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Evaluation of a conceptual distributed rainfall-runoff model in the Besòs catchment in Catalunya using radar information

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Abstract. A weather radar network is covering Catalunya, a region affected by Mediterranean climatological features and thus by severe flood events. The Besòs (1000 km^2) is one of the most important catchments of this country from a socio-economic point of view. Inside a general framework to develop an integrated system for hydrometeorological forecasting, the basics of the conceptual distributed rainfall-runoff model TOPDIST are shown. This hydrological model is able to use radar rainfall estimates and it seeks to work in real time operation, using a rainfall short term forecasting based on radar advection methods. Nowadays, it is integrated in the Besòs Riverside Park Flood Warning System (SAHBE). In this work some events are analysed from the point of view of real time operation, and also from the rainfall field input, in particular the rainfall forecasts.

1 Introduction

Floods are the most important natural hazard in the Mediterranean area, and warning systems providing forecasts in many sensitive risky points are needed. Nevertheless, some particularities of this area (meteorology, morphology, urbanisation degree) make the anticipation of floods difficult. Particularly, high variability of rainfall exists both in time and space, and river basins have in general small response times. Therefore, hydrometeorological models taking into account the rainfall variability should play an important role in flood warning systems in Mediterranean basins. In this sense, radar information is a key element in flood forecasting. A number of works have shown that this is an essential information to provide accurate flow estimates using a rainfall-runoff model, even when a dense raingauge network exists. Furthermore, radar information is interesting to estimate the rainfall short term forecasting needed to produce reliable flow estimates.

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A weather radar network is covering Catalunya (32 000 km^2): nowadays 2 radar systems are operative, and 2 more will be installed during the next two years. Additionally, a network of telemetered raingauges and stage sensors are also in operation in the frame of the SAIH Spanish national program. Inside a general framework to develop an integrated system for hydrometeorological forecasting mainly based in this radar network, this paper is focused on the evaluation of a rainfall-runoff model working in real-time, in particular its sensitivity to the rainfall field forecasts used.

2 The SAHBE warning system in the Besòs catchment

The Besòs catchment (1024 km^2) crosses the Barcelona metropolitan region, and it is a typical example of a Mediterranean complex catchment. It is quite heterogeneous, from forested mountains over 1000 m to rural planes that have been suffering a continuous urbanisation process during last decades. It is instrumented nowadays by several telemetered sensors (see Fig. 1), and the area is well covered by the Spanish Weather Service (INM) radar of Puig de les Agulles (the maximum distance to the radar site is 60 km), and also covered by the new Catalan Weather Service (SMC) radar of Puig d'Arques (at a range between 50 and 90 km). Considered last years one of the most degraded rivers in Europe, the Besòs is now inside a recuperation program. The urban sector crossing Barcelona to the outlet is now suffering the restructuring of the delta zone in a modern urban area and the construction of a riverside park. These uses have motivated the development of the SAHBE, a flood warning system operated by CLABSA (the sewer management company of Barcelona city). In the SAHBE Control Centre, supervisors have access to TV cameras, radar images, raingauge information, permanent contact with weather services, and finally the runoff estimates provided by different hydrological models. With all this information, but having more confi-

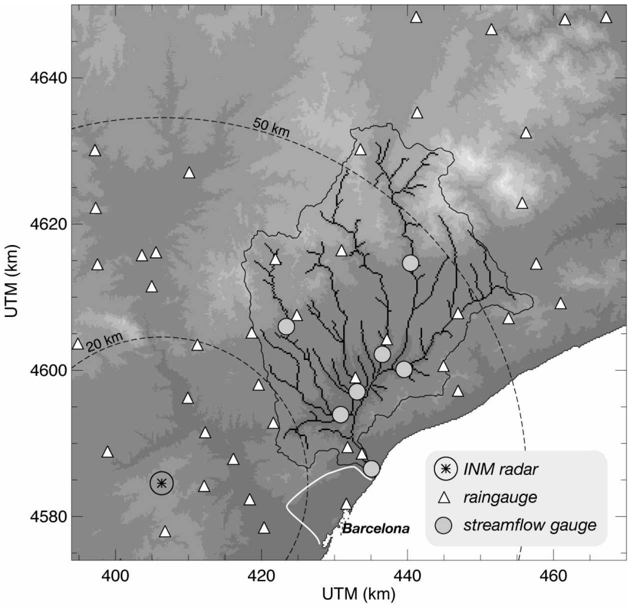

Fig. 1. The Besòs catchment and the hydrological instrumentation used in this study.

