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Temporal variation and scaling of parameters for a monthly hydrologic model

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ABSTRACT

The temporal variation of model parameters is affected by the catchment conditions and has a significant impact on hydrological simulation. This study aims to evaluate the seasonality and downscaling of model parameter across time scales based on monthly and mean annual water balance models with a common model framework. Two parameters of the monthly model, i.e., k and m, are assumed to be time-variant at different months. Based on the hydrological data set from 121 MOPEX catchments in the United States, we firstly analyzed the correlation between parameters (k and m) and catchment properties (NDVI and frequency of rainfall events, α). The results show that parameter k is positively correlated with NDVI or α, while the correlation is opposite for parameter m, indicating that precipitation and vegetation affect monthly water balance by controlling temporal variation of parameters k and m. The multiple linear regression is then used to fit the relationship between ε and the means and coefficient of variations of parameters k and m. Based on the empirical equation and the correlations between the time-variant parameters and NDVI, the mean annual parameter ε is downscaled to monthly k and m. The results show that it has lower NSEs than these from model with time-variant k and m being calibrated through SCE-UA, while for several study catchments, it has higher NSEs than that of the model with constant parameters. The proposed method is feasible and provides a useful tool for temporal scaling of model parameter.
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1. Introduction

Parameters of conceptual hydrological models are simplified representations of the physical characteristics controlling rainfall-runoff processes. Consequently, it plays a significant role in producing accurate and credible predictions. In hydrological modeling, model parameters are usually assumed to be constant and calibrated using a particular data record, with the purpose of obtaining an optimal parameter set (Duan et al., 1993) or stationary parameter distributions (Beven and Freer, 2001). However, it is no longer appropriate to treat parameters as time-invariant for the following reasons. Firstly, the climatic condition in a catchment may change during the calibration period. Numerous studies have reported that model parameter estimations depend on the historical records used for calibration (Merz et al., 2011; Zhang et al., 2011). For example, Wu and Johnston (2007) found that the soil evaporation compensation coefficient, which is a parameter related to evapotranspiration process, has relatively smaller value during normal years than that in drought years. Secondly, catchment conditions may change due to natural disturbances (e.g., bushfire and soil erosion) or human interferences (e.g., urbanization and deforestation). For example, the water storage capacity in a catchment showed an increasing trend due to land use and land cover change (Deng et al., 2016). Finally, seasonal variations of model parameters have been noted by Ye et al. (1997) and Paik et al. (2005). Coron et al. (2012) also reported seasonal variations in model parameters owing to differences of the dominant runoff generation mechanisms among seasons for particular catchments. Therefore, it is necessary to use time-variant parameter(s) for accurately simulating state variables and fluxes, particularly under a changing environment.

Allowing the model parameters to vary with time provides one possible approach for better representation of the catchment process in hydrological models. Time-variant parameters have been

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studied recently (Merz et al., 2011; Brigode et al., 2013; Patil and Stieglitz, 2015). Three approaches have been proposed to estimate the time-variant model parameters in previous studies: (1) Available data set is divided into consecutive subsets, and parameters are calibrated separately for each subset (Gharari et al., 2013; Thirel et al., 2015); (2) A functional form of the selected time-variant model parameters is developed and, the parameters of the function are estimated using an optimization algorithm based on the entire historical record (Jeremiah et al., 2013; Westra et al., 2014); and (3) Data assimilation technique is used to identify the temporal variation of parameters based on hydrologic observations (Deng et al., 2016; Pathiraja et al., 2016). Model parameters are treated as time-variant continuously or from period to period in the above studies, with the objective of estimating the time-variant parameters of hydrologic models.

Along with the time-variant model parameters, parameter scaling at different spatial and temporal scales is another issue. Scale issues exist due to the heterogeneity and variability of catchments properties, and it is crucial to hydrological modeling. In a hydrological context, scaling means transferring information from a larger scale to a smaller scale spatially or temporally, and vice versa. There are two scaling approaches to achieve the above objective (Tian et al., 2006). One is process scale, which is to re-define new governing equations to reflect the catchment heterogeneity. The other is modeling scale, which is to devise effective parameters to account for the catchment dynamics. The representative elementary watershed concept (REW) (Reggiani et al., 1998), which is a strategy for the process scale, has been used and extended to cope with the hydrological scaling (Reggiani and Rientjes, 2005; Tian et al., 2006). In the modeling scale, the spatial and temporal scaling of parameters provides another useful strategy to enhance hydrologic understanding and model predictive capabilities (Blöschl and Sivapalan, 1995). For instance, hydraulic conductivity can be measured at the point scale based on Darcy's law, while upscaling involves when it is applied to the catchment scale by the governing equation such as Richards' equation.

