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The use of distributed hydrological models for the Gard 2002 flash flood event: Analysis of associated hydrological processes

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SUMMARY

This paper presents a detailed analysis of the September 8–9, 2002 flash flood event in the Gard region (southern France) using two distributed hydrological models: CVN built within the LIQUID® hydrological platform and MARINE. The models differ in terms of spatial discretization, infiltration and water redistribution representation, and river flow transfer. MARINE can also account for subsurface lateral flow. Both models are set up using the same available information, namely a DEM and a pedology map. They are forced with high resolution radar rainfall data over a set of 18 sub-catchments ranging from 2.5 to 99 km^2 and are run without calibration. To begin with, models simulations are assessed against post field estimates of the time of peak and the maximum peak discharge showing a fair agreement for both models. The results are then discussed in terms of flow dynamics, runoff coefficients and soil saturation dynamics. The contribution of the subsurface lateral flow is also quantified using the MARINE model. This analysis highlights that rainfall remains the first controlling factor of flash flood dynamics. High rainfall peak intensities are very influential of the maximum peak discharge for both models, but especially for the CVN model which has a simplified overland flow transfer. The river bed roughness also influences the peak intensity and time. Soil spatial representation is shown to have a significant role on runoff coefficients and on the spatial variability of saturation dynamics. Simulated soil saturation is found to be strongly related with soil depth and initial storage deficit maps, due to a full saturation of most of the area at the end of the event. When activated, the signature of subsurface lateral flow is also visible in the spatial patterns of soil saturation with higher values concentrating along the river network. However, the data currently available do not allow the assessment of both patterns. The paper concludes with a set of recommendations for enhancing field observations in order to progress in process understanding and gather a larger set of data to improve the realism of distributed models.

1. Introduction

Flash floods represent the most destructive natural hazard in the Mediterranean region, causing around one billion Euros worth of damage in France over the last two decades (Gaume et al., 2009). Flash floods are associated with extreme and rare rainfall events and usually occur in ungauged river basins. Amongst them, small-ungauged catchments are recognized as the most vulnerable to storm driven flash floods (Ruin et al., 2008).

In order to limit damage to the population, there are several currently accepted methods for predicting flash floods in ungauged river basins. The flash flood guidance (Georgakakos, 2006; Norbiato et al., 2008) and the discharge threshold exceedance approach (Reed et al., 2007; Younis et al., 2008) are built to give an early flash flood warning with suitable time to organise the civil protection. These operational methods are very efficient for warning, but must be complemented with field experiments and modelling studies to improve the understanding of the major hydrological factors associated with the flood events. In order to progress in process understanding related to flash floods, large scale in situ experiments are scheduled in the context of the HyMeX program (www.hymex.org). This project aims at improving our understanding and prediction of the Mediterranean Sea water balance. The latter can be highly impacted by extreme events which provide a sudden input of fresh water to the sea (Drobinski et al., 2008). One of the focuses of HyMeX is therefore extreme events and, in particular, flash floods over the whole Mediterranean region. The

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objective is to better understand these events and to improve the predictive capability of hydro-meteorological models in simulating and anticipating them. The quantification of global change impact on the frequency and magnitude of these extreme events will also be analyzed within HyMeX. To achieve these goals, the HyMeX program is planning to enhance the observation capabilities of the scientific community in the Mediterranean region in order to better document extreme rainfall events and flash floods during a 10-year period, with an enhanced period of 4 years and two special observation periods in the fall. This experimental framework offers a good opportunity to enhance hydrological process observations and understanding. Progress in hydrological modelling of these events are also expected. As all the catchments cannot be surveyed, it is important to determine which type of observations are required and, where and when these observations are needed.

Distributed hydrological models, representing physical mechanisms, are interesting tools for hypothesis testing and field design (Loague et al., 2006). Sensitivity studies to process representation, spatial discretization, input data and parameters can be performed that allow the quantification of the impact of various functioning hypotheses on the hydrological response (Piñol et al., 1997; Sangati et al., 2009). Vivoni et al. (2007), using the tRIBs distributed model (Ivanov et al., 2004), explored the complex interactions between the various runoff contributions (infiltration excess, saturation excess, perched return flow, groundwater exfiltration) and the rainfall and catchments characteristics (soil, land use, topography). They showed how various responses can be observed at the outlet according to spatial and temporal variability of these factors and that threshold effects can be observed. Using the same model, Noto et al. (2008) focused on the impact of initial moisture (specified using a variable initial groundwater level) on the catchment response; they highlighted the complexity of the hydrological response to rainfall and soil characteristics. These studies focused on synthetic rainfall events and the studied catchment was about 800 km^2. Extreme events were not considered in these studies and the analysis was performed for the whole catchment without describing the internal variability.

