Hydro-meteorological modeling study of a flash-flood event over Catalonia: Sensitivities of the Llobregat river response to the rainfall uncertainty

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Purpose

During the early morning on 10 June 2000, the Catalonia region was affected by a hazardous convective rainfall episode which produced a large increase on flow regimes in many internal catchments of the region. The present modeling study is focussed upon the Llobregat basin, the biggest internal catchment with a drainage area of 5040 km2. The first objective of the study is the characterization of the watershed hydrological response to this flash-flood event based on rain-gauge data and HEC-HMS runoff model. The HEC-HMS model has been calibrated using five episodes of similar torrential characteristics, and the effects of the spatial segmentation of the basin and of the temporal scale of the input rainfall field have been examined.
These kind of episodes present short recurrence intervals in Mediterranean Spain and the use of mesoscale forecast driven runoff simulation systems for increasing the lead-times of the emergency management procedures is a valuable issue to explore. The second objective uses NCEP and ECMWF analyses to initialize the MM5 non-hydrostatic mesoscale model in order to simulate the 10 June 2000 flash-flood episode with appropriate space and time scales to force the runoff model.
The final objective analyses the sensitivity of the catchment's response to the spatial and temporal uncertainty of the rainfall pattern based on an ensemble of perturbed MM5 simulations. MM5 perturbations are introduced through small shifts and changes in intensity of the precursor upper-level synoptic scale trough. Main results indicate that: **(1)** an optimum configuration of the runoff model can be clearly defined that best adjusts the simulated basin's hydrological response to observed peak discharges, their timing and total volume; **(2)** the MM5-control driven runoff simulation shows a reasonable reproduction of the observed discharge at the basin's outlet and appears to be a suitable tool for the hydro-meteorological forecasting of flash-floods in the Llobregat basin as a whole; **(3)** the ensemble of perturbed runoff simulations does not exhibit any relevant degradation of the forecast skill and some of the members even outperform the control experiment at different stream-gauges locations.

Introduction

Case study area

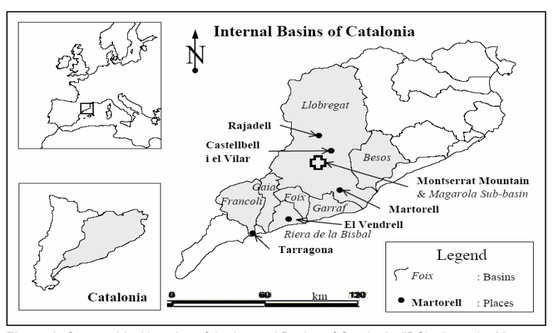


Figure 1. Geographical location of the Internal Basins of Catalonia (IBC) where the Montserrat flash-flood event wad produced. Several catchments (shaded) and locations affected by the episode are indicated

The Llobregat basin is the most important of the internal hydrographic catchments in Catalonia in terms of size, river length, mean flow and population living inside. It is composed of the Llobregat river and its main tributaries, the Anoia and the Cardener. Llobregat basin extends from the Pyrenees through the Pre-Pyrenees and the central depression. The last section of the river crosses the Mediterranean orographic systems, formed by two mountainous alignments almost parallel to the coast line: the pre-coastal and the coastal range, consisting of small altitude mountains. The basin has a drainage area of 5040 km^2 and a maximum length close to 170 km.

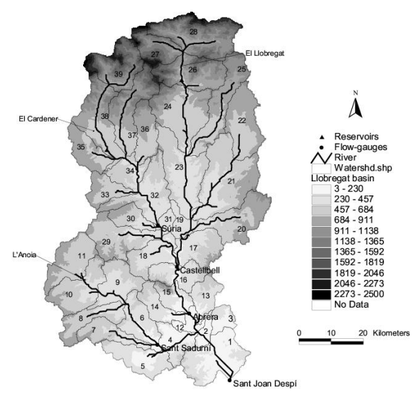


Figure 2. Digital terrain model of the Llobregat river basin. It has a cell size of 50 m and displays the basin division (numbered), tributaries, stream-gauges (circles) and reservoirs (triangles)

The rain and stream gauge networks

On 10 June 2000, heavy rainfall took place over the north-eastern part of Spain and the most intense episode affected the whole of the Internal Basins of Catalonia (IBC). An analysis of the pluviometric evolution of the episode used 5-minute rainfall data recorded at 126 stations inside the IBC. These stations belong to the Automatic Hydrological Information System (SAIH) network of the Catalan Agency of Water (ACA). Out of the 126 stations, about 40-50 lie inside the Llobregat basin or near its boundaries.

