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Performance of a distributed semi-conceptual hydrological model under tropical watershed conditions

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ABSTRACT

Conceptual rainfall-runoff models at the watershed scale are useful tools for assisting in managing and planning water resources, making it possible to estimate streamflow and to predict hydrologic impacts due to land-use changes. The objective of this study was to calibrate and to validate the LAvras Simulation of Hydrology (LASH Model) (Beskow, 2009) in a Brazilian Tropical Watershed for daily streamflow. LASH is a continuous, distributed, semi-physically based model for simulation of different hydrologic components on a daily basis. The Shuffled Complex Evolution (SCE-UA) global search method was used with the LASH model in order to optimize model parameters that were found to be the most sensitive or not directly measurable. The LASH model was calibrated over a 2-year period, thereafter, the parameters obtained through the calibration were kept constant for the validation step using a different period of time from that analyzed during the calibration. The Nash–Sutcliffe coefficient (C_{NS}) values found were 0.820 and 0.764 during calibration and validation, respectively, whereas, the C_{NS} (log Q) values equal to 0.821 and 0.770 were obtained for the same periods. The SCE-UA method was found to be an efficient algorithm for searching 'optimal' model parameter values. It was possible to conclude that the model has a great potential for being applied in generating the long-term streamflow as well as flow-duration curves. Therefore, the model can reliably be applied under tropical conditions of this medium-sized watershed or other similar watersheds, thus making it useful to plan the sustainable development of similar tropical and subtropical watersheds.

1. Introduction

Hydrologic modeling has been extensively used to quantify the impact of different land-use scenarios and climate change on water resources in watersheds. In addition, hydrologic models can be valuable tools to perform flood forecasts, and in water resources management, as well as providing design criteria for hydraulic structures.

Traditionally, many hydrologic models have been structured with distributed approaches to account for the spatial variation of physical processes related to the hydrological cycle. This type of model is usually composed of a large number of parameters and presents a high level of complexity (Blasone et al., 2008). In addition, there are parameters whose measurement is both difficult and unfeasible at the watershed scale (Duan et al., 1994; Gan and Biftu, 1996). According to Lin and Radcliffe (2006), hydrologic models have been calibrated through optimization methods for some decades. Under these circumstances, some calibration parameters are required in order to make application of models easier.

Most developing tropical and subtropical countries like Brazil have a scarcity of data inputs at small to medium watershed scales, except when watersheds are gaged for research purposes (Beskow et al., 2009b). Therefore, in case of scarcity of data, it is unfeasible to apply a complex hydrologic model which is driven with a large amount of data, such as SWAT (Arnold et al., 1998; Gassman et al., 2007), WEPP (Flanagan and Nearing, 1995), or AGNPS (Young et al., 1987). To overcome this drawback, hydrologic models based on simple approaches using a small amount of data are preferable due to these limitations. The LASH model, which was developed by Beskow (2009), employs a simple approach and was especially designed to predict streamflow in watersheds in regions where there is scarcity of data concerning weather, soil, land-use, and discharge.

The study watershed presented in this paper is located in Minas Gerais State (Brazil) and has both a high water yield capacity and has potential for electric energy generation. In addition, it drains into Camargos Hydroelectric Plant Reservoir (installed capacity of 48,000 kW), which is important for the future development of Minas Gerais State. For many watersheds in Brazil, it is necessary to apply

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simulation models because quantitative streamflow results are less commonly available than rainfall data. Therefore, a rainfall-runoff model is needed for obtaining reliable streamflow series in ungaged watersheds which include physical characteristics of a given watershed as well as its land-use and soil types. Such a model can also be applied to predict the effects of land use or climate change on runoff, sediment transport, and water quality. Quantitative streamflow assessments and potential strategies for management of watersheds are necessary for both local planning and governmental agencies associated with sustainable development. This kind of work has not been carried out and we have serious problems with land-use change and its effects on water resource management in Brazil.

In order to test the quality of a watershed model for a given application, White and Chaubey (2005) recommended running a sensitivity analysis, calibration, and validation of the model. Sensitivity analysis expresses the influence of different parameters on the response of an output variable in that the greater the difference in output response, the more sensitive the respective parameter. Moreover, sensitivity analysis is extremely useful for establishing the parameters that should be taken into account during the calibration step (Blasone et al., 2008). This analysis has become usual prior to the calibration step of hydrologic models (Francos et al., 2003; Benaman and Shoemaker, 2004; Muleta and Nicklow, 2005; White and Chaubey, 2005; Griensven et al., 2006; Arabi et al., 2007; Blasone et al., 2008).

A calibration effort is required to search for a set of parameters which represents a process appropriately and generates satisfactory results regarding output of interest. This task is achieved by either maximizing or minimizing efficiency measures such as Root Mean Square Error and Nash–Sutcliffe coefficient. According to Arabi et al. (2006), the calibrated model should be run with a set of measured data not used in the calibration stage. This step is known as validation and is useful for verifying whether predictions are acceptable even on different data sets.

