Journal of Hydrology 553 (2017) 651–661

Contents lists available at ScienceDirect

Journal of Hydrology

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

Research papers

Estimating hydrological parameters based on rainfall patterns in river basins with no long-term historical observations

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ARTICLE INFO

Article history:
Received 27 May 2017
Received in revised form 19 July 2017
Accepted 19 August 2017
Available online 30 August 2017
This manuscript was handled by G. Syme, Editor-in-Chief, with the assistance of Bellie Sivakumar, Associate Editor

Keywords:
Hydrological parameter estimation
Rainfall patterns
Digital Yellow River Integrated Model (DYRIM)
Small and medium river basins

ABSTRACT

Small and medium river basins may frequently suffer from the destructive hydrological extremes (e.g., floods). However, the common problem in such regions is a lack of long-term historical observations. Meteorological and hydrological station networks in some river basins in China were newly-built only a few years ago, and it is infeasible to estimate hydrological parameters from calibration and validation with a long time period directly. This paper aims to develop a method to estimate the feasible hydrological parameters based on rainfall patterns in such regions. Digital Yellow River Integrated Model (DYRIM) is adopted as the hydrological model, and the feasible hydrological parameters can be estimated based on limited rainfall-runoff events. First, for each rainfall-runoff event, the parameters are independently calibrated with the observed rainfall and hydrological data using a double-layer parallel system. Then, the performances of the simulation results are comprehensively evaluated, and the value ranges of the parameters can be obtained. Finally, the statistical relationships between hydrological parameters and rainfall patterns (i.e., amount and intensity) are established, which are expressed by the statistical equations and the distribution of hydrological parameters with the rainfall patterns. From a sample demonstration, it is concluded that this parameter estimation method will be useful to estimate the feasible hydrological parameters for future rainfall-runoff events in river basins with no long-term historical observations.

1. Introduction

Hydrological extremes (e.g., floods) in small and medium river basins are regarded as an important factor that can affect the social and economic development. In such regions, high-intensity rainstorms frequently occur during the rainy season, which may lead to serious flood disasters and cause enormous losses of lives and property (Liu et al., 2010; Ye et al., 2012; Shi et al., 2015). However, the mechanism of the occurrence of rainstorms is quite complicated so that it is difficult to have an in-depth understanding of it. Moreover, another problem in such river basins is a lack of long-term historical observations (e.g., Skaugen et al., 2015; Athira et al., 2016; Garambois et al., 2017; Yoo et al., 2017). For example, the meteorological and hydrological station networks in some small and medium river basins in China are usually poor. No meteorological and hydrological stations can be found in some river basins; even if there are several stations, the series of the observed data are usually not long enough for calibration and validation of hydrological models with a long time period. Consequently, more technical and financial supports should be provided for such river basins; moreover, it is important and necessary to develop an effective method to estimate hydrological parameters in river basins with no long-term historical observations.

In the past few years, many researchers have made efforts to address this problem in ungauged or poorly gauged river basins (e.g., Bardossy, 2007; Hundecha et al., 2008; Bulygina et al., 2012; Woldemeskel et al., 2013; Shi et al., 2015; Yu et al., 2016; Gao et al., 2017; Garambois et al., 2017; Yoo et al., 2017), mainly focusing on the following two types of methods. The first type is the methods based on regional information representing river basin characteristics (e.g., Bardossy, 2007; Hundecha et al., 2008; Bulygina et al., 2012; Yoo et al., 2017). It is supposed that river basins with similar characteristics may show a similar hydrological behavior and thus can be simulated with similar hydrological parameters. As a result, hydrological parameters in an ungauged

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http://dx.doi.org/10.1016/j.jhydrol.2017.08.030
0022-1694/

or poorly gauged river basin can probably be transferred from a reference river basin which is adjacent or has similar characteristics with this river basin (Bardossy, 2007; Tang et al., 2010). Moreover, for a designated river basin, correlation analysis between hydrological parameters and river basin characteristics can be conducted to improve the model performance (e.g., Merz and Blöschl, 2005; Wagener and Wheater, 2006; Coff et al., 2009; Bulygina et al., 2012). For example, using a formal Bayesian procedure, Bulygina et al. (2012) combined three different sources of knowledge (i.e., physical properties, regionalized signatures of flow and available flow measurements) into a distributed model for a river basin in the UK and found that the physical properties source could contribute most to improving the model performance. Recently, the global-scale satellite-based meteorological datasets have been developed rapidly with the development of science and technology, which are regarded to be an effective supplement for the gauge-station measurements (e.g., Pappenberger et al., 2008; Li et al., 2012; Woldemeskel et al., 2013). Hence, the second type is the methods based on the utilization of the satellite-based meteorological datasets (e.g., Shi et al., 2015; Yu et al., 2016; Gao et al., 2017). For the river basins with poor historical observations, especially for the ungauged river basins, the satellite-based meteorological datasets may provide the necessary input data to overcome the problem of lacking data when estimating the hydrological parameters through calibration and validation of models (e.g., Sun et al., 2012; Maswood and Hossain, 2016; Garambois et al., 2017).