dence in the model results, supervisors activate different levels of warning. One of the models of the system is TOPDIST, recently implemented jointly with a radar based short term rainfall forecasting, both now in a testing period.

3 The rainfall-runoff model

TOPDIST is a grid based model used for rainfall runoff transformation in a watershed (Corral et al., 2000). It is able to incorporate distributed rainfall (from radar), and its structure easily allows to provide runoff information in different points of the basin. The catchment is split into hydrological square cells (usually 1×1 or $2\times2\,\mathrm{km}^2$). Each one is treated as a hydrological unit, where a lumped model is applied. The runoff generated by each cell is routed to the outlet following a single unit hydrograph process, which is obtained from the definition of a simplified drainage network. Finally, the sum of all cell runoffs provides the total discharges at the outlet.

3.1 The loss function at cell scale

Two models are selected to reproduce the rainfall-runoff transformation at cell scale, depending on the degree of urbanisation. Topmodel (Beven et al., 1995) is a model that performs well in rural and permeable catchments, and it is applied in rural cells. On the other hand, the SCS loss function (Mockus, 1957), more adapted to non-permeable soils, is applied in highly urbanised cells.

About 23% of the cells are considered urban in the Besòs catchment. The two parameters needed in the SCS model are obtained directly from Curve Number (CN) tables for each hydrological cell, basically from the urbanisation degree. Due to the difficulty in assessing correct values using this methodology (mainly in setting the initial humidity conditions), a global parameter (FS) to be fixed has been introduced into the model, in order to proportionally scale the CN values of each cell.

The Topmodel version used in rural cells has some particularities that make it different to that commonly used (Beven et al., 1995). This version does not include the runoff routing from the source area to the outlet (time-area method) because it will be done inside the routing module in a distributed manner. Both excess and base flows are assumed to come to surface inside the hydrological cell, ready to be routed. The topographic index is derived from DEM analysis for the whole catchment using a multidirectional algorithm. Then, a different density function of the topographic index is provided for each hydrological cell to apply the model. This version is led by 2 parameters, according to the 2 classic Topmodel stores: the Root Zone (1st store) and the Saturated Zone (2nd store). In the 2nd store, the exponential storage emptying parameter (m), and the lateral transmissivity at saturation (T_0) have to be fixed. The initialisation of this 2nd store is done from the initial value of the observed runoff. The 1st store initial deficit (Dr_0) is considered an event parameter that depends on the humidity state of the basin. It is now fixed in a simple way from the identification of the hydrograph initial rising time. Since evapotranspiration estimates are not included now in the model, the maximum capacity of the 1st store (Sr_{max} parameter) does not need to be fixed.

3.2 The routing model

A water pathway to the basin outlet, derived from topography, is defined. For each hydrological cell, this pathway is divided into hillslope path (slow response) and river path (fast and channelled response). The separation is made fixing a threshold in its draining area, which is deduced from geomorphologic analysis. Figure 2 shows the drainage system derived to apply the model in the Besòs catchment, where the threshold has been fixed in $24\,\mathrm{km}^2$. In the hillslope path, the Gamma function $G(n, K)$ of the Nash Unit Hydrograph (Nash, 1957) is applied. This function is led by 2 parameters: n is the number of cells of the hillslope path to reach the river, and K is the storage constant (a model parameter). The hydrographs are routed through the river applying a time delay (t_r), supposing that water travels to the outlet with constant velocity. It depends on the length of the river path (l_r), derived from topographic analysis, and on the river velocity (v_r), considered uniform, which is the last parameter of the model. The result is the same unit hydrograph obtained in the hillslope, but delayed in time (Fig. 2).

