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Influence of mesh structure on 2D full shallow water equations and SCS Curve Number simulation of rainfall/runoff events

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SUMMARY

Hydrological simulation of rain-runoff processes is often performed with lumped models which rely on calibration to generate storm hydrographs and study catchment response to rain. In this paper, a distributed, physically-based numerical model is used for runoff simulation in a mountain catchment. This approach offers two advantages. The first is that by using shallow-water equations for runoff flow, there is less freedom to calibrate routing parameters (as compared to, for example, synthetic hydrograph methods). The second, is that spatial distributions of water depth and velocity can be obtained. Furthermore, interactions among the various hydrological processes can be modeled in a physically-based approach which may depend on transient and spatially distributed factors. On the other hand, the undertaken numerical approach relies on accurate terrain representation and mesh selection, which also affects significantly the computational cost of the simulations. Hence, we investigate the response of a gauged catchment with this distributed approach. The methodology consists of analyzing the effects that the mesh has on the simulations by using a range of meshes. Next, friction is applied to the model and the response to variations and interaction with the mesh is studied. Finally, a first approach with the well-known SCS Curve Number method is studied to evaluate its behavior when coupled with a shallow-water model for runoff flow. The results show that mesh selection is of great importance, since it may affect the results in a magnitude as large as physical factors, such as friction. Furthermore, results proved to be less sensitive to roughness spatial distribution than to mesh properties. Finally, the results indicate that SCS-CN may not be suitable for simulating hydrological processes together with a shallow-water model.

1. Introduction

Runoff processes at the catchment scale have been modeled extensively with empirical and lumped methods as to generate the hydrograph response of storm events for various applications. It is nevertheless possible to make use of two-dimensional shallow-water models to perform distributed and physically-based runoff analysis at the catchment scale. This is not done in many instances because of possibly large computational time as well as the resolution of available spatial data and difficulties when it comes to parameter calibration. Shallow water models allow to obtain the same type of results as lumped models, namely runoff volume and outflow hydrographs, but also spatial distribution of water as well as runoff flow vectors. Hence, results are physically-based and therefore arguably better, but more complete, in the sense that more information is obtained.

In this paper, a 2D shallow-water model is used to simulate the response of a Pyrenean catchment during a storm event. Experimental data for the catchment exist and are used to validate numerical results. The objective is to understand the interactions of various model parameters with the numerical model and comprehend the effect that such interactions have on runoff simulation. In the matter of hydrologic and hydraulic parameters subject to the choice of modelers, it is necessary to characterize the response of the model to each parameter in order to provide parameter sensitivity information and a grasp of the effects of uncertainty of parameter selection. Manning's roughness coefficient and Soil Conservation Service Curve Number (SCS-CN) parameters are those of particular interest in this work.

The solution of the shallow-water equations is done by means of a first order, explicit, upwind finite volume numerical scheme (Murillo and Garcia-Navarro, 2010; Murillo et al., 2007). It is widely known that finite volume schemes are heavily dependant on mesh properties such as cell shape (triangular, rectangular, etc.) and size as well as the general mesh structure (Leveque, 2002). It is quite clear that as the number of cells increases, CPU time increases. This becomes an important issue since the very complex topography of mountain catchments requires a large number of cells. Furthermore, the explicit nature of the scheme imposes a time step constraint so as to satisfy the CFL condition

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(Murillo et al., 2009). The time step is smaller as finer meshes are used. From another perspective, the finest mesh resolution for a given problem is given by the available topography data, and is seldom chosen by the modeler. However, cell shape and mesh structure are modeler choices. Hence, it appears important to exploit such control in order to obtain a mesh that will allow to adequately represent the complex topography and the hydraulic phenomena of interest at the same time that a minimal number of cells is obtained, thus generating the largest possible cells and only refining locally, where the topography demands it. In this paper, the effects of mesh resolution, combined with square and triangular cells are examined. This is further studied by using uniformly refined triangular meshes versus terrain-adapted locally-refined triangular meshes.

The methodology for this work consists of separating the analysis for each of the mentioned issues (i.e., mesh effects, SCS-CN, Manning's n) with a spectrum of cases, as well as combining scenarios in which interactions between the parameters can be seen. With such methodology it is possible to assess the magnitude of the variations and to which parameter or combination of parameters they can be attributed.

