Comparison in terms of RPS about the performance of hourly QPFs provided by the best and worst analogue-based solutions of the scheme A (i.e. respectively, the fifty-member analogue subset of ZW and WQ, both selected by ED), fifty random selected analogues and climatology, as a function of the forecast range (h).

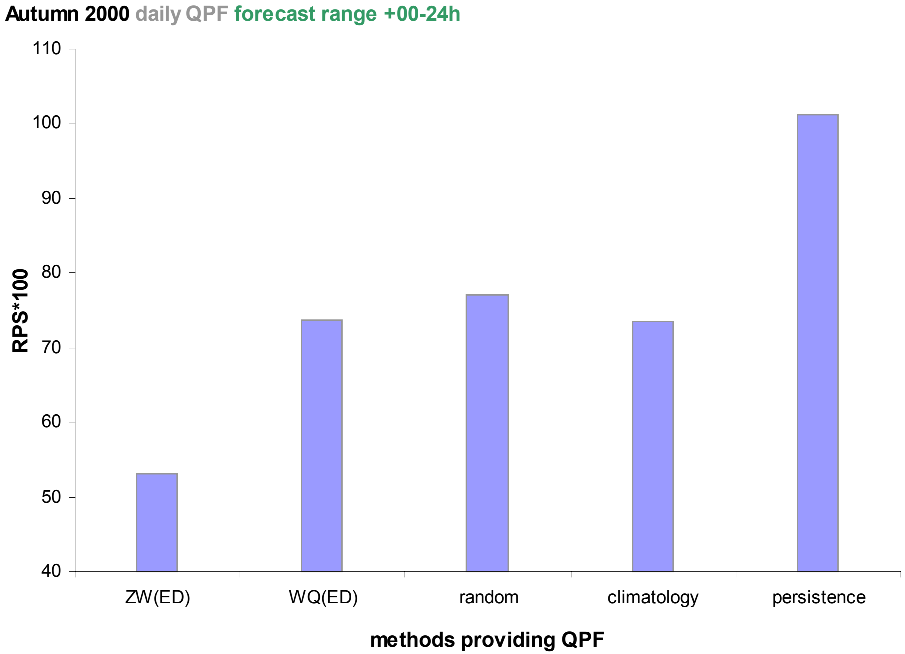


**Fig. 6.** Comparison in terms of RPS about the performance of daily QPFs provided for the first 24 forecast hours by different methods: two analogue-based solutions of the scheme A (the fifty-member analogue subset of ZW and WQ, both selected by ED), random selected analogues, persistence and climatology.



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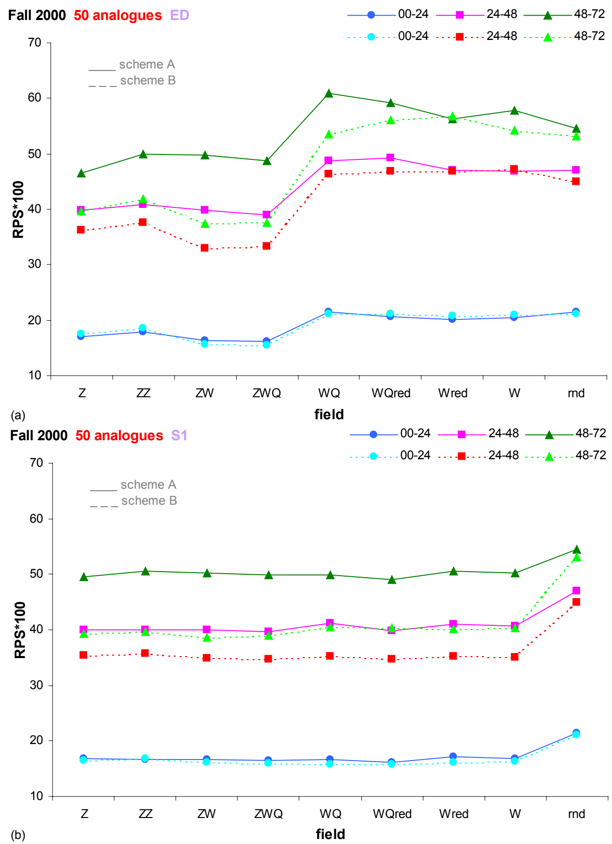


**Fig. 7.** Comparison in terms of RPS on the performance decay of analogue-based discharge forecasts provided by the schemes A and B, considering the QPFs of the fifty member analogue subset corresponding to different meteorological variables, and combination of them, selected by ED **(a)** and S1 **(b)**.

