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Geomorphological instantaneous unit hydrograph model with distributed rainfall

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ABSTRACT

Two variants of the Instantaneous Unit Hydrograph model based on a Geomorphological association of linear Reservoirs (IUHGR), incorporating the Spatial Variability of Rainfall (SVR), have been developed. The proposed models are based on the Geomorphological Reservoirs (GR) scheme consisting of a cascade of linear reservoirs aggregating sub-watersheds. The model, in its first version, was formulated so that it incorporated a spatial variability pattern of rainfall associated with a certain frequency and oriented towards its application in the field of hydrological design. This model was considered to be stationary in the time (GRSVR(s)) for being linked to some design conditions. The second version of the model is applicable to the simulation of real events, where there is a dynamic (GRSVR(m)) spatial distribution of rainfall that varies in time, as in the case of the movement of rainstorms. Both models permit the input of relevant information on the spatial variability of the rainfall, taken from different rain gauge records, without losing the simplicity of the GR model with a single parameter, which represents the hydrological time response of the watershed. The models have been calibrated and validated with the data from one gauged watershed in northern Spain. The analysis conducted in both cases showed that the models which contemplated the spatial variability of the rainfall, GRSVR(s) and GRSVR(m), were capable of simulating rainfall variability effects in the surface runoff hydrograph better than the GR model, which averages the precipitation values recorded in the different rain gauges.

1. Introduction

The unit hydrograph (UH) technique is part of the so-called conceptual models and can simulate the direct runoff hydrograph (DRH), generated in a watershed, from the effective rainfall hyetograph (ERH); when the ERH is instantaneous, it is called “Instantaneous Unit Hydrograph” or IUH. This method has been widely used in the field of hydrological design and simulation using mathematical models, such as, for example HEC-HMS (HEC, 2016), AnnAGNPS (Bingner et al., 2015), etc. Basically, the technique is based on the establishment of a unit pulse response function of the watershed (UH) to generate, through convolution, its response to any pulses of different magnitudes. One of the key features of the model is that the rainfall unit pulse is uniform in time (pulse duration interval) and space (watershed). The temporal variability of the rainfall is solved by the convolution of the different hyetograph rainfall pulses. However, the rainfall is considered to be uniform throughout the length of the watershed. The only way to contemplate rainfall spatial variability is as a uniform precipitation averaged by the different rain gauges in the watershed. These assumptions, together with the original conception of aggregate model (lumped model), in which the parameters do not vary spatially within the watershed, limit the applicability of the method to small and medium watersheds (Ponce, 1989, §153).

The linear reservoir theory is a widely accepted method for simulating the rainfall-runoff process, and also, specifically, for determining the unit hydrograph of a watershed (e.g. Chow et al., 1988 §8.5). In this model, the storage equation is combined with the continuity one to give the effective rainfall rate in terms of a storage constant, k. Many conceptual IUH models are based on this theory (e.g. Singh, 1988, §13; Bras, 1990 §9.6), including single reservoir ones (e.g. Clark, 1945) or those with connected reservoirs, in series or in parallel. Nash (1957) associated the watershed with a cascade of linear reservoirs, obtaining the unit hydrograph that bears his name. Dooge (1959) already associated a structure of reservoirs and of linear channels with the watershed, according to the surface drainage. Later, other researchers have developed many models of this type associating linear reservoirs with river network elements (Diskin et al., 1984; Chutha and Dooge, 1990; Diskin, 1994; Wang and Chen, 1996; Jeng and Coon, 2003). López et al. (2005) proposed an IUH based on a cascade of linear reservoirs delimited from the drainage network of the watershed,

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Geomorphological Reservoirs (IUHGR), henceforth referred to as the GR model. This model can be regarded as being a special case of Dooge's general IUH model without channel reservoirs. In addition to the good results obtained (Agirre et al., 2005; López et al., 2012), its simplicity and versatility make it a useful hydrological tool. Li et al. (2008), based on the conceptual scheme of the Nash IUH, obtained a methodology for determining the value of storage coefficient, *k*, of each reservoir associated with the topography of the basin. Nourani et al. (2008) developed the SLRC model (Semi-distributed version of Linear Reservoir Cascade). A similar one to that of López et al. (2005), it uses a nonlinear equation (kinematics wave) for flow routing through the watershed's main channel. Nourani et al. (2009) compared this model with others of similar characteristics. Saeidifarzad et al. (2014) presented a multi-site optimization of two adapted, event-based geomorphological rainfall-runoff models, the first model being developed as based on Unequal Cascade of Reservoirs (UECR), and the second one presented as a modified version of a Geomorphological Unit Hydrograph based on Nash's model (GUHN). Nourani et al., 2015 studied the effect of land use on the Geomorphological Cascade of Unequal linear Reservoirs (GCUR) model. The proposed modelling considered the effects of watershed geomorphology and land use/cover.

