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Comparison of performance of twelve monthly water balance models in different climatic catchments of China

Peng Bai, Xiaomang Liu *, Kang Liang, Changming Liu

Key Laboratory of Water Cycle & Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

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ABSTRACT

Multi-model comparison can provide useful information for model selection and improvement. In this study, twelve monthly water balance models with different structures and various degree of complexity are compared in 153 catchments with different climatic conditions in China. Generally, the GR5M model has the best performance, followed by the GR2M and WBM model. We investigate the relations between model performance and catchment characteristics and find that the climatic characteristic of a catchment is the most important factor impacting model performance. The models have better performance in wet catchments than in dry catchments. Large differences of model performance exist in dry catchments and model users should pay attention to model selection in dry catchments. In addition, we analyze the model performances among different models and conclude that increasing the model complexity does not guarantee a better model performance. Simple models can achieve comparable or even better performance than complex models. For the monthly simulation of hydrological processes, a two-parameter model is sufficient to achieve a good result. Moreover, by comparing the impacts of evapotranspiration simulation and runoff generation simulation on model performance, we find that evapotranspiration simulation has limited influence on the model performance. We suggest model builders focus on runoff generation process rather than evapotranspiration process to improve the performance of a monthly hydrological model.

1. Introduction

Hydrological models use different mathematical formulas to conceptualize processes of hydrologic cycle and are commonly used for simulating and predicting various hydrological processes (Vrugt et al., 2005; Viney et al., 2009). Currently, numerous hydrological models have been developed for different time scales (Mouelhi et al., 2006 monthly and yearly). Among them, the monthly water balance model (MWBM) offers simple yet refined methods to describe hydrological processes and has low input requirement, well-behaving conceptual platform and simple model calibration (Nasseri et al., 2014). For most of the MWBMs, runoff can be simulated using only monthly precipitation and potential evapotranspiration, and the number of model parameters ranges from two to five. Hence, these models are more parsimonious than daily or hourly models for estimating runoff at monthly or yearly time scales and are widely used for various purposes, e.g., seasonal streamflow forecasting (Alley, 1985; Schär et al., 2004), climate change and/or human activity impact assessment (Gleick, 1987; Jiang et al., 2007; Li et al., 2012; Liu et al., 2013) and snowmelt runoff simulation (Xu et al., 1996; Racoviteanu et al., 2013).

The first MWBM was developed in the 1940s by Thornthwaite (1948) and was subsequently revised by Thornthwaite and Mather (1955). Thereafter, different MWBMs were developed based on the framework of the Thornthwaite model. In 1965, Palmer (1965) proposed a two-layer soil moisture storage model based on a meteorological drought index. This model assumes that soil moisture in the lower layer cannot move to the upper layer until all of the available soil moisture in the upper layer has been exhausted. In 1973, Pitman (1973) developed a MWBM with twelve parameters to describe the hydrological processes in South Africa. Since then, new model functions such as reservoir sub-model, wetland sub-model and groundwater recharge sub-model have been successively added to Pitman model (Hughes, 2004; Hughes et al., 2013). This model including more than 20 parameters is likely the most complex model among the existing MWBMs (Hughes, 2013). In 1981, Thomas (1981) proposed a four-parameter “abcd” water balance model based on Thornthwaite’s (1948) conceptual framework, while this model incorporates a more realistic representation of the infiltration process (Martinez and Gupta, 2010). As the concern regarding

* Corresponding author. Tel.: +86 10 64889083.
E-mail addresses: liaoxfxm@163.com, liuxm@igsnrr.ac.cn (X. Liu).

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climate change began to increase in the 1990s, additional MWBMs were developed for evaluating the impacts of climate change on hydrological processes. During this period, some representative models were successively developed, such as the Belgium model (Vandewiele and Xu, 1992), GR2M model (Makhlouf and Michel, 1994), MWB-6 model (Xu et al., 1996), Xiong model (Xiong and Guo, 1999) and DWBM model (Zhang et al., 2008). Besides the conceptual MWBMs, the artificial intelligence methods are also important tools to simulate monthly rainfall–runoff processes (Komorník et al., 2006; Shu and Ouarda, 2008; Wang et al., 2009; Yilmaz et al., 2011). In some studies, artificial intelligence models exhibited better performances than conceptual MWBMs (Hsu et al., 1995; Shamseldin, 1997; Machado et al., 2011; Rezaeianzadeh et al., 2013). However, artificial intelligence models have also been criticized for their lack of explanation capability, over-parameterization and over-fitting (Kaastra and Boyd, 1996; Gaume and Gosset, 2003; de Vos and Rientjes, 2005).

