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Experiences of dealing with flash floods using an ensemble hydrological nowcasting chain: implications of communication, accessibility and distribution of the results

F. Silvestro[1], N. Rebora[1], G. Cummings[2] and L. Ferraris[1]

1 CIMA Research Foundation, Savona, Italy
2 Hydrometeorological Service, Ministry of Agriculture, Georgetown, Guyana

Correspondence
Francesco Silvestro, CIMA Research Foundation, University Campus Armando Magliotto, 2, 17100 Savona, Italy
Tel: +39 019 861418
Email:
francesco.silvestro@cimafoundation.org

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Abstract

The forecast of flash floods is sometimes impossible. In the last two decades, Numerical Weather Prediction Systems have become increasingly reliable with significant improvements in terms of quantitative precipitation forecasts. However, despite the application of modern probabilistic hydrometeorological chains, some significant flood events remain unpredicted. This was also the case with an event that occurred on the 8th and 9th of June, 2011 in the eastern part of the Liguria Region, Italy. This event affected in particular the Entella basin, a small watershed that flows into the Mediterranean Sea. The application of a hydrological nowcasting chain as a tool for predicting flash floods in small basins with an anticipation time of a few hours (2–5) is presented here. This work investigated the 'behaviour' of the chain in the cited event as well as in other verification cases and showed how the chain could be exploited for operational purposes. The results were encouraging. However, the analysis provided evidence that the difficulties in using operational hydrometeorological tools are not always and only dependent on the performance of such systems, but also on the way the results are made available to forecasters and on the efficiency of communication with the civil protection officials.

Introduction

In a number of situations, which cannot be ignored, modern meteorological forecast systems such as Numerical Weather Prediction Systems (NWPS) and Ensemble Prediction Systems do not allow for the prediction of precipitation with sufficient accuracy in terms of rainfall quantity and the particular locality of the rainfall events.

Very localised severe events with very high rainfall intensities are often very difficult to forecast (Alfieri *et al.*, 2012; Buzzi *et al.*, 2013). This is true because the current meteorological forecast systems cannot reliably describe and simulate the evolution of the atmosphere at fine spatio-temporal resolutions (Done *et al.*, 2004; Kain *et al.*, 2006). These events have very small spatial scale and are caused and triggered by local atmospheric conditions; as a consequence, often they are not correctly predicted by meteorological models, especially when referring to Quantitative Precipitation Forecast (QPF). In the best cases, meteorologists can predict that these kinds of events could occur in a certain time window (12–48 h) and in a certain large portion of territory (10^3–10^4 km^2). Recent assimilation techniques aim to improve the performance of QPF (Rossa *et al.*, 2010); however, it is often a challenge to say exactly where in the territory (and if) the event will actually occur. Further, even if there is a high probability that an event will occur, it is difficult to be precise with regard to the quantity of rainfall that may be associated with the event.

Events of this type are similar, in terms of intensities and localisation, to the common thunderstorms. However, they are often much more persistent, with durations ranging between 4 and 8 h (Silvestro *et al.*, 2012; Buzzi *et al.*, 2013; Rebora *et al.*, 2013). These characteristics produce high rainfall totals as well as high rainfall intensities for short durations. High rainfall volumes and intensities as described make these events potentially very dangerous because they can produce unexpected flash floods resulting in huge amounts of damage to significant infrastructures. The danger posed by these events is amplified when they occur in small or very small basins that respond rapidly to the precipitation impulses. Because of the nature of these events, basins can change from conditions of drought with significantly reduced streamflow to a state of devastating floods in only a few hours.

The concept of design storm (a rainfall event with spatial, temporal, intensity characteristics that result to be critical for a certain basin) can be helpful for planning purposes but it is not the best option when the aim is forecasting an occurring event.

The unpredictable nature of the aforementioned storms poses a great problem from the point of view of civil protection (for many countries, surely for Italian case), since warning messages must be issued at least 12–24 h in advance of an event (Siccardi *et al.*, 2005). In the case of these events, this is not possible for two reasons. Firstly, as explained before, these events can hardly be forecasted with the existing hydro-meteorological forecast chains (Cloke and Pappenberger, 2009; Rossa *et al.*, 2010; Silvestro *et al.*, 2011) that are based on precipitation forecast derived from NWPS. And secondly, as a result of the reduced dimensions of the basins, when the objective is to predict floods on small catchments, it is not recommended to base the streamflow forecasts on rainfall observations and rainfall-runoff models without rainfall prediction, because the response time for such small basins is of the order of only a few hours. As a consequence, when the most recent measurements are available and they are used in the models to produce the streamflow predictions, the event is practically already occurring or, at least, there is no time to take any kind of action with regard to civil protection.

Many works have focused on the exploitation of the most recent observations (especially radar-based products) and hydrological modelling in order to predict streamflow with a certain lead time. Berenguer *et al.* (2005) presented a hydrological nowcasting technique based on radar data, while Vivoni *et al.* (2006) proposed a method to extend the predictability of flood events using radar nowcasting. We intend with term nowcasting the forecast of the weather and ground effects for the next hours (e.g. 1–6 h).

Liechti *et al.* (2013) analyzed the results of a forecasting early warning system with different input configurations, and used, among others, a nowcasting technique of rainfall based on analogues (Panziera *et al.*, 2011); the results proved to be very useful in predicting events with well-defined characteristics that repeat from one event to another, while isolated convective systems were discarded from the analysis. However, the method requires a large database of events with complete datasets for successful application. Price *et al.* (2012) presented a flood forecasting system driven by radar rainfall and NWPS products, while Addor *et al.* (2011) demonstrated the benefit of using probabilistic over deterministic prediction systems.

Rossa *et al.* (2010) tried to deal with the problem of convective rainfall by assimilating radar data into NWPS. While the method seems credible, there is still the need for a verification exercise with a large set of events and in different environments; moreover, the kind of tools required are not available to all operational flood forecast centres.

This work focuses on the application of an ensemble hydrological nowcasting system (Silvestro and Rebora, 2012), based on a nowcasting algorithm and a hydrologic model, to a typical case study with the objective of proposing a method to address the issue of unpredicted flash floods. We also present results for other test cases in order to give an idea of the overall performance of the system. In addition, we give some suggestions on how to use the results of the system for operational civil protection purposes by exploiting modern communication technologies.

Various types of flash floods exist (Barrera *et al.*, 2006; Rebora *et al.*, 2013), they can be even due to karst phenomenon or to rapid snow melting (Bonacci *et al.*, 2006); in this work, we refer to those caused by very intense and localised rainfall events as defined in Quevauviller (2014). These phenomena occur with relative frequency in the Mediterranean environment. The risk of having great damage and lost of human lives is exacerbated by the fact that, in many cases, urban areas and towns have been established along the coast, often at the mouths of rivers or in the few flat areas along the riverbeds (Silvestro *et al.*, 2012).

The proposed system, as well as similar ones, does not allow for forecasting flash floods with an anticipation time sufficient to carry out the typical procedures of alerts with all the related bureaucracy, but it can help forecasters and decision makers avoid being completely unprepared for the occurring event. In some cases, it allows for some ‘in extremis’ actions by exploiting the authorities or the public officers (such as police, fire men) that are on duty near the area under threat by the storm. What we are interested in is increasing the time window between the forecast time and the instant of the flood event. The analysis shows that, in some cases, the ease of availability of the forecasts and quick communication with civil protection personnel become crucial elements in order to effectively exploit the information furnished by the hydro-meteorological tools. These elements should be a part of the final forecasting ‘toolkit’ that allows forecasters and decision makers to avoid having to face potential lawsuits and possible loss of public confidence in the effectiveness of operational forecasting centres.

The article is organised as follows: in Application context and measurement systems and Ensemble Hydrological Nowcasting Chain, the territorial context and the hydrological nowcasting framework are described. The application and the results are presented and discussed in Case studies, while Conclusions is dedicated to an overview of the presented work and to final comments.

Application context and measurement systems

The hydrological nowcasting system used in this work was applied to the Entella Basin in the Liguria Region, Italy. The Entella basin has a total area of approximately 370 km^2 and it is characterised by a mountainous topology given its proximity to the Apennines. The Apennines is a mountain range with elevations between 1000 and 1700 m.a.s.l. in the study area, and which rapidly decrease to sea level with relatively steep slopes. The concentration time (t_c) of the Entella basin is approximately 5–6 h, and its lag time, t_l (defined as the temporal distance between the centre of mass of the hydrograph and the centre of mass of the mean hyetograph over the basin area), is approximated at 3 h. The Ligurian Region is hit by Mediterranean perturbations that often have quite short durations (12–36 h), but accompanied by high rainfall intensities (Deidda *et al.*, 1999; Boni *et al.*, 2007). Moreover, the orographic conformation of the Region often causes local and severe precipitation events, which, in some cases, have a significant persistence when compared with the common thunderstorms. These events are typically very difficult to predict with the NWPS.

The last 6 km of the Entella River are heavily urbanised; there are towns, factories and infrastructures which are exposed to a high risk of flooding.

These two factors, proneness of the Region to flash flood occurrence and the presence of an urban area near the riverbed, contribute towards creating a situation where the risk for infrastructural damage and for the safety of the citizenry is very high.

