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Sensitivity of the hydrological response to the variability of rainfall fields and soils for the Gard 2002 flash-flood event

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SUMMARY

In the general context of field experiment design, this paper presents a modeling study that quantifies the respective impact of rainfall estimation and soil variability on the simulated discharge for an extreme event in southern France. The CVN distributed hydrological model, built within the LIQUID® modeling platform is used. The method is illustrated for two medium sized catchments, Saumane (99 km^2) and Uzès (88 km^2) using raingauges and two radar estimates. The soil properties are extracted from an existing soil database provided for the whole region. The model parameter specification uses available observation and a priori hydrological knowledge. No parameter adjustment is performed. For model evaluation on the regional scale, simulated maximum peak discharges are compared with post-flood estimations for 32 catchments. The area of these catchments ranges from 2.5 to 99 km^2 and model results are satisfactory. Then, the study focuses on the Saumane and Uzès catchments. A sensitivity analysis highlights the role of the Manning roughness coefficient on the simulated hydrographs dynamics. The impact of the bottom boundary condition of the infiltration and water redistribution module is also shown for the gauged Saumane catchment. Then the impact of rainfall input and soil spatial variability is presented. The results show that (i) the use of radar data is necessary to properly simulate the flood dynamics; (ii) although radar volume-scanning strategy has been shown to give more accurate results on a pixel/gauge comparison of the rainfall estimations, it is not necessarily the case when catchment averaged amounts are considered, especially for catchments in mountainous areas; (iii) the impact of the variability in soil properties on the simulated discharges is of the same order of magnitude as the impact of differences in rainfall estimation; (iv) the flood dynamics presents two phases: the first one, mainly controlled by the soil properties and the second one, since the soils are saturated, controlled by the rainfall variability. Therefore, uncertainties on both observations need to be mitigated in order to improve flash-flood understanding.

1. Introduction

There is no doubt that flash-floods represent one of the most destructive natural hazards in the Mediterranean region (Gaume et al., 2009) and are still poorly understood. During the last two decades, several extreme flood events occurred in Southern France (i.e. Nîmes, 1988; Vaison-la-Romaine, 1992; Aude, 1999; Gard, 2002). These events are still poorly understood, mostly due to the lack of experimental sites and long-term hydro-meteorological data with adequate space–time resolution (Foody et al., 2004; Anquetin et al., 2004; Borga et al., 2008).

Flash-floods result from the combination of meteorological and hydrological conditions. Recognition of the coupled meteorological/hydrological nature of flash-floods is now obvious in interpretative studies and in the development of predictive models (Creutin and Borga, 2003; Anquetin et al., 2004; Collier, 2007).

It has been shown that most flash-flood events are attributed to precipitation generated in stationary Mesoscale Convective Systems (MCSs) (Hernandez et al., 1998; Homar et al., 1999). Due to their very localized nature and to their wide variability in space and time, the observation of such events using raingauge networks is problematic. Weather radars provide better spatial rainfall resolution, even if radar assessment of rainfall is significantly influenced by orography (Joss and Waldvogel, 1990; Pellarin et al., 2002; Germann et al., 2006). Moreover, it has been demonstrated that the more intense the rainfall, the less reliable the radar rainfall

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estimates become (BASC, 2005). Thus, accurate monitoring of severe storm rainfall intensities remains a major challenge.

Flash-floods are rare events that usually affect small to medium basins. The mitigation of the resulting distributed risk imposes the study of specific questions dealing with ungauged river basins. Indeed, people exposure to the dangerousness of the event is the highest in small-scale catchments because traditional defenses are usually weak (Montz and Gruntfest, 2002; Ruin et al., 2008; Creutin et al., 2009). Several methods for predicting flash-floods in ungauged river basins are now accepted. 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 warning suitable for the organization of civil defense. These methods rely either on conceptual or physically based hydrological models. To improve the forecasting chain, there is a real need for research to improve (i) the understanding of the major atmospheric and hydrologic factors leading to extreme flood event and (ii) their representations within the prediction models.

