Flood forecasting using a coupled hydrological and hydraulic model (based on FVM) and high-resolution meteorological model

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Abstract. A forecasting systems based on the coupling of meteorological, hydrologic, hydraulic and risk models is used to minimize the risks associated to water scarcity and flooding. The fulfilment of such complex forecasting chains can allow obtaining information of the most plausible scenarios of water and risk management up to 96 hours ahead. In the present work, flood forecasting was carried out for different events in the upper La Muga basin (including the reservoir), within the European project "Flood Risk Assessment and Management in the Pyrenees" (http://pgri-epm.eu/). The main purpose of the project was to develop a method to optimize the management of flood scenarios in order to minimize the flood risk while maximizing the water resources. The good fit of all the models, obtaining the forecasting rainfall and converting the overland flow in water levels in the reservoir, can give tools and important information to the authorities or dam managers for suitable management during the extreme rainfall and flood events.

1. Introduction

The implementation of real-time forecasting systems based on the coupling of meteorological, hydrologic, hydraulic and risk models is paramount over the topographically complex Spanish Mediterranean region. New strategies for the optimized management of water resources are needed in order to minimize the risks associated to water scarcity and flooding. The fulfilment of such complex forecasting chains can allow obtaining information of the most plausible scenarios of water and risk management up to 96 hours ahead.

Nowadays, high-resolution numerical weather prediction (NWP) models render quantitative precipitation forecasts (QPFs) that capture realistically the initialization and subsequent development of convective precipitation systems. These structures are related to small-scale dynamics and are strongly modulated by local orography [1-2]. Therefore, convection-permitting NWP models are run at suitable spatial and temporal scales so as to properly solve precipitation over small-to-medium sized catchments. Meteorological outputs can directly be used as inputs for hydrological models to calculate the rainfall-runoff without the need of implementing any additional regionalization procedure [3-5]. Furthermore, flood risk management also requires hydraulic modelling in order to determine the flooded area and the hydrodynamics with the aim to evaluate the flood hazard, and so the flood risk. Thus, three processes are involved in the whole modelling chain.

In parallel way, hydrologic and hydraulic coupled models have had a fast development in the recent years [6-9]. These models have the capability to simulate the rainfall-runoff process and flood propagation simultaneously taking into account different hydrological process (as spatial and temporary variations in the rain, losses methods, etc.) and hydraulic process (e.g. distributed land uses, hydraulic structures, etc.). Hence, the flood forecast is reduced to a meteorological modelling and a hydrological-hydraulic coupled modelling.

In the present work, flood forecasting was carried out for different events in the upper La Muga basin (including the reservoir), within the European project "Flood Risk Assessment and Management in the Pyrenees". The main purpose of the project was to develop a method to optimize the management of flood scenarios in order to minimize the flood risk while maximizing the water resources. An accurate simulation of the rainfall generation (meteorological modelling), the rainfall-runoff processes (hydrological modelling) and the flood propagation (hydraulic modelling), is therefore needed.

2. Methods and Materials

2.1. Meteorological modelling

QPFs have been provided by the Weather and Research Forecasting (WRF) model [10]. The WRF model has been configured with a single computational domain of 767x575 grid-points centred over the Western Mediterranean region and spanning the entire Spanish Mediterranean region (Fig. 1). The horizontal spatial resolution is 2.5 km, while the vertical has been discretized by using 50 eta-levels. The model time-step integration time-step is 12 s. This high-resolution spatial and temporal numerical set-up aims at explicitly resolving deep convection systems [11-13]. The same model configuration is used by the Group of Meteorology at UIB when issuing daily weather forecasts (http://meteo.uib.es/wrf).

