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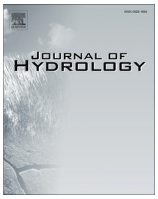

Multi-metric calibration of hydrological model to capture overall flow regimes

Yongyong Zhang [a,*], Quanxi Shao [b], Shifeng Zhang [a,*], Xiaoyan Zhai [c,d], Dunxian She [e]

[a] *Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China*
[b] *CSIRO Computational Informatics, Leeuwin Centre, 65 Brockway Road, Floreat Park, WA 6014, Australia*
[c] *China Institute of Water Resources and Hydropower Research, Beijing 100038, China*
[d] *Research Center on Flood and Drought Disaster Reduction of the Ministry of Water Resources, Beijing 100038, China*
[e] *State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China*

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SUMMARY

Flow regimes (e.g., magnitude, frequency, variation, duration, timing and rating of change) play a critical role in water supply and flood control, environmental processes, as well as biodiversity and life history patterns in the aquatic ecosystem. The traditional flow magnitude-oriented calibration of hydrological model was usually inadequate to well capture all the characteristics of observed flow regimes. In this study, we simulated multiple flow regime metrics simultaneously by coupling a distributed hydrological model with an equally weighted multi-objective optimization algorithm. Two headwater watersheds in the arid Hexi Corridor were selected for the case study. Sixteen metrics were selected as optimization objectives, which could represent the major characteristics of flow regimes. Model performance was compared with that of the single objective calibration. Results showed that most metrics were better simulated by the multi-objective approach than those of the single objective calibration, especially the low and high flow magnitudes, frequency and variation, duration, maximum flow timing and rating. However, the model performance of middle flow magnitude was not significantly improved because this metric was usually well captured by single objective calibration. The timing of minimum flow was poorly predicted by both the multi-metric and single calibrations due to the uncertainties in model structure and input data. The sensitive parameter values of the hydrological model changed remarkably and the simulated hydrological processes by the multi-metric calibration became more reliable, because more flow characteristics were considered. The study is expected to provide more detailed flow information by hydrological simulation for the integrated water resources management, and to improve the simulation performances of overall flow regimes.

1. Introduction

Flow simulation has always been one of the hot topics in applied hydrology for water resources management for over a century. It plays a vital role in the design and operation of water resource projects, water supply schemes, water resources planning, flood mitigations and drought control, etc. (Ghumman et al., 2011). Numerous water resource indicators (WRIs) were proposed to depict flow components, such as average monthly, seasonal and annual flows, magnitude and timing of peak or low flows (Shrestha et al., 2013). Moreover, the prediction of extreme events (floods and droughts) was taken more and more seriously because of their disastrous damages to society, economy and environment, especially in the arid and semi-arid regions (Smakhtin, 2001; Coulibaly et al., 2001; Held et al., 2005; Kumar et al., 2010). However, the simulation performances of WRIs were still far from satisfactory, particularly for the low flow events (Wenger et al., 2010; Staudinger et al., 2011; Pushpalatha et al., 2012; Shrestha et al., 2013). The critical reasons were that the most widely used goodness-of-fitness measures (e.g. mean squared errors, correlation coefficient, coefficient of efficiency) are sensitive to peak and low flows (Krause et al., 2005; Gupta et al., 2009; Pushpalatha et al., 2012) and that certain uncertainties exist in model inputs and structures (Beven, 2006; Staudinger et al., 2011; Najafi et al., 2011).

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* Corresponding authors.
E-mail addresses: zhangyy003@igsnrr.ac.cn (Y. Zhang), zhangsf@igsnrr.ac.cn (S. Zhang).

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Along with the rapid development of water related sciences (e.g. environmental hydrology, eco-hydrology), several flow components have been detected to have close relationships with physical, chemical, environmental and biological processes of aquatic systems (Carlisle et al., 2010). For example, natural flow paradigm has implications for several key processes and life history of aquatic organisms including growth, breeding, spawning, migration, recruitment and mortality (Poff et al., 1997; Poff and Zimmerman, 2010b; Bunn and Arthington, 2002; Arthington et al., 2010). Similarly, the simulation performance of low flow events significantly affects the prediction errors of water quality concentrations (van Griensven et al., 2006). Thus, the term "flow regime" was put forward (Langbein and Iseri, 1960), and the ecologically relevant metrics (ERMs) system was gradually formed to describe overall flow paradigm using magnitude, frequency, variability, timing, duration and rating of flow events (Richter et al., 1996; Olden and Poff, 2003; Poff et al., 1997, 2010a; Knight et al., 2008, 2012; Kennard et al., 2010). It is necessary and urgent to enrich WRIs to predict the entire flow regimes, which will provide hydrological foundations for the integrated water resources management, particularly for flood control, river environment improvement and restoration, and water project regulations.