Hydro-Meteorological Monitoring Centre of Liguria Region (CMIRL) is the institution responsible for making hydrometeorological forecasts and for the related activities of nowcasting and the monitoring of rainfall events for civil protection purposes in the Liguria Region. CMIRL developed and maintains a website where all the hydrometeorological observations and the results of the flood forecasting systems are displayed so that they are easily available. On the basis of the analysis, the technical considerations, and the suggestions of the CMIRL forecasters, the civil protection of Liguria Region decides whether or not to issue alert messages.

The Liguria Region is covered by a Doppler polarimetric C-band radar, located on Monte Settepani at a height of 1386 m, that works operationally with scansion time (e.g. time interval when radar data are available) of 5–10 min (Figure 1).

A dense automatic micrometeorological network of about 120 rain gauges covers the Region (about 15 stations are located in the Entella catchment or are located in its neighbourhood), providing real-time rainfall measurements with time resolution of 5–10 min. A water-level gauge with a time resolution of 15 min and with an available rating curve is located at Panesi, approximately 4 km upstream of the mouth of the river (area 364 km^2).

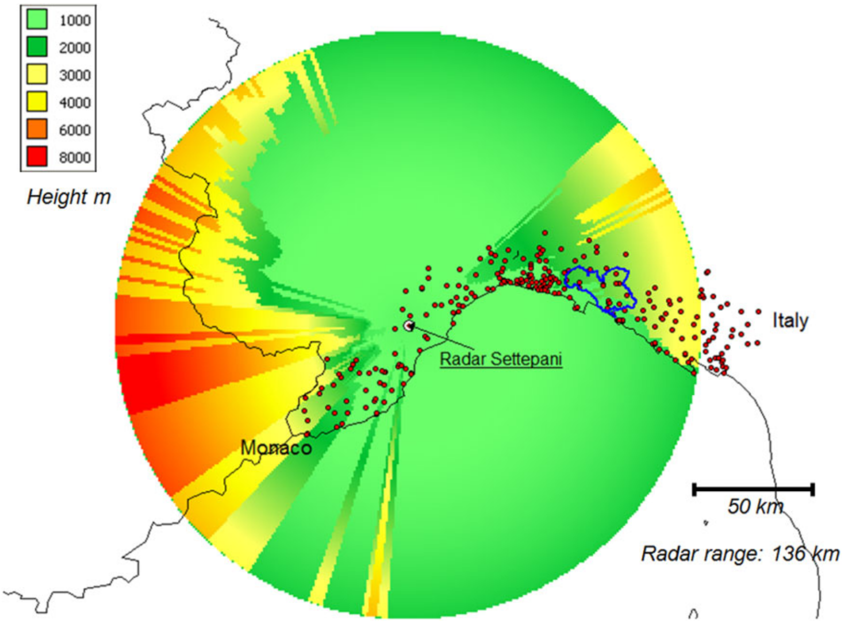

Figure 1 Visibility map of the Mount Settepani radar, the watershed of the Entella basin (blue line), and the rain gauge network (red points).

The Ensemble Hydrological Nowcasting Chain (EHNC)

The EHNF (Silvestro and Rebora, 2012) consists mainly of three components: a technique for rainfall estimation by using radar and rain gauge data, an algorithm for probabilistic nowcasting of precipitation fields and a rainfall-runoff model. This last component is important because the task is to generate future discharge scenarios and not only rainfall fields. The results are operationally used in ensemble mode without producing probability graphs, but by referring to the plot of all streamflow histories on the same graph (for sake of simplicity we will call this kind of visualisation spaghetti plots). In the following paragraphs, the three elements of the EHNF are briefly described. The EHNF used was derived from studies carried out by other authors (Berenguer *et al.*, 2005; Vivoni *et al.*, 2006, 2007; Schröter *et al.*, 2011), who introduced probabilistic approaches for the generation of nowcasted rainfall fields and, thereafter, streamflow scenarios.

The methodology for rainfall field estimation is described in Silvestro and Rebora (2012). The methodology uses the algorithm named Radar Intensity Multi-parameter Estimator (RIME) shown in Silvestro *et al.* (2009) to estimate the rainfall fields from radar data, and then it adjusts them with a technique derived from the algorithms described in Koistinen and Puhakka (1981) and Gabella *et al.* (2001) by using rain gauges data.

The nowcasting model PhaSt (Metta *et al.*, 2009) furnishes an ensemble of equi-probable future precipitation scenarios on time horizons of 1–3 h starting from the most recent radar observations. It is based on the combination of an empirical nonlinear transformation of measured precipitation fields and the stochastic evolution in spectral space of the transformed fields. An initial phase velocity is obtained from a two-dimensional fast Fourier transform of two successive observed rainfall rate fields. This phase velocity is evolved as a Langevin process. In the operational configuration, 10 ensemble members are used with a time step of 10 min.

The semi-distributed event scale rainfall-runoff model DRiFt (Giannoni *et al.*, 2000, 2003; Gabellani *et al.*, 2008) uses the rain gauge adjusted radar precipitation estimates and the rainfall fields generated by PhaSt as inputs. The model is focused on the description of the drainage system in its essential parts: hillslopes and channel networks. The drainage network is delineated by using a digital elevation model and each cell is classified as hillslope or channel through a geomorphologic filter. The implemented infiltration scheme (Gabellani *et al.*, 2008) allows the modelling of 'multi-peak' events since the propagation of water in the first soil layer is described, and in this way, an auto initialisation of the model is reproduced between an event and another; the schematisation is valid and applicable when the simulation period is not too long and the evapotranspiration does not become crucial in the mass balance equation. The runoff estimated at cell scale is routed through convolution to the outlet section without accounting for the storage in the channels and re-infiltration. The model has five parameters: one morphologic parameter that regulates the drainage network density (number of hillslope and channel cells), two kinematic parameters that represent the velocity of surface flow and two soil parameters that regulate infiltration and soil moisture propagation. These parameters are calibrated using geomorphological information (of the reference drainage network) and hydro-meteorological data (rainfall and discharge observations). In particular, in the presented application, they are calibrated referring on some historical events using as objective the good reproduction of peak flows and times to peak. In its operational configuration, DRiFt runs at hourly time step with a spatial resolution of 225 m. Using the input data and the parameter settings, the final output of the model is an ensemble of equiprobable hydrographs.

In Figure 2, the flow chart that represents the scheme of functioning of the hydrological nowcasting framework is reported.

Each rainfall scenario is made up in part of observed rainfall and of the forecasted rainfall generated by using PhaSt – in this application, a forecast time window of 2 h is used (see Figure 3). PhaSt is configured to forecast rainfall fields for a time window of 2 h. The 1 h observed rainfall before the forecast time is generally estimated using radar fields only, because of the delay time in receiving the rain gauge data.

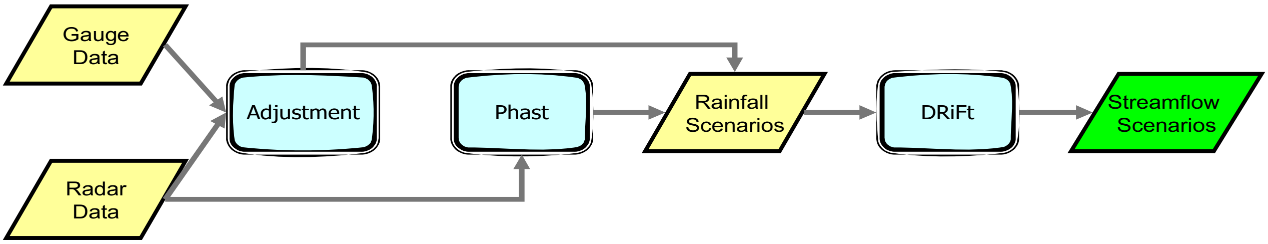

Figure 2 Flow chart that represents the elements of the hydrological nowcasting chain and their input/output inter-connections.

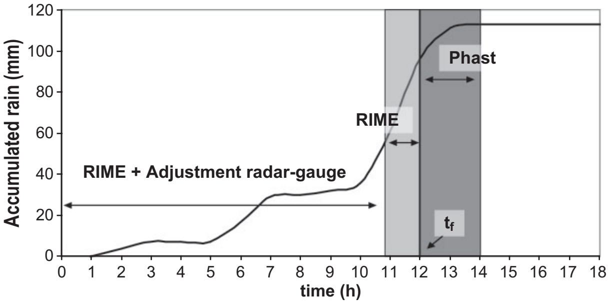

Figure 3 Reference schematisation for the building of a rainfall scenario. The first part is generated using the algorithm RIME and the radar-gauge adjustment, the rainfall of the hour before the forecast time (t_f) is estimated using only radar observations (RIME) and the forecasted part using the algorithm PhaSt.

Table 1 NWPS used by CMIRL for meteo-hydrological forecast

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

Case studies

Event on 9th June 2011: analysis and suggestions

During the night of 8 June and the early morning hours of 9 June 2011, an unexpected flash flood occurred in the Entella basin. On 8 June, the eastern part of the Liguria Region was hit by sparse rainfall and some thunderstorms that did not generate particular problems or damage. The event was correctly predicted by the forecasters using the NWPS. No civil protection alert was issued because the situation was not particularly alarming; however, the day was spent monitoring the event's evolution.