Runoff in the Llobregat basin was recorded in five flow gauges located in: (i) **Súria** town, on the Cardener river, with a drainage area of 940 km^2; (ii) **Sant Sadurní d'Anoia** city, on the Anoia river, with a drainage area of 736 km^2; and (iii) **Castellbell** (3340 km^2), (iv) **Abrera** (3587 km^2) and (v) **Sant Joan Despí** (4915 km^2) towns along the Llobregat river. During the episode, 5-minute runoff measurements were collected, jointly with the rainfall records, for the SAIH database.

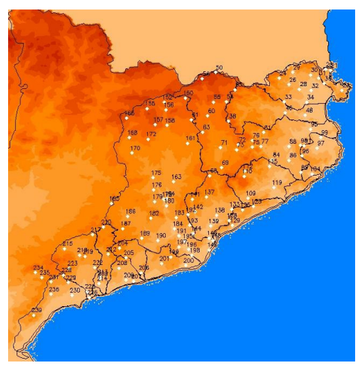


Figure 3. Distribution of the rain-gauges from the Automatic Hydrological Information System (SAIH) in the IBC. It includes a total of 126 automatic rainfall stations distributed over an area of 16000 km^2 (Llobregat basin is enhanced)

The hydro-meteorological chain

HEC-HMS model set-up

HEC-HMS is a physically based model. A semi-distributed and event-based configuration is used. The loss rate is calculated using the Soil Conservation Service Curve Number (SCS-CN). A synthetic unit hydrograph (UH) model provided by SCS is used to convert precipitation excess into direct runoff. The flood hydrograph is routed using the Muskingum method. Model's calibration is carried out using five episodes of similar extraordinary characteristics to the Montserrat case of study.
Calibration of the infiltration parameters and the flood wave celerity for the main streams combines a manual procedure and an automatic procedure, using as an objective function the peak-weighted root mean square error and applying the univariate-gradient search algorithm method. The calibrated parameters were then used to run HEC-HMS, in a single evaluation test, for the 'Montserrat' case during a 96h simulation, from 9 June 2000 at 00:00 LT to 12 June 2000 at 24:00 LT, with a 10 minute time-step. The previous calibration process and subsequent rain-gauge driven runoff simulations have been repeated for three spatial disaggregations of the catchment (21, 39 and 60 subbasins) with 1h accumulated rainfall discretization and varying temporal resolutions of the incoming rainfall data (30-min, 1-h and 3-h) with a 39 subbasins segmentation, in order to explore the sensitivities of the Llobregat basin and find an optimum configuration of the modelling system.

	NSE 21-sb	% EV 21-sb	NSE 39-sb	%EV 39-sb	NSE 60-sb	%EV 60-sb
Súria	0.64	23.9	0.84	4.8	0.50	-33.7
Sadurní	0.46	11.6	0.67	12.4	0.50	-23.3
Castellbell	0.64	12.3	0.68	14.5	0.78	-5.4
Abrera	0.91	12.3	0.93	12.6	0.89	-2.1
Despí	0.82	3.6	0.84	1.1	0.76	8.4

Table 1. NSE efficiency criterion and percentage of error in volume (%EV) for the Montserrat event. The SAIH rain-gauge driven simulations are carried out with 3 different basin segmentations (21, 39 and 60 subbasins) at the five stream-gauges indicated. Hourly accumulated rainfall is used in all cases.

	NSE 30-min	% EV 30-min	NSE 1-h	%EV 1-h	NSE 3-h	%EV 3-h
Súria	0.91	-12.7	0.84	4.8	0.80	-9.9
Sadurní	0.58	23.5	0.67	12.4	0.64	12.3
Castellbell	0.62	18.5	0.68	14.5	0.39	16.0
Abrera	0.91	16.0	0.93	12.6	0.87	13.0
Despí	0.73	-0.5	0.84	1.1	0.90	2.4

Table 2. NSE efficiency criterion and percentage of error in volume (%EV) for the Montserrat event. The SAIH rain-gauge driven simulations are carried out with 3 different time-scale discretizations (30-min, 1-h and 3-h) at the five stream-gauges indicated. 39 subbasins segmentation is used in all cases.