The importance of considering the spatial distribution of rainfall for process-oriented hydrological modeling is now accepted. Sensitivity studies of the runoff response to the spatial variability in precipitation highlight that detailed rainfall information is necessary for small catchments in complex terrain, and for runoff processes that respond directly to precipitation (Yates et al., 2000; Nicotina et al., 2008; Sangati et al., 2009). Morin et al. (2006) note that one of the key issues is the spatial resolution at which the rainfall data are represented in the hydrological model. They performed sensitivity analysis of maximum radar cell intensity and its extensions to simulated peak discharges. Their results show that peak discharge could be twice as high if the convective cell was initiated just a few kilometres away from the catchment. Delrieu et al. (2009b), in the introduction of the special issue dedicated to "Weather radar and Hydrology", suggest that "*weather radar technology offers a unique means for characterizing the rainfall variability over the range of scales and with the space–time resolutions required for a large variety of hydrological problems*". However, radar-based precipitation estimation may lack consistent, quantitative accuracy. Moreover, the formulation of hydrological models in distributed form may be problematic due to process complexity and scaling issues. The literature addressing this problem includes numerous approaches recently reviewed in the *Advanced in Water Resources* special issue (32 (7), 2009). The qualification of the different radar treatment is either done using a regional radar pixel – raingauge comparison (Joss and Waldvogel, 1990; Westrick et al., 1999; Pellarin et al., 2002; Germann et al., 2006; Delrieu et al., 2009a) or by examining the resulting simulated discharge at the event scale (Carpenter and Georgakakos, 2004; Tetzlaff and Uhlenbrook, 2005; Chancibault et al., 2006; Cole and Moore, 2008). The results of a regional evaluation are obviously linked to the observation ground network that may introduce bias in mountainous regions where the density of raingauges is the smallest. Furthermore, the hydrological evaluation is shown to be strongly dependent on the catchment size (Tetzlaff and Uhlenbrook, 2005; Morin et al., 2006). Therefore, the evaluation of the radar-based quantitative precipitation is not straightforward. However, radar rainfall estimation remains a natural approach to area-wide flood forecasting and warning at any location, whether gauged or ungauged.

The first objective of this paper is to propose an assessment of radar-based precipitation estimation complementary to the regional radar pixel – raingauge comparison proposed by Delrieu et al. (2009a). We analyse the response of the non-calibrated distributed hydrological model CVN (Manus et al., 2009) to different radar data sets issued from various data processing. We investigate the influence of the spatial and temporal rainfall variability in terms of peak discharge time and amplitude as proposed by Sangati et al. (2009). The September 2002 Gard flash-flood event (Delrieu et al., 2005), shortly described in Section 2, is the case study and the simulations are focused on small catchments ranging from a few km^2 to about 100 km^2.

For the same event, Le Lay and Saulnier (2007) used the event-based *n*-TOPMODELs calibrated model. They showed that the model efficiency significantly increases when the spatial variability of rainfall is taken into account. Nevertheless, for some of the catchments, mis-performance remained unexplained and further insight is required in order to better understand the missing factors that are influential on the hydrological response for such extreme events. Our hypothesis is that soil spatial variability can be a significant factor, which is usually neglected, in existing distributed models (for some reviews see Todini, 2007; Kampf and Burges, 2007; Furman, 2008).

The second objective of this paper is to quantify the respective impact of rainfall estimation and soil variability on the simulated discharges. The model CVN, built within the LIQUID® hydrological modeling platform and presented in Section 3, takes into account both the rainfall variability as described by raingauges or radar and the soil variability as described using an existing soil data base. Sensitivity studies on (i) radar rainfall processing, (ii) space and time resolution of the rainfall and (iii) soil properties are presented and discussed in Section 4. Conclusions and perspectives for future work are finally drawn in Section 5.

2. The region of interest and the case study

2.1. Studied area and main characteristics of the catchments

The Cévennes–Vivarais region (Fig. 1), located in the South-eastern part of the Massif Central, is especially prone to flash-floods during the fall season. The topography starts from the Mediterranean shore, and ranges up to 1700 m (Mount Lozère; Fig. 1b) over less than 100 km. The main Cévennes rivers (Vidourle, Gard, Cèze, Ardèche; Fig. 1b) have a typical intermittent hydrological regime: low water levels during the summer, floods occurring mainly in the fall. The above-mentioned catchments are medium size catchments (i.e. 2300 km^2 for the largest) with travel times of less than 12 h.

In this study, soil characteristics are extracted from the Languedoc–Roussillon soil database (later referred as BDsol-LR) provided by the INRA[1] from the IGCS[2] program. The soil depth in the studied region and the variability of soil classes are given in Fig. 2b and c, respectively. These graphs illustrate the spatial resolution of the database. The average depth does not exceed 55 cm and more than 50% of the soils are shallow (depth below 50 cm). Manus et al. (2009) show that the average texture over the whole region consists of around 50% sand, 30% silt and 20% clay. Even if the modeling approach is built for the whole Cévennes–Vivarais region, this study is mainly focused on two meso-scale catchments (Saumane, 99 km^2 and Uzès, 86 km^2; Fig. 1b) and on one extreme event that caused severe flooding in the entire Gard region. These two catchments are representative of the soil diversity of the region. The Saumane catchment is located in a hilly area (i.e. mean slope of the whole catchment 0.38 m m^{-1}) while the Uzès catchment is located in a flat area (i.e. mean slope of the whole catchment 0.06 m m^{-1}) with an average river slope four times lower than that of the Saumane basin (Fig. 2a). The average soil depth for Saumane is of less than 20 cm whereas the Uzès soil is much deeper (80 cm) leading to a maximum water storage capacity four times larger than in Saumane (300 mm

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[2] http://gissol.orleans.fr/