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Improved calibration scheme of SWAT by separating wet and dry seasons

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ABSTRACT

Simulation of low flow process is critical to water quality, water supply, and aquatic habitat. However, the poor performance of Soil and Water Assessment Tool (SWAT) in dry seasons has impeded its application to watersheds characterized largely by low-flows. Aiming at overcoming this shortage, a seasonal calibration scheme was proposed, in which SWAT was calibrated separately for the dry and wet periods and the "optimal" simulation results of these two periods were combined into a complete runoff series. An extended SWAT model incorporating with the proposed seasonal calibration scheme, named SWAT-SC was constructed and compared with the original SWAT to simulate daily runoff in the Jinjiang watershed dominated by a typical subtropical monsoon climate in southeastern China. The study reveals that when Nash-Sutcliffe efficiency (ENS) of the original SWAT model indicated a satisfied model performance in a wet season or a whole year, it may not guaranty acceptable performance for the dry period. A significant improvement was achieved by using SWAT-SC for simulating runoffs in the dry period, and although not as notably as the dry period, improvements for runoff simulation of the wet and overall periods were observed as well.

1. Introduction

Riverine and wetland ecosystems are largely subject to the flow regimes (magnitude, frequency, duration, seasonal timing, rates of change and water quality) (Zhang et al., 2012). Many ecological problems, such as harmful algal blooms, loss of habitat and natural resources, hypoxia, and reduced water clarity, are exacerbated during low-flow periods (Dakova et al., 2000; Rolls et al., 2012). To fully understand effects of low flow on these ecosystems, many hydrological-ecological researchers have been trying to identify qualitative or quantitative hydrological-ecological relationships between the attributes of low flow and ecosystem functions or patterns of biodiversity (Arthington et al., 2014; Dakova et al., 2000; Gebremariam et al., 2014; Rabalais et al., 2009; Rolls et al., 2012). These relationships and linkages among flow regimes and ecosystems are useful for predicting responses of riverine ecosystems to global changes and helping watershed managers to identify effective measures to maintain the balance for the riverine and wetland ecosystems. Among these studies, relationships between the sustainable development of in-stream and off-stream ecosystems and the minimum flow are extensively studied (Arthington et al., 1992; Bonacci et al., 1998; Ferrar, 1989; Petts, 1996). Lots of concepts or terminologies, such as "Minimum Flow", "Environmental Flow Requirements", "Ecological Flow Requirements", "Ecology Acceptable Flow Regime", "Minimum Acceptable Flows", are introduced and proposed. Although meanings and scopes of these concepts may be slightly different, all of them address on the relationships between the sustainable development of the riverine ecosystems and the low flow.

Flow variations are highly associated