2. Catchment description

The Arnás catchment is located in the northern Spain Pyrenees, in the Borau valley, and has a surface of 2.84 km^2, ranging in altitude from around 900 to 1340 m.a.s.l. The catchment has been gauged since 1995 which allows a vast recollection of hydrological data. The primary channel in the catchment is the Arnás ravine which flows into the Lubierre river. Flow measurements have been performed at the outlet on the Arnás ravine (see Fig. 1) with 5 min frequency. Meteorological data have been collected by a meteorological station at the outlet location, and rainfall has been registered by a tipping bucket rain gauge with a frequency of 5 min. Geologically, the catchment lies over Eocene flysch formations and has suffered land use and coverage changes in recent decades, generating a mixed vegetation cover which ranges from forest patches, dense and open shrubs, grassland cover and bare land (Garcia-Ruiz et al., 2005). Previous studies (Garcia-Ruiz et al., 2005; Lana-Renault, 2007; Lana-Renault et al., 2007; López-Barrera, 2011; Serrano-Pacheco, 2009) have provided information such as geological description and vegetation maps which are the basis for hydrological characterization of the catchment.

From the experimental perspective, the response of the Arnás catchment to storms has been described as fast, and the shape of the hydrograph has been found to reflect the precipitation structure (Seeger et al., 2004). From the analysis of experimental data it has been concluded that the response to large storms shows seasonal variation, with highest runoff generation in springtime, while in autumn and summer runoff generation is strongly limited (Lana-Renault et al., 2007). Some of the studied storms with moderate precipitation (total precipitation larger than 10 mm) did not generate runoff and, in general, high storm-runoff variability is observed. Furthermore, Lana-Renault et al. (2007) conclude that the rainfall magnitude and the type of rain influence the response, while maximum rainfall intensity was found to correlate poorly. They also conclude that it is likely that runoff is generated mainly by infiltration excess during the dry season (Hortonian flow), while saturation excess appears to be the primary runoff generation process during the wet season. Garcia-Ruiz et al. (2005) characterize spring and autumn as wet season, winter as an intermediate period and summer as the dry season and also argue that a large spatial variability of the runoff-contributing areas exists in the catchment. Both studies (Garcia-Ruiz et al., 2005; Lana-Renault et al., 2007) conclude that the water table depth has limited influence on catchment response to storms.

From the numerical simulation point-of-view, López-Barrera et al. (2011) simulated the Arnás catchment using a distributed approach, based on a 2D diffusive wave model for surface flow, and both Horton and Green-Ampt models for infiltration, finding difficulties in reproducing outflow hydrographs. López-Barrera (2011) also used the SCS-CN method to estimate infiltration losses in the Arnás catchment, not with a distributed modeling approach (as the aforementioned 2D diffusive wave model), but with a lumped approach, namely the SCS Unit Hydrograph method. Serrano-Pacheco (2009) simulated the catchment with a distributed approach, but using the complete 2D shallow-water equations for surface flow and Horton's model for infiltration. Both studies conclude that infiltration plays a major role in the catchment response and very large precipitation losses occur because of infiltration. Therefore, infiltration modeling plays a major role in the numerical response.

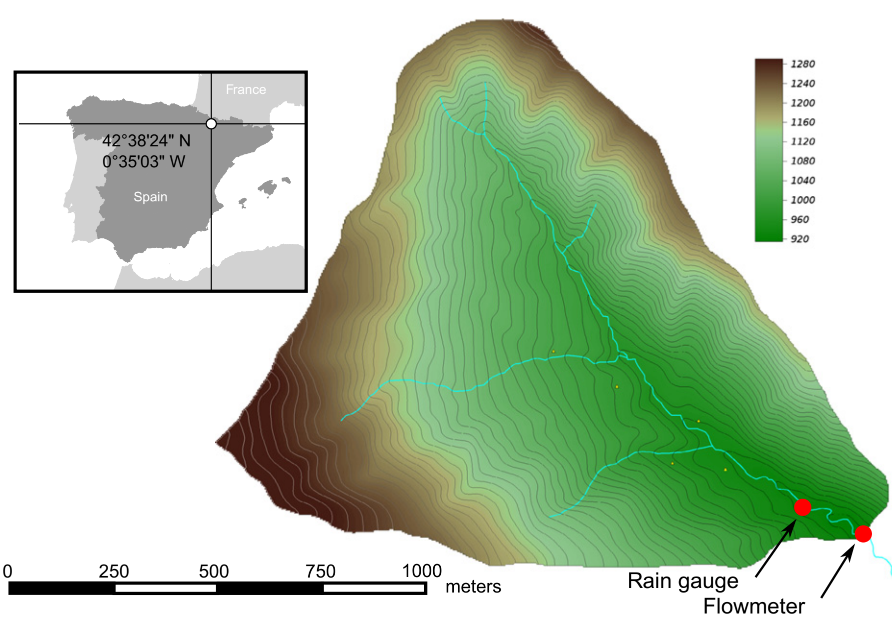

Fig. 1. Arnás catchment.