3.3 Model parameters

The model has been calibrated by means of a best-fit process (optimisation and validation) over a set of events using the runoff data at the outlet. 12 events have been used for optimisation, and 6 for validation. After adjusting the range of the parameter space, the process has converged in

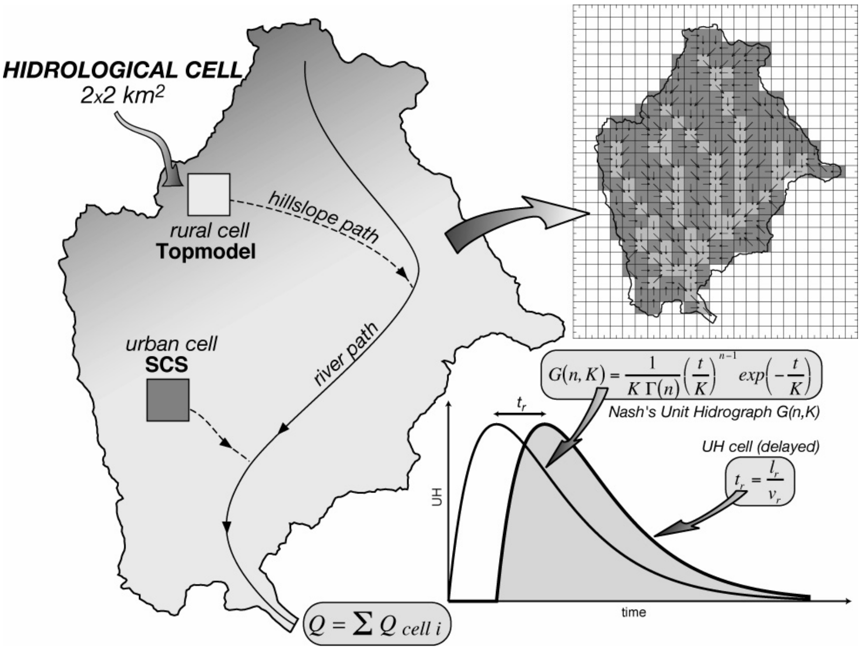

Fig. 2. Scheme of the model, with the drainage system used in the Besòs catchment.

the following values: K: 1.8 h; v_r: 3.5 m/s; m: 0.040 m; $ln(T_0)$: 4.0 m^2/h; FS: 0.60. A value of 0.77 for the Nash efficiency has been obtained for the optimisation process, and 0.53 for validation. Knowing the uncertainty associated to hydrological modelling (including the model structure), it is assumed that this calibration process is only a first approximation to the problem, thinking that model outputs achieved in this way serve as indicators of the catchment responses in different situations, like the case study presented here.

4 The rainfall field and the short term forecasting

A radar-raingauge merging procedure is used in the SAHBE system to build the rainfall field inputs. Nowadays, it is based on a distributed and dynamic correction factor applied to the radar image, obtained in each raingauge location comparing raingauge values and radar rainfall estimates (INM radar images, previously converted to rainfall by means of a Z-R relationship: $Z = 525 \cdot R^{1.28}$, from Sempere-Torres et al., 1997). This correction factor is applied to its influence area (its associated Thiessen polygon), and it is additive for very small values of rainfall, or multiplicative on the contrary. In some cases raingauge data is the only information used to build the rainfall fields, because radar information is not available for all flood events (in this default case the single Thiessen method is applied).

