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An attempt to deal with flash floods using a probabilistic hydrological nowcasting chain: a case study

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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 very relevant improvements in terms of quantitative precipitation forecasts. However, some types of events, those that are intense and localized in small areas, are still very difficult to predict. In many cases meteorological models fail to predict the volume of precipitable water at the large scale. Despite the application of modern probabilistic chains that uses precipitation downscaling algorithms in order to forecast the streamflow, some significant flood events remain unpredicted. This was also the case with an event which occurred on 8 and 9 June 2011 in the eastern part of the Liguria Region, Italy. This event affected in particular the Entella basin, which is quite 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 and medium size basins with an anticipation time of a few hours (2–5) is here presented. This work investigated the "behaviour" of the chain in the cited event and how it could be exploited for operational purposes. The results in this particular case were encouraging.

1 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 (EPS) 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 localized severe events with very high rainfall intensities are often quite impossible to forecast. 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

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have very small spatial scale and are caused and triggered by local atmospheric conditions; as a consequence, often they are not predicted by meteorological models. 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). 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 localization, to the common thunderstorms, however they are often much more persistent, with durations ranging between 4 and 8 h. These characteristics produce high total rainfall quantities 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 damages to significant infrastructures. The danger posed by these events is amplified when they occur in small or very small basins that have a rapid response 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.

These are phenomena which occur with relative frequency in the Mediterranean environment. The risk of having great damages is exacerbated by the fact that, in many cases, urban areas and towns have been established along the coast, often at the mouth of a river or in the rare flat areas along the riverbeds.

The unpredictable nature of the aforementioned storms is a great problem from the point of view of the Civil Protection, 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 cannot be forecasted with the hydrometeorological forecast chains (Cloke and Pappenberger, 2009; Rossa et al., 2010; Silvestro et al., 2011) that are based on precipitation forecast derived from Numerical Weather Prediction Systems (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 impossible to base the streamflow forecast on rainfall observations and rainfall-runoff models, because the response time 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 carry out any kind of action with regard to Civil Protection.

In this work we present the application of a probabilistic hydrological nowcasting system (Silvestro and Rebora, 2012) to a typical case study with the objective of proposing a method to address the issue of unpredictable flash floods. In addition, we give some suggestions on how to use the results of the system for operational Civil Protection purposes, exploiting also modern communication technologies.

The proposed system 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 (like police, fire men) that are on duty near the area under threat by the storm. What we are interested in, is to increase the window time between the forecast time and the instant of the flood event.

The article is organized as follows: in Sects. 2 and 3 the territorial context and the hydrological nowcasting framework are described. The application and the results are discussed in Sect. 4, while in Sect. 5 discussions and conclusions are presented.

2 Application context and measurement systems

The probabilistic hydrological nowcasting system presented in this work has been applied to the Entella Basin in Liguria Region, Italy. Entella basin has a total area of approximately 370 km^2 and it is characterized by a mountainous topology given

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its proximity to the Apennines. The Apennines is a range of mountains with heights between 1000 and 1700 m that rapidly decrease to sea level with relatively high slopes. The concentration time (t_c) of the Entella basin is approximately 5–6 h and its lag time, t_b (the characteristic lag time of the basin is usually defined as the temporal distance between the centre of mass of the hydrograph and the centre of mass of the mean hyetograph) 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 (Boni et al., 2007; Deidda et al., 1999). Moreover, the orographic conformation of the Region often causes local and severe precipitation events, which in some cases, have a significant persistence when compared to the common thunderstorms. These events are typically very difficult to predict with the NWPS.

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

These two factors: proneness of the Region to flash floods 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.

CMIRL (Hydro-Meteorological Monitoring Centre of Liguria Region) 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 of 5–10 min.

A dense automatic micrometeorological network of about 120 rain gauges covers the Region, providing real-time rainfall measurements with time resolution of 5–10 min.

3 Probabilistic hydrological nowcasting framework (PHNF)

The framework (Silvestro and Rebora, 2012) consists mainly of three components: a technique for observed 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. In the following paragraphs the three elements are briefly described. The framework 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 (2011), it uses the algorithm 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 gage 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.