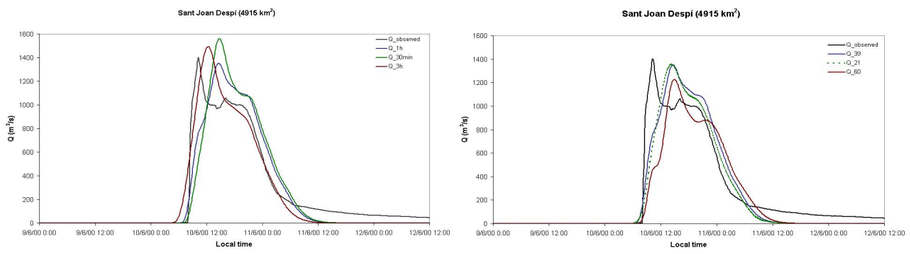


Figure 4. SAIH rain-gauge driven runoff discharge at Sant Joan Despí for the different spatial and temporal discretizations

MM5 model set-up

MM5 is a non-hydrostatic, high resolution and short-range numerical model used to perform the meteorological simulations. Simulations are designed using 24 vertical sigma-levels and three spatial domains with 82 x 82 grid points with horizontal resolutions of 54, 18 and 6 km respectively. The interaction between the domains follows a two way nesting strategy. To initialize the model and to provide the time-dependent boundary conditions, NCEP and ECMWF meteorological grid analysis are used. **MM5-NCEP** simulation is updated every 12 hours with a 2.5º spatial resolution. **MM5-ECMWF** simulation uses the analysis with a spatial resolution of 0.3º and an update frequency of 6 hours. In both cases the analyses on the MM5 model grid are improved using surface and upper-air observations. To parameterise moist convective effects the Betts-Miller cumulus scheme is used in the large domain and the Kain-Fritsch parameterization scheme in the intermediate domain. No convection scheme is used in the inner one owing to the high horizontal resolution. Since it is debatable whether a 6 km resolution domain can resolve convection appropriately without a convection scheme, an additional experiment has been designed. The **MM5-NCEP-4D** simulation, coincides with MM5-NCEP except that it applies the Kain-Frist scheme for the third domain. It also incorporates a fourth domain of 2 km horizontal resolution forced in two way mode, in which convection is fully explicit.

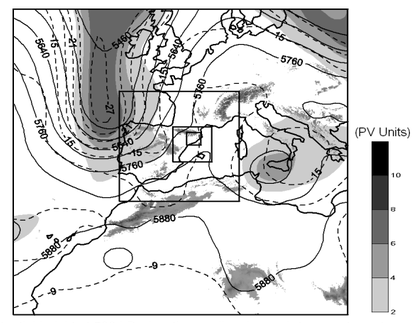


Figure 5. Configuration of the 4 computational domains used for the MM5 numerical simulations and MM5-NCEP initial state, showing geopotential height at 500 hPa (continuous line, in gpm), temperature at 500 hPa (dashed line, in ºC) and isentropic PV on the 330 K surface (shaded, according to scale) at 9 June 2000 0000 UTC

The invertibility principle of Ertel potential vorticity (PV) is applied to generate the ensemble of perturbed simulations in order to study the sensitivity of the Montserrat hydro-meteorological event to uncertainties in the precise representation of the upper-level precursor trough (fig. 5) since small scale aspects of the circulation are propitious to analysis or forecast errors. The piecewise PV inversion scheme is used as a clean approach to manipulate the upper-level synoptic trough in the model initial conditions. This method has already shown its value for assessing the predictability of flash flood events in the western Mediterranean area. Using the NCEP-derived initial conditions, the upper-level trough intensity is perturbed ± 5\% (simulations **-5\% PV** and **+5\% PV**) and its position is displaced ± 54 km along the zonal direction (experiments **WEST** and **EAST**). This short ensemble of simulations is a approximation to the problem of incorporating the spatio-temporal uncertainty of the rainfall forecast into a medium size catchment like the Llobregat basin. The whole set of MM5 simulations comprises a 36 hour period, from 9 June 2000 at 00:00 UTC to 10 June 2000 at 12:00 UTC, after the end of the rainfall event in Catalonia.