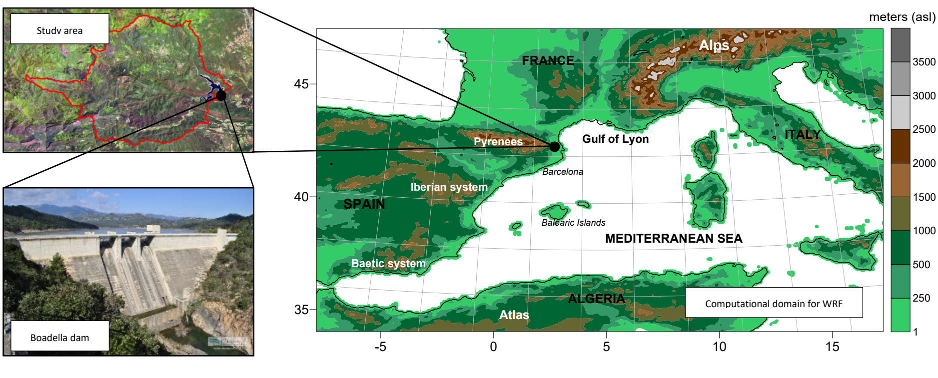

Fig. 1. Configuration of the computational domain used for the WRF numerical simulations (right), the study area (upper-left) and the Boadella dam (lower-left).

Microphysics processes have been parameterized using the WRF single-moment 6 class numerical scheme (WSM6; [14]). The planetary boundary layer has been modelled by the Mellor-Yamada-Janjic order 1.5 scheme (MYJ; [15]). Long- and short wave radiation have been parameterized by using the Rapid Radiative Transfer Model (RRTM; [16]) and the

Dudhia models [17], respectively. Finally, the NOAH surface model [18] has been employed in the WRF simulations. Finally, forecast hourly-accumulated precipitation was obtained as an output in raster format.

2.2. Hydrological and hydraulic modelling

A coupled two-dimensional distributed hydrologic and hydraulic model was developed on the basis of Iber [19], and was used to transform the rainfall data into overland flow and, in the same time, for the flood propagation. The model solves the full two-dimensional Shallow Water Equations (2D-SWE) using the Finite Volume Method (FVM) [20-21] based on Roe scheme [22]. The model has been enhanced to be used as a hydrological model by adding the precipitation (R) and losses (f) processes as new source terms on the mass conservation Equation 1:

$$\frac{\delta h}{\delta t}+\frac{\delta q_x}{\delta x}+\frac{\delta q_y}{\delta y}=R-f \quad (1)$$

where h is the water depth, q_x and q_y are the two components of the unit discharge, R and f are the source terms that represents the rain and the infiltration process respectively.

The model has the capability to simulate the rainfall-runoff process taking into account the rainfall variations in time and in space (e.g. Thiessen polygons, radar data), different land uses (e.g. to consider bed roughness and losses method) and some of the most used infiltration methods as simplified losses process (f). In addition, rainfall in raster format can be used as input, which allows representing properly the rainfall spatial variability. As shown in section 3.2, three different rainfall data sources have been used in the study case.

Looking for an accurate and robust tool, the new DHD numerical scheme [6] based on the FVM was used in order to solve more efficiently and properly the 2D-SWE.

3. Study case

3.1. La Muga basin

The flood forecasting study was carried out in the upper part of La Muga basin (181.2 km^2), located in the northeast of the Iberian Peninsula (Fig. 1). It is characterized by a typical Mediterranean climate, with heavy rain events concentrated in a few days or hours, and rural land uses characterized by large dense-forest extensions, low storage capacity and low permeability [23]. The reservoir (Boadella Dam, 61 hm^3) was also included in the model in order to represent the variation of the water elevation during the simulation.

3.2. Rain events

The selected episodes are characteristic of the upper tail of the precipitation distribution frequency found over the eastern Spanish Pyrenees. These episodes are responsible for the majority of floods affecting the region, including La Muga basin. In fact, the rain gauges inside this catchment registered total rainfall amounts higher than 125 mm for all the episodes. In particular, the observed cumulative precipitations were very close or above 200 mm in three of them.

The whole set of numerical experiments have been run over a 48 hours forecasting period, starting at 00 UTC on the day of the beginning of the intense precipitations. Additional 48 hours forecasts have been performed in successive days for the episodes lasting more than 2 days. Initial and lateral boundary conditions have been obtained from the daily deterministic forecasts issued by the European Centre for Medium-Range Weather Forecasts (ECMWF). These products have a spatial resolution of 10 km, whereas lateral boundary conditions have been updated every 3 hours.

