Peak flow estimation under parameter uncertainty in a real-time flood warning system for ungauged basins

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Abstract An operational flood forecasting system designed to produce peak flow predictions at multiple ungauged sites is described. The system is based on the ensemble approach and uses a simple conceptual rainfall–runoff model. This paper accounts only for parameter uncertainty; to this end, parameter sampling distributions with Monte Carlo generated simulations are related to basin geomorphic characteristics and event antecedent moisture conditions. Application to four gauged sites exhibited satisfactory system performance in terms of reproducing observed peak flows. Further assessment evaluated the system's forecasting skill with a back-analysis performed on 40 ungauged basins over the period 2002–2005. Results showed that the system yielded a reasonable number of warnings and that all the selected floods events, characterized by high documented social impacts, were successfully detected.

Key words flood forecasting system; rainfall–runoff model; ungauged basin; parameter uncertainty; Monte Carlo simulation; southern Italy

INTRODUCTION

Uncertainty is an unavoidable element in any hydrological modelling study (Beven, 2006; Gupta *et al.*, 2003). Prediction accuracy of watershed model simulations is affected by uncertainty in the model structure, model parameters and measurements of input and output data. The importance of considering uncertainty in an operational flood management and warning context in order to enable a critical assessment of model output reliability is emphasized in many studies.

Uncertainty is likely to be particularly severe in ungauged basins for which no streamflow measurements are available to reduce, at least, the uncertainty in the hydrological parameterization process (Sivapalan *et al.*, 2003).

A well-established technique used for addressing the issue of uncertainty of rainfall–runoff models for ungauged basins is the probabilistic or ensemble prediction approach. The growing availability of computing power has made ensemble simulations a viable approach in which several sources of model uncertainty can be accounted for, as a number of contributions in the literature prove (Beven & Binley, 1992; Butts *et al.*, 2004; Georgakakos *et al.*, 2004; Carpenter & Georgakakos, 2006).

This paper concerns the development and application of a flood forecasting system for real time warnings, issued for a set of small–medium size ungauged basins located in southern Italy. The aim of the forecasting system design is the development of a relatively simple and robust framework to produce simultaneous streamflow forecasts, with acceptable accuracy, at multiple sites. For this purpose, a lumped conceptual rainfall–runoff model, with a low computational demand and data requirement, is employed.

The system is based on ensemble streamflow predictions from the rainfall–runoff model under uncertainty in both precipitation input and model parameters. For each forecast, the time frequency distribution of the forecast peak flow is evaluated. The probability of exceedence of a critical discharge value is used, according to a threshold criterion, to assess the appropriate warning level.

Only the impact of parametric uncertainty is considered here. Flood risk evaluation assumes as input observations of precipitation from telemetering raingauges, but meteorological or stochastic forecasts can also be used to further extend the forecast lead times.

The ensemble streamflow predictions over a time horizon into the future are produced within a Monte Carlo framework wherein probability distributions are used to describe uncertainty about the true model parameters. It is assumed that the range and shape of the probability distribution of the model parameters can be inferred from the available basin characteristics and they are allowed to vary according to the event antecedent moisture condition.

In the next sections a description of the main features of the system framework, along with an illustration of its performance assessment are described. System skills were first evaluated on watersheds equipped with streamgauges, through the reconstruction of several historical extreme events in terms of reproducing the observed peak flow magnitude. Finally, the framework was tested through a back-analysis carried out for about 40 ungauged basins. Within this application, results were compared, where information were available, with actual soil impacts in order to evaluate the number of hits and misses forecasts.

FLOOD FORECASTING SYSTEM FRAMEWORK (METHODS)

Rainfall–runoff model structure

The guideline principle in model construction was to assume a structure characterized by a reduced computational time, suitable for Monte Carlo simulation and for simultaneous real time applications in several (up to a few hundred) locations. Also, parameterization followed a parsimonious approach depending on the knowledge of processes and on the data available on the river sites and the related drainage basins.

An event-based, lumped, conceptual rainfall–runoff model is employed. The hydrological model considers each watershed as a single unit with model parameters and input applied to its entire area. The rainfall–runoff transformation process is described by an abstraction loss component, aimed at estimating the rainfall excess through the Soil Conservation Service Curve Number method (SCS, 1972), and a runoff routing component which uses the Nash cascade form (Nash, 1960) of the Instantaneous Unit Hydrograph (IUH) approach. Due to the focus on high flow events, the output of the model is limited to basin surface outflow, which is the main component of this kind of events for the study region. The model works at hourly or a finer time step, depending on the temporal resolution of the rainfall data.

