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A new adaptation of linear reservoir models in parallel sets to assess actual hydrological events

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SUMMARY

A methodology based on Parallel Linear Reservoir (PLR) models is presented. To carry it out has been implemented within the software SHEE (Simulation of Hydrological Extreme Events), which is a tool for the analysis of hydrological processes in catchments with the management and display of DEM and datasets. The algorithms of the models pass throughout the cells and drainage network, by means of the Watershed Traversal Algorithm (WTA) that runs the entire drainage network of a basin in both directions, upwards and downwards, which is ideal for incorporating the models of the hydrological processes of the basins into its structure. The WTA methodology is combined with another one based on models of Parallel Linear Reservoirs (PLR) whose main qualities include: (1) the models are defined by observing the recession curves of actual hydrographs, i.e., the watershed actual responses; (2) the models serve as a way to simulate the routing through the watershed and its different reservoirs; and (3) the models allow calculating the water balance, which is essential to the study of actual events in the watershed. A complete hydrometeorological event needs the combination of several models, each one of which represents a hydrological process. The PLR model is a routing model, but it also contributes to the adjustment of other models (e.g., the rainfall–runoff model) and allows establishing a distributed model of effective rainfall for an actual event occurred in a basin. On the other hand, the proposed formulation solves the rainfall distribution problem for each deposit in the reservoir combination models.

1. Introduction

In hydrological disciplines, hydro-meteorological methods are old known but, still, they remain in force and continue to be performed numerous works and publications that, on the basis of these ideas, add new techniques and concepts that help to understand the complexity of hydrological processes. Our work aims to be one of them, while it uses classical concepts, it presents a new formulation that contributes to improving the application of the method. In this way, you can improve the problem of sharing at the entrance of deposits of the dynamics of systems, allowed obtaining very accurate results in the simulation of actual events, and this has contributed significantly in the setting of different models or parts of the hydrometeorological methods.

This article presents a new formulation with Parallel Linear Reservoir models (PLR models) which allows simulating actual hydrological events with great accuracy, thus obtaining many characteristics of the events and the basin behaviour. The formulation originates from two classic equations, the discharge or storage equation and the continuity or water balance equation. These models describe water circulation through the basin, but it is not the only hydrological process occurred in a hydrological event. Therefore, when simulating all the participating processes, this model needs to be accompanied by other models like a Digital Elevation Model (DEM) of the basin, a rainfall spatial–temporal distribution model, a rainfall–runoff transformation model (in this case, the curve number model, SCS-CN has been used) and, in a complementary way, a model describing the flow through the drainage network (in this case, Muskingum–Cunge was used). A model composed by a combination of parallel linear reservoir is applied to each DEM cell and they receive inputs which are the result of the pass through the rainfall distributed model and the SCS-CN model. The PLR model outputs pour into the ramified drainage network, defined by means of the DEM, and there is where the routing is simulated with the Muskingum–Cunge model. In order to remove complexity to the development of the article, knowledge about the remaining models of hydrological processes is taken for granted, and the PLR model is developed in greater detail.

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Reservoir models have been traditionally used in hydrology to represent different watershed features. Moore (1997), Griffiths and Clausen (1997), and Dewandel et al. (2003) synthesized several works in this area of research. The base flow in streams and springs has been studied for more than a century (Boussinesq, 1877; Maillet, 1905). The characterization and prediction of the base flow rate are necessary in hydrology to determine the possibilities of storing and exploiting surface water resources and to determine the impact of the contamination provoked by the spills (Thomas and Cervione, 1970; Tasker, 1972; Parker, 1977; Vogel and Kroll, 1992). Woods (2003) proposed set of coupled analytical models and makes predictions for the water balance of the canopy, root zone, saturated zone and catchment system. Each of the processes is represented as a conceptual nonlinear store.

The study of hydrograph recession curves provides data regarding the structure and functions of different reservoirs present in a watershed (Mijatovic, 1974; Brutsaert and Nieber, 1977; Troch et al., 1993; Szilagy et al., 1998). Wittenberg (1999), uses a non-linear reservoir algorithms supported by an analytical derivation. Rupp and Selker (2006) present a new method for analysis of the recession limb of a hydrograph, which differs from the previous methods in that the time increment over which the slope is estimated is not held constant over the entire recession curve. Instead, the time step for each observation is properly scaled to the observed drop in discharge. Sujono et al. (2004) perform a comparison between commonly used techniques for hydrograph recession analysis and a relatively new approach based on wavelet transform, and conclude that direct flow and the location of the base flow component are easily determined through the wavelet maps.