In the early afternoon of 8 June, a complete and detailed analysis of the weather was carried out by using the most updated runs of the meteorological models (Table 1). As usual, the following models were used: the limited area models COSMO-LAMI (Steppeler *et al.*, 2003), BOLAM (Buzzi *et al.*, 1994) and a high-resolution limited area model called MOLOCH (e.g. Diomede *et al.*, 2008). The result of the forecast process was the following: the perturbation was rapidly coming to an end and only occasional and sparse light rain was predicted for the next 24 h.

All the forecasters and the decision makers (meteorologists, hydrologists and civil protection personnel) were persuaded that the forecasted weather conditions posed no threat. The surveillance of the evolution of the weather situation and the analysis of all the available NWPS led to the cessation of monitoring and the return to routine activities during the regular office hours.

Table 2 Skill estimators calculated in order to evaluate the capability of the DRiFt model to reproduce the observed streamflow. Rain gauge adjusted radar precipitation data are used as input data

Parameter	Value	Unit
Nash Sutcliffe coefficient	0.91	(–)
MacMahon coefficient	0.93	(–)
Root mean square error	0.65	(m^3/s)
Peak flow percentage error	+9	(%)
Correlation coefficient	0.96	(–)

During the late afternoon and the early evening of 8 June, no rainfall was recorded. However, at approximately 20:00 UTC (22:00 local time), in the eastern part of the Liguria Region, it started to rain again and a new intense event began. The event lasted approximately 6 h and mainly affected the Entella basin and some adjacent catchments. Approximately 90 mm of rainfall was recorded in 6 h in the Entella watershed at basin scale. One rain gauge, located inside the basin, recorded 100 mm in 1 h and a total accumulated rainfall of 200 mm in 6 h. This intense rainfall caused a rapid increase in streamflow. The Panesi stream level gauge measured 0.1 m at 20:00 UTC (which corresponds to 60 m^3/s) and had a peak of 4.72 m at 3:00 UTC on 9 June (which corresponds to approximately 870 m^3/s). This was the highest water level recorded at the location in 10 years, while the rainfall event was completely unpredicted.

In Figure 4, the comparison between the observed hydrograph and the hydrograph obtained using radar rainfall estimation adjusted with rain gauge observations as the input to the rainfall runoff model is shown. In this work we define the latter as the 'reference hydrograph' (Borga, 2002; Vieux and Bedient, 2004). As can be noted, the rainfall-runoff model gives a good reproduction of the behaviour of the basin response in terms of streamflow. This is confirmed by the values of some statistics commonly used for evaluating the performance of the hydrological models that are reported in Table 2: Nash Sutcliffe coefficient (Nash and Sutcliffe, 1970), MacMahon coefficient (Chiew and Mc Mahon, 1994), correlation coefficient, root mean square error and percentage error of peak flow. See Moriasi *et al.* (2007) for information on the values of these statistics.

Fortunately, in the period before 8 June, there was very little precipitation and the soil was quite dry with a low level of moisture. Moreover, after 02:00 UTC on 9 June, the perturbation started to dissipate and rainfall ceased. River levels rose very high and caused the inundation of small areas near the riverbed affecting isolated buildings only. There were only minor damages and no loss of lives, but the towns located along the terminal section of the Entella River were close to experiencing a devastating flood.

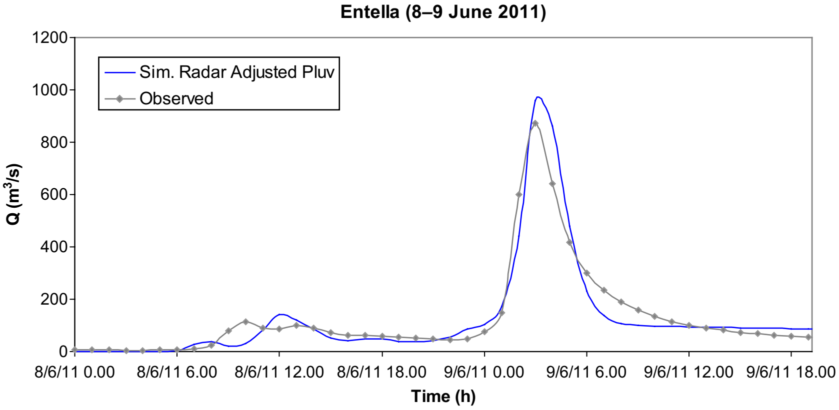

Figure 4 Comparison between the observed hydrograph and the hydrograph obtained using radar rainfall estimation adjusted with rain gauge observations as input to rainfall runoff model is shown.

The entire event, previously described, occurred in a temporal horizon of 6–8 h without any meteorological forecasts that would have allowed any anticipation of what was going to happen. In addition, the event occurred during the night and therefore the civil protection personnel, meteorologists and hydrologists realised its severity too late for any meaningful action to be taken.

But in retrospect, what did the EHNF detected before and during the event?

Addor *et al.* (2011), Liechti *et al.* (2013) and Ramos *et al.* (2013) showed that, in general, probabilistic and ensemble systems outperform deterministic approaches. At this stage, one can pursue evaluating the skill of probabilistic forecasts with standard methods (Wilks, 2006; Bartholmes *et al.*, 2009; Liechti *et al.*, 2013). However, from an operational point of view, this would not be very helpful; in fact, there is always a degree of subjectivity in the evaluation of a probabilistic (or ensemble) forecast. For example, let's consider the forecast of a generic system: if there are 100 streamflow ensemble members and 98 indicate that there will be no significant streamflow, while 2 indicate that an alarm threshold will be exceeded (the probability is therefore low, i.e. <2%). What must the forecaster do? It depends on how much risk he/she wants to assume. And, after the event has occurred, if the threshold is exceeded by the observations, did the forecast chain work well? The answer could be: (i) yes, two ensemble members forecasted what was later observed, or (ii) no, the probability was too low. On the other hand, if a deterministic system is used the forecaster would have to be very fortunate, hoping that the system produced the 'right' forecast. Probably the deterministic forecast would be simpler to interpret and the forecaster would not be obliged to make a decision based on several ensemble members, but the amount of information available for making such a decision would be generally less than when using a probabilistic (or ensemble) system.

In this analysis, we present what the system, which displays its output in common spaghetti plots, would have shown to the forecaster together with a probability plot (not operationally available). Alfieri *et al.* (2012) supports the idea that visual assessment is a standard and quick way to evaluate the performance of an ensemble chain. We considered the fact that even one ensemble member which predicted a critical condition could have been enough to warn the forecaster/decision maker of the impending event; this fact was also demonstrated by Ramos *et al.* (2013) through laboratory style experiments conducted on several cases of flood forecast.

Figure 5 reports the results in terms of a spaghetti plot. Each panel represents the hydrological ensemble forecast for the indicated forecast time.

The dotted line is the run of the hydrological model using as input only the rain gauge adjusted radar precipitation estimates that are available until the time indicated by the thick black vertical line; the grey lines are the forecasted scenarios obtained using the observed and forecasted (PhaSt: 2 h) rainfall as input to the rainfall runoff model, and the dashed line represents the 'reference hydrograph'. The reference hydrograph is obviously not available in real time, but it was inserted for ease of comparison. The thick black vertical line is useful to separate the skill of the precipitation forecast from the skill of the hydrological forecast (due to observed rainfall routed through the hydrological model). Figure 6 reports the results in terms of a probability plot (Ferraris *et al.*, 2002; Alfieri *et al.*, 2012), the empirical cumulative distribution function (cdf) is built using the peak flows of each ensemble member, the thin vertical line represents the peak of the run using as input only the rain gauge adjusted radar precipitation, while the dashed vertical line represents the peak of the reference hydrograph.