A rainfall forecast is needed to obtain reliable flow forecasts in the Besòs. The original methodology implemented in the SAHBE system consisted in a persistence methodology, which repeats the last obtained rainfall field during some hours, but with the additional possibility to define a time-variable correction in order to take into account the single persistence, growing or dropping of the storm. This methodology, affected by the subjectivism, is rarely used and in general a single persistence is applied. For this reason another procedure based on radar advection methods has been implemented. It consists in a cross-correlation technique (Bellon and Austin, 1978), finding the best displacement between two consecutive images (providing the best correlation). Afterwards, the forecasting is carried out moving the last radar field with the estimated displacement every time. In order to be coherent with the rainfall field used in the period before, the radar-raingauge correction factors must be applied. Since the raingauge forecasts are not known, the last computed set of correction factors are applied. It must be pointed out that this methodology is only able to provide reliable forecasts in the case of storms with a well defined structure, having a general movement without major convective processes causing appearance and evolution of cells.

5 Results

Some events have been evaluated from the perspective of real time operation. It has consisted in simulating the conditions of real time for several time steps, analysing the decisions taken by the SAHBE supervisors and the variability of results in consecutive time steps, comparing the results obtained using the two rainfall forecasting procedures. In the case of persistence, a 6-hour forecast using the single procedure has been chosen (steady rainfall field). For the case of cross-correlation, the same limit has been imposed (no rainfall after 6 h).

Figure 3 shows some results obtained in a particular event. The vertical dashed line, indicating the current time, divides two stages: before the current time, the rainfall is known; after the current time, the rainfall is estimated by the two

