Journal of Hydrology 539 (2016) 141–161

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Evaluation of TOPLATS on three Mediterranean catchments

Javier Loizu *, Jesús Álvarez-Mozos, Javier Casalí, Mikel Goñi

Department of Projects and Rural Engineering, Public University of Navarre, Pamplona, Navarre, Spain

ARTICLE INFO

Article history:
Received 20 November 2015
Received in revised form 18 March 2016
Accepted 9 May 2016
Available online 24 May 2016
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Yasuto Tachikawa, Associate Editor

Keywords:
TOPLATS
Sensitivity analysis
Morris and Sobol methods
Calibration and validation strategies
Optimization algorithm
Hydrological modeling time scale

SUMMARY

Physically based hydrological models are complex tools that provide a complete description of the different processes occurring on a catchment. The TOPMODEL-based Land–Atmosphere Transfer Scheme (TOPLATS) simulates water and energy balances at different time steps, in both lumped and distributed modes. In order to gain insight on the behavior of TOPLATS and its applicability in different conditions a detailed evaluation needs to be carried out. This study aimed to develop a complete evaluation of TOPLATS including: (1) a detailed review of previous research works using this model; (2) a sensitivity analysis (SA) of the model with two contrasted methods (Morris and Sobol) of different complexity; (3) a 4-step calibration strategy based on a multi-start Powell optimization algorithm; and (4) an analysis of the influence of simulation time step (hourly vs. daily). The model was applied on three catchments of varying size (La Tejeria, Cidacos and Arga), located in Navarre (Northern Spain), and characterized by different levels of Mediterranean climate influence. Both Morris and Sobol methods showed very similar results that identified Brooks–Corey Pore Size distribution Index (B), Bubbling pressure (ψ_c) and Hydraulic conductivity decay (f) as the three overall most influential parameters in TOPLATS. After calibration and validation, adequate streamflow simulations were obtained in the two wettest catchments, but the driest (Cidacos) gave poor results in validation, due to the large climatic variability between calibration and validation periods. To overcome this issue, an alternative random and discontinuous method of cal/val period selection was implemented, improving model results.

1. Introduction

The intense development in the field of hydrological simulation offers researchers worldwide dozens of models capable of simulating streamflow and other processes, at different time and spatial scales (e.g., Burnash et al., 1973; Chiew and McMahon, 2002; Brocca et al., 2011). Although they can easily be applied on different conditions (in terms of climate, catchment size or time-step), achieving the best simulation results depends largely on the users' knowledge of model structure and available tools to maximize the accuracy of the results (Khakbaz et al., 2012). Thus, achieving optimal calibrated and validated streamflow values requires, first, detailed sensitivity analyses to provide the modeler with objective criteria to identify the parameters to include on the calibration procedure and next, calibration and validation strategies to find the parameter values that optimize model results (Van Werkhoven et al., 2009). Model performance and optimal parameter values will depend then largely on: (1) catchment size, (2) rainfall pattern and climate conditions, (3) modeling time-scale, and the suitability of model structure to all of them (Demaria et al., 2007).

Sensitivity Analysis (SA) techniques can identify influential parameters, i.e. those whose uncertainty reduction will have the most significant impact on improving model performance (Gan et al., 2014) and provide model users with useful information to reduce calibration dimensionality (Garambois et al., 2013). If some insensitive parameters are identified through SA, they can be fixed reasonably at given values over their variation range. Thus, reducing calibration computational cost without decreasing model performance.

Sun et al. (2012) classified SA methods into three types: (1) local, (2) screening and (3) global, depending on the way parameters were perturbed. Local methods quantify the percentage change of outputs due to the change of model inputs relative to their baseline (nominal) values (Tang et al., 2007). These methods, also referred to as One-at-A-Time (OAT), evaluate the response of output variables to fractional changes in one single input parameter and are therefore less efficient on complex models. Even on models where parameters are independent, the combination of single-parameter influences can make local methods to fail on

* Corresponding author at: Public University of Navarre, Department of Projects and Rural Engineering, Laboratorio de Hidráulica, Edificio Los Olivos, Campus Arrosadia, 31006 Pamplona-Iruña, Spain. Tel.: +34 948168962.

E-mail addresses: javier.loizu@unavarra.es, jloizu@ono.com (J. Loizu).

http://dx.doi.org/10.1016/j.jhydrol.2016.05.025
0022-1694/

capturing model behavior due to non-linearity of model response (Norton, 2009). Screening methods also analyze the model response to a change in the inputs by varying one parameter at a time, but they provide a global sensitivity measure, since different elementary effects (EE) for each parameter are calculated and averaged (Campolongo et al., 2011). They are commonly applied to cases where a large number of parameters needs to be analyzed, or to computationally expensive models where more demanding quantitative techniques might lead to extended simulation times. Finally, global methods, vary simultaneously all studied parameters within their defined parameter space, thus providing information on both individual sensitivity and parameter interaction degrees. Global methods look at the entire input parameters distribution, using specifically designed Monte Carlo sampling techniques of various levels of sophistication, but their application to computationally demanding models might be constrained due to the large number of model runs required (Song et al., 2015). Global methods are recognized as appropriate for hydrological modeling, as they have to evaluate nonlinear processes and high parameter and data uncertainty due to spatial heterogeneity (Spear et al., 1994). Global methods include the following groups (Tang et al., 2007): (1) Regional SA (Young, 1978), (2) Bayesian SA (Oakley and O'Hagan, 2004), (3) regression based approaches (Spear et al., 1994), and (4) variance decomposition methods (Saltelli et al., 2000). Screening and global SA methods include two steps: first, a strategy is used to sample the parameter space (i.e. Design of experiment, DoE) and next a numerical measure is used to quantify the impacts of sampled parameters on model output (Wagener and Kollat, 2007).