The nowcasting chain runs every hour and the results are available with a delay time of approximately 15 min with

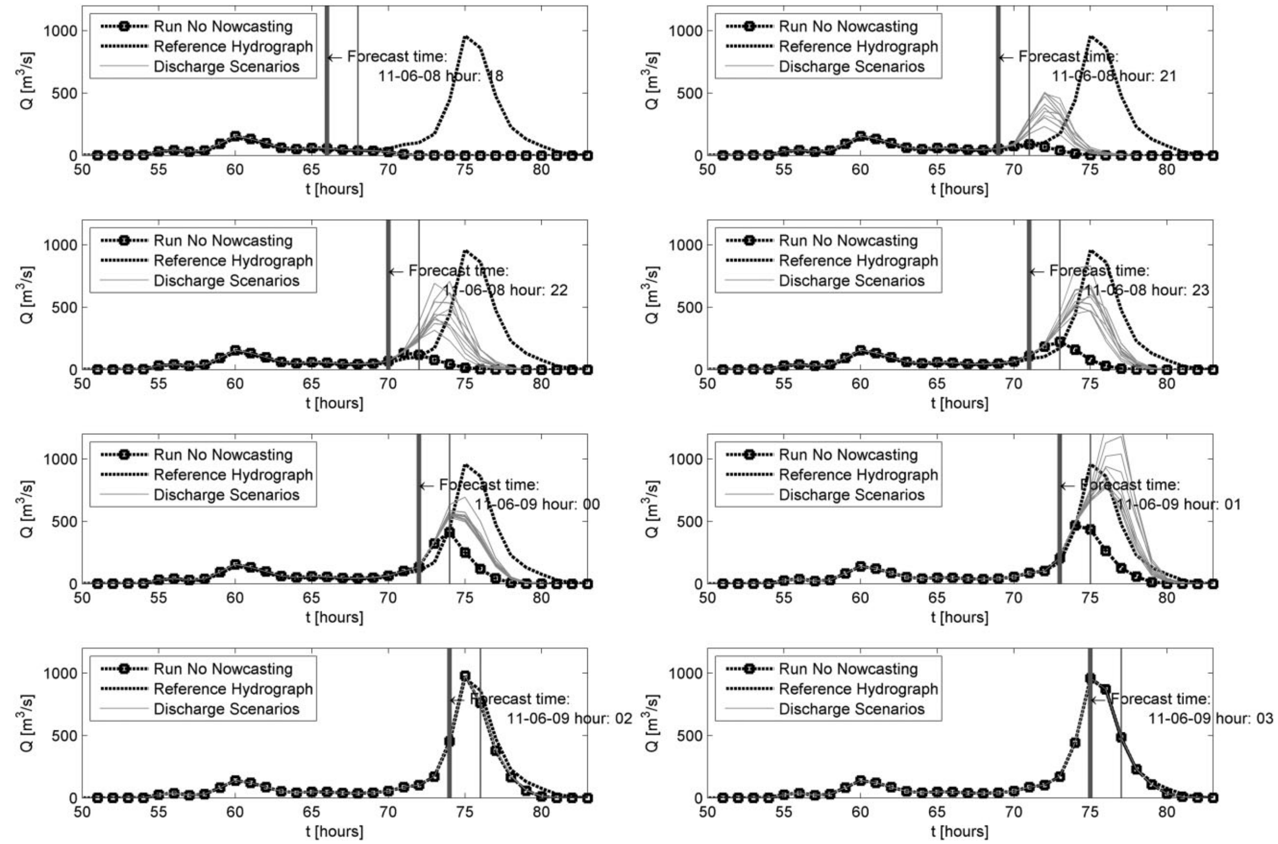

Figure 5 Results of hydrological nowcasting framework for the Entella Basin closed at Panesi (area = 364 km^2) for the event on 08–09 June 2011 is shown. Each panel shows the forecast obtained at the indicated forecast time. The dotted line is the run of the hydrological model using as input only the observed rainfall data that are available until the time indicated by the thick black vertical line; the grey lines are the forecasted ensemble members obtained using the observed and forecasted (2 h) rainfall as input to the rainfall runoff model, and the dashed line represents the 'reference hydrograph'.

respect to the minute 00 of each hour, so for example, the forecast with reference time 21:00 h is actually available at 21:15 h. The reference hydrograph shows that the peak flow occurred at 3:00 UTC. The first subpanel (top left corner) is representative of the results of the nowcasting system prior to 21:00 UTC. At 21:00 and 22:00 UTC, the streamflow scenarios provide evidence of notable peaks and show that something is going to occur. The presence of these peaks is evident for the next 3 h. The forecast at the various times is not perfect: the peak flow times are often affected by an error and before the forecast at 01:00 UTC, the peak flows are always smaller than the peak of the reference hydrograph. If we evaluate the system based on its ability to predict the exceedance of the reference hydrograph peak, then the EHNF works well starting from 01:00 UTC (Figure 6); if we consider a lower warning threshold (for example 600 m^3/s), then there is good performance starting from 22:00 UTC.

On the other hand, it is evident that the system signals a warning that indicates that the meteorological and hydrological forecast used as support to decide the level of the alert were wrong: an unexpected event is occurring. In this case, the hydrologist and/or the decision maker would have known with a certain anticipation time (4–5 h) that the streamflow would have reached potentially dangerous levels. A period of 4–5 h represents a reduced time, but it is better than observing the peak flow while it is occurring.

With such a short period of time, it is not possible to start all the elements of the complex 'Civil Protection Machinery' which involves a number of institutional levels that have different responsibilities and tasks. The machinery has a sort of 'inertia' due to predefined procedures and the time needed for dealing with the bureaucracy. In general, anticipation times of about 12–24 h are preferred (Siccardi *et al.*, 2005; Silvestro *et al.*, 2011).

However, civil protection personnel can activate some elements of the civil protection chain that have an operational and direct role on the territory. For example, in the case of the Italian system, we can refer to the prefectures, the majors, the municipal police and firefighters. These authorities can carry out a number of emergency actions such as

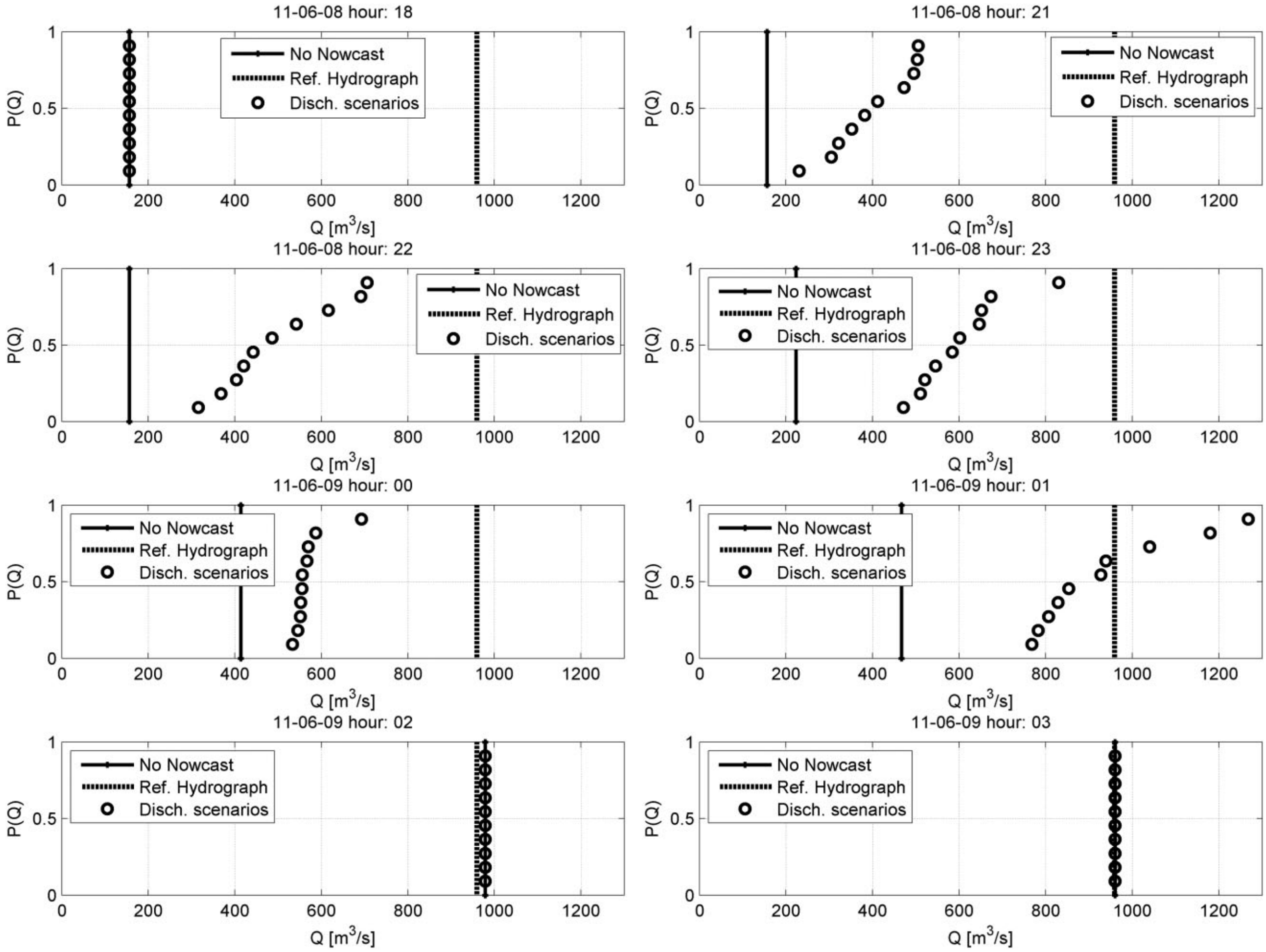

Figure 6 Results of hydrological nowcasting framework for Entella Basin closed at Panesi (area = 364 km^2)for the event on 08–09 June 2011 shown in terms of a probability plot. Each panel shows the forecast obtained at the forecast time indicated in the title. The thin line is the peak flow of the run of the hydrological model using as input only the observed rainfall, the dashed vertical line is the peak of the reference hydrograph, the small circles represent the empirical cumulative distribution function (cdf) of the peak flows.

evacuating buildings that could be flooded, monitoring and closing infrastructures such as bridges and subways near the river bed, and evacuating depressed areas near the riverbed. A few hours can be enough to perform these kinds of activities which can significantly reduce the impacts of the occurring flood.