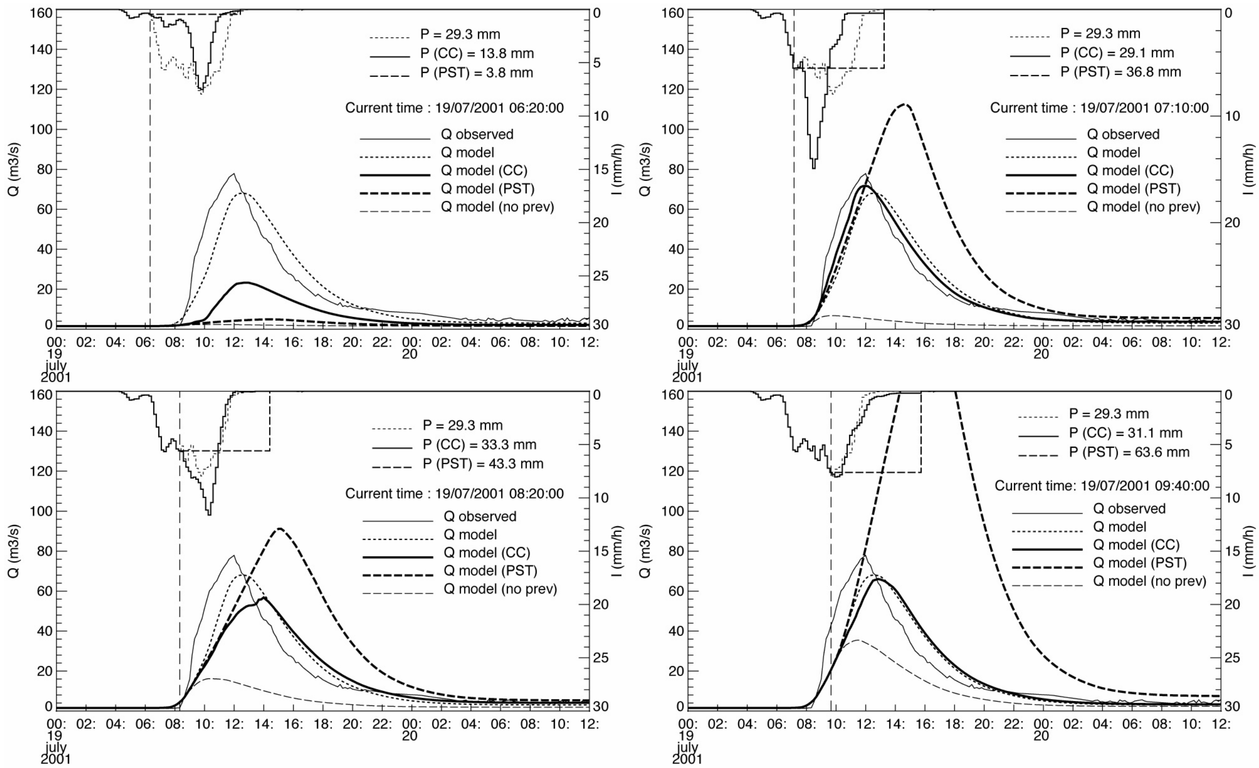

Fig. 3. Model simulations for the 19 July 2001 event, from different rainfall forecasts and different current times. PST: persistence; CC: cross-correlation; no prev: without any rainfall forecast.

different forecasting methodologies (PST: persistence; CC: cross-correlation), and they can be compared against the reference rainfall (albeit the comparison is made in terms of the average catchment rainfall, loosing any spatial description). Then, every rainfall forecast produces a hydrograph simulation, and they can be compared together and against the reference hydrograph (simulated by the model using the reference rainfall) and also against the observed hydrograph. Moreover, it can be made a comparison against the model simulation without any rainfall forecast, in order to see the importance of providing some rainfall forecast.

In the case of the Fig. 3 (event of 19 July 2001, used for optimisation), the rainfall consisted in a band crossing Catalunya from West to East, showing some ordered structure. It should be noticed different situations depending on the current time. First of all, it must be pointed out that the model simulation produces a delay in the hydrograph rising phase, of about 1 h in the peak; moreover, a small underestimation exists. At 6:20 of 19 July 2001, in the beginning of the event, the CC method produces a late estimate of the rainfall peak, greatly underestimating the rainfall rate during some 2 h. Then, it is clear that CC does not work in this situation, although a far-off storm (more than 100 km) is introduced into the basin after some time (but without any relationship with the real occurred situation). At 7:10 the CC method provides an excellent agreement with the reference rainfall during 40 min; after that, the storm peak is overestimated and advanced. For this reason the model simulation shows an advancement in comparison with the reference hydrograph. In any case, rainfall volume is better estimated than using PST, which provides rainfall overestimates after 4 h, when the storm decreases, and then providing hydrograph overestimates beyond this time. At 8:20 and 9:40, CC provides a good agreement with the reference rainfall, describing very well the leaving of the storm from the catchment, even after 4 h. Another time, PST produces high rainfall (and consequently hydrograph) overestimates.

Figure 4 shows some results for the event of 15th and 16th November 2001 (optimisation event too). It was a complex event, with sudden appearance of convective cells near the coast growing to the interior land, which is a typical situation in this zone of the Mediterranean during the autumn. At 6:20 of 16 November 2001, in the beginning of the main event, the CC forecast is only good during 10 or 20 min; later, it provides a strong underestimation. A similar situation can be observed at 8:20, in the middle of the storm, when the CC method forecasts the leaving of the rainfall in 3 time steps (30 min), while the reference rainfall continues 2 h from the current time. This is because in this kind of climatological situations, convective cells grow into the sea and move to the land, but later they remain stationary and grow in the basin due to orographic effects. In consequence, the CC hydrograph forecast is very close to that obtained without any prevision, contrasting with the overestimation produced using