With the existence of numerous hydrological models, model users may require help to select a suitable model for a specific hydrological practice. To provide scientific guidance on the application of hydrological models, several model comparisons have been conducted with various types of hydrological models, such as flood forecasting models (WMO, 1975; Toth et al., 2000; Chau et al., 2005), snowmelt runoff models (WMO, 1986; Gurtz et al., 2003; Kumar Pokhrel et al., 2014), daily lumped rainfall–runoff models (Ye et al., 1997a; Yew Gan et al., 1997; Perrin et al., 2001) and distributed hydrological models (Yang et al., 2000; Reed et al., 2004; Smith et al., 2012). These studies mainly focus on the hourly and daily hydrological models. For the comparison of monthly hydrological models, Vandewiele and Xu (1992) compared a set of MWBMs in 79 catchments with areas less than 4000 km^2 and found that their new proposed models presented better performance than the existing models; Makhlouf and Michel (1994) compared a two-parameter MWBM with four widely used models in 91 French catchments with area between 315 and 5560 km^2 and concluded that the simple two-parameter model has comparable performance with the four models; Jiang et al. (2007) applied six MWBMs in a humid catchment of China and found that all the models have similar performance in spite of a wide range of model complexity.

Here, we intend to extend these previous comparative studies by testing twelve MWBMs on a large set of 153 catchments in China with different climatic conditions. The main objective of this study is to investigate differences in model performance and provide valuable information for model selection and improvement. The paper is structured as follows. Section 2 briefly describes the models used in this study. Section 3 presents the data used and the methodology, followed by results and discussion in Section 3. Finally, the main findings are summarized in Section 4.

2. Models used and parameter calibration

2.1. Model descriptions

For a catchment, the general water balance equation at the monthly time scale can be written as:

$$P(t) = S(t+1) - S(t) + E_a(t) + R(t) + I_{deep}(t) - \Delta O(t) \quad (1)$$

where $S(t)$ and $S(t+1)$ represent the soil moisture storage at the beginning and end of the time interval t, respectively. P represents the precipitation, E_a represents the actual evapotranspiration and R represents the runoff at the outlet of the watershed. I_{deep} is the infiltration loss to deep aquifer and ΔO is the water recharge from neighboring basins. Among these variables, S, E_a and R are the three basic variables included in most of the MWBMs (Xu and Singh, 2004; Jiang et al., 2007). I_{deep} and ΔO are rarely considered in MWBMs, with the exception of the SFB3 model considering I_{deep} (Boughton, 1984) and the GR2M mode considering ΔO (Mouelhi et al., 2006).

This water balance equation describes the storage, transformation and movement of water at watershed scale with simple concepts. Generally, complex models are inclined to employ more storage or nonlinear formulas to describe these hydrological processes and have more model parameters. For example, the Pitman model (Pitman, 1973) including three types of storage (canopy, soil moisture and groundwater) and four nonlinear formulas has more than 20 parameters. The calibration of parameters becomes more difficult as the number of parameters increases. However, an inadequate complexity often results in over-parameterization (Ye et al., 1997a; Perrin et al., 2001). Therefore, the models with too many parameters (e.g., Pitman model) are excluded from this comparative study. Through an extensive literature review, twelve MWBMs are selected for the model comparison (Table 1). These models cover a relatively wide range of complexities with the parameter number ranging from two to five. The detailed structural characteristics of the selected models are summarized in Fig. 1. The main expressions for estimating the actual evapotranspiration and runoff are summarized in Table 2.

Although the selected models have a similar conceptual framework to describe the hydrological processes, the main mathematical equations simulating the hydrological processes are different. Among the twelve models, six models have single moisture storage, the others have two moisture storage. Moreover, complex models consider more runoff components than simple models. The models with more than three parameters have at least two runoff components: surface runoff and groundwater runoff, while all the two-parameter models consider runoff as a single component (Fig. 1).

The actual evapotranspiration is controlled by both water and energy availabilities. In general, the soil moisture storage and potential evapotranspiration are the most commonly used water-limited and energy-limited conditions for monthly hydrological models, respectively. In all of the selected models, except for XM, the actual evapotranspiration is estimated as a function of the potential evapotranspiration and soil moisture storage. However, obvious differences can be identified in the calculations of actual evapotranspiration (Table 2). Some models (e.g., the SFB3, WM and SM model) adopt a simple linear function to calculate the actual evapotranspiration, while the other models (e.g., the

Table 1
Main characteristics of the model structure of the twelve selected models.

Model abbreviation	Derived from	No. of parameters	No. of storages	No. of runoff components
TM	Thornthwaite and Mather (1955)	2	2	1
XM	Xiong and Guo (1999)	2	1	1
GR2M	Mouelhi et al. (2006)	2	2	1
VUB	Vandewiele and Xu (1992)	3	1	2
SFB3	Boughton (1984)	3	2	2
WM	Wang et al. (2013)	3	1	2
DWBM	Zhang et al. (2008)	4	1	2
abcd	Thomas (1981)	4	2	2
WBM	Leaf et al. (1973)	4	1	4
GR5M	Mouelhi et al. (2006)	5	2	2
SM	Schaake and Liu (1989)	5	1	2
TVGM	Xia et al. (1997) and Wang et al. (2009a)	5	1	2