Another unfortunate (even though quite normal and due to chance) occurrence with this event was the fact that the intense rainfall began in the late evening. We should keep in mind that the event was not predicted and no alert was issued; as a consequence, hydrologists, meteorologists and civil protection personnel were not monitoring the evolution of the situation. No one was monitoring and analysing the results of the hydrological nowcasting chain, so it was completely useless. From another perspective, this situation was fortunate indeed, since the number of human lives exposed to the risk was small (people were neither going to work nor children going to school, etc.).

In this case, the use of technology and modern communication systems could have been very helpful. For example, the CMIRL uses a system that automatically sends short message service (SMS) with warning messages to the forecasters' (hydrologists and meteorologists) mobile phone based on the rain gauge observations. When the accumulation of rainfall of predefined duration exceeds the established thresholds, the warning SMS is sent together with the information about the measured rainfall and the weather station that recorded that data. A similar outcome can be achieved by using an e-mail service, eventually adding more data and information to the current system.

Recently, CMIRL adopted a threshold alarm system based on the radar rainfall field that automatically sends e-mails to the forecaster by connecting through smart phone services to the web site where the results of hydrometeorological tools are published in real time and the forecaster can start monitoring the event. New technologies, such as smart

Table 3 Characteristics of the selected events: duration, maximum hourly precipitation recorded by a gauge during the event, and accumulated rainfall at basin scale estimated using rain gauge adjusted radar precipitation data

No.	Date	Duration (h)	Max hourly rain (mm/h)	Accumulated rain (mm)
1	05 November 2011	11	27	76
2	08 November 2011	10	10	15
3	09 June 2011	6	101	86
4	22 October 2013	6	86	60
5	30 October 2013	5	51	35
6	09 November 2013	8	57	64
7	09 February2014	12	35	82

phones, are potentially very helpful in this regard by allowing connection to web monitoring tools or to dedicated applications from almost any location.

An analogous system can be adopted based on the comparison of the results of the hydrological nowcasting chain with thresholds on streamflow defined for the modelled outlet sections. The system checks the sections where a certain number of streamflow scenarios exceed the threshold and sends the SMS, if there is at least one section that satisfies this condition. The forecaster can then analyze the evolution of the unexpected event and then carry out those actions necessary to advise the responsible civil protection personnel and the local authorities. This kind of system was not present/operational at the time of the event.

Verification events

Even though the main focus of the manuscript is on the analysis of the event which occurred on 8th and 9th June 2011, we collected other events in order to show the functioning of the chain in other situations and thus carried out a verification of the system. We identified six additional events in the Entella basin in recent years. Four of these events are characterised by high and concentrated rainfall intensities and with relatively short durations (Nos. 4, 5, 6 and 7 in Table 3). Similar to the principal case (8–9 Jun, 2011), these events were also unexpected and, for some of them, only a general forecast of the presence of an intense storm at the regional scale was forecasted. Two events are of lower rainfall intensities with correspondingly low streamflow values (Nos. 1 and 2 in Table 3).

The number of events available was limited by the operational status of the radar.

In Table 3, the events (the event discussed in Event on 9th June 2011: analysis and suggestions is shown in italics) with their main characteristics with reference to the Entella basin is presented: duration of the event, accumulated rainfall at basin scale, and maximum hourly rainfall intensity recorded by a gauge.

To illustrate the potential benefit of the system, we plotted what would have been available to the forecaster during the monitoring of the event (Figures 7–11).

An interesting case is the event which occurred on 21–22 October 2013 (Figure 9). In this case, the ability of the nowcasting system to predict the rainfall was limited; even though the event lasted approximately 6 h, the most intense period was concentrated over a short duration of 2 h (one rain gauge recorded two hourly showers of about 75 and 85 mm/h) probably caused by a very local convective cell. In this case, the skill of the ensemble forecast system was similar to the forecast generated solely from the observed rainfall routed with the hydrological model.

The system produced better results for the other three intense events (Figures 10–12) with a good anticipation time of the peak flow, ranging from 2 to 4 h, and provided an indication that a flood event was going to occur up to 4–5 h before the peak flow.

In the case of the 30 October 2013 event, the forecaster suddenly (between 6:00 and 7:00 UTC) issued a warning to the regional civil protection personnel who contacted local authorities (municipalities, police and volunteers) who then stopped traffic circulation on the bridges within the basin and took action to ensure the safety of the citizens who live near the river bed. Fortunately, no flooding occurred.

Even during the two smaller events (Figures 7 and 8), the EHNF gave good indications of the occurring peak flow events with quite a large anticipation time. In these two cases, we adjusted the limits of the y-axis in order to make the figures more readable.

Table 4 summarises the seven events with respect to the times associated with the maximum rainfall intensity (T_p), maximum discharge (T_{Qmax}), issuance of an alert (T_a) message, issuance of an alarm message for the basin (T_{alm}) and the time interval between the occurrence of the maximum discharge and the issuance of the alarm (T_{Qmax}–T_{alm}). We note here, that in the context of the Liguria Region, there is a difference between an alert message and an alarm (as produced by the nowcasting system described in this paper). Under normal circumstances, using the existing forecasting system (NWPS, etc.), the local forecast office issues an alert for expected bad weather to the local civil protection authority and the general population – usually in excess of 24 h or more before the actual occurrence of the storm in a particular geographical area. There are three alert levels: no alert, level 1 and level 2. The level 2 alert indicates the most dangerous condition/situation (Silvestro *et al.*, 2012). On the other hand, in an operational context, each monitored basin within the Liguria Region has its own defined pre-alarm and alarm flow levels that, in the case of Entella basin, correspond to approximately 510 m^3/s and 700 m^3/s, respectively. However, in this work, since the alarm flows were not surpassed in all of the events, the 'time of alarm' is taken as the

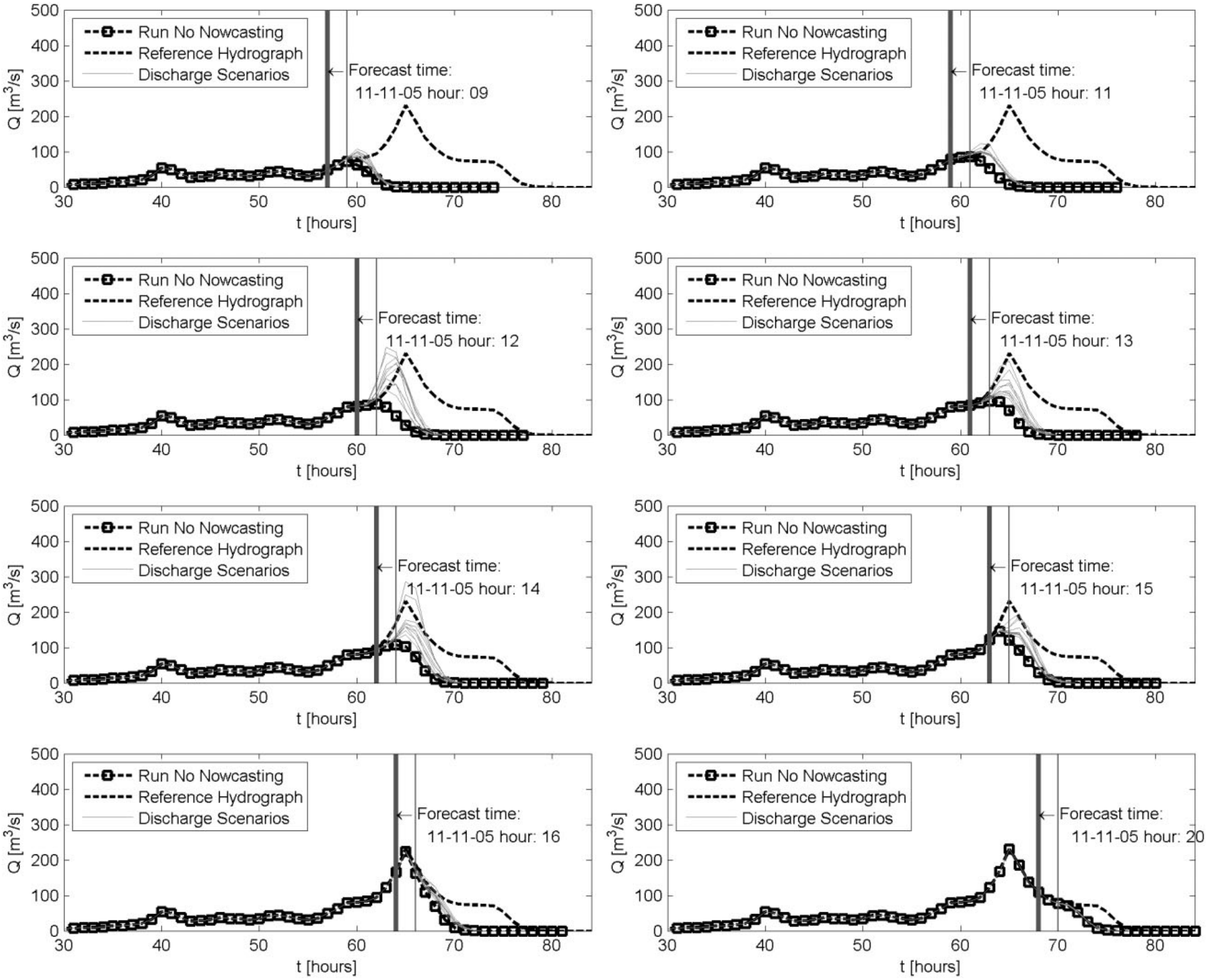

Figure 7 Same as Figure 5 for the 05 November 2011 event.