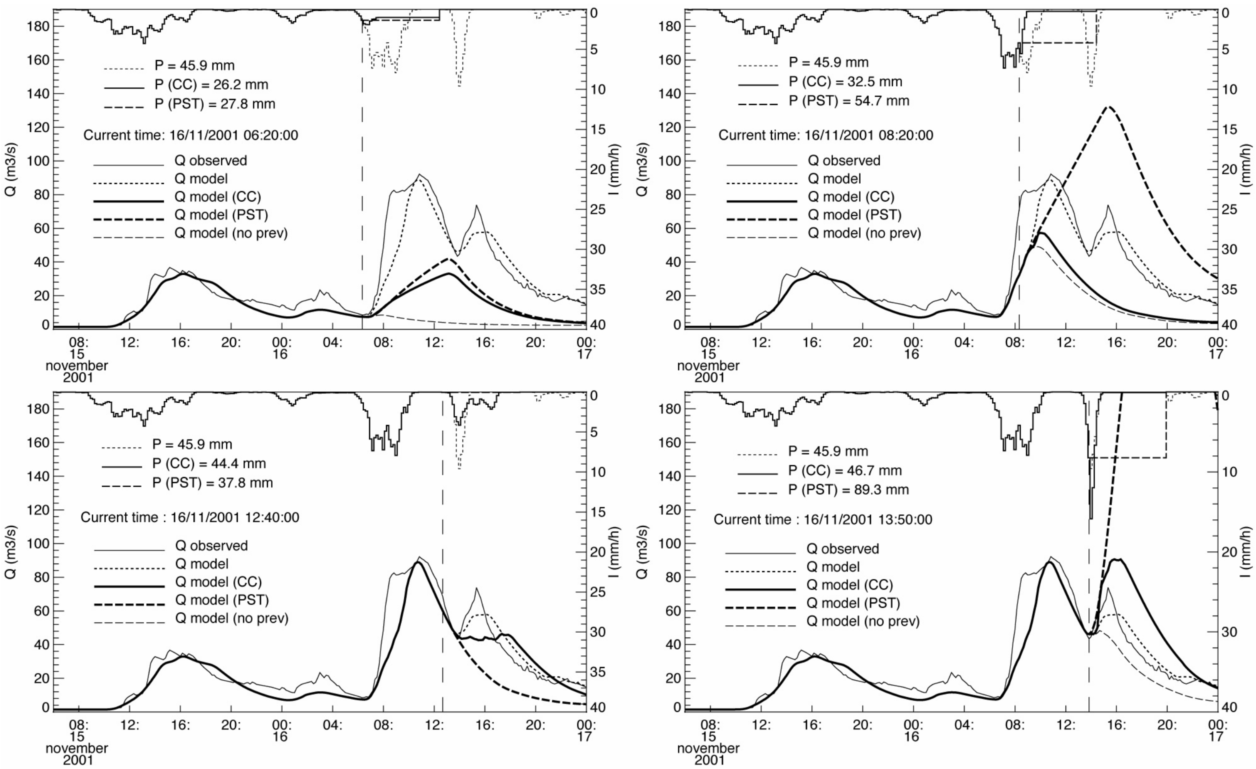

Fig. 4. Model simulations for the 15 November 2001 event, from different rainfall forecasts and different current times. PST: persistence; CC: cross-correlation; no prev: without any rainfall forecast.

the PST method. In front of these situations, the results obtained in the next rainfall event (at 12:40 and 13:50) using CC show a better agreement with the reference rainfall, particularly in the second case, and clearly if compared with the results obtained using PST (no rainfall at 12:40, the peak at 13:50). It must be seen that the CC forecasting methodology only finds the best displacement between images. Then the radar rainfall field is affected by the correction factors of the last time step. It introduces some errors in the rainfall forecast, that can be systematically observed when the radar rainfall becomes zero (the storm goes outside the catchment) but additive corrections are still applied, which extends a persistent rainfall in all the last section of the 6-h forecast.

One way to show the quality of the forecasting method is by means of evaluating the model performances at a fixed forecasting (lead) time, and doing that for all time steps. Figure 5 shows the results obtained in the 15 July 2001 event, for a 2 h and 3 h forecasting time respectively (the hydrograph represents the runoff estimates forecasted 2 or 3 h before). It can be noticed that no big difference exists between the reference hydrograph and the hydrographs obtained using both CC and PST methods when the forecasting time is 2 h. On the other hand, when the lead time is 3 h, strong differences can be observed. Particularly when using PST, the hydrograph divergence (usually overestimation) occurs more frequently than when using CC. Figure 6 shows the results obtained for the 15 November 2001 event using this scheme. The delay observed in the hydrograph rising obeys