Model parameters include the Curve Number parameter, *CN*, along with the estimates of the number of reservoirs N and the storage constant K required to model the instantaneous unit hydrograph.

Monte Carlo simulation

Ensemble streamflow simulations are generated, in real time, incorporating uncertainty due to potentially erroneous model parameters. At each forecast time, the rainfall–runoff model is run in advance in a Monte Carlo fashion with sampling from defined probability distributions for parametric input. A set of 10 000 streamflow simulations is generated.

It is assumed that the assessment of feasible range and probability law distribution of the three model parameters (*CN*, *N* and *K*) can be inferred from geomorphic characteristics and land-use type of the watershed. The *CN* probability distribution is also allowed to vary according to the event antecedent moisture condition as described below.

***CN* probability distribution** Curve number parameter uncertainty is described via a triangular probability distribution with its maximum at the effective value of the parameter, which accounts for the variation in *CN* at a site from storm to storm. The Curve Number of the basin can be estimated through the weighted mean of the values resulting for the soil groups and the land cover types that characterize the watershed assuming an average antecedent moisture condition. Moreover, in a real time system application, the effective Curve Number is obtained by further adjusting the estimated *CN*, as prescribed from the US Soil Conservation Service, to reflect the antecedent moisture condition (AMC) of the watershed according to the total rainfall observed in the five previous days and whether it is the dormant or the growing season.

Figure 1(a) shows an example of the effects of different antecedent moisture conditions on the location and the shape of the *CN* probability distribution.

***N* and *K* probability distribution** In this case the formulation for parametric uncertainty assumes that parameters are dependent from each other: indeed, it is well known that the product of these two parameters is the first moment of the instantaneous unit hydrograph, indicating the time to peak (t_p).

A uniform random sampling procedure is used to explore the respective feasible parameter space. However, the pair of parameter values, randomly sampled from each

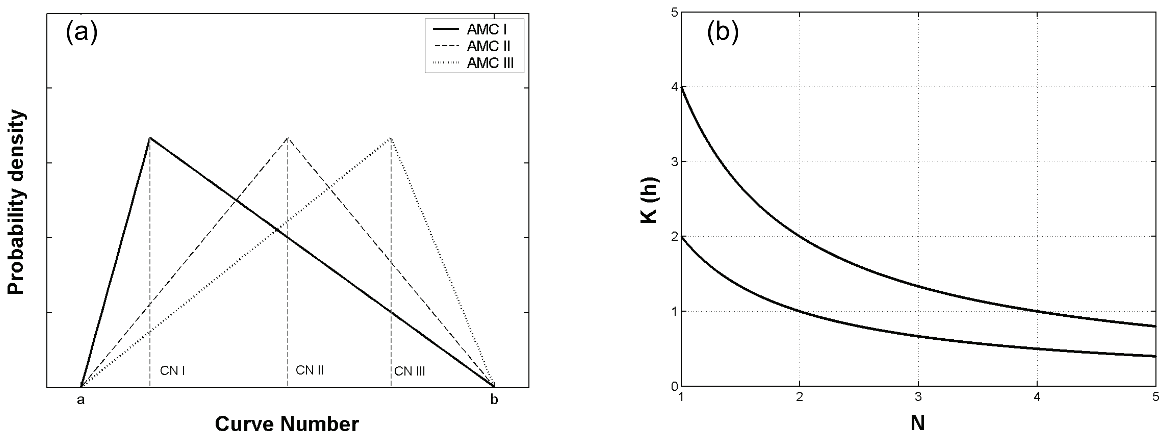

Fig. 1 (a) Effect of antecedent moisture condition on the location and shape of the *CN* probability distribution; (b) example of the limits defining the acceptable region in the IUH parameters space.

distribution, is retained for the ensemble simulation only if the product $N \times K$ falls between ±30% of the t_p of the hydrograph, which several empirical formulas intimately link to the geomorphic attributes of the watershed. An example of the limits of the corresponding acceptable region in the N, K plane is shown in Fig. 1(b), referred to a t_p value of three hours.