3.3. Rainfall-runoff process

The coupled hydrologic and hydraulic modelling was performed using the same configuration for all events and looking for balancing the results accuracy and the computational time. The study area was discretized spatially by triangular mesh elements of 30 to 1000 meters-size using high-resolution 2x2 meters-size DTM (Fig. 2). The lad uses were taken into account with a spatial distributed map (Fig. 2) based on CORINE Land Cover 2012 project [24].

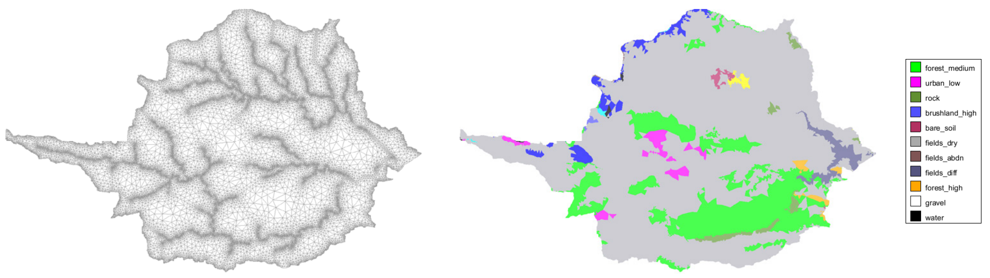

Fig. 2. Properties of the numerical model. Calculation mesh (left) and land uses (right).

The bed roughness was computed by the Manning formula which values varies from 0.02 to 0.11 $s \cdot m^{-1/3}$, following the reference literature [25]. SCS losses method [26] was used in order to perform the rainfall-runoff process with a different Curve Number (CN) for each rain event. Both were calibrated by means of *ad hoc* calibration process using two different rainfall sources: a rain gauge (non-distributed spatially) and a meteorological radar (distributed spatially).

In addition, DHD numerical scheme and special treatment of the wet-dry waterfronts (0.0001 m) was implemented in order to warranty suitable and efficiency simulation. This configuration allowed to simulate events lasted from 2 to 6 days on a reduced computational time (1.5 to 4 hours). Thus, the model can be used suitably as a flood-forecasting tool.

The flood modelling with rain-forecast data was performed with the first 24 h of each experiments, i.e. there were no overlap between the last 24 h of the day *n* and the firsts 24 h of the day *n+1*.

4. Results

4.1. WRF model performance

Daily QPFs were compared against rain gauge (point scale) and radar (whole Catalonia) observations data from Servei Meteorologic de Catalunya (SMC). QPFs have been bilinearly interpolated at each rain gauge and radar cell-point [27]. Note that for the March 2011 and March 2013 events, weather radar data are not available.

A general underestimation has been found in the temporal-averaged simulated precipitation amounts at point scale, but a general overestimation of the spatial-averaged cumulative rainfalls at large scale for all Catalonia, and in consequence for the study area. Nevertheless, in general the spatial correlations were high (RMSE < 40 mm; r > 0.5),

 https://doi.org/10.1051/e3sconf/20184006028

illustrating anew the benefits of using permitting-convection NWP models for simulations realistic cumulative precipitations, and thus for flood forecasting purposes (Fig. 3), resulting in an excellent predictive guidance as input for the hydrologic model.