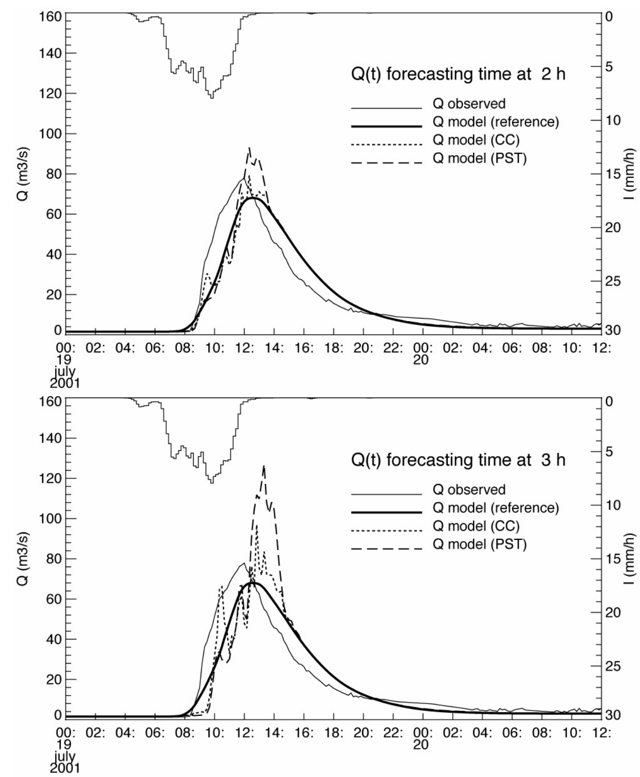

Fig. 5. Model forecasts for a fixed lead time (forecasted 2 and 3 h before), using different rainfall forecasts. 19 July 2001 event. PST: persistence; CC: cross-correlation.

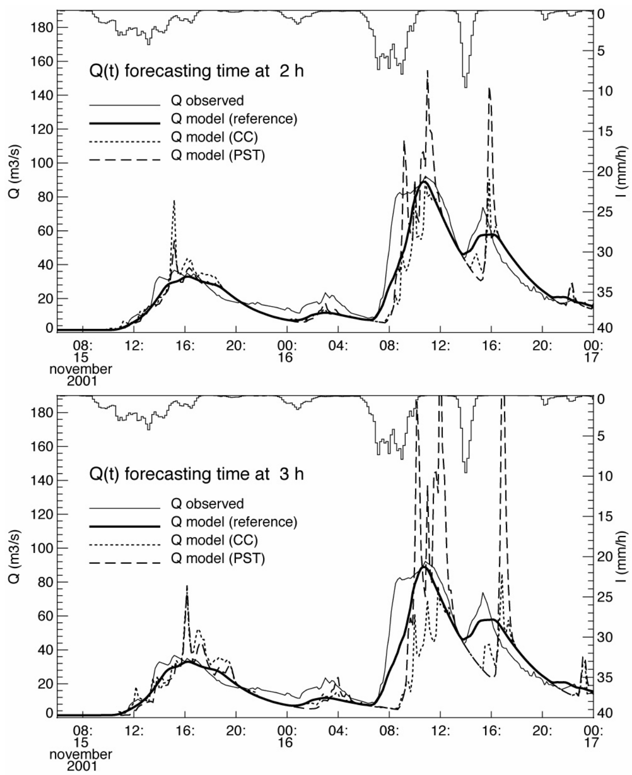

Fig. 6. Model forecasts for a fixed lead time (forecasted 2 and 3 h before), using different rainfall forecasts. 15 July 2001 event. PST: persistence; CC: cross-correlation.

to the reason that during the first part of the event neither of the methods (PST and CC) are able to slightly reproduce the reference rainfall. But in this case, the hydrograph overestimation produced by PST is very large and frequent (even with forecasting times of 2 h), while CC rather provides some underestimation.

Till now, the comments have been focused on the analysis of the rainfall forecasting methods and the hydrograph simulations, looking at the goodness in comparison with a reference rainfall or hydrograph. Now, the question goes further and looks if the integrated model is helpful for forecasters and decision makers. In other words, can the model provide enough information in order to assess a good level of warning with an adequate anticipation? After the evaluation of the integrated model for the events previously shown (and two more), we have arrived to some conclusions.

In general, it has been observed that the transcendental information to reproduce the hydrograph rising (particularly the peak flow) is a good estimation of the rainfall peak (this denotes a certain linear behaviour in the Besòs catchment). Thus, in the beginning of the rainfall event, it is very difficult to achieve good model forecasts. Of course, PST is unable to forecast any rainfall when it is not raining. CC is able to forecast some rainfall, but in general it is frequent to have rainfall underestimations, at least for lead times of more than 2 h. Then, as in general there are more than 3 or 4 h to the reference peak flow, the rainfall forecast is rarely good enough to estimate it.

As the current time approximates to the rainfall peak, CC can forecast it better. However, in many cases the rainfall forecast produces underestimations, particularly after some time, producing certain underestimation of the peak flow. Since the PST method does the forecasts with the last rainfall field, as the rainfall increases it provides higher rainfall forecasts, and tends to produce important hydrograph risings. In principle, as the current rainfall is smaller than the peak, the peak flow is underestimated; but when the duration of the rainfall event is smaller than the forecasting time (6 h in this study), the forecasted hydrograph can have a peak flow near to the reference, or even an overestimation. In this case, albeit it is due to an error of the rainfall forecast, if actually a dangerous flow rising is coming, it serves to activate the warning earlier. Thus, it is more conservative.

After the rainfall peak (when the rainfall event decreases), CC uses to provide good estimates. PST is very bad, since produces systematically overestimations. Then, in this case CC is clearly superior. Since the warning has been previously given, this is not important in case of important flow events. But it can be useful for small events in order to avoid false alarms.

6 Summary

In this paper, an analysis of two simple rainfall forecasting methodologies inside an integrated rainfall-runoff model working in real time has been done. The study has allowed to see the sensitivity of the model simulations to the rainfall forecasts, taking into account the feelings of the decision makers in different stages of the event, in order to reach some general useful ideas for real time operation.

Using rainfall persistence as forecast, it has been noticed that for forecasting times of more than 2 h (in the Besòs catchment), the model simulations begin to diverge to the reference hydrograph (0-h forecasting time). Then, it can be assumed that a time of 2 h is a good approximation for the mean lead time in the Besòs outlet. In front of this, using a cross-correlation technique, in general it is possible to appreciate a good agreement in the mean rainfall in the first 30 min. Evermore, sometimes this agreement is appreciated for more than 1 and even 2 h. It can be concluded that an improvement of at least 30 min is introduced in the lead time, extending it from 2 to 2.5 h approximately. For lead times greater than 2 h, the persistence method produces more frequent and important errors (usually overestimations in rainfall and runoff simulations). Then, cross-correlation, although a simple radar based procedure for rainfall forecasting, represents a qualitative improvement in front of a simple persistence, at least when the storm presents a general ordered movement.

From a decision maker point of view, it has been noticed that cross-correlation is a more stable method than simple persistence, incurring in strong errors less frequently. Mainly for this reason but also due to inherent errors of the method, it is in general less conservative, which can be a problem in some situations.

As a summary of the developments, some improvements are thought to be implemented into the model. The analysis of the model performances in different subcatchments will improve the parameterisation, increasing the parameter distribution inside the catchment. The radar-raingauge merging methodology used in this study is too simple and does not take profit of the radar field structure; moreover, the quality of the original radar images is not good enough to apply them without incurring in other error sources. For this reason, future work is directed to the more reliable co-kriging methods, having previously implemented a radar correction procedure. Finally, other rainfall forecasting methodologies are under study.

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