Once the most sensitive parameters of a model have been identified through SA procedures, they need to be calibrated, i.e. estimated through an inverse method so that observed and predicted output values are in agreement (Zhang et al., 2009). Therefore, successful application of any hydrological model depends on how accurately the model is calibrated (Duan et al., 1992). Although model calibration used to be a labor intense task that depended largely on modeler knowledge and experience, nowadays computers allow automatic calibration techniques. These are commonly optimization algorithms that search for a set of parameters values that minimize the model prediction error relative to available measured data for the system being modeled (Tolson and Shoemaker, 2007). Gupta et al. (1998) pointed out that automatic calibration success depends largely on three aspects: (1) adequate calibration data (mainly in terms of data length and climate variability contained), (2) the objective function (maximum likelihood functions for measuring the "closeness" of the model and the data), and (3) the selected optimization algorithm. However, some studies reported difficulties in finding unique (global) optimum parameter values due to parameter nonuniqueness or equifinality, parameter correlation, or other limitations (Duan et al., 1992).

Calibration of hydrological models for areas with irregular rainfall patterns, such as Mediterranean ones, implies an extra effort in terms of model adaptability and data availability (Loaiza-Usuga and Pauwels, 2008). Several authors (Gan and Biftu, 1996; Li et al., 2010; Perrin et al., 2007) noted that arid catchments are generally more difficult to model than humid ones due to the complexity and variability of hydrological processes there. This can be related to model's response to intense rainfall events and to large inter-annual rainfall variability. Conventional continuous calibration and validation period selection (i.e., selection of a calibration period of *n* years, followed by a validation period of *m* years) may be a limitation when large differences on climate variables are found among both periods. Thus, alternative (random and discontinuous) period selection methods that lead to a similar calibration and validation climatological conditions and to a minimum of high flows included on the calibration period are worth being explored (Kim and Kaluarachchi, 2009). As stated by (Sorooshian and Gupta, 1983) it is not the length of the data series used but the information contained in it and the efficiency with which that information is extracted that are important. Random sampling approaches are expected to overcome different difficulties, which could include: (1) data availability discontinuity (i.e. Kim and Kaluarachchi, 2009), (2) lack of data series long enough to achieve proper calibration and validation results, or (3) large climate variability between calibration and validation periods.

Optimization algorithms used on hydrological model calibration are divided into local (Tolson and Shoemaker, 2007) and global search methods (Duan et al., 1993). One of the first optimization algorithms was proposed by Powell (1964), and was applied for the first time to hydrological modeling by Kobayashi and Maruyama (1976). This algorithm is a local, derivative-free method where one parameter value is changed at-a-time. Chen et al. (2005) applied a modified multi-start version of the Powell method for model calibration, which is also implemented on this study.

Hydrological models cover a range of variability in terms of parameter complexity, running time-scale, conceptual structure and spatial distribution design (lumped and distributed). According to these characteristics, they may offer better results under certain terrain or climate conditions. Among them, there has been a significant development of catchment models based on the TOPMODEL concept (Beven and Kirkby, 1979). From this initial conceptualization, Famiglietti and Wood (1994), started the development of a full hydrological catchment model that incorporated a separate computation of water and energy balances. This model was called TOPMODEL-based Land–Atmosphere Transfer Scheme (TOPLATS).

TOPLATS can be run at any user-specified time step, from daily (Bormann et al., 2007) to hourly (Loaiza-Usuga and Pauwels, 2008), or even on less than a minute time-step (Seuffert et al., 2002). While this permits the model to be applied for an extensive range of purposes, it can also affect model performance, especially in terms of runoff and soil moisture processes simulation. It has been applied on a wide range of locations worldwide but TOPLATS simulations on Mediterranean catchments was only reported in Loaiza-Usuga and Pauwels (2008) and in Loaiza-Usuga and Poch (2009). The complexity of TOPLATS makes it necessary to use efficient SA methods to get a better understanding of its behavior. To the authors' knowledge, no comprehensive SA of TOPLATS has been performed and published so far. Thus, a detailed SA of the different hydrological processes calculated by TOPLATS could be a worthwhile contribution to improve the understanding and to facilitate the calibration of this model.

This study aims to evaluate TOPLATS as a streamflow simulation tool in Mediterranean catchments. This evaluation includes a detailed SA of TOPLATS model to identify influential parameters that should be included on a subsequent calibration/validation (CAL/VAL) approach, so that optimum streamflow simulation is achieved. This is done for three catchments of different sizes located on an area of Mediterranean climate, and considering different modeling time-steps. This broad objective expands to achieve the following specific objectives: (1) to provide a detailed review of previous works carried out with TOPLATS, specifically those related with model parameterization and calibration, (2) to develop a sensitivity analysis of selected parameters on: surface runoff, baseflow, evapotranspiration, soil moisture patterns and streamflow simulation (discriminating between peaks, average and low flows), (3) to compare two SA methods of different complexity and computational requirements, (4) to evaluate the performance of an optimization algorithm for model calibration at different time-scale simulations (daily and hourly), (5) to appraise the influence of continuous or random period selection for