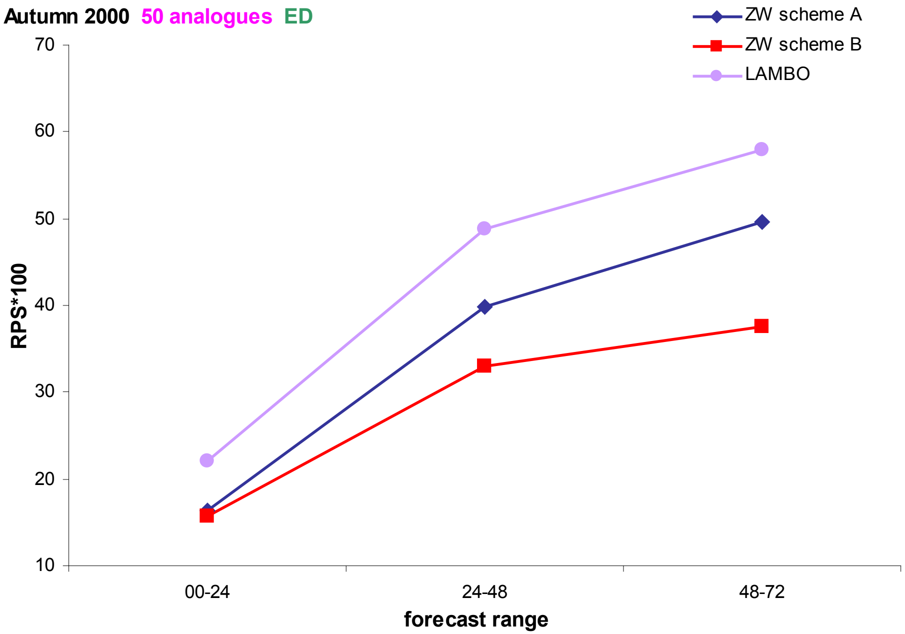


**Fig. 8.** Comparison in terms of RPS on the performance decay of discharge forecasts driven by QPFs provided by LAMBO and by the schemes A and B considering the fifty-member analogue subset of ZW, selected by ED.