Table 4 Summary of the selected events showing time of: maximum rainfall intensity (T_p), maximum discharge (T_{Qmax}), issuance of alert (T_a) message, issuance of alarm message (T_{alm}), and the time interval between the occurrence of the maximum discharge and the issuance of the alarm ($T_{Qmax} - T_{alm}$)

No.	Date	Time of max intensity rainfall, T_p (hh:mm)	Time of max discharge, T_{Qmax} (hh:mm)	Level of alert	Time of alert, T_a (dd/mm/yyyy)	Time of alarm, T_{alm} (hh:mm)	Alarm time interval, ($T_{Qmax} - T_{alm}$) (hh:mm)
1	05 November 2011	15:00	17:00	1	04/11/2011	12:20	4:40
2	08 November 2011	06:00	09:00	1	07/11/2011	05:20	3:40
3	09 June 2011	01:00	03:00	null	–	8th 22:20	4:40
4	22 October 2013	21st 23:00	01:00	null	–	21st 23:20	1:40
5	30 October 2013	08:00	09:00	null	–	06:20	2:40
6	09 November 2013	01:00	9th 04:00	null	–	00:20	3:40
7	09 February 2014	01:00	03:00	null	–	8th 23:20	3:40

time when the pre-alarm discharge was first forecasted by the system (at least one ensemble member) in the cases where the pre-alarm threshold was exceeded during the event, while we referred to the time when the maximum discharge was first forecasted by the system in the other cases. We did not refer to the nominal starting time of the chain run (which is always at the minute 00) but at the time when the results of the chain are generally available.

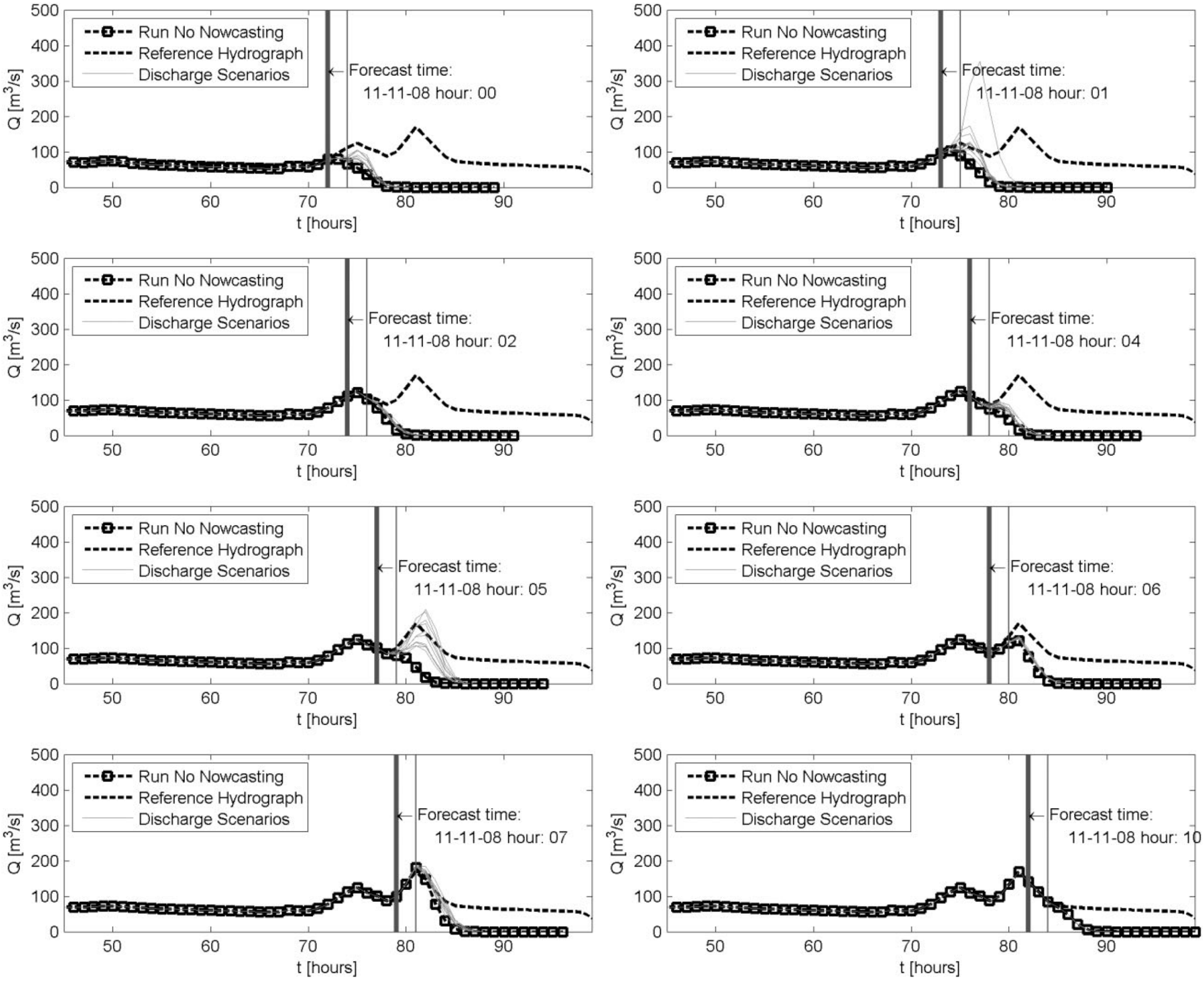

Figure 8 Same as Figure 5 for the 08 November 2011 event.

In order to show the performance of the hydrological model in reproducing the observed streamflow the percentage error on peak flow has been calculated for each event (Table 5). This should help to evaluate the ability of the system to provide a good hydrological forecast and to assess the errors that are not caused by the rainfall nowcast. Table 5 shows that for five events the performance is quite good with errors lower than 15%, while two events have larger errors that could be due to a bad estimation of the observed rainfall fields or to a bad estimation of the initial soil moisture distribution.

Table 5 Percentage error on peak flow calculated in order to evaluate the capability of the DRiFt model to reproduce the observed streamflow in the considered events. Rain gauge adjusted radar precipitation data is used as input data

No.	Date	Peak flow percentage error (%)
1	05 November 2011	−15
2	08 November 2011	+25
3	09 June 2011	+9
4	22 October 2013	−7
5	30 October 2013	+43
6	09 November 2013	+6
7	09 February 2014	+12

Discussion

This work highlights the importance of two aspects of the hydrometeorological forecasting framework: (i) the usefulness of having real-time hydrological nowcasting systems that fully exploit the potential that meteorological data (especially radar data) and hydrological models present and, (ii) the importance of setting up communication systems that make effective and prompt use of the existing hydrological tools, even when unexpected events occur.