The present paper deals with extreme events at the regional scale and aims at addressing small-ungauged catchments ranging from a few km^2 to about 100 km^2. In the context of the Prediction of Ungauged Catchments (PUB) initiative, the questions addressed in the paper are the following: (i) is it possible to set up physically-based distributed hydrological models at the regional scale using available data and information for flash flood simulation?; (ii) are post-flood data of maximum peak discharge useful to assess the relevance of the modelling?; (iii) are they relevant to discriminate between various model structures?; (iv) are sensitivity studies, based on distributed hydrological models outputs, useful to assess the limits of current observations and highlight which information should be acquired in future field experiments, in order to progress in the understanding and simulation of flash flood events for such catchments. For this purpose, two distributed hydrological models with different model structures are used. The study is conducted for the September 8–9, 2002 event, which affected the Gard region in south-east France. This event was exceptional, both in its extent (more than 20,000 km^2 affected) and duration, with more than 600 mm accumulated rainfall in 24 h in some locations. For this event, radar rainfall and post flood field data of maximum peak discharge are available.

The case study, rationale for model choice, model description and set up are presented first. The methodology used for model evaluation based on maximum peak discharge and sensitivity studies is also presented. The second part of the paper describes the model results in terms of simulation of maximum peak discharge. This analysis is complemented by local sensitivity studies and a discussion of model results in terms of hydrograph, runoff coefficient, and soil saturation dynamics. After a discussion of the results, guidelines for future experiments are proposed. These includes the processes, variables and parameters that require further description and investigation.

2. Materials and methods

2.1. Case study and available data

The case study is the September 8–9, 2002 event which affected the Gard region located in the south-east of France (Fig. 1). This event is the most important event ever recorded in this region. It was responsible for 24 casualties and caused roughly 1.2 million euros worth of damage. This event was extensively described in Delrieu et al. (2005) and in Manus et al. (2009). Thus, we shall only present the data used in the present study. In terms of rainfall input, we used rainfall intensity data from the Bollène radar with a 1×1 km^2 grid resolution and a 5 min time step, with the ST-AD3 processing protocol described by Delrieu et al. (2009). The spatial variability of soils is described using the Languedoc-Roussillon soil data base (later referred as BDSol-LR), provided by National Institute of Agronomic Research (INRA) from the French IGCS (Inventory, Management and Conservation of Soils) program. This database provides information (i.e. texture, horizon depth, etc.) on pedological landscape units called Soil Cartographic Units (SCUs). These units are established with a resolution of 1/250,000 and they are geo-referenced. They are composed of Soil Typological Units (STUs), the vertical heterogeneity of which is described by stratified homogeneous layers of soil. The proportion of STUs is given within a particular SCU, but the precise location of STUs within this SCU is unkown. Each STU is described through tables providing both quantitative and qualitative information from which quantities such as percentage of sand, clay, silt, organic matter or soil depth can be derived. Pedo-transfer functions are used to derive the hydraulic parameters of the various soil horizons (see details below).

For model evaluation, we use data from an extensive post-flood investigation carried out during the months following the event. The methodology of Gaume and Bouvier (2004) was used during this field survey. The survey gathered a regional information about the flood, allowing the analysis of the hydrological behaviour of watersheds with an area of 2–300 km^2. The procedure provides estimation of maximum discharges based on water level marks and simple hydraulic hypotheses for the derivation of the flow velocity. The flood chronology is documented based on witnesses interviews. A sub-set of data corresponding to the same 17 sub-catchments, already studied by Manus et al. (2009), is chosen. The area of these catchments ranges from 2.5 to 50 km^2 (Table 1). In addition, one 99 km^2 gauged catchment, the Saumane catchment, is also considered. Catchment locations are shown in Fig. 1 and their main characteristics are summarized in Table 1. The catchments located in the north-western part of the domain have steep slopes, whereas the catchments located in the south-eastern part of the domain are situated in flatter areas (Fig. 1). Table 1 shows a large variability in average soil depth and maximum storage capacity of these catchments. The variables in Table 1 are derived from the BDsol-LR using the dominant STU in each SCU.

2.2. Modelling hypotheses and model choice

First of all, the choice of the model should be dictated by the objectives of the modelling exercise (e.g. Kampf and Burges, 2007). Concerning regional flash flood modelling, model requirements are presented in Borga et al. (2008) and Sangati et al. (2009). They