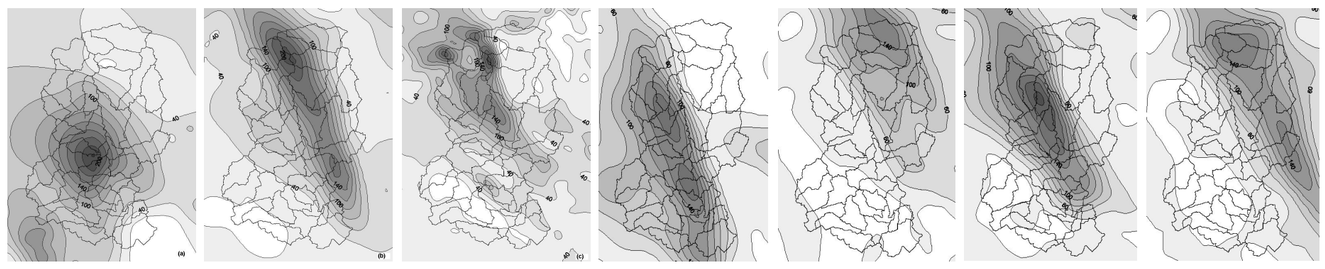
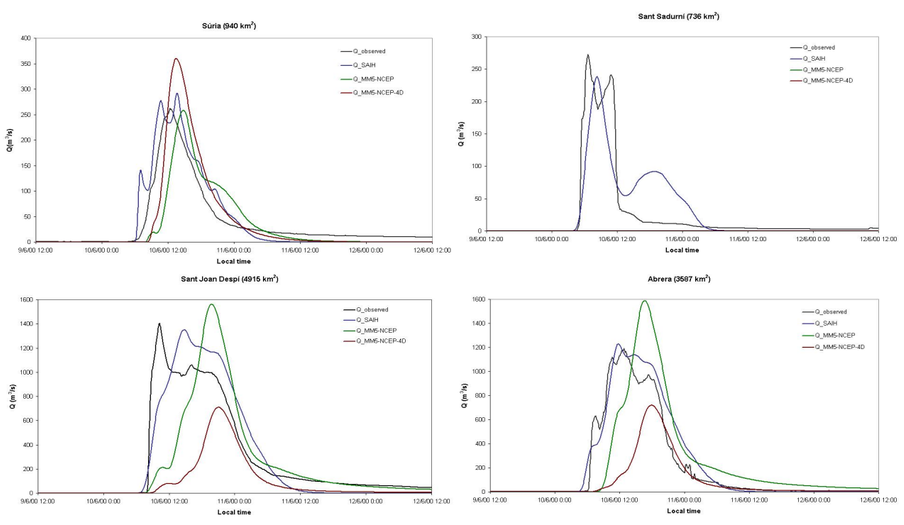


Figure 6. Spatial distribution of accumulated rainfall during the 'Montserrat' event in the Llobregat basin from: SAIH rain-gauges, MM5-NCEP, MM5-NCEP-4D, -5%PV, +5%PV, WEST and EAST simulations