Flood risk evaluation

After performing the Monte Carlo simulation the system provides a frequency distribution of the predicted peak flow. The probability of exceedence, p, of a critical discharge value (e.g. a T-year return period flood), Q_c, is assumed as an indicator of possible flooding. To this end, according to a threshold based criterion, increasing values of p correspond to more critical warning levels for the expected event. Three threshold values for the probability of exceedence are assumed: 0.4, 0.6, and 0.8. These values correspond to three warning levels, coded into levels 1, 2 and 3, indicating respectively low, moderate, and high probability of river flooding. The operational warning system assumes Q_c as the 50-year quantile of annual peak flow maxima.

STUDY WATERSHEDS AND MODEL PARAMETER ESTIMATION

The methodology outlined in the previous section is employed in an operational real-time flood warning system for ungauged basins controlled by the regional structure for hydro-meteorological forecasts. In this first phase of application, the study watersheds are 40 river basins, all located in Calabria, southern Italy, with a high potential risk of flooding in urban areas. In addition, four basins, where historical streamflow measurements are available, were considered for assessment of the system performance. Figure 2 shows the location of the selected watersheds.

The watersheds' size ranges from a few square kilometres to about 300 km^2; maximum elevation reaches 1800 a.m.s.l. They have different shapes, different land cover type and are geologically and morphologically heterogeneous. The whole study area is characterized with a semiarid climate and receives much of its rainfall during the cold season, but the eastern region is characterized by less frequent but high intensity storms.

The precipitation input for the real time warning system consists of the 20-minute data coming from the telemetering sensors network. The input is averaged as mean areal precipitation over each entire watershed using the Thiessen polygon method.

A preliminary hydrological analysis was performed in order to estimate, for each watershed, the parameters values that drive the Monte Carlo generation. Functionality and tools of a geographic information system (GIS), specifically ARC/Info, were used to delineate the selected watersheds and to process digital elevation data, Corine land-use data and soil hydraulic parameters from the regional database in order to determine CN and t_p.

In this study t_p was determined as explained by the following empirical equation:

$$t_p = t_c \frac{H_m - H_{\min}}{H_{\max} - H_{\min}} \tag{1}$$

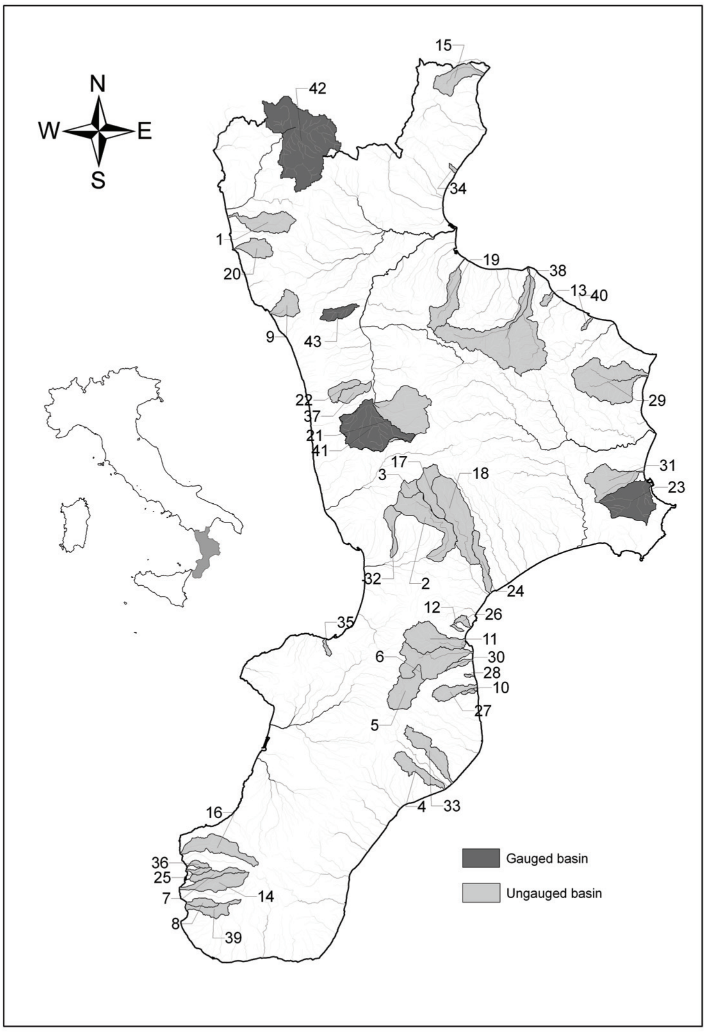

Fig. 2 Location of study watersheds. The light grey background indicates the ungauged basins; the dark grey highlights the gauged ones.

where t_c is the watershed time of concentration; H_m (m) is the mean elevation; H_{min} and H_{max} (m) are, respectively, the minimum and the maximum elevation.