The semi-distributed event scale rainfall-runoff model DRiFt (Giannoni et al., 2000, 2003; Gabellani et al., 2008) uses as its input the rainfall fields generated by PhaSt and produces a streamflow simulation.

In Fig. 1 the flow-chart that represents the scheme of functioning of the hydrological nowcasting framework is reported.

The input data are radar rainfall estimation and rain gauge measurements and the final output is an ensemble of streamflow scenarios with the same probability of occurrence.

Each rainfall scenario is made-up in part of observed rainfall and of forecasted rainfall generated by using PhaSt – in this application the last two hours (See Fig. 2).

4 Case study: 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 Liguria Region was hit by sparse rainfall and some thunderstorms that did not generate particular problems or damages. That event was correctly predicted by the forecasters through 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. Usually, the following models are used: the limited area models 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 weather situation and the analysis of all the available NWPS led to the cessation of monitoring and the return to routine activities during the ordinary office hours.

During the late afternoon and the early evening of 8 June, no rain occurred. However, at approximately 20:00 UTC (22:00 LT) in the eastern part of Liguria Region it started to rain again and a new intense event had begun. It lasted about 6 h and mainly affected the Entella basin and some adjacent catchments. Approximately 100 mm of rainfall occurred in 6 h on the Entella watershed at basin scale. A rain gauge located inside the basin measured 100 mm in one hour 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 $m^3 s^{-1}$) and a peak of 4.72 m at 03:00 UTC on 9 June (which corresponds to approx. 870 $m^3 s^{-1}$).

In Fig. 3, 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 the following we call the latter as "reference hydrograph" (Borga, 2002; Vieux and Bedient, 2004). As can be noted, the rainfall-runoff model well reproduces the behavior 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 1: Nash Sutcliffe coefficient (Nash and Sutcliffe, 1970), Mac Mahon coefficient (Chiew and Mc Mahon, 1994), correlation coefficient (CORR), root mean square error (RMSE) and percentage error of peak flow (PEP). See Moriasi et al. (2007) for information on these statistics values.

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 of 9 June rainfall ceased and the perturbation started to dissipate. The water rose to very high levels 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.

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 realized its severity too late for any meaningful action to be taken.

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

Figure 4 reports the results. Each panel represents the hydrological forecast for the indicated forecast time. The dotted line is the run of the hydrological model using as input only the rainfall observations 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,

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the dashed line represents the "reference hydrograph". The reference hydrograph is obviously not available in real-time, but it was inserted for ease comparison.

The nowcasting chain runs every hour and the results are available with a delay time of approximately 15 min with 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 03:00 UTC. The first sub-panel (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 evidence of these peaks is maintained for the next three hours. 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.

On the other hand, it appears evident that the system signals a warning and it indicates that the meteorological and hydrological forecast used as support to decide the level of 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 reach 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 Machine", it involves a certain number of institutional levels that have different responsibilities and tasks. The machinery has a sort of "inertia" due to predefined procedures and the bureaucracy times. In general, anticipation times of about 12–24 h are needed (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 cite the prefectures, the majors, the municipal Police and fire-fighters. These authorities can carry out a number of emergency

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actions such as 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 looking and analyzing the results of the hydrological nowcasting chain, so it was completely useless. From another point of view this situation was fortunate indeed, in fact, 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 can be 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 registered that data. A similar outcome can be achieved by using e-mail service, eventually adding more data and information to the current system.

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 personnel of Civil Protection and the local authorities.

Moreover, other new technologies, such as smart phones, could also be very helpful in this regard by allowing connection to web monitoring tools or to dedicated applications.

5 Conclusions

This work presented the application of a system of probabilistic hydrological nowcasting (Silvestro and Rebora, 2012) to an event which occurred on the Entella basin on the night between 8 and 9 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 in charge to carry out the forecast of intense events and of floods.