Since 1930, rainfall–runoff models based on a combination of linear and non-linear reservoirs have been used in hydrology research. The linear reservoir model presented by Zoch (1934) is one of the oldest and simplest models to simulate the rainfall–runoff relation. The linear reservoir model constitutes the base for many conceptual models (Chow et al., 1988). However, Nash (1957) proposed a conceptual model composed of a cascade of linear reservoirs with equivalent storage coefficients. Dooge (1959) extended Nash's model to include the transition effect between the flow and account for the concept of a linear canal. Because it is not easy to obtain an explicit expression for the UIH when establishing the rainfall distribution in the complex geomorphology of watersheds, simplified models have been proposed, such as the models of in series (in cascade) linear reservoirs presented by Wang and Chen (1996) and Jeng and Coon (2003).

Recently, reservoir models distributed in agreement with geomorphological trajectories inside a watershed have been established. Boyd (1978) developed a conceptual model based on the geomorphological properties of watersheds. By introducing a probabilistic framework, Rodríguez-Iturbe and Valdés (1979) and Gupta et al. (1980) presented an instantaneous geomorphological unit hydrograph that uses an exponential probability distribution for the routing time equivalent to utilize a linear reservoir. Karnieli et al. (1994), Hsieh and Wang (1999) and Nourani and Monadjemi (2006) developed models of geomorphological runoff using a method that are similar the model of Boyd et al. (1987). Szilagy and Parlange (1999) perform a nonlinear, semi-distributed model for simulating watershed dynamics that utilizes spatially distributed physical characteristics of the catchment, and López et al. (2005) presented instantaneous unit hydrograph models applying linear reservoirs distributed in cascade according to the watershed geomorphology.

To perform this work, the SHEE (Simulation of Hydrological Extreme Events) package developed for the Authors of this paper in the Department of Earth Sciences from The University of Zaragoza was used. In essence, the program is an adaptation of traditional hydrological models to DEMs and databases. The catchment is divided into elemental fractions, i.e., the cells and connections between the DEM nodes. Each cell gets, e.g., a rainfall model and a rainfall–runoff model. The connection between two nodes is the elemental fraction of the watershed drainage network, and also the point where the routing model is applied, starting from a hydrograph at the input node and obtaining another hydrograph for the output node. Finally, several flow lines can reach a node, thus performing out the sum of the input hydrographs and obtaining only one input hydrograph for the next network section.

To integrate all these hydrological models into each elemental fraction of the DEM, in such a way that it follows a logical sequence, the nucleus of the SHEE program uses the WTA algorithm, which intends to cover all cells in the DEM in an ordered way. These cells within a given catchment define, differentiate or distinguish the watershed and its cells from the rest of the DEM. The flow chart in Fig. 1 shows the structure of the algorithm (in Mateo-Lázaro et al., 2013 there is a further explanation). For a given root node, all nodes in its catchment must be run orderly. In Fig. 1, for the node 1, the algorithm follows the path indicated by the arrows: blue arrows for up direction and red arrows for down direction.

With this procedure, all cells are covered following a logic sequence with the following qualities: (1) Other algorithms can be created by introducing models, placing them in the right places. (2) These new models will be able to obtain the necessary data from the right places and provide data to other models. (3) There are two travel directions, upslope and downslope. Depending on the type of calculation which a particular procedure makes, one direction or another will be the most interesting. (4) When a node is passed for the last time in a downward direction, all nodes in the watershed which were located above it will be covered; when applying measures or models, the influence of all nodes is thus perceived. (5) When a node is reached in an upward direction, the influence of all nodes of the main flow to the first point in the watershed is perceived.

This methodology also provides the hydrological process information and the watershed features, thus permitting the application of distributed models of all processes and features considered. The SHEE program has resulted in several publications, including those related to hydrology we have Mateo-Lázaro et al. (2014a), and García-Gil et al. (2014). In the first mentioned a sensitivity analysis of the flash flood episodes in response to changes in the main hydrological processes involved has been made, such as spatial and temporal distribution of rainfall, soil moisture status and water flow through channel network. In this work, we found that the antecedent moisture condition is the most influential factor in the magnitude of flash floods produced by the same amount of rain. The temporal distribution of the storm represents the second characteristic in order of relevance. In addition, terrain morphology (specially the slope) is found to be decisive in the results differences obtained.

The SHEE software uses powerful libraries (e.g., OpenGL, GDI, GDAL, Proj4) for the management and display of DEM and datasets, its interface provides rapid and great quality OPENGL graphics, in both RASTER and VECTOR formats. The software has numerous applications for either DEM management or hydrological processes simulation (Mateo-Lázaro et al., 2014c). Obtaining new cartographic coverage with the combination of DEM and simulated processes is also possible. The DEM management is achieved using the GDAL (Geospatial Data Abstraction Library), which permits to import and export different archive formats and to make new coverage from multiple archives. The program can combine coverage with different coordinate system thanks to the use of the PROJ4 library from the USGS. Thousands of terrestrial geodetic systems can be represented, transformed and converted between them.