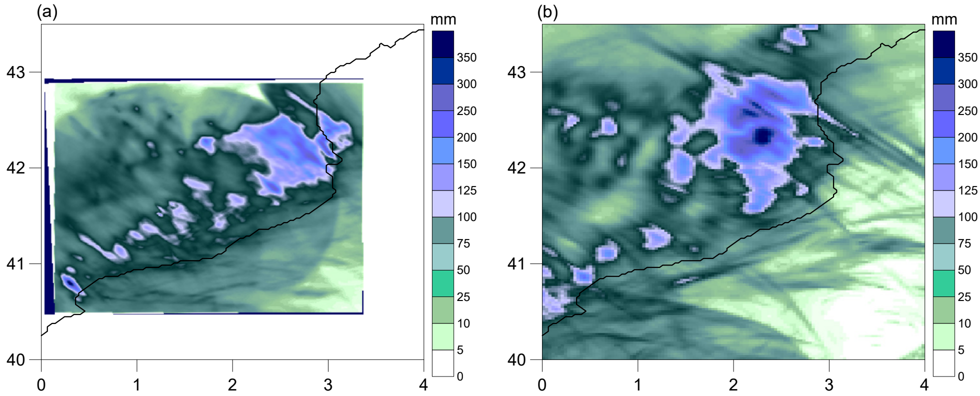

Fig. 3. 48 hours accumulated precipitation starting on November 2014, 29th at 00 UTC according to the (a) radar-based observations, and (b) WRF deterministic experiment.

4.2. Coupled hydrologic-hydraulic modelling

The results of the flood forecast were evaluated through the water elevation (WE) in the Boadella reservoir. Figure 4 shows the evolution of the observed WE (dotted line) compared with the simulated WE (solid line). The grey bars represent rain intensities measured in the Boadella dam gauge station.

For all the study cases, the shape of the forecasting water evolution is quite similar than the observed data. The maximum differences presented were presented for 2014 event, which forecasted WE was 0.9 m higher than the observed one. Nevertheless, the relative error was less than 1 % in all simulated cases. The March 2011 event presents lack of data (voids) and some errors (jumps), as a result some differences in the WE were produced at the beginning of the simulation. Furthermore, rainfall antecedents forced to choose a high CN value (close to 100: almost no infiltration) which was slightly far from mean values for this kind of catchment (between 50 and 80 depending on the season). In March 2015 the forecasted rainfall was practically negligible from noon of the fourth day simulated, thus the simulation was finished on the third day (similar issues occurred for the 2011 event). Nevertheless, the trend of the forecasting WE matches accordingly to the observed WE in all the analysed events.

In general, the numerical modelling represents properly the hydrological response of the catchment. In addition, the importance of using spatially and temporarily distributed rainfall data was clearly observed in November 2014 event, where the WE simulated using the rain gauge information during the calibration process was highly underestimated (+2 m of difference). A similar behaviour was detected for the March 2015 event, but in a lower quantity (less than 1 m). In these cases, the calibration process of the CN was only made by means of the radar data.

Knowing the evolution of the water elevation in the dam is a useful information for the dam managers. The current model is able to simulate daily events in few hours in suitable way thanks to its configuration and the numerical scheme (DHD), so it possible to design hydrographs and evaluate its consequences downstream few hours or days before the rain event occurs.