In equation (1), t_c was estimated by means of an empirical formula, often used in Italy, derived by Giandotti (1934). The limits of the range observed in the selected watersheds for t_p and other hydrological attributes requested by the forecasting system framework, are given in Table 1.

According to these findings and to the values usually observed in the study region, parameter spaces vary over the feasible ranges of 35–95 for parameter *CN*, 1–5 for parameter *N*; 0.5–6 for parameter *K*. The *CN* parameter range was assumed wide enough to encompass the different hydrological response of the basins and bracket the observational data.

System application also involves deriving estimates of the critical discharge values. Owing to the lack of streamflow observations at most of the selected sites, this may be a difficult term to quantify, and its estimation introduces further uncertainty in flood risk warning.

Table 1 Ranges of the main hydrological attributes over the 40 selected watersheds.

Watershed attribute	Upper limit	Lower limit
A (km^2)	288.80	1.60
CN	90.00	52.00
t_p (h)	3.62	0.43
Q_{50} (m^3 s^{-1})	682.00	22.00

A: watershed area; CN: Curve Number (AMC II); t_p: time to peak; Q_{50}: 50-year quantile of annual flood peak maxima.

As stated earlier, the adopted critical discharge value for each outlet corresponds to the 50-year quantile of the annual flood peak maxima. An indirect estimation approach, specifically a regional approach, to frequency analysis was undertaken to define the selected quantiles.

Guidelines of a simple hierarchical regional frequency analysis were provided, for the whole of Italy, in the framework of the Flood Evaluation (VAPI) project carried out by the National Group for Prevention from Hydrological Disasters (GNDCI) supported by the National Research Council (CNR) of Italy. The lowest level of this hierarchical approach, suited for analysis of ungauged basins and corresponding to the index flood method, was adopted for the present study.

The T-year quantile, Q_T, of the annual flood peak maximum was estimated as:

$$Q_T = X'_T \cdot Q_{index} \tag{2}$$

where X'_T is the T-year growth factor, or dimensionless flood quantile; Q_{index} is the index flood represented by the expected value of the maximum annual flood peaks.

The growth factor X'_T was computed via a proper regional frequency distribution (growth curves) defined for statistically homogeneous areas. By applying the results obtained in the above study for annual maxima of daily precipitation in the Calabria region, three smaller homogeneous sub-regions were determined dividing the whole study area mainly along the north–south direction. The Two Components Extreme Value (TCEV) distribution (Rossi *et al.*, 1984), in Italy one of the most commonly adopted distributions for this purpose, was used for the growth curves' estimation.

Since no streamflow observations are available, the evaluation of Q_{index} was assessed as a function of watershed geomorphoclimatic characteristics. The expected value of maximum annual flood peaks was estimated using the following rational formula, calibrated for the Calabria region using hydrological data from gauged basins:

$$Q_{index} = \psi A \overline{i_{t_p}} / 3.6 \tag{3}$$

where ψ is a reduction coefficient = 0.158; A (km^2) is the basin drainage area; $\overline{i_{t_p}}$ (mm h^{-1}) is the average of annual maximum rainfall intensity for a storm of duration t_p.

TESTING ON GAUGED BASINS

A total of 17 events were selected from the historical records for the gauged watersheds. The dates of the events, along with the observed peak flows, are listed in

Table 2 Main characteristics of selected test events for the gauged basins.

ID	Watershed	Date	Q_{peak} ($m^3 s^{-1}$)	AMC class
23	Esaro di Crotone	21 November 1960	56.68	I
		9 November 1962	501.22	II
		15 November 1962	445.28	III
		30 October 1964	146.49	II
		1 November 1964	298.14	III
		7 December 1967	186.28	III
41	Busento	1 January 2003	48.95	II
		27 January 2004	39.33	II
42	Lao a Piè di Borgo	28 November 1996	189.33	III
		28 December 2000	57.11	III
		7 January 2003	86.71	III
		22 December 2003	54.48	I
43	Turbolo	15 April 2001	4.75	II
		14 November 2001	2.96	II
		28 November 2001	4.08	III
		23 December 2001	5.10	II
		25 December 2001	14.32	II

Table 2. The proper AMC class was also assigned to each event as prescribed by the US SCS. Very few significant flow peaks, compared to the estimated Q_{50} values, were found in the selected events: only two events, in November 1962 for the Esaro River basin, have an observed peak flow (Q_{peak}) that exceeds the critical discharge.