In China, an increasing number of meteorological and hydrological station networks have been built in some small and medium river basins to acquire the necessary data for hydrological simulation; however, due to the lack of long-term historical observations, it is still difficult to estimate the hydrological parameters from calibration and validation of hydrological models with a long time period directly. To this end, this paper aims to propose a feasible hydrological parameter estimation method in such river basins through establishing the relationships between hydrological parameters and rainfall patterns (i.e., amount and intensity). A physically-based hydrological model, the Digital Yellow River Integrated Model (noted as DYRIM hereafter) (Wang et al., 2007, 2015; Li et al., 2009), is adopted in this paper to conduct hydrological simulations, and the Leli River basin, a sub-basin of the Pearl River basin in China, is selected as the study area. From a sample demonstration, it is concluded that the proposed method will be useful to estimate the feasible hydrological parameters for future rainfall-runoff events in such river basins. The remainder of this paper is organized as follows. Section 2 shows the main methodologies. Section 3 gives a brief introduction to the study area and research data. Section 4 shows results and discussion of the case study. The final section displays the conclusions of this paper.

2. Methodology

2.1. The hydrological parameter estimation method

In order to conduct hydrological simulations using distributed hydrological models, the applicable hydrological parameters for the designated river basin should be determined first. Normally, they can be calibrated and validated with long-term historical observations; however, with respect to small and medium river basins with few available observations, such method will probably be invalid. Therefore, in consideration of the uncertainty of the hydrological parameters, the hydrological parameter estimation method for river basins with no long-term historical observations is proposed based on the rainfall patterns derived from limited rainfall-runoff events (Fig. 1). In this paper, the rainfall-runoff events (i.e., the flood events in the subsequent sections) are selected based on the observed streamflow data. For a designated river basin, the observed streamflow data is equal to the base flow of this river basin during the period with no rain. When the rain occurs, there is a significant increase in the observed streamflow data until reaching the peak, and then a decrease in the observed streamflow data until returning to the base flow. Therefore, the day when the observed streamflow data begin to increase can be identified and the day before this day is regarded as the start date of a rainfall-runoff event. Moreover, the day when the observed streamflow data return to the base flow can be identified and the day after this day is regarded as the end date of a rainfall-runoff event. Then, the proposed method involves the following three steps.

2.1.1. Step 1

For each rainfall-runoff event, the hydrological simulation is conducted using the DYRIM (Wang et al., 2007, 2015), and the hydrological parameters in the DYRIM are independently calibrated with the observed rainfall and hydrological data using a double-layer parallel system for hydrological model calibration (Zhang et al., 2016). In recent years, there have been several studies (e.g., Choi et al., 2015; Reshma et al., 2015; Huang et al., 2016; Fuentes-Andino et al., 2017) on event-based calibration of hydrological models, including some of our previous studies (e.g., Shi, 2013; Zhang et al., 2016).

2.1.2. Step 2

For each rainfall-runoff event, the performance of the hydrological simulation result is separately evaluated using the selected assessment criteria (see subsection 2.4 for details). Then, all the rainfall-runoff events are regarded as a whole and comprehensive evaluation is conducted to show the overall simulation accuracy. Moreover, the value ranges of the hydrological parameters can be determined from multiple sets of calibrated parameters through identifying the maximum and minimum values.

2.1.3. Step 3

For each rainfall-runoff event, the rainfall patterns (i.e., amount and intensity) are obtained based on the observed rainfall data. In this paper, the rainfall amounts of all the stations during the period of each rainfall-runoff event are calculated, and then the average rainfall amount over the river basin can be derived using the Thiessen polygon method (Thiessen and Alter, 1911; Brassel and Reif, 1979). In addition, the observed rainfall data recorded at all the stations are converted into the rainfall intensities in millimeters per hour, and then the maximum one can be derived. Correlations between hydrological parameters and rainfall patterns (i.e., amount and intensity) are analyzed, and the variables applicable for establishing the statistical relationships are determined. Using the regression method, the statistical equations including the selected variables can be obtained; moreover, the distributions of hydrological parameters with rainfall patterns can be mapped. Both of them will be valuable for estimating hydrological parameters for future rainfall-runoff events with limited observed data.

2.2. Brief introduction of the DYRIM

The DYRIM is a physically-based, distributed-parameter, and continuously-simulated model developed by Tsinghua University for hydrological and sediment simulations in river basins based on the high-resolution digital drainage network (Wang et al., 2007, 2015; Li et al., 2009), which is extracted from the 30-m-resolution Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) dataset (ASTER GDEM Validation Team, 2011; Bai et al., 2015a,b) and