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Relative roles of geomorphology and water input distribution in an extreme flood structure

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Abstract An extreme flood is often caused by a highly variable rainfall event on a basin. We propose a method for taking this variability into account in a geomorphological unit hydrograph computation. We apply this method to a basin in central Tunisia and show how the combination of geomorphology and water input distribution effects the flood composition.

Key words rainfall–runoff modelling; geomorphological unit hydrograph; rainfall variability; semiarid

INTRODUCTION

The river network is the main key of the basin structure since it is made of locations of flow convergence and circulation. The global evolution of the flood at the outlet is the integration of temporal and spatial variations and scaling properties of processes within this structured system. In the case of extreme floods from rainfall, the water input is highly variable most of the time due to extreme meteorological situations. The purpose of this paper is to introduce a description of the space and time variability into a geomorphological unit hydrograph (GUH) computation.

THE GEOMORPHOLOGICAL UNIT HYDROGRAPH (GUH)

The unit hydrograph h(t) initiated by Sherman (1932) is a linear mathematical operator used as the transfer function of the basin. If the mean effective rainfall $\overline{R}_{\text{eff}}$ is deduced from the rainfall through the production function, the unit hydrograph gives the flow at the outlet $Q(t)$ by convolution, knowing the area of the basin A:

$$Q(t) = A\int_0^t \overline{R}_{\text{eff}}(\tau)h(t-\tau)\,\mathrm{d}\tau \quad (1)$$

The unit hydrograph can be interpreted as the probability density function of arrival time at the outlet and deduced from the geomorphology. This concept, called the GUH, was developed in two directions. On the one hand, Rodriguez-Iturbe & Valdès (1979) and Gupta *et al.* (1980) proposed theoretical reasoning based on the residence times in the streams of different Strahler orders (Strahler, 1952). Thus this direction, followed by Kirshen & Bras (1983) and Rinaldo *et al.* (1991), requires the river network to have a topological hierarchy.

On the other hand, Surkan (1969) proposed the estimation of the probability density function of the arrival time from the normalized area function i.e. the probability density function of surface according to the hydraulic distance to the outlet. Since then, the width function (Shreve, 1969), which is the number of links of the network according to the hydraulic distance to the outlet, is often used as an approximation to the area function (Kirkby, 1976; Gupta & Waymire, 1983; Troutman & Karlinger, 1985; Snell & Sivapalan, 1994). The width or the area function is transformed into the probability density function of the arrival time through an hypothesis of river flow hydraulics such as mean velocity (Kirkby, 1976; Troutman & Karlinger, 1985) or an estimation of hydrodynamic and geomorphological dispersions (Troutman & Karlinger, 1985; Snell & Sivapalan, 1994).

In the case of extreme events we think that the effective rainfall variability has a greater effect than river flow variability. Thus we propose to deduce the GUH from the area function and a mean velocity parameter, and to take the effective rainfall variability into account in the convolution.

INTRODUCING THE TEMPORAL AND SPATIAL VARIATIONS OF EFFECTIVE RAINFALL INTO THE GUH

The area function is a one-dimensional synthetic function mapping the two-dimensional basin. The deduced GUH can be discretized into isochrones, whose geographical extensions are identified and the effective rainfall variability can be observed over these isochrones. Then the discretized expression of the convolution (equation (1)) with time Δt is:

$$Q(t) = \frac{A}{\Delta t}.\sum_{\tau=1}^{t} \overline{R}_{\text{eff}}(t-\tau+1)\,h(\tau) \tag{2}$$

can be made more precise by using the effective rainfall $R_{\text{eff},\tau}$ for each isochrone τ:

$$Q(t) = \frac{A}{\Delta t}.\sum_{\tau=1}^{t} R_{\text{eff},\tau}(t-\tau+1)\,h(\tau) \tag{3}$$

This equation can be formulated as follows:

$$Q(t) = \frac{A}{\Delta t}.\sum_{\tau=1}^{t} \overline{R}_{\text{eff}}(t-\tau+1)\,V_{\tau}(t-\tau+1)\,h(\tau) \tag{4}$$

in which appears the factor:

$$V_i(j) = \frac{R_{\text{eff},i}(j)}{\overline{R}_{\text{eff}}(j)} \tag{5}$$

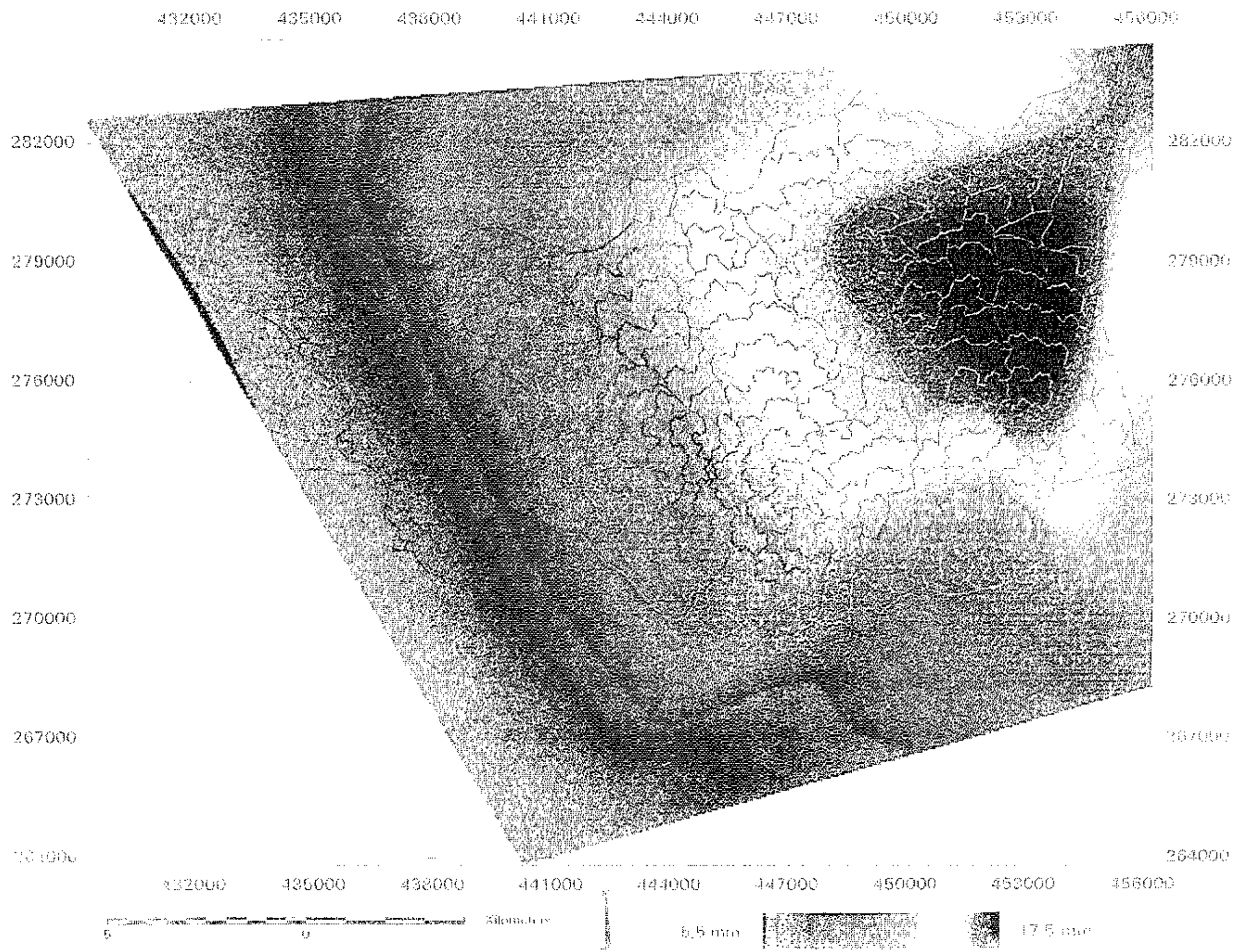

Fig. 1 Superimposition of the isochrone polygonal vector images and a rainfall field raster image for the River Skhira basin. This example shows the time step 20:39–20:44 h, of 10 May 1996.

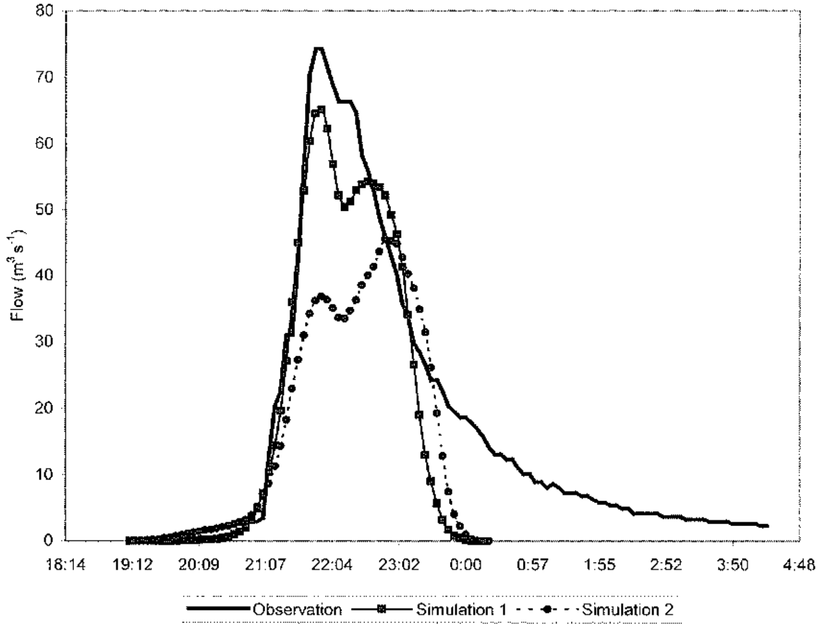

Fig. 2 Observed and simulated hydrographs of 10 May 1996. Simulation 1 is based on the variable effective rainfall and simulation 2 on the mean effective rainfall.