The aim of this validation was twofold. The tests were focused first to evaluate the suitability of the adopted parameters distribution, particularly for *CN* which has a major effect on the simulated response, and secondly to assess the capabilities of the system to adequately provide warnings for the available events.

For the first task, a Monte Carlo simulation was performed for each event using a uniform sampling distribution for all the model parameters, including *CN*. Specifically, to investigate the adequacy of the triangular sampling distribution for *CN* and of its variation according to the basin antecedent wetness condition, the frequency distribution of the *CN* values associated with "best" ensemble members was determined. This was done by distinguishing and grouping events according to the assigned AMC class, and then retaining the ensemble simulations which produced peak flows within ±20% of the observed peak flow magnitude. Finally, the fractions of simulations falling into assigned intervals of *CN* were computed. Figure 3 shows the results obtained.

The above analysis shows that the retained simulations identify quite distinct zones of the *CN* parameter space with regard to the event AMC class. These findings result in a model performance that is deemed as adequate and strengthens the choice made regarding the *CN* triangular sampling distribution and the variations according to the event AMC class.

Furthermore, other test results, not shown here, confirm the peculiar hydrological response already found in previous studies of basins characterized by a major soil textural class consisting of low infiltration capacity, impervious clay. Remarkably this is the case for two of the selected watersheds, numbers 23 and 31 in Fig. 2, including the Esaro River basin. Actually, it was pointed out for this gauged basin that the

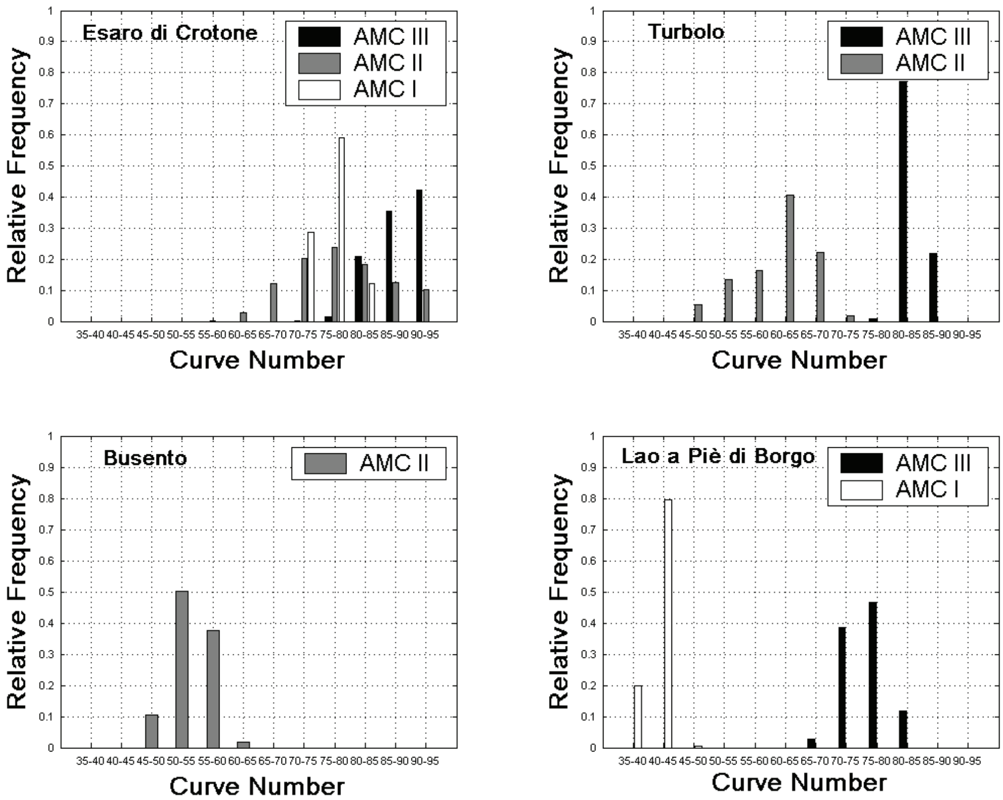

Fig. 3 Histograms of relative frequency distribution of the *CN* parameter obtained for the gauged sites from the ensemble members that have a peak flow magnitude between ±20% of the observed one.

estimated values of return periods of the flood events which occurred immediately after another storm are about 3–4 times the value of the return periods of the concurrent rainfall. The soil texture is deemed to be responsible for high soil moisture content after the occurrence of a relevant storm and hence, for the increased basin capacity to produce runoff. These observations suggested the use of a constant value of CN = 100 within the ensemble simulation, only for the events characterized by an AMC class III.