The PHNF is affected by a number of sources of uncertainty, (Carpenter and Georgakakos, 2006; Silvestro and Rebora, 2012; Zappa et al., 2011) otherwise it allows for predicting possible streamflow scenarios with an anticipation time of 3–5 h in basins with very fast response time (1–3 h). This could be a very useful tool when faced with unpredicted/unpredictable intense rainfall events. A few hours is not sufficient time to start up the Civil Protection machine, but it could be enough time to adopt some emergency actions that reduce the effects 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 consequences for hydrologists, meteorologists and Civil Protection personnel that have the responsibilities to forecast and monitor intense rainfall events and for issuing alert messages. It has, in fact, already happened 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 can not predict the flash floods with 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.

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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 probabilistic hydrological nowcasting chain outside the ordinary office hours when, without an issued alert, no monitoring and nowcasting activities are carried out. They are based on commonly used communication technologies such as SMS and e-mails.

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Table 1. Skill estimators calculated in order to evaluate the capability of the model DRiFt to reproduce the observed streamflow.

Parameter	Value	Unit
Nash Sutcliffe Coefficient	0.91	[–]
Mac Mahon Coefficient	0.93	[–]
Root Mean Square Error	0.65	[$m^3 s^{-1}$]
Peak flow Percentage Error	9	[%]
Correlation Coefficient	0.96	[–]

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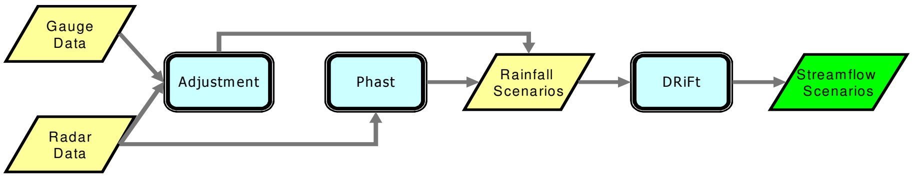

Fig. 1. Flow chart that represents the elements of the hydrological nowcasting chain and their input/output inter-connections.

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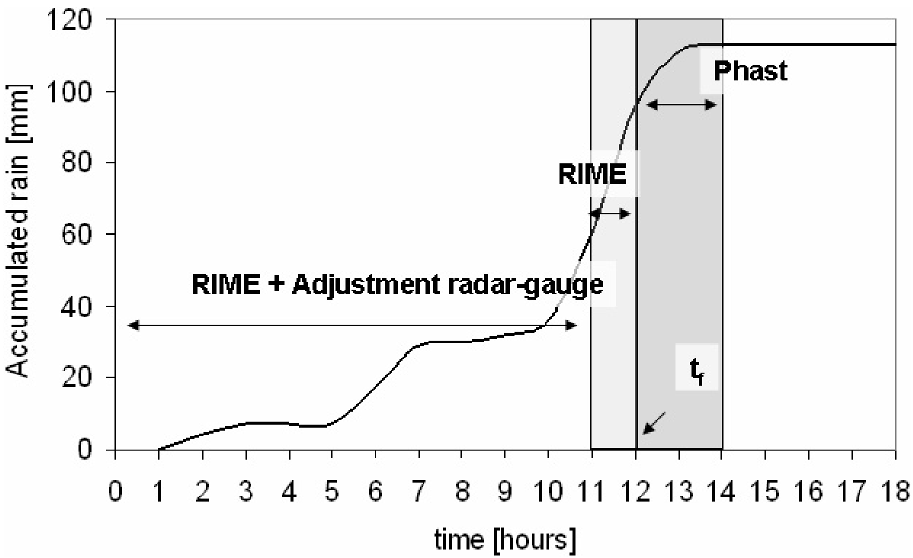

Fig. 2. Reference schematization for the building of a rainfall scenario. The first part is generated using the algorithm RIME and the radar-gauge adjustment, the rainfall of the hour before the forecast time (t_f) is estimated using only radar observations (RIME) and the forecasted part using the algorithm PhaSt.