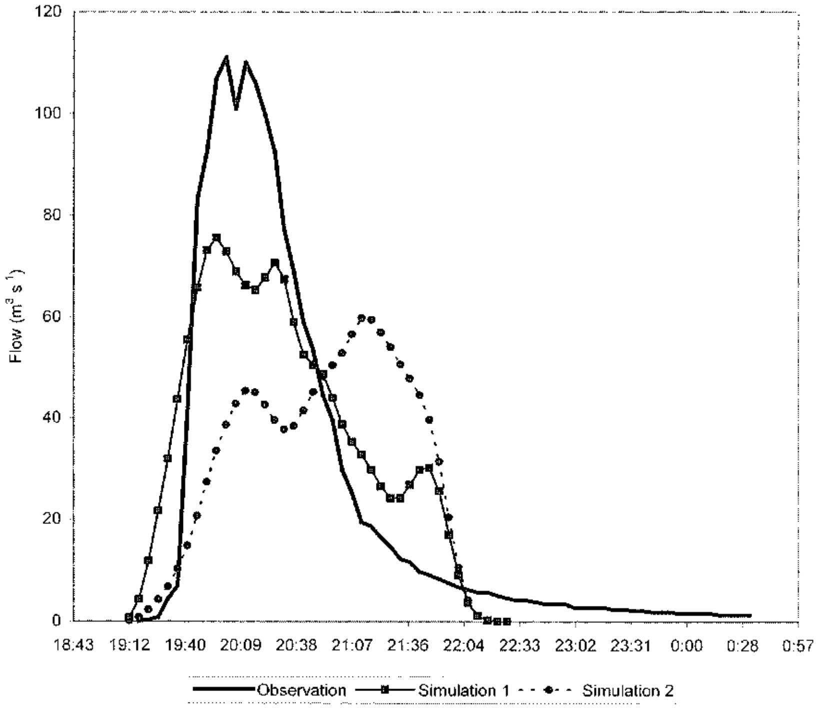

Fig. 3 Observed and simulated hydrographs of 9 September 1997. Simulation 1 is based on the variable effective rainfall and simulation 2 on the mean effective rainfall.

APPLICATION TO SEMIARID FLOODS

This methodology was applied to the Skhira basin in central Tunisia. The outlet coordinates are 35°44′15″N and 9°23″05″E in UTM (Universal Transverse Mercator) system and the basin area is 192 km^2. The climate is semiarid: it is located between the 300 and 400 mm isohyets and most of the rainfall comes from violent and highly variable storms during spring and autumn. Moreover rainfall intensities and the arid soil cover lead to flows dominated by runoff. These points make this site particularly interesting for our study.

The river network is derived from 1:50 000 topographic maps of Maktar and Djebel Barbou. An estimation of the mean flow velocity (2.8 m s^{-1}) and an image processing protocol allow the area function and the GUH to be deduced, and the isochrone areas to be mapped as vector polygons. The time discretization rate is that of the rainfall recording in order to process the convolution.

By interpolation between three raingauges and observations at three rain recorders, at each time step we create rainfall field raster maps. Then GIS tools allow the crossing of the isochrone vector image and rainfall raster images. Figure 1 shows this crossing for the storm of 10 May 1996 at 20:39 h.

The production function is not our priority, so we use one of a simple reservoir type, adapted for a semiarid climate (Wey, 1990) where infiltration is limited by the soil maximum storage capacity and runoff is rainfall minus infiltration. The application of this function to the rainfall variability matrix, for each isochrone and each time step, gives the effective rainfall variability matrix $[V_i(j)]$.

RESULTS

Figures 2 and 3 show the observed hydrograph for two flood events (10 May 1996 and 9 September 1997), one simulated with the GUH and a mean effective rainfall estimation and the other simulated with the GUH and the variability matrix. The simulated values do not fit the observed values very well, mostly because of the simple production function and maybe also because of the small number of raingauges. But Figs 2 and 3 show the relevance of the proposed method. Indeed, in both cases two peaks are simulated and the simulation with the variability matrix leads to more closely matched peaks of relative values and dates.

The method proposed here is robust since the rainfall field is estimated from only a few point measurements. But it could also be applied using rainfall observations by remote sensing which would provide numerical mapping directly. Moreover, this method can be applied with a better estimation of the production function. Finally, it shows the relative roles of geomorphology and effective rainfall distribution in the flood structure.

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