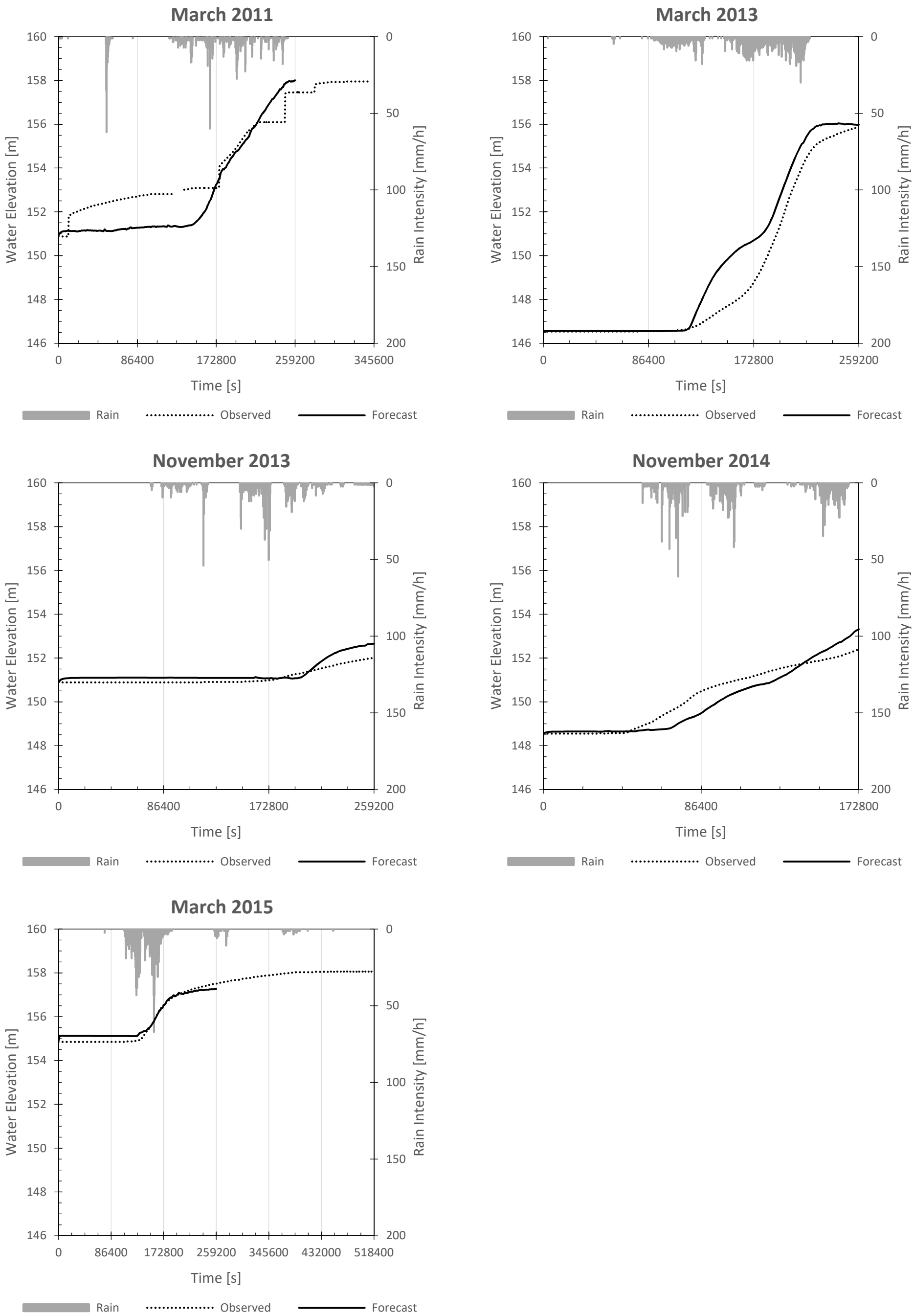

Fig. 4. Results of the simulations. Representation of the evolution of the water elevation (WE) in the Boadella reservoir for the observed (dotted line) and forecasted (solid line) event.

5. Conclusions

In the present work, a methodology for flood forecasting water levels in Boadella dam (La Muga basin) up to 48 hours ahead has been evaluated through five extreme rainfall events in a Mediterranean basin. For that, high-resolution rainfall forecasting data (QPFs by WFR) have been used to calculate the flood forecast by means of a hydrological and hydraulic coupled model based on FVM (Iber).

Weather forecasts have been checked with non-distributed (rain gauge) as distributed (radar) spatially and temporarily data (radar). In spite of a slight underestimation in the temporal-averaged simulated precipitation being found at local scale, in general suitable correlations for the cumulative rainfall have been obtained over the catchment of interest.

In general, the meteorological and hydrologic-hydraulic modelling performed in La Muga basin fits well to properly represent the water elevation in the reservoir, giving tools and important information to the authorities or dam managers for suitable management of the extreme rainfall and flood events.

Within this context, the use of QPFs to feed hydrologic-hydraulic coupled models could significantly enhance the assessment and management of water resources of dry and wet weather extremes in Mediterranean areas.

This work has been partially funded by the Pyrenees – Mediterranean Euroregion under the PGRI-EPM Project, under the call "Water Resources – Risk Management (Floods, Droughts, Submersion)". More info at http://pgri-epm.eu/.

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