SAIH, MM5-NCEP and MM5-NCEP-4D driven runoff simulations

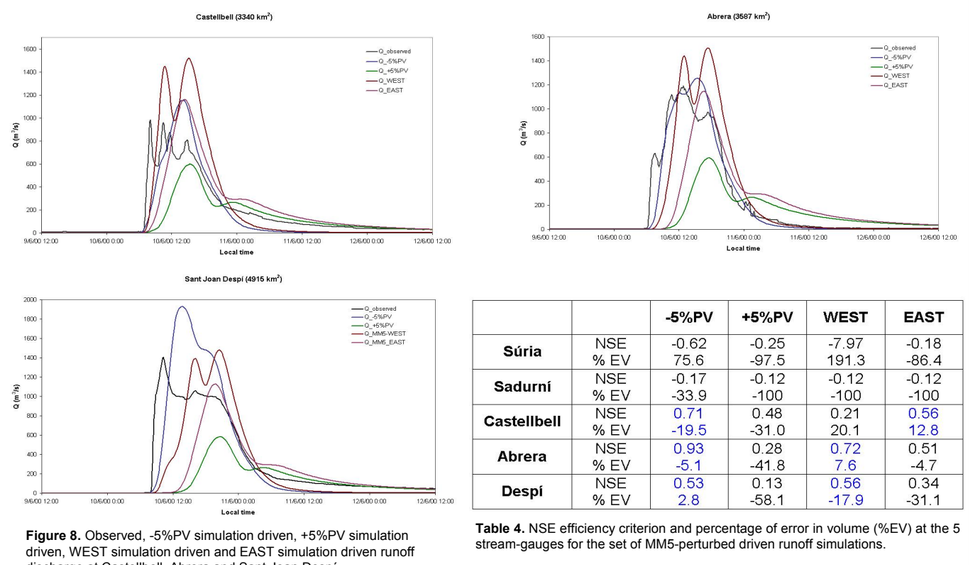


	NSE SAIH	% EV SAIH	NSE NCEP	%EV NCEP	NSE NCEP-4D	%EV NCEP-4D
Súria	0.84	4.8	0.60	-16.9	0.67	-2.3
Sadurní	0.67	12.4	-0.12	-100	-0.12	-100
Castellbell	0.68	14.5	0.19	35.5	0.47	-49.2
Abrera	0.93	12.6	0.58	15.9	0.36	-55.8
Despí	0.84	1.1	0.51	-12.0	0.21	-66.8

Table 3. NSE efficiency criterion and percentage of error in volume (%EV) at the 5 stream-gauges for the SAIH rain-gauge driven and MM5-NCEP driven runoff simulations with 3 (NCEP) and 4 domains (NCEP-4D).

Figure 7. Observed, SAIH rain-gauge driven, and MM5-NCEP simulation driven runoff discharge at Súria, Sant Sadurní, Castellbell, Abrera and Sant Joan Despí

Ensemble of MM5-perturbed driven runoff simulations



		-5%PV	+5%PV	WEST	EAST
Súria	NSE	-0.62	-0.25	-7.97	-0.18
	% EV	75.6	-97.5	191.3	-86.4
Sadurní	NSE	-0.17	-0.12	-0.12	-0.12
	% EV	-33.9	-100	-100	-100
Castellbell	NSE	0.71	0.48	0.21	0.56
	% EV	-19.5	-31.0	20.1	12.8
Abrera	NSE	0.93	0.28	0.72	0.51
	% EV	-5.1	-41.8	7.6	-4.7
Despí	NSE	0.53	0.13	0.56	0.34
	% EV	2.8	-58.1	-17.9	-31.1

Figure 8. Observed, -5%PV simulation driven, +5%PV simulation driven, WEST simulation driven and EAST simulation driven runoff discharge at Castellbell, Abrera and Sant Joan Despí

Table 4. NSE efficiency criterion and percentage of error in volume (%EV) at the 5 stream-gauges for the set of MM5-perturbed driven runoff simulations.

- Most appropriate coherence between the spatio-temporal scales of the flash-flood that the rain-gauge network is capable to resolve is for the **39 subbasins and 1-h precipitation discretizations** in the configuration of the hydrological model
- **Rain-gauges simulation:** indices indicate a goodness-of-fit in time peak and volume in all stream-gauges
- **MM5-NCEP simulation:** best performance for outflow at the basin outlet, amount of precipitation and hourly precipitated volume ⟶ **control simulation**

- Different members of the ensemble outperform the control simulation at different stream-gauges
- The set of perturbed driven runoff simulations does not exhibit any remarkable degradation of the forecast skill at large scale exempting the MM5-ECMWF element
- Llobregat basin shows relatively insensitive to forecasted precipitation patterns with spatial shifts of few tenths of km or temporal changes around 1-2

Conclusions and further remarks

- It seems feasible to introduce driven runoff simulations by NWP mesoscale models over the Llobregat basin
- The used methodology can be automated to obtain short-range runoff forecasts driven by high resolution mesoscale predictions available in real-time (e.g. **http://mm5forecasts.uib.es**)
- A multi-analysis ensemble prediction system (EPS) to account for the forecast variance associated to the initial conditions uncertainty can avoid poor detection of a flash-flood event from a deterministic hydro-meteorological system
- None of the experiments was able to reproduce adequately the flow increase in l'Anoia catchment (736 km2): forecasting limitations for smaller hydrological scales

References

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