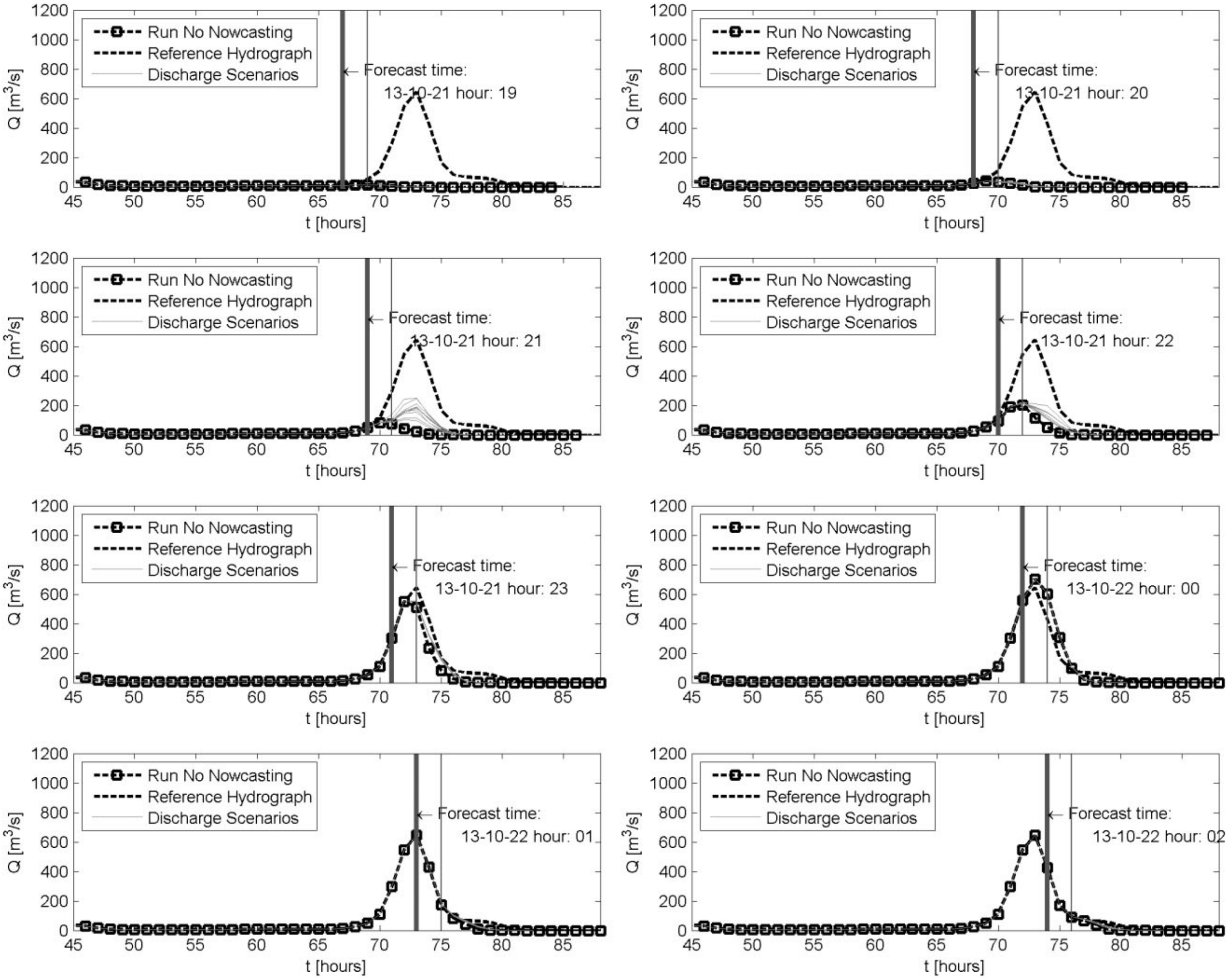

Figure 9 Same as Figure 5 for the 22 October 2013 event.

Related to these two considerations, there is also the matter of the responsibility of the forecasters and decision makers and the legal consequences that may follow their action or inaction.

In recent years, the Italian population as well as the judicial authorities have become increasingly sensitive to the issue of natural hazards, especially in cases where there were the loss of human lives. Some devastating flood (Silvestro *et al.*, 2012; Buzzi *et al.*, 2013) and earthquake (Contreras *et al.*, 2014) events have triggered the interest of the population and of the media on these issues. Research activities, such as this work, assist in increasing the attention being given to these topics while, at the same time, the pressure on scientific and technical institutions that deal with natural disasters also increases. Citizens and authorities both expect effective and efficient responses on the prediction of these events; sometimes the expectation is next to impossible, with the demands exceeding the scientific limits of the existing systems. This often leads to questioning of the competence and professionalism of personnel who are involved in the research and operational aspects of forecasting natural hazards. The natural result is controversy and criticism regarding the real necessity of investing resources (both human and public finance) to improve the existing technical and research activities.

These factors make it extremely important that the stakeholders on the forecasting end of the civil protection chain are fully prepared to exploit at the highest level, and with the highest degree of efficiency, the available forecasting system to combat a growing perception of inaction in the public space.

In cases similar to those presented in this work, problems could arise because even though the hydrological nowcasting system is operational, in the absence of adequate communication systems, an unexpected event may occur with the system correctly providing a nowcast,

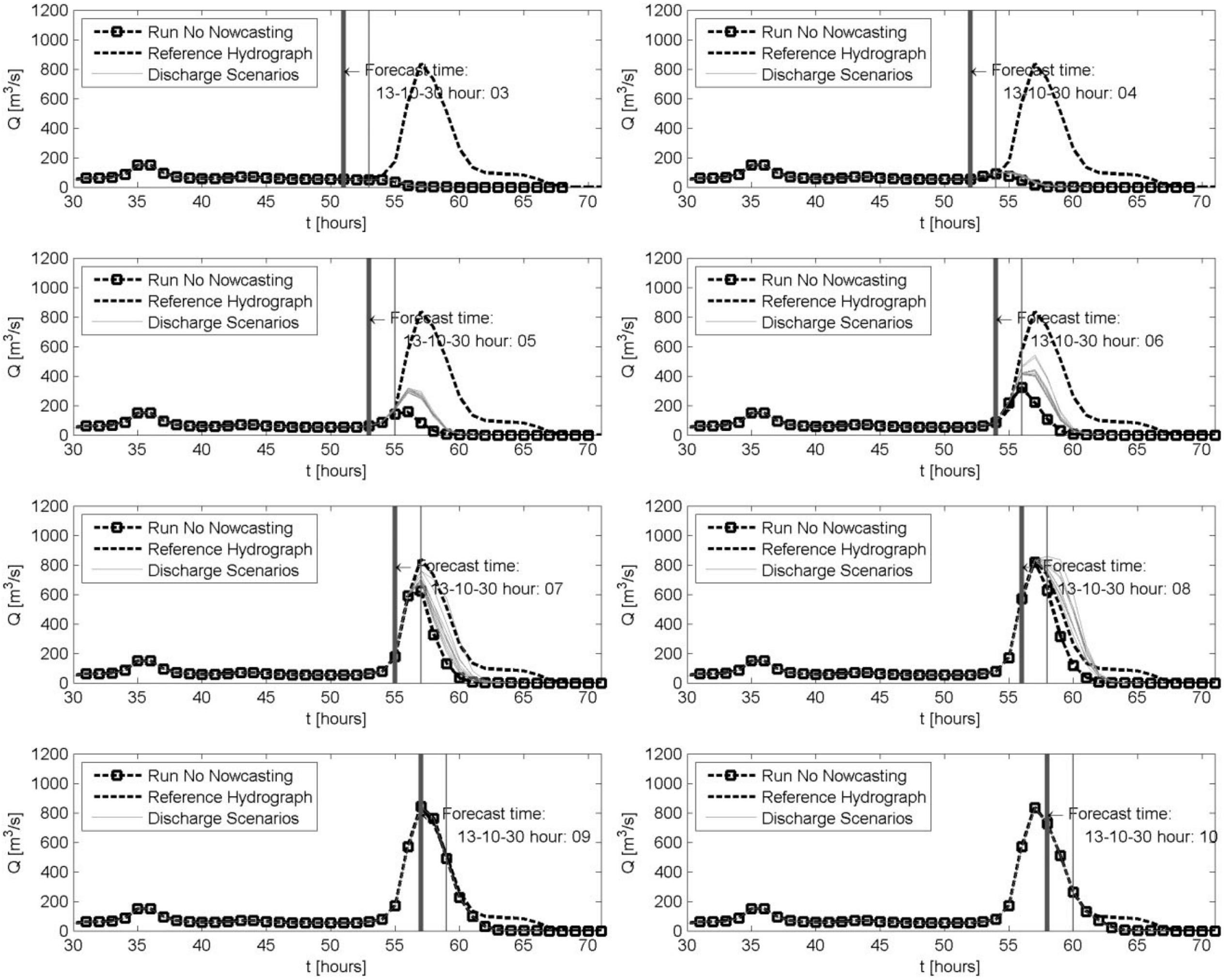

Figure 10 Same as Figure 5 for the 30 October 2013 event.

but nobody is aware and therefore there is no analysis of the results (because the event occurs during the evening as in the case study presented). Citizens or legal authorities may ask the forecaster: why do you have such sophisticated systems and yet you do not fully exploit them? Did you really do all you could in this case? Moreover, even in cases where the forecaster provides a timely forecast, it is expected that the full civil protection machinery is able to respond in a short time. As a consequence, communication, availability of products and fast distribution of information are becoming more crucial elements required to make effective the information given by the hydrometeorological prediction systems.

Conclusions

This work presented the application of an ensemble hydrological nowcasting framework (Silvestro and Rebora, 2012) to an event that occurred on the Entella basin on the night between the 8th and 9th of June 2011. The aim was to evaluate how such a system could be used (and could be useful) in a typical case of flash flood which was not predicted by the NWPS and was completely unexpected by meteorologists and hydrologists responsible for providing forecasts of intense rainfall events and of floods. Six other events were considered in order to provide a verification of the chain. Certainly, the results cannot be completely generalised since each catchment has particular morphologic, geological and vegetation cover characteristics.