Further assessment evaluated the model performance in terms of reproducing the observed events and providing correct warnings. An example of the 10 000 ensemble simulated hydrographs compared with the observed flow for the event of 30 October 1964 for the Esaro River basin, is presented in Fig. 4 (a).

The observed spread in the ensemble members is mainly due to the wide range of the parameter space assumed for the CN sampling distribution. With respect to the peak flow magnitude, in all the 17 selected events, the ensemble simulations successfully bracketed the observed peak.

For the same basin the empirical probability distributions of the peak flow obtained for the events of 9 November 1962 and 15 November 1962, which have an observed peak magnitude that exceeds the critical discharge Q_{50} = 356 m^3 s^{-1}, are shown in Fig. 4(b). The figure also shows the thresholds of the probability of exceedence (0.4, 0.6 and 0.8) associated with the three defined warning levels.

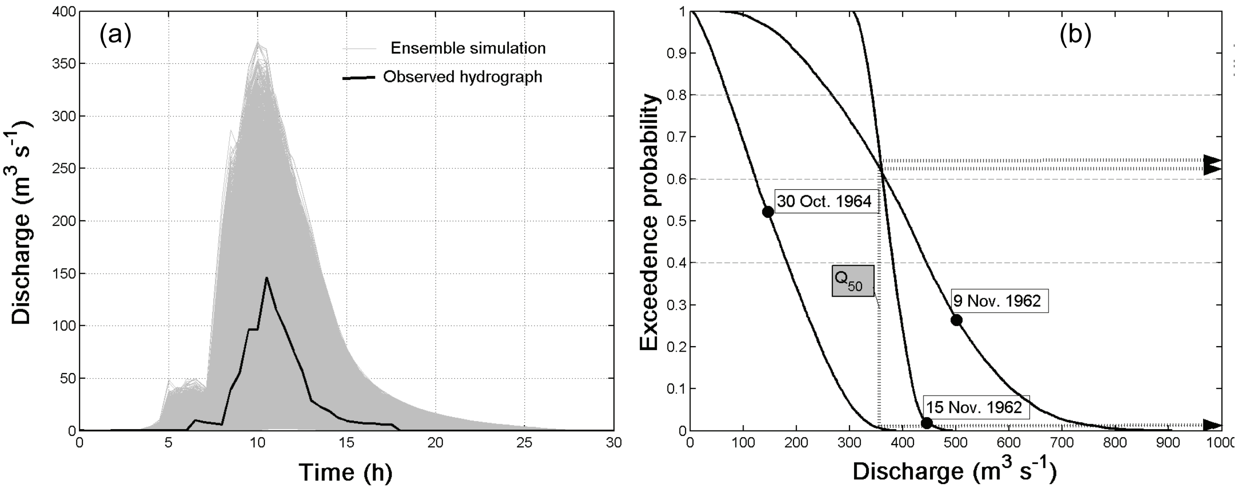

Fig. 4 (a) Example of ensemble simulation along with the observed hydrograph for the 30 October 1964 event of the Esaro River. (b) Peak flow exceedence probability distribution (solid black line) obtained for three events occurred for the Esaro River, along with the observed peak flow magnitude (black dots) and the Q_{50} value.

It can be easily seen (Fig. 4(b)) that the peak flow exceedence probability distribution of the 15 November event, which is characterized by a wet AMC, has narrower prediction limits (roughly from 300 to 500 $m^3 s^{-1}$) compared with those of the other events presented. This is obviously related to the assumed sampling strategy for the *CN* parameter. In both cases the ensemble simulation resulted in an exceedence probability corresponding to a moderate risk level.