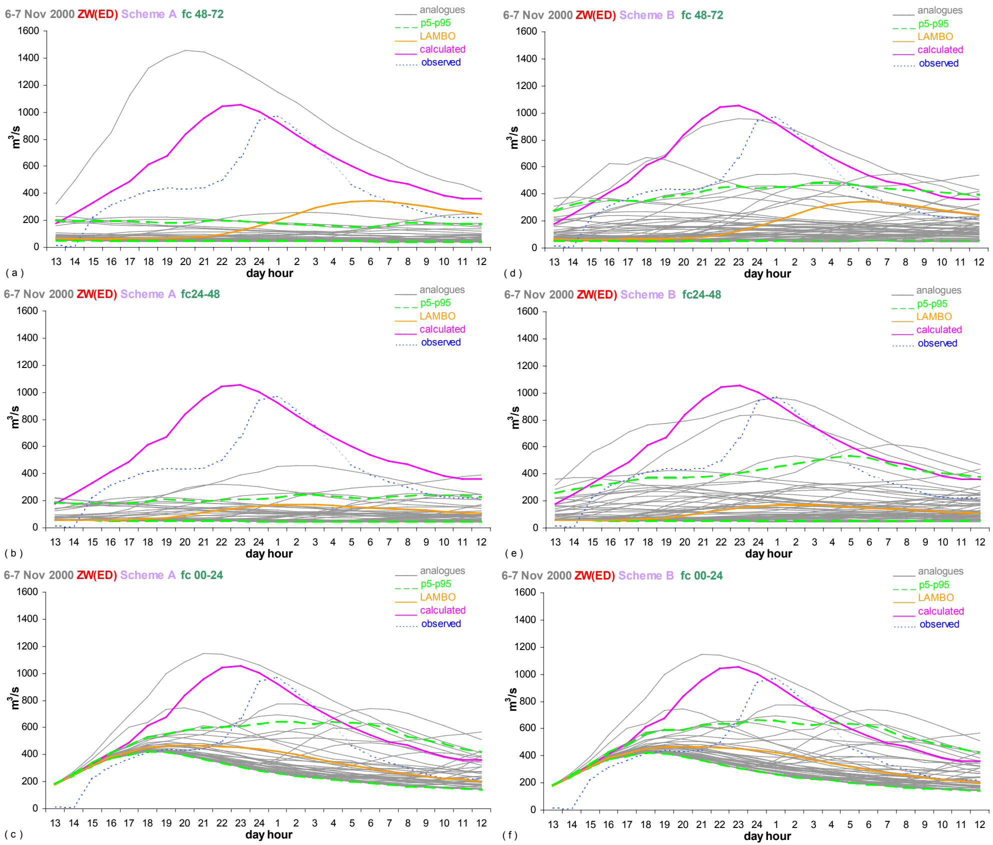


**Fig. 9.** Discharge predictions issued one day (fc 00–24), two days (fc 24–48) and three days (fc 48-72) before the 6–7 November 2000 event, driven by QPFs provided by LAMBO and the fifty-member analogue subset of ZW, selected with ED following the methods A **(a, b, c)** and B **(d, e, f)**.