The EHNF is affected by a number of sources of uncertainty, (Carpenter and Georgakakos, 2006; Zappa *et al.*, 2011; Silvestro and Rebora, 2012); otherwise it allows for predicting possible streamflow scenarios with an anticipation time of 3–5 h in basins with very fast response times (1–3 h). This could be a very useful tool when faced with unpredicted/unexpected intense rainfall events. Moreover, the possibility of running the system with data at higher time

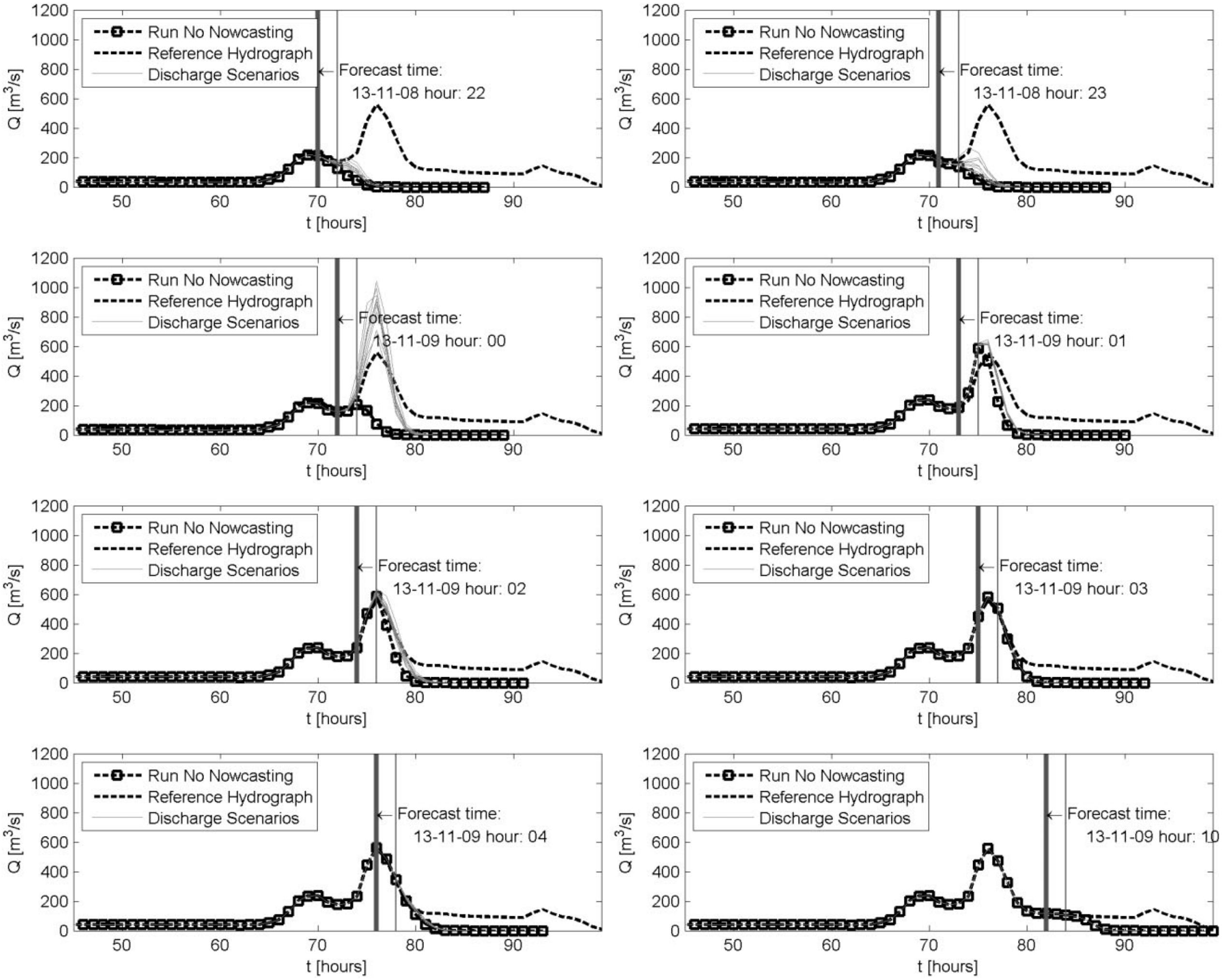

Figure 11 Same as Figure 5 for the 09 November 2013 event.

resolution (i.e. 10 min instead of 1 h) and with higher scheduling frequency (i.e. 10 min instead of 1 h) could probably allow for an improvement in the results and an augmentation of the anticipation time of the forecast. A few hours (2–5) is not sufficient time to start up the civil protection machinery, but it could be enough time to adopt some emergency actions that reduce the impact of the occurring flood in terms of loss of human lives and damage to property. The decisions and actions taken in those few hours could also help to avoid the possibility of legal action against hydrologists, meteorologists and civil protection personnel that have the responsibility of forecasting and monitoring intense rainfall events and issuing alert messages. There were already cases where the leaders of the Italian civil protection have been involved in penal trials as a result of unpredicted devastating rainfall events, similar to the one illustrated in this work, which caused the loss of human lives.

Systems like the one applied in the presented work cannot always predict flash floods with 100% certainty and they are certainly not the definitive solution to the problem of flash flood forecasts, but the authors are persuaded that they are very useful in many cases.

Some very elementary approaches were also suggested to keep the personnel involved in forecast activities constantly informed. The approaches allow for the receiving of information and warning on the results of the ensemble hydrological nowcasting chain outside the ordinary office hours when, without an issued alert, no monitoring and nowcasting activities are carried out. These are based on commonly used communication technologies such as SMS and e-mails.

From the analysis of the results, as well from other similar works, some recommendations arise in order to improve flash flood forecasting systems and their effectiveness:

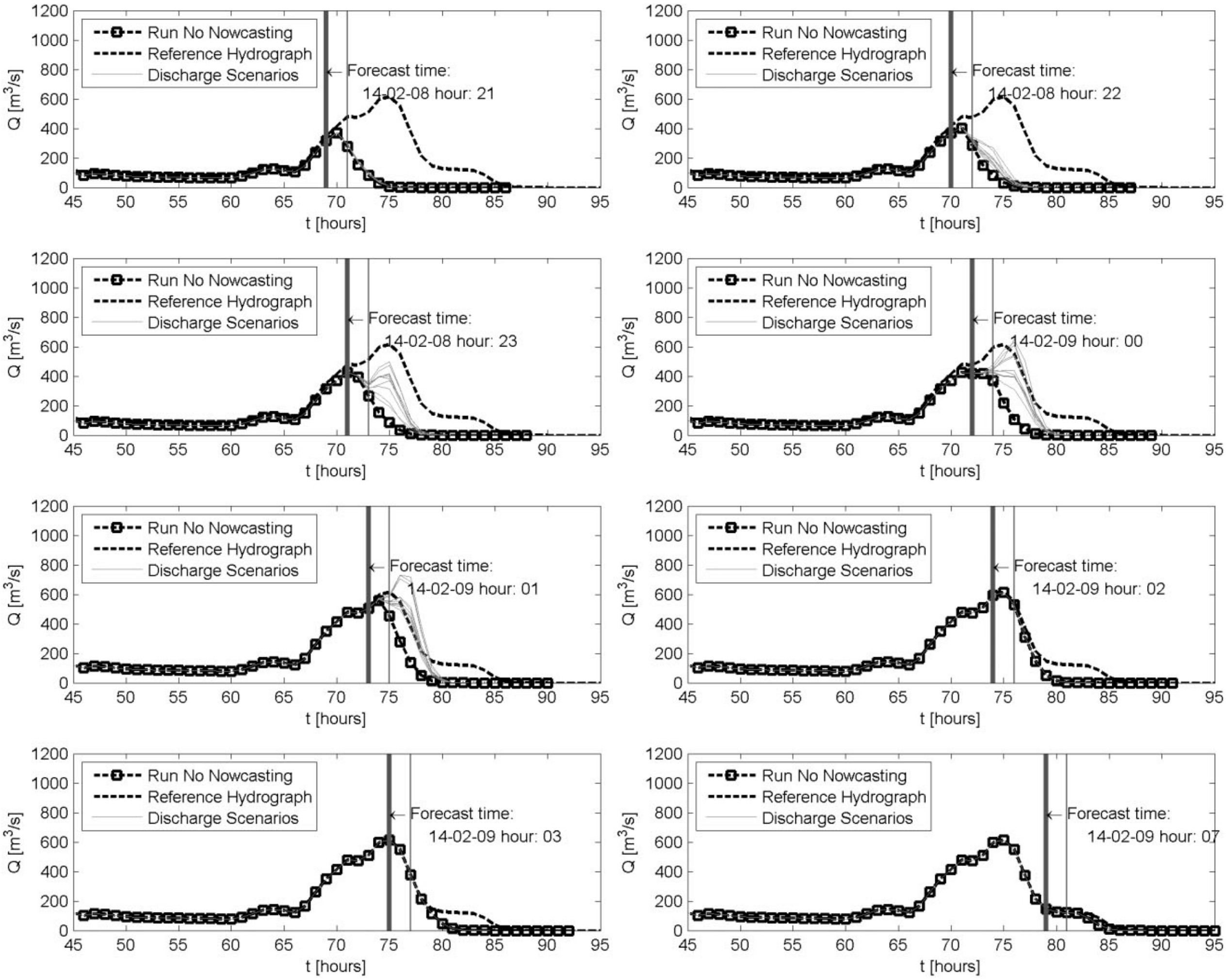

Figure 12 Same as Figure 5 for the 09 February 2014 event.

1. Always work on probabilistic approach.
2. Set up systems to have results promptly and easily available (web sites, apps, etc.).
3. Continue the research activity with the aim of improving the models and methods to nowcast and forecast the rainfall at high spatial and temporal scales. This is probably the most important and crucial element that drives the considered type of flash floods.
4. Continue the research activity regarding the hydrological models refining the techniques of their parameterisation even where discharge observation are not available, and using data assimilation techniques in operational context to exploit the availability of remote sensed data (for example soil moisture estimations retrieved from satellite).

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