In all the other simulations, not shown here, the low warning threshold was never exceeded. As an example, the 30 October 1964 event is also presented in Fig. 4(b). In this case, the exceedence probability of Q_{50} is negligible (about 0.6%) and actually the observed peak flow is significantly lower than the critical discharge.

The overall performance of the system can be regarded as quite satisfactory, considering the limited amount of available significant events.

TESTING ON UNGAUGED BASINS

Finally a back-analysis was carried out for the ungauged basins to assess the forecasting skill of the system. The back analysis was performed over the period 2002–2005, when the present telemetering raingauges network configuration was operative in the study area. In this application every 20 minutes, when a new precipitation input is available, the system produces a streamflow ensemble prediction.

A first global evaluation of the model performance is provided by the number of instances where the predicted probability of exceedence of Q_{50} is above each of the three defined thresholds. Overall, the system produced, respectively, 81 low, 50 moderate and 31 high level warnings; in 10 of the 40 watersheds the system did not show exceedence of the thresholds. The number of warnings attained appears to be quite acceptable, if referred to the entire 4-year period.

An example of the probability of exceedence over the selected period for the Valanidi basin is presented in Fig. 5 along with the probability thresholds.

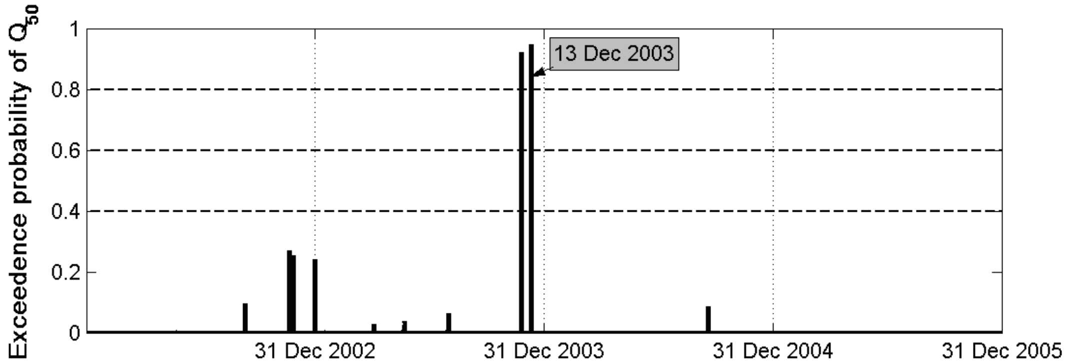

Fig. 5 Time series of simulated exceedence probability of Q_{50} for the Valanidi basin and the mark of the date of occurrence of a documented severe flood event.

Another check considered the correspondence of the predictions with the observations of flood events that had occurred in the past. This analysis was performed using the records stored in the A.S.I.Cal. (Aree Storicamente Inondate in Calabria) database, which collects information concerning historical severe flood events that occurred in the study region. Four events were selected in the study period, which correspond to flood episodes when the hydraulic capacity of the river channel was exceeded and produced very high documented social impacts.

Referring to Fig. 5, the time series of simulated exceedence probability of Q_{50} for the Valanidi basin produced two high level warnings: the first corresponds to a flood with less severe soil impacts and thus was not included in the events study set; the second matches one of the selected flood events, i.e. one that occurred on 13 December 2003.

As skill measures of the system, the total number of correct event forecasts (*hits*) and the total number of forecasts misses (*misses*) were computed. Events are captured well as they all were detected by the system. This result corresponds to the maximum probability of detection (POD), calculated as the ratio *hits*/(*hits* + *misses*), of 1.

SUMMARY AND CONCLUSIONS

In this paper the definition and the assessment of an operational flood forecasting system suited for simultaneous application in several ungauged basins are described.

The adopted approach provides an easy framework to account for parametric uncertainty in peak flow prediction based on ensemble streamflow simulations. The system involves the application of a simple conceptual rainfall–runoff model whose parameter sampling distributions in Monte Carlo generation are related to basin geomorphoclimatic characteristics.

The paper also presents the results from the application of the system to a set of different watersheds in southern Italy. The results obtained from simulating flood events which occurred at selected gauged sites, confirm the suitability of the adopted parameters distributions and the capabilities of the system to adequately provide warnings for the observed events.

Finally a back analysis over a limited period, 2002–2005, was performed for several ungauged basins. The system outcomes yield a reasonable number of warnings over this period. Moreover, model ability to detect severe documented historical events was also evaluated. All the selected historical floods were successfully detected by the system.

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