Several existing studies on flow regime simulation have been reported using statistical models or hydrological models. For the statistical model approach, Rajurkar et al. (2002) applied the ANN methodology to model daily flows during monsoon flood events for a large catchment of the Narmada River in Madhya Pradesh, India. Knight et al. (2012) identified several predictive equations for 19 ecologically relevant streamflow characteristics with independent variables (climate, landscape features, regional indicators and land use) using step-backward regression. However, all of the existing statistical models are specific to the study area, and lack robust physical mechanisms to account for hydrological changes induced by human interferences and climate change (Wenger et al., 2010; Knight et al., 2012). Hydrological model is a robust and widely-accepted alternative which can represent critical hydrological processes using physical mechanism equations at different spatial and temporal scales (Wenger et al., 2010; Shrestha et al., 2013). Kennen et al. (2008) integrated TOPMODEL and multiple linear regression models to predict 78 flow variables at 856 sites in New Jersey, U.S., but the results were limited to the input of average daily discharges and withdrawals. Wenger et al. (2010) and Shrestha et al. (2013) applied VIC model to simulate seven ERMs in the Pacific Northwest United States, six WRIs and 32 ERMs in two headwater sub-basins in the Fraser River, Canada, respectively. Zhang et al. (2012) derived 80 hydrological metrics from monthly regulated and unregulated flow series simulated by SWAT in the upper and middle stream of the Huai River Basin. However, all the metric values in the existing studies were calculated from the well calibrated hydrographs using a single evaluation criterion (e.g. mean squared errors, coefficient of efficiency). Not all of the flow regime metrics were well captured, such as low flow magnitude, duration and rating of flow pulses (Shrestha et al., 2013), and frequency of high and low flows (Wenger et al., 2010).

Multi-Objective Optimization (MOO) is an efficient solution to improve the accuracy of overall flow regime simulation by calibrating different flow metrics simultaneously. Note that the flow regimes relate to many hydrological processes, such as flow yield process which directly affects the whole flow regime characteristics; flow routing and storage processes which probably involve the variability, timing and duration of flow events. In term of model calibration, considering the flow regime characteristics rather than the single flow magnitude could relieve the problems caused by parameter uncertainties and equifinality, because the detailed information of an observed hydrograph is efficiently used. As a result, more reliable hydrological processes would be captured and the model performance would be improved by MOO. However, for current hydrological model calibration, MMO usually focused on the calibrations of different evaluation criteria (Duan et al., 1992), peak and low flow magnitude (Madsen, 2000) or different observed series from different gauges (Bekele and Nicklow, 2007). The major common algorithms were weighted sum approaches (Madsen, 2000; van Griensven and Bauwens, 2003; Kim and De Weck, 2006) and Pareto multi objective optimization algorithms (Das and Dennis, 1998; Deb et al., 2002; Khu and Madsen, 2005). Moreover, the existing studies about Pareto multi-objective optimization algorithms were confined to two or three conflicting objectives, because the current algorithms were difficult to overcome the curse of dimensionality, and were impossible to obtain the reasonable Pareto fronts in practice along with the increasing of objective number (Madsen, 2000; van Griensven and Bauwens, 2003). Therefore, the weighted sum approach would be an effective alternative to implement the current multi-metric calibration.

The objective of this study was to implement the hydrological model coupling with the equally weighted MOO approach to well capture the overall flow regime characteristics. Two headwater watersheds in the arid Hexi Corridor were selected for the case study. The reasonable agreements between observations and simulations of flow regime metrics were obtained simultaneously by considering the multi-objective functions (including flow magnitude, frequency and variation, duration, timing and rating of change). Moreover, model performances were validated by making a comparison with the single evaluation criterion. The study would provide more flow information by hydrological simulation for the integrated water resources management, and promote the further application of ERMs to capture more reliable hydrological processes of mathematics models.

2. Material and methods

2.1. Study area

Hexi Corridor, as the most representative arid and semi-arid region of the Northwest China, is selected as the study area (Fig. 1). Hexi Corridor is located in the northwest of the Yellow River Basin, and includes a long and narrow passage stretching for over 1000 km from east (the steep Wushaoling hillside) to west (the Yumen Pass), and 100–200 km from south (the Qilian Mountain) to north (the North Mountain). The corridor is the most important route from the North China to the Central Asia for traders and militaries, a critical part of the historic Silk Road, and a famous granary in the Northwest China. The region has a continental arid climate with drought weather, dramatic temperature variability and highly frequent sandstorm. The differences in precipitation and dryness are quite remarkable from east to west.

There are three river basins (i.e., Shiyang River Basin, Hei River Basin and Shule River Basin) in Hexi Corridor bounded by the Hei, Kuantai and Dahuang Mountains, respectively. All of these rivers originate from snowmelt and precipitation of the Qilian Mountains, and provide continuous flows for downstream oases and farmlands. However, most rivers disappear in the Gobi desert after flowing out of mountains due to infiltration and irrigation consumption, except in the mainstreams which reach to rump lakes, i.e., Qingtu Lake for Shiyang River, Juyanhai Lake for Hei River and Luobupo Lake for Shule River which is out of Hexi Corridor.

The current studies of hydrological simulation in the arid Hexi Corridor always focused on small catchments in the upper and middle regions because of data sparsity and complicated hydrological mechanism in the downstream region (Wang et al.,