The influence of spatial rainfall variability on the modelling of the hydrograph at the catchment outlet has long been a concern for hydrologists. Interest in this topic has been growing thanks to both the increasing availability of weather radar data and the development of distributed hydrological models (e.g.: Wilson et al., 1979; Ogden et al., 1995; Morin et al., 2006; Nicotina et al., 2008, Zoccatelli et al., 2010; Viglione et al., 2010; Lobligeois et al., 2014; Emmanuel et al., 2015). As indicated by Emmanuel et al. (2017) this subject is important for both research and practical reasons. From the research point of view, it contributes to a better understanding of how the spatial rainfall variability propagates up to the catchment outlet. From the research point of view, the incorporation of spatial rainfall variability into hydrological models may lead to more accurate flood modelling results. Although the literature on this topic is abundant, the results are contrasting and sometimes contradictory, as reflected in the recent reviews of Emmanuel et al. (2017), Emmanuel et al. (2015), Lobligeois et al. (2014) and Cristiano et al., 2017 for urban areas. Several studies concluded that the inclusion of the spatial variability of rainfall improved the simulation of output hydrographs, whereas others, surprisingly, did not show significant improvement in the simulations. In sum, as concluded Emmanuel et al. (2017), Nicotina et al. (2008) and Cristiano et al. (2017), it appears that the influence of spatial rainfall variability on hydrograph modelling results is a complex issue that depends on a combination of factors, namely: rainfall patterns, catchment characteristics, and runoff generation processes. These works induce to explore the timescale parameters of the hydrological response of the catchment, properly reviewed by Cristiano et al. (2017), and, in particular, of the catchment response timescale introduced by Morin et al. (2002). The movement of a rainstorm is a typical case of the spatial variability of the rainfall, which has a relevant effect on the generation of the runoff hydrograph (e.g. Yen and Chow, 1969; Wilson et al., 1979; Singh, 1998, 2002; de Lima and Singh, 2002, 2003; Seo et al., 2010; Seo and Schmidt, 2013; Sigaroodi and Chen, 2016).

As has already been mentioned, the spatial rainfall in UH is taken as an averaged precipitation value according to the different methods available (Thiessen, kriging, etc.) introducing an important source of uncertainty, as was pointed out by Rew and McCuen (2012). The latter analysed the factors that influence unit hydrograph accuracy, especially the spatial characteristics of rainfall. Therefore, the aim of the work presented in this manuscript was to incorporate the spatial variability of the rain into the actual formulation of the GR model (López et al., 2005) taking advantage of its structure of linear reservoirs associated with the river network of the watershed. López et al. (2012) have already extended the formulation of the GR model to include the spatial variability of the basin, GR(v), leaving the door open to the inclusion of physical characteristics such as slope, land use, etc., as Nourani et al. (2015) have done.

Two variants of the GR model incorporating the spatial distribution of rainfall in its formulation are presented for different applications. In its first version, the model's formulation incorporates the spatial variability of rainfall (SVR) through a stationary (s) pattern of spatial distribution of rainfall, hence its denomination of GRSVR(s). If this pattern is associated with a frequency level (return period) then it can be applied to design conditions. In this case, it starts from a design storm with a temporal distribution and a spatial rainfall pattern which is kept constant in the time. To analyse the effect of this variant, the hydrographs resulting from the application of different spatial distributions of the rain in the watershed of Oiartzun (Gipuzkoa-Spain) were compared. The second variant of the GR model is applicable to the simulation of real events, where there is a dynamic spatial distribution of rainfall that varies in time. In this model, each area of influence associated with each rain record generates a hydrograph that circulates through the cascade of deposits. The resulting hydrograph of the entire watershed will be the sum of all those hydrographs. Consequently, we have called this model GRSVR(m), "SVR" due to its incorporation of the spatial variability of rainfall, and "m" for multiple hydrographs. This variant has been evaluated with real events recorded in the Oiartzun watershed, and the capacity of the model for simulating hydrographs produced by storms in movement, in this case synthetic ones, has been analysed.

2. Location and description of the watershed

The Oiartzun watershed, of 56.6 km^2, an average slope of 36.3%, and a drainage density of 1.1 km^2, is located in the province of Gipuzkoa to the north of Spain (Fig. 1). The watershed outlet is located on an industrial estate in the town of Oiartzun, where a gauging station is found. The height of this point is 11 m, and the elevation of the basin's highest point 832 m. The main channel is 14,668 m long and has an average slope of 5.6% with a southeast-northwest direction. The head of the watershed sits on a granitic area, specifically granodiorites and coarse-grained granite, while in the lower part the originating material there are slate, loams and limestone. In terms of permeability, in most areas it is low, becoming impermeable in places close to the channels. Areas of high porosity are minimal, and correspond to sandstone ones. In relation to the land uses, in the upper part of the watershed the surface is covered by deciduous forests (52.4%), scrub (9.6%), rock (2.0%) and upland pastures (4.5%). In the lower part, there are grassland (28.5%) and urban areas (3.1%), corresponding to the urban core of Oiartzun and the industrial estate where the gauging station is.

The climate of this area is Atlantic, humid, temperate, practically without a dry season. Due to its proximity to the sea, it has oceanic characteristics. The summers are temperate (20–22 °C on average), and the winters mild (7–8 °C on average), with an annual average temperature of around 12 °C with small brusque temperature fluctuations. The precipitations are abundant, around 1500 mm of average annual precipitation, and they are distributed throughout the whole year, although it is in spring and autumn that it rains most.

Two seasons can be distinguished: a wet season, which spans from October to the end of April, and a drier season, from May to September. The wet season accumulates > 70% of the annual precipitation, with two peaks before and after winter: the primary rainfall peak is recorded in autumn (October–November) and the secondary peak in early spring (March–April). The wet season starts in October with the collapse of the summer eastward extension of the Azores High, which ridges over the Bay of Biscay and southern France in October. This is concurrent with more frequent intrusions of cold fronts and a marked increase of the probability of precipitation, associated with a southward displacement of the polar front and the Atlantic depressions in early autumn. During this period (October–November), frontal and orographic rain episodes