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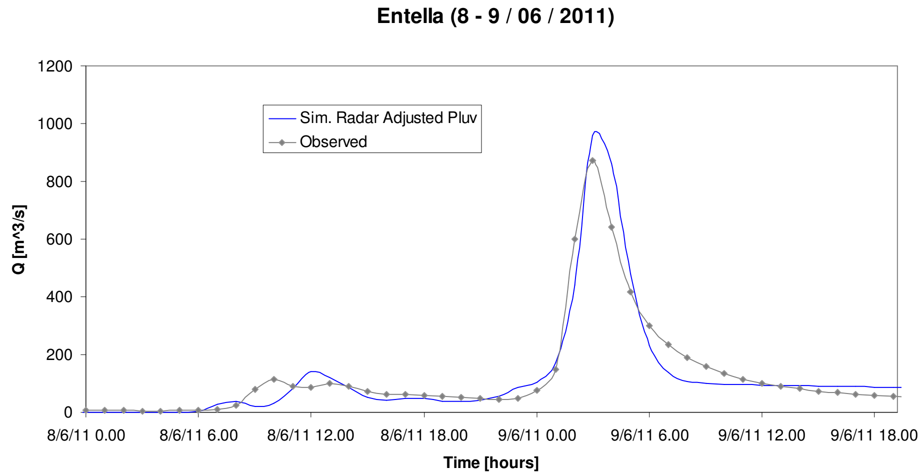

Fig. 3. Comparison between the observed hydrograph and the hydrograph obtained using radar rainfall estimation adjusted with rain gauge observations as input to rainfall runoff model is shown.

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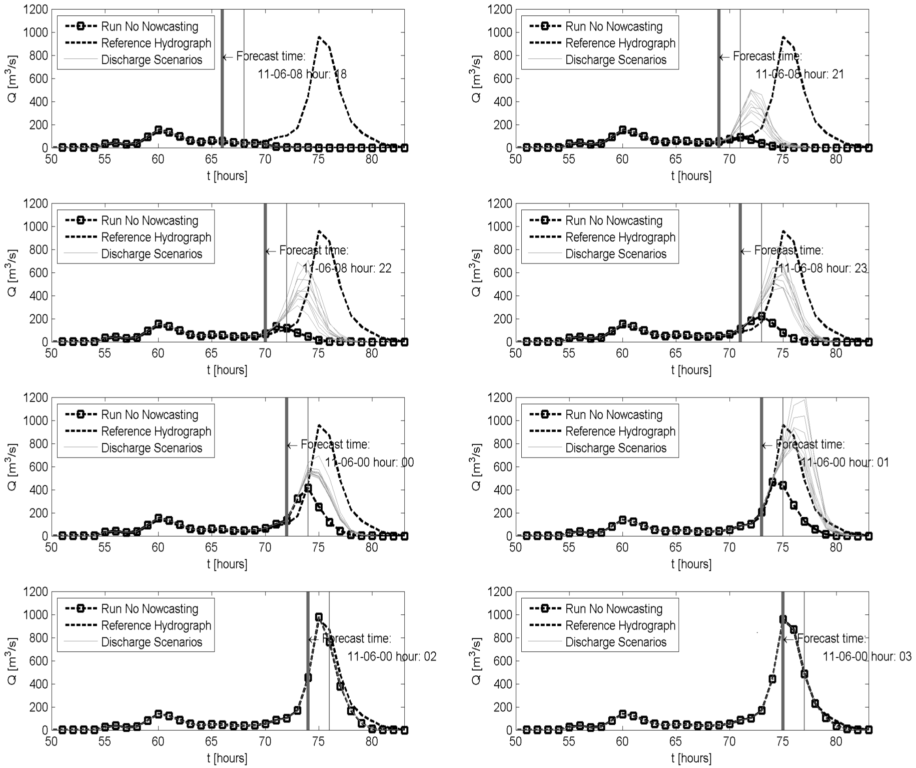

Fig. 4. Results of hydrological nowcasting framework for Entella Basin closed at Panesi (Area = 364 km^2). The event on 08–09 June 2011 is shown. Each panel shows the forecast obtained at the indicated forecast time. The dotted line is the run of the hydrological model using as input only the observed rainfall 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 (2 h) rainfall as input to the rainfall runoff model, the dashed line represents the "reference hydrograph".

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Hydrological nowcasting to deal with flash floods: a case study

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