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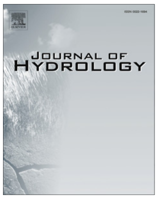

Modeling flash floods in southern France for road management purposes

Béatrice Vincendon [a,*], Simon Édouard [a], Hélène Dewaele [a], Véronique Ducrocq [a], Franck Lespinas [b], Guy Delrieu [c], Sandrine Anquetin [c]

[a] CNRM-GAME/MICADO (Météo France, CNRS), Toulouse, France
[b] Meteorological Research Division, Environment Canada, Canadian Meteorological Centre, Canada
[c] Laboratoire détude des Transferts en Hydrologie et Environnement, UJF-Grenoble1/CNRS/G-INP/IRD, Grenoble, France

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SUMMARY

Flash-floods are among the most devastating hazards in the Mediterranean. A major subset of damage and casualties caused by flooding is related to road submersion. Distributed hydrological nowcasting can be used for road flooding monitoring. This requires rainfall–runoff simulations at a high space and time resolution.

Distributed hydrological models, such as the ISBA-TOP coupled system used in this study, are designed to simulate discharges for any cross-section of a river but they are generally calibrated for certain outlets and give deteriorated results for the sub-catchment outlets. The paper first analyses ISBA-TOP discharge simulations in the French Mediterranean region for target points different from the outlets used for calibration. The sensitivity of the model to its governing factors is examined to highlight the validity of results obtained for ungauged river sections compared with those obtained for the main gauged outlets. The use of improved model inputs is found beneficial for sub-catchments simulation. The calibration procedure however provides the parameters' values for the main outlets only and these choices influence the simulations for ungauged catchments or sub-catchments. As a result, a new version of ISBA-TOP system without any parameter to calibrate is used to produce diagnostics relevant for quantifying the risk of road submersion. A first diagnostic is the simulated runoff spatial distribution, it provides a useful information about areas with a high risk of submersion. Then an indicator of the flood severity is given by simulated discharges presented with respect to return periods. The latter has to be used together with information about the vulnerability of road-river cross-sections.

1. Introduction

Flash floods (FF) are among the most devastating and deadly natural hazards in the Mediterranean (Llasat, 2009; Gaume et al., 2009). Many flood victims are motorists (Handmer and Gruntfest, 2001; Jonkman, 2005), especially during FF (Staes et al., 1994; Bourque et al., 2006). In addition, roads represent an important part of the damaged infrastructures due to FF. The 30-year database built in the framework of HYMEX (HYdrological cycle in the Mediterranean EXperiment) by Llasat et al. (2013) shows that all the floods reported have caused cuts and the occasional partial destruction of roads, streets and bridges. Petrucci and Pasqua (2012) considered floods that occurred in Italy over a 10-year period and stated that motorists represented the totality of the victims either because of drowning caused by floods or due to trauma suffered in car accidents. Motor vehicles are involved in more than half of all FF fatalities in the US (Drobot et al., 2007). Haynes et al. (2009) noticed that more than 75% of casualties due to FF in Australia occurred outside when people entered the flood waters in a vehicle. This high death toll among motorists when caught by FF can be partially explained by a weak risk perception (Ruin et al., 2007). FF concern mostly small catchments and thus affect mainly secondary road networks. Motorists, who are familiar with this network, feel secure (Petrucci and Pasqua, 2012) and underestimate the danger especially as FF are generally sudden and extreme in magnitude.

Better identification of at-risk areas is required so that the civil protection services and road network managers can take the appropriate safety and emergency measures in order to protect civilians. This is a particularly challenging issue in the case of Mediterranean FF for several reasons (Sene, 2008), one of them being that they are often due to severe storms with complex space–time patterns. Early flood warning should not only concern main streams and well gauged river sections, but also all road sections regardless of size, even those crossing small ungauged rivers.

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[*] Corresponding author at: Béatrice Vincendon, GAME/CNRM (Météo-France, CNRS), 42 avenue Coriolis, 31057 Toulouse cedex 1, France.

E-mail address: beatrice.vincendon@meteo.fr (B. Vincendon).

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Flash-flood warnings for small catchments can be issued by evaluating the risk of exceeding a given discharge return-period (Coppola et al., 2007; Javelle et al., 2014). The risk that rainfall reaches a critical volume on a given catchment is also considered in the Flash Flood Guidance method (Norbiato et al., 2008). Flash flood early warnings increasingly intend to consider the uncertainty that affects quantitative precipitation estimates (QPE) products (Germann et al., 2009; Liechti et al., 2013). Indeed estimating rainfall variability on a catchment scale is not an easy task and is often to the detriment of flood forecasting. Many studies showed the usefulness of taking rainfall spatial variability for runoff response modeling into account (Woods and Sivapalan, 1999; Dong et al., 2005 among others). Radar QPE are of great interest for hydrological applications (Bell and Moore, 2000; Liang et al., 2004; Vincendon et al., 2010; *etc*), included for flash flood nowcasting (Smith et al., 2007). Uncertainty also clearly affects the rainfall–runoff modeling itself (Morin et al., 2006). Calibrating hydrological models is a well known means of reducing this modeling uncertainty. Does it however allow one to have faith in the calibrated model in every context, even for the smallest watersheds where the model has not been calibrated?