According to Eckhardt et al. (2005), manual calibration is subjective, time consuming and potentially biased, and procedures of automatic calibration can overcome these problems. Although manual calibration sounds bad in this context, if it is done by an experienced hydrologist it can be better than an automatic calibration based simply on a given objective function. Among automatic optimization methods, the Shuffled Complex Evolution (SCE-University of Arizona (UA)) developed by Duan et al. (1992) has been widely employed and found to be robust and computationally efficient. The SCE-UA method has been successfully applied to several hydrologic models (Duan et al., 1992; Gan and Biftu, 1996; Yapo et al., 1996; Eckhardt and Arnold, 2001).

This study has the objectives to: (a) calibrate and validate the LASH model to a representative tropical watershed by using a distributed approach; (b) investigate whether the SCE-UA optimization method is efficient for the specific case of the LASH model.

2. The LASH model

The LAvras Simulation of Hydrology Model (LASH) (Beskow, 2009) is a time continuous, spatially distributed, semi-physically based model for simulation of hydrologic components on a daily basis, under tropical and subtropical pedologic and weather conditions.

The LASH model is composed of three fundamental modules (Fig. 1). Its first module simulates surface runoff flow, sub-surface flow, base flow and capillary rise to compute water balance. There is a module destined to compute the flow from each cell to the stream network taking into account the lag effect. The last module employs the Muskingum–Cunge Linear Model to propagate the flows through the channel network.

LASH was written in Delphi (Windows Environment) and provides a Graphical User Interface (GUI). Its GUI allows users to import maps from various Geographical Information Systems (GIS), thus making the use of the model easier. Furthermore, LASH has an automatic optimization routine embedded in it which is based on the Shuffled Complex Evolution method (SCE-UA, Duan et al., 1992), allowing users to calibrate as many parameters as necessary.

All the physical processes simulated by the model are based on the soil water balance equation, which is updated at each time step (daily) for each grid cell in the watershed according to Eq. (1). The number of grid cells depends on both the cell size and how large the watershed is.

$$A_{t_i}^{j} = A_{t_i}^{j-1} + \left(P_i - ET_i - \frac{D_{S_i}}{\Delta t} - D_{SS_i} - D_{B_i} + D_{CR_i}\right)\cdot\Delta t \quad (1)$$

where j and i are indexes associated to time step and grid cell, respectively; $A_{t_i}^{j}$ and $A_{t_i}^{j-1}$ are, the soil water availability (mm) for the grid cell i at the end of the time step j and at the start of the time j, respectively; Δt is the time step (daily); P_i corresponds to the precipitation (mm day^{-1}) minus interception of rainfall by land cover; ET_i is the evapotranspiration (mm day^{-1}); D_{S_i} is the surface runoff (mm); D_{SS_i} represents the sub-surface flow (mm day^{-1}); D_{B_i} is the base flow (mm day^{-1}); and D_{CR_i} corresponds to the capillary rise depth (mm day^{-1}).

Once precipitation begins, it is stored on the vegetation cover until maximum interception storage (I_{max}) is reached, which is calculated for each grid cell as a linear function of Leaf Area Index (LAI, Eq. (2)) (Almeida et al., 2007; Collischonn et al., 2007; Zhou et al., 2006). The model considers the interception reservoir in which it is emptied after each time step as a function of evapotranspiration ratio. The Penman–

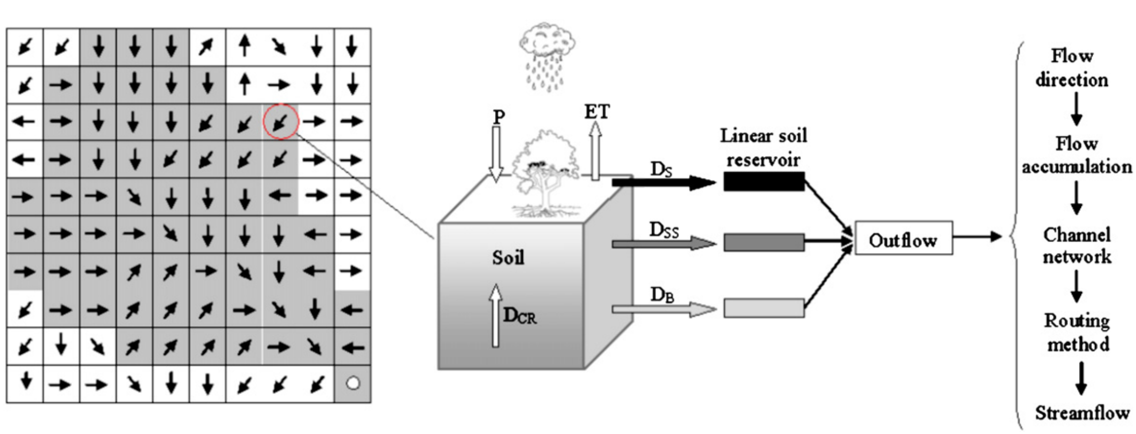

Fig. 1. Hydrological model setup.