As an analog to spatial scaling of model parameters, the temporal scaling of model parameters represents the relationship of parameters among different time scales at which the governing or conceptual equations are developed. However, research on temporal scaling of hydrologic model parameters is limited compared with spatial scaling. Previous research is mainly focused on the effect of different time-steps of forcing data on model parameters and their temporal transferability. For example, Littlewood and Croke (2008; 2013) assessed the influence of sub-daily time-steps of model input data on the calibrated model parameters. Melsen et al. (2016) investigated the temporal transferability of model parameter under three relevant temporal resolutions of discharge data, i.e., hourly, daily, and monthly, using the Variable Infiltration Capacity (VIC) model at the Thur basin in Switzerland. In order to evaluate the temporal scaling of parameters, one way is to develop a hydrologic model applicable to two time scales (e.g., monthly and mean annual). This is challenging due to the large time scale gap. Instead, it is practical to develop two models for different time scales but with the same model framework. Consequently, the corresponding parameters at the two time scales will have the same physical or conceptual meaning.

To serve the purpose of evaluating the temporal scaling of hydrologic model parameters, we use the Budyko-type model proposed by Wang and Tang (2014) and the monthly water balance model derived by Zhao et al. (2016). The Budyko framework (Budyko, 1974), which depicts the climate control on water balance, has been widely used to investigate the relationship between model parameters and catchment conditions (e.g., climate and landscape) at the long-term scale (Zhang et al., 2008; Potter and Zhang, 2009; Yang et al., 2009; Cheng et al., 2011; Istanbulluoglu et al., 2012; Li et al., 2013; Yang et al., 2014). For example, Chen et al. (2013) modeled the seasonal evaporation based on the extended Budyko framework with consideration of soil water storage changes. Wang and Tang (2014) derived a one-parameter Budyko-type model for mean annual water balance, and found that the parameter is mainly controlled by vegetation and temporal variability of rainfall. Zhang et al. (2016) established a relationship between the landscape parameter and vegetation based on a Budyko model, and applied it for evaluating the regional hydrological response to vegetation change.

In this study, the rainfall-runoff model, in which the soil water content is explicitly described, is used to analyze the temporal variation of model parameters at monthly scale. Furthermore, the temporal scaling of parameters is explored based on monthly and mean annual water balance models with the same modeling framework. The objectives of this research are to (1) examine the relationship between the catchment properties and the time-variant parameters in a water balance model at monthly scale, and (2) investigate the temporal scaling of model parameters from mean annual to monthly scale. The remainder of this paper is organized as follows. Section 2 presents a brief review of the monthly water balance model and the discussions of the seasonality of model parameters. The study catchments and data are described in Section 3, followed by results and discussion in Section 4. Conclusions are presented in Section 5.

2. Methodology

The temporal variation and scaling of parameters are investigated as follows. The seasonality of two parameters for the monthly model and its linkage to the parameter of mean annual model are firstly quantified. Afterwards, parameters of the two models across time scales are estimated based on the observations. Secondly, the correlations between monthly parameters and catchment properties are analyzed, and multiple linear regression is used to fit the empirical equations between the mean annual parameter and the monthly parameters. Then, the relationship between mean annual parameter and monthly parameters (i.e., the temporal scaling of model parameters) is developed based on the fitted equations and the correlations between the monthly parameters and catchment properties.

2.1. Monthly water balance model

The monthly water balance model is based on the optimality principle of entropy or power or the generalized proportionality relationship (Wang et al., 2015; Zhao et al., 2016). This model is a modification of the "abcd" model developed by Thomas (1981). Both the "abcd" model and the SCS curve number method for surface runoff at the event scale use the Budyko-type functions. The monthly water balance model and its parameters are briefly described below and more detailed information is referred to Zhao et al. (2016).

The general monthly water balance can be represented by the following equation:

$$P_t + S_1 = S_2 + E_t + Q_t \quad (1)$$

where P_t is monthly precipitation; S_1 and S_2 represent the soil water storage at the beginning and end of the month, respectively; E_t is actual evaporation; and Q_t is runoff. The left hand side of Eq. (1) is the available water for competition, and it is denoted as A_t:

$$A_t = P_t + S_1 \quad (2)$$

The available water is partitioned into three components (i.e., S_2, E_t and Q_t). In order to formulate this partitioning into two-component

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