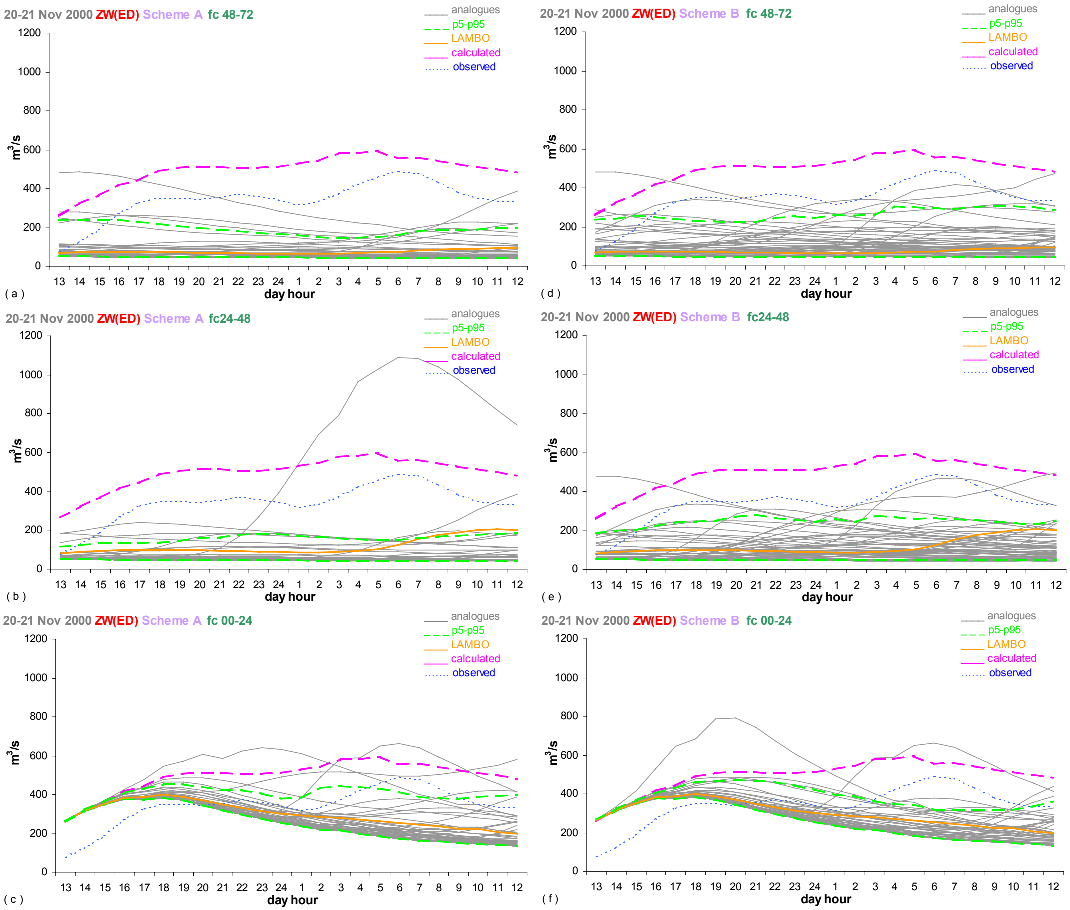


**Fig. 10.** As in Fig. 9, but for the 20–21 November 2000 event.

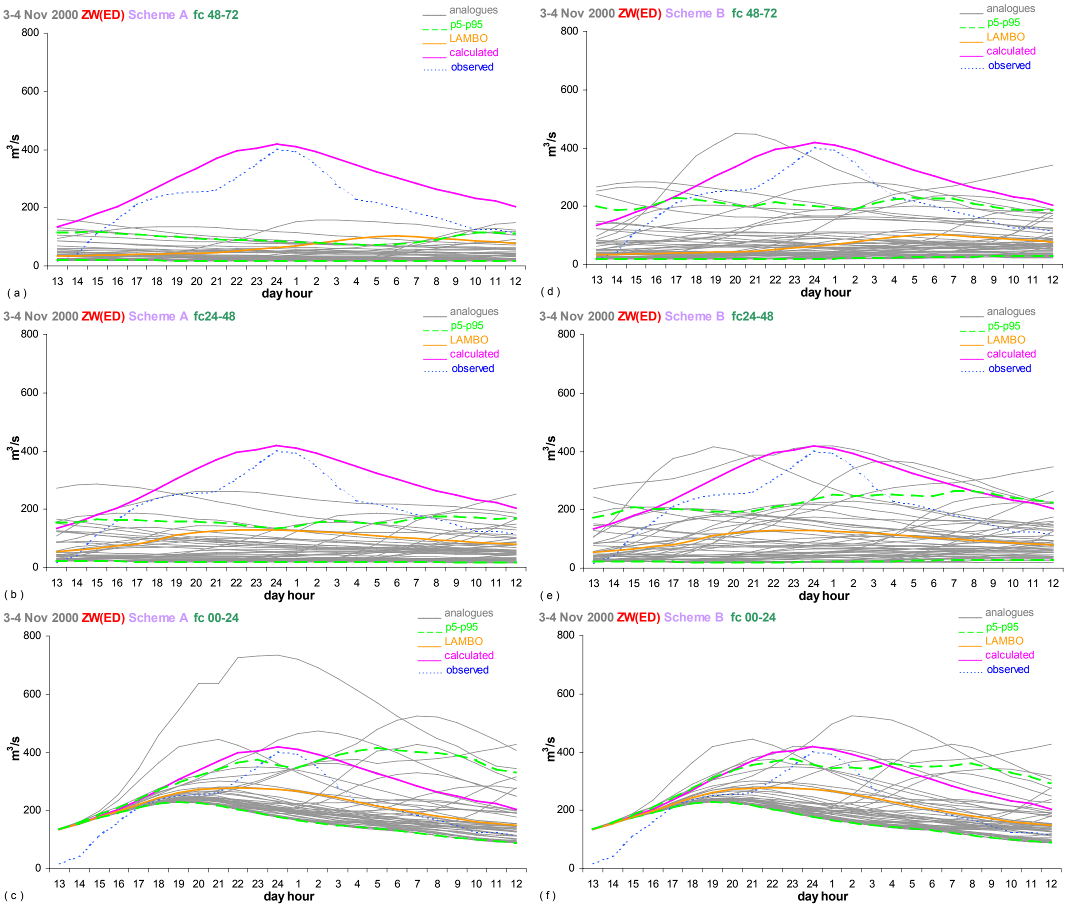


**Fig. 11.** As in Fig. 10, but for the 3–4 November 2000 event.



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