Some recent studies address the issue of road submersion monitoring and how distributed hydrological nowcasting can be used for road network management purposes. Naulin et al. (2013) described a warning system prototype for road inundation over a region in the south of France. The dynamics of road flooding scenarios are derived from hydrological simulations. Questions remain open as to the ability of distributed hydrological models dedicated to FF to provide information about highly distributed river sections, and in particular concerning points where roads cross the river network. Are distributed hydrological models able to provide valuable results for target points which differ from the outlets used for calibration? Can one trust results for small ungauged rivers?

This paper studies the benefit of using a distributed model, the ISBA-TOP coupled system, to deduce useful information about possible road submersion. This study is conducted in two stages. The first step is to investigate whether ISBA-TOP is able to simulate discharges for any river sections even those not used for calibration. Conclusions demand the use a more advanced description of the soil in the model so as to remove the parameters to calibrate. The second stage of the study consists of comparing ISBA-TOP simulations with road cuts data. To achieve this, various ISBA-TOP outputs are evaluated on a very small scale.

Section 2 of the paper describes the context of the study and the ISBA-TOP system. Section 3 presents results concerning ISBA-TOP performances for main and secondary catchments depending on various FF governing factors and Section 4 proposes an approach with which to compare ISBA-TOP outputs with road cuts data. Conclusions and further work are presented in Section 5.

2. Context of the study

Distributed hydrological models are the best candidates for capturing hydrological processes on a small scales but they are obviously affected by modeling uncertainties (Morin et al., 2006). Their parameters are generally set by calibrating the model against observed discharge using efficiency criteria with which to evaluate the model performance. This calibration is valid for a given outlet, a given type of QPE and of soil moisture. All these choices may impact model performances for simulations of events not only outside the calibration sample but also when changing one of the model inputs.

2.1. Crucial inputs for FF modeling

The main governing factor in FF modeling is precipitation. FF are enhanced by thunderstorms, which exhibit high space–time variability (Nuissier et al., 2008; Vincendon et al., 2011). Quantitative precipitation estimates combining weather radar observation and rain gauge observation are able to capture the rainfall space and time variability. Delrieu et al. (2013) explored such a data merging method in order to improve radar QPE in the French Mediterranean. The high time frequency of radar data is also a determining factor (Michaud and Sorooshian, 1994; Bouilloud et al., 2010 or Wetterhall et al., 2011). Results are sensitive to the radar time-step (Atencia et al., 2011; Anquetin et al., 2010; Bastola and Misra, 2013). O'Loughlin et al. (2012) suggested that the calibration depends on the QPE time-step.

The antecedent soil content is moreover crucial in FF modeling (Zehe et al., 2005; Le Lay and Saulnier, 2007; Brocca et al., 2009; Sheikh et al., 2010), even for empirical models (Tramblay et al., 2010). Castillo et al. (2003) showed how important antecedent soil moisture is in the triggering of runoff. Zehe and Blöschl (2004) came to the same conclusions for subsurface flows triggering. The runoff over saturated areas is particularly influenced as it is directly linked to soil water contents.

The following study investigates the impact on the model performance when changing the type of inputs on different catchment scales with the ISBA-TOP coupled system. ISBA-TOP is an event-based model dedicated to the modeling of Mediterranean FF (Bouilloud et al., 2010; Vincendon et al., 2010). Its baseline version has two calibrated parameters, whereas a new version with no parameter to calibrate has been developed. Both versions are described in the following section.

2.2. Model description

ISBA-TOP consists of a 2-way coupling between the land surface model ISBA (Noilhan and Planton, 1989) and a TOPMODEL (Beven and Kirkby, 1979) approach. ISBA is a surface scheme that deals with water and energy budgets on a rectangular domain divided into 1-km^2 meshes. It governs the overall budget across soil columns. The watersheds are described due to a 50 m-digital terrain model (DTM). TOPMODEL computes the sub-surface lateral water fluxes and space–time dynamics of the saturated areas using the watershed topography. ISBA-TOP is designed to simulate fields of all the water budget components (evaporation, runoff, soil water contents, etc.) across the entire area presented in Fig. 1 as well as discharges on several points of the four main rivers: the Vidourle, the Gardons, the Cèze and the Ardèche.

The soil covers are provided by the ECOCLIMAP II (Masson et al., 2003; Faroux et al., 2013) database and the soil properties are provided by Harmonized World Soil Database, HWSD (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012).

2.2.1. The original calibrated ISBA-TOP

Initially, ISBA-TOP was based on the 3-layer ISBA version, called ISBA-3L (Mahfouf and Noilhan, 1996). Each soil column is partitioned into three vertical layers: the first very thin surface layer where soil-atmosphere interactions are managed, the root zone where the water is available for plants and the deep-soil below which soil moisture no longer varies. A "Force-Restore" principle is adopted: the time evolution of a given variable is due both to the "forcing", which modifies its value, and to the "restoration" towards the background value of the variable (see Appendix C.1 for details). The lateral distribution of water is performed using a TOPMODEL approach over each catchment. It is allowed in the root-zone soil only, as roots and organic matter favor the development of macropores and allow the motion of water, whereas the compaction of the deeper soil layers inhibits water transfers. The time variation of the root-zone water content computed by ISBA over the 1 km-mesh grid is used to update both the hill slope recharge and the storage deficit for each TOPMODEL pixel every hour.