Forecasting flash floods in ungauged basins with satellite data

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Abstract Nowadays, research progress makes it possible to simulate very complex hydrological phenomena. Nevertheless, there still remain some cases where these advances are ineffective. This is the case for flash floods, which are so rare and violent that the acquisition of observed data during the flood is very difficult, and so classical hydrological model calibration is impossible. We focused our interest on this special kind of floods. Our main goal is to develop an operational and robust methodology for flash flood forecasting (MARINE). This methodology should provide relevant data about the flood evolution and should be applicable even if historical and observed data are sparse. The flash flood evolution model developed is composed of two parts: first, the flood runoff generation in the upstream part of the basin, and then its propagation in the main rivers. The flash flood generation model is a rainfall–runoff model that only integrates data from space. Classical hydrological equations are resolved with enough hypotheses to allow real time exploitation. The flood propagation model we developed resolves the Barré de Saint Venant equations and simulates flood propagation in main rivers. MARINE has been developed to help forecast services to take decisions during the flash flooding, thus it works in real time conditions. Even if faults introduced by lack of measurements make the model's precision less than that which hydrologists are accustomed to, it supplies relevant flood hydrographs with enough precision for forecasting services' purposes. This model has been integrated into a real situation to test our methodology on some recent flash floods events on French Mediterranean catchments.

Key words flash floods; forecasting; MARINE; remote sensing

FIELD OF INTEREST

Flash floods are characterized by their violence and the rapidity of their occurrence. Damage caused by flash floods can be dramatic. Because they do not occur frequently and are so unpredictable, their calibration in classical hydrological models is difficult. To avoid this problem, one solution can be to work with other kinds of data: such as satellite data, with some models that limit calibration. This is our field of interest. To help forecasting services in their decision taking, it is not necessary to supply very precise forecasts but some pertinent information on the flood peak, such as its time to peak, and its value, is more often sufficient.

FLASH FLOOD FORECASTING

To realize flash flood forecasts, we have chosen to work with simplified hydrological equations. Our goal is to make a model that retains maximum physical meaning so as to avoid calibration, and that allows forecasting services to correctly and quickly interpret results, so as to have a rapid overview of the basin reaction.

Some hypotheses linked to the nature of flash floods

In the past, statistical and empirical methods were used to model rainfall–runoff relationships. But when past observed data are sparse, these methods are not applicable. Nowadays, physically-based hydrological models have become an alternative solution (Beven *et al.*, 1984). They are robust, stable and efficient enough to provide credible results for operational forecasting.

The model proposed here is a distributed physically-based hydrological model. It simulates flooding from its runoff generation caused by the rainfall event until its propagation in the main river. It has two modules: the rainfall–runoff model on the watershed and the flood propagation model. These modules take into account topographic and hydrographic data, the heterogeneity of the precipitation and land cover maps, to model overland flow and river overflow. The model is able to integrate only data resulting from space observation. Furthermore, the time for calculation is short and the required parameters are limited as far as possible to allow this model to evolve into a useful tool for forecasting in real time.

MARINE model

MARINE (Modélisation de l'Anticipation du Ruissellement et des Inondations pour des éváNements Extrêmes) is a runoff and inundation anticipation model for extreme events. This model requires at least:

- a Digital Elevation Model (DEM) which can come from satellite data (SPOT);
- the characteristics of the ground surface that are observable by satellite and have a hydrological influence (land use and precise network with SPOT or LANDSAT);
- some additional information makes it possible to improve the DEM at the end of hydrological modelling (Borgniet *et al.*, 2001), (Estupina Borrell & Dartus, 2001);
- the rainfalls used are heterogeneous in time and space. They come from observations by a weather radar, and can eventually be precisely quantified using local pluviometers. They are confronted in certain cases with the results of some anticipated rainfall made by Météo France.

Surface runoff genesis

One can consider that water on the catchment area flows quickly into drains (Puech, 2000) and can be approximated by the diffusing wave equations (Tregarot, 2001). The coefficients of runoff are connected to the Manning coefficients on the watershed (Chow, 1959). This model is able to run in real time.

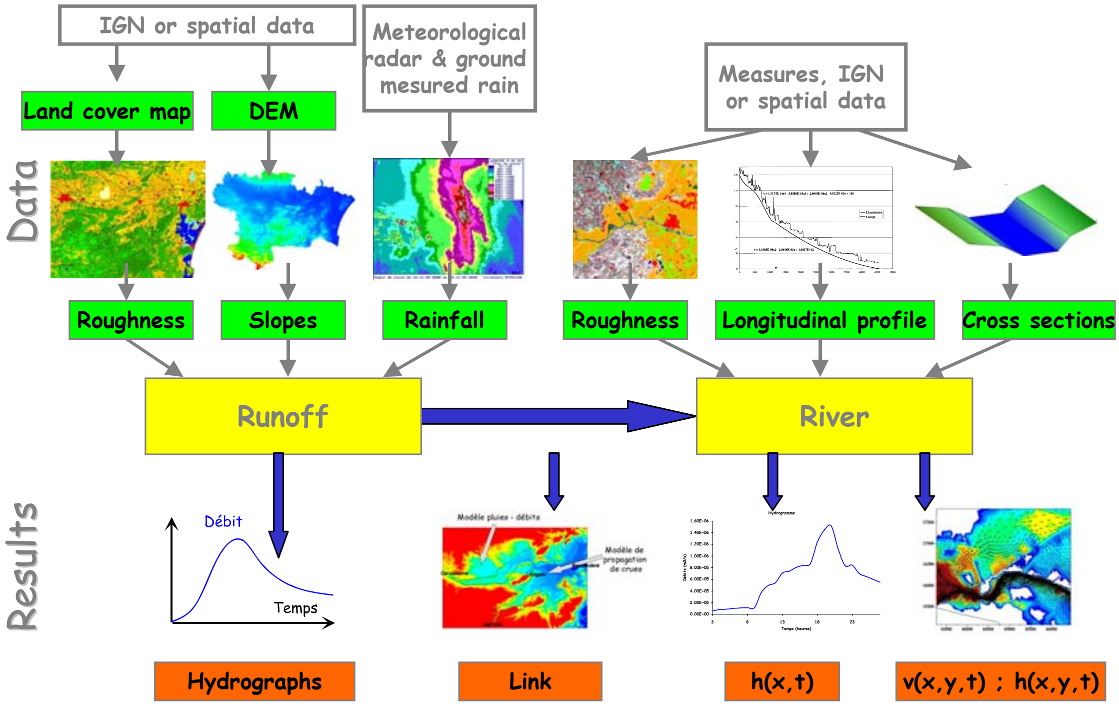

Fig. 1 Data used by MARINE for the Gard experiment. MARINE integrates spatial variability of information and uses a structured grid corresponding to the DEM one.

The diffusive wave equation is with an *x,y* uniform flow (where *n* is the Manning's coefficient and *h* the water depth) is:

$$|U| = \frac{h^{2/3}}{n}.\sqrt{|slope|}$$

The Manning coefficient determination can be estimated from the values of the roughness coefficient over the flood plain (Chow, 1959). According to (Llamas, 1993), there are other methods to determine the roughness coefficient. These expressions are in accordance with ours.

The particles' flow direction is determined by finding the direction of the steepest descent from each cell (Leymarie & Fairfield, 1991) taking into account its eight neighbouring cells.

Then, hydrograph expressions for each sub-basin outlet can easily be estimated either by a Lagrangian or by a Eulerian computing methodology.

Infiltration

It is possible to use the Horton infiltration programme within the Eulerian computation. But this part still requires some calibrated or observed data. Remenieras (1986) states that:

$$f_p = f_c + (f_0 \quad f_c).e^{\ \beta.t}$$

can express the infiltration rate (Horton, 1933) where f_p is the infiltration capacity of the soil; f_c is hydraulic conductivity at saturation; f_0 is the maximum infiltration capacity value at the beginning of the rainfall; β is a constant; and *t* is time from the beginning of the rainfall. Infiltration is a threshold phenomenon related to the rainfall intensity.

MARINE uses only three parameters: two fixed, defined by the soil type and one function of the humidity of the soil at the beginning of the rainfall. These parameters are difficult to evaluate on ungauged basins, but some simulations in "off-line" mode with rainfall scenarios make the forecasting service able to evaluate theses values using their basin behaviour knowledge. In any case, it is also possible to forecast the worst flood only with the Lagrangian approach which uses a simple rainfall reduction.

River propagation

The river routing part of the model can be either 1-D or 2-D resolution. The TELEMAC2D system is a finite element method software dedicated to free surface flow modelling by solving the classical St Venant 2-D equations integrated along verticals (EDF-DFR, 1998; Hervouet & Petijean, 1999). The methodology has been developed by Chorda & Maubourguet (2000); it cannot run in real time forecasting because of the time resolution needed.

One can also use a 1-D model for operational simulations. The MAGE 1-D software (CEMAGREF) has been tested. It can run with roughly estimated data and allows real time forecasting (Alquier *et al*., 2002).

APPLICATIONS

This model has been being tested on different events: on some gauged basins to validate our methodology, but also on ungauged basins to test it in real conditions. Some of the MARINE applications are presented below.

Aude

One flash flood occurred in the Aude Valley, in the south of France, on the 12th and 13th of November 1999. This event would have been locally exceptional without considering the entire regional area. For the whole Languedoc-Roussillon region, such heavy precipitation might appear from 2 to 4 times in 100 years. But locally, this event appears to be very exceptional. Maximum precipitation reached 620 mm in 48 hours in the village of Lézignan Corbières (Aude department). The flood's geographical extent and the size of the emergency rescue force (over 3000) are considered exceptional (MATE, 2000).

It is known (Musy, 2001) that for the generation of floods, the important flows are overland flow and subsurface flow. But for this event, soils will quickly become impermeable, runoff will play an important role, and subsurface flow will become negligible because of:

– duration and intensity of the rainfall: continuous duration in two steps, exceptional intensity (Horton's overland flow);
– impossible upward flux of air in soil (so impossible infiltration) because of the exceptional intensities.

The final toll of the event was 35 deaths and 1 person disappeared.

The European Spatial Agency with the collaboration of the DDSC, explored the possible uses of spatial techniques for the operational management of natural risks. This includes anticipation, forecast, crisis management and post-crisis analysis for the "Water and Fire" project (Alquier *et al*., 2000). A part of this project deals with flash floods, thus we have used MARINE to simulate the Aude 1999 flash flood, using only spatial data. Comparing our results with the observed phenomena has validated this approach.

We used MARINE, with the Lagrangian approach linked to TELEMAC 2-D software, to simulate such an event afterwards in the frame of the project (Alquier *et al*., 2000). Some results are presented below and are extracted from Estupina Borrell *et al*. (2002) and Estupina Borrell & Dartus (2001).

The DDE 11 (DDE11, 1999) supplied the evolutions of water levels *vs* time at Moussoulens (outlet) for the Aude 1999 flash flood. The charge–discharge relationship was also supplied but the data may not be very reliable because of the strong extrapolation on *in situ* calibrated data at very high discharge. After the simulations with MARINE, we obtained the simulated hydrograph at the Moussoulens station.

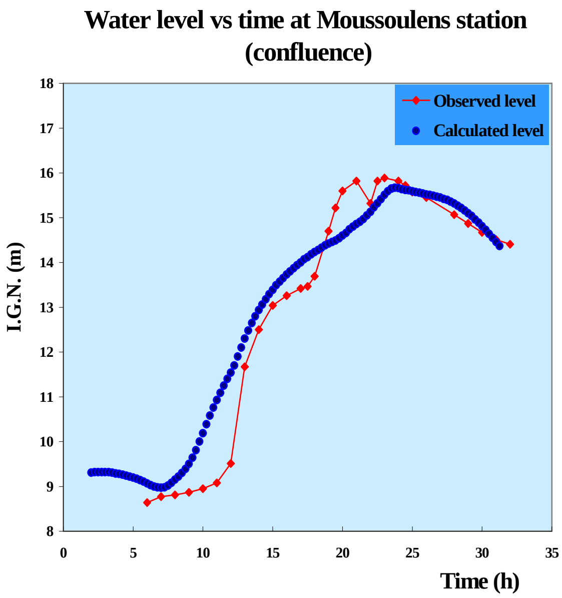

Fig. 2 Flood hydrograph for the Aude 99 flash flood at Moussoulens.

Earth observation data can also supply some inundation extent images. We have superposed the results above to a SPOT image (treated by SCOT society). The maximum extension of the flood seems to be comparable to the observed event (Fig. 3). This experiment was realized to test the ability of MARINE to reproduce a particular flash flood. The results were particularly encouraging.

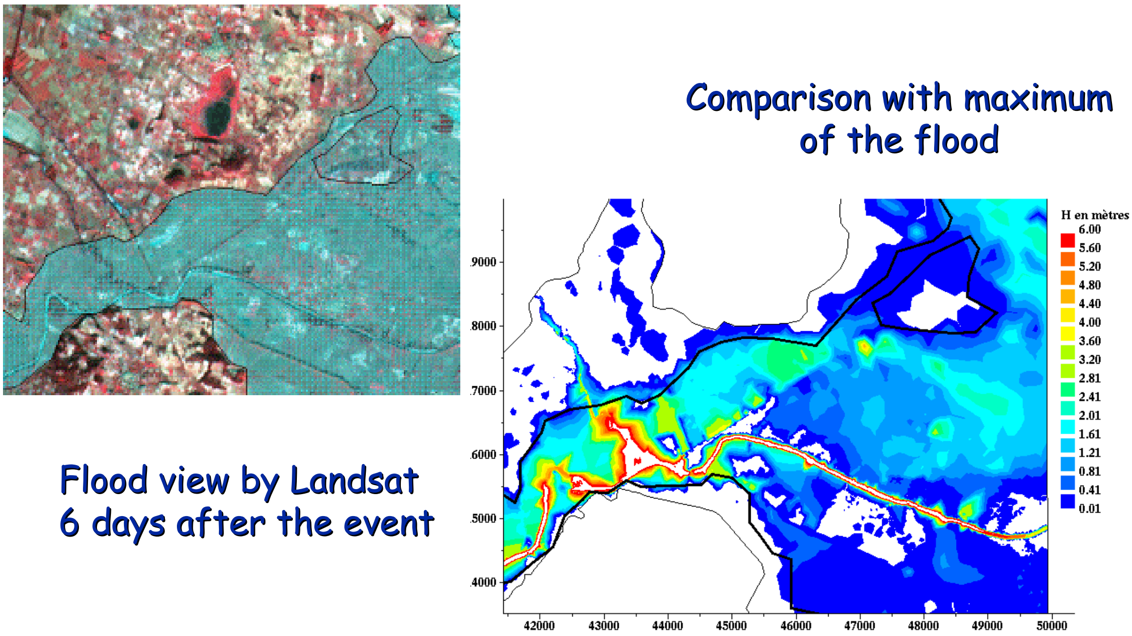

Fig. 3 Comparison between interpreted inundation marks image and model results (Chorda & Maubourguet, 2000).

Gard

We chose the southeast of France, in the Gard department of the Languedoc Roussillon region, to make simulations because lots of rapid floods recently occurred in this region. During these floods, infiltration took a non-negligible part in the phenomenon, which is why these experiments allowed us to test the infiltration part of MARINE.

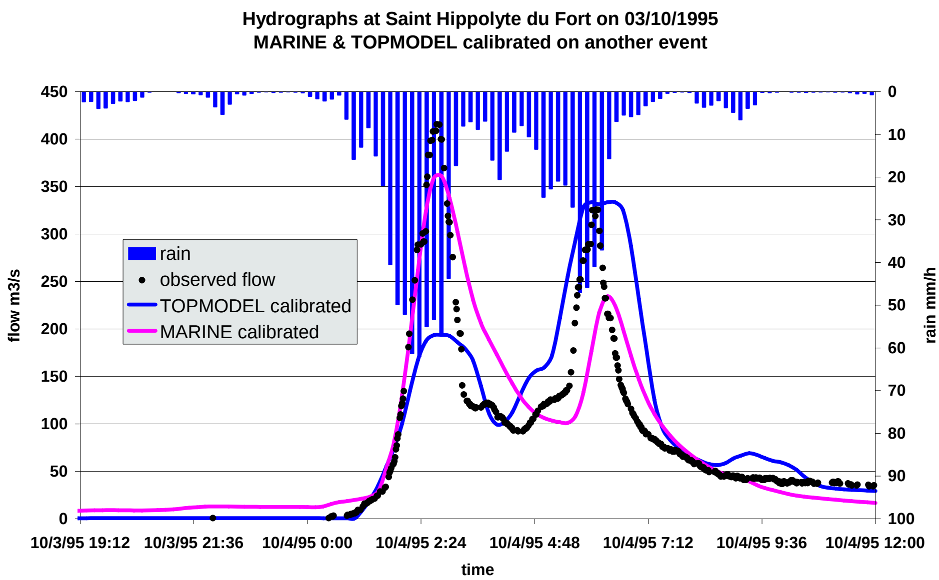

Fig. 4 Comparison of MARINE and TOPMODEL calibrated on another event.

The results obtained with MARINE have been compared with TOPMODEL (Beven & Kirkby, 1979) simulations. Figure 4 presents the results for one particular flood (about 50% estimated losses). This flood was not a flash flood, but the Eulerian version of MARINE supplies good results with less observed information than TOPMODEL.

Thoré

The PACTES (Prévisions et Anticipation des Crues aux moyens de TEchniques Spatiales) project aims at improving the existing tools for the management of flood risk in France, firstly by using spatial technologies (Alquier *et al*., 2002). This project was proposed to improve flash flood forecasting and help the civil security services during events. Our model has to be able to forecast flash flooding early enough in order to support the forecast service's decision-making regarding the alert process. To validate this, we have simulated the Thoré 1999 flash flood.

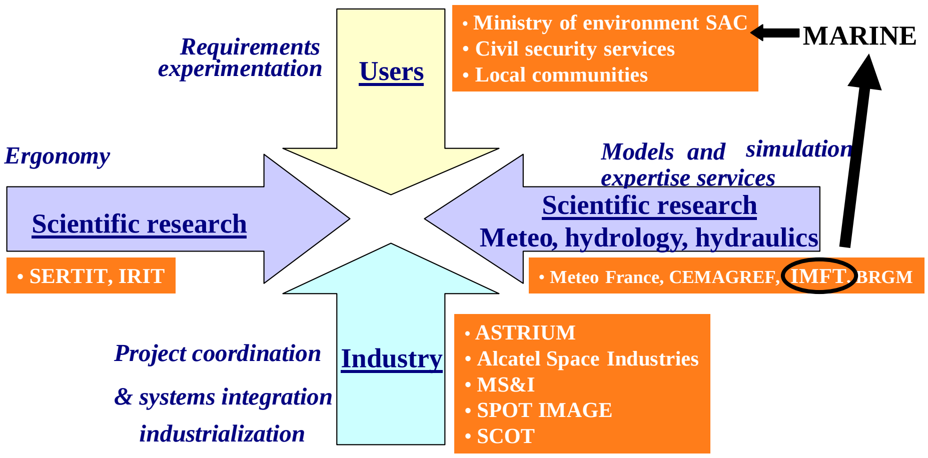

Fig. 5 Interaction between the partners (Grazzini, 2001).

In this study, MARINE has been used first with the Lagrangian approach and then with the Eulerian one. The Thoré basin is very poorly gauged. At the moment MARINE is implemented by the French Forecast Service and it has been tested under real time conditions.

CONCLUSIONS

MARINE is the formulation of a relatively basic physical approach with adequate numerical methodology. This particularity makes this model conform to the objective of forecasting flash floods on some ungauged basins with sufficient precision. The minimum information needed to make MARINE run are:

– essential observations from satellite;

– rainfall radar observations and if possible a rainfall forecast;
– eventually some additional ground observations to improve the forecast's precision.

But MARINE will not replace the knowledge of the forecasting service. Their experience still remains an impossible point to circumvent. They have to interpret MARINE results in real time, to evaluate the possibility of such an event happening, to evaluate the pertinence of the results supplied by MARINE.

MARINE has been being improved on several points:

– Increase of the model applicability to other events
– Amelioration of the infiltration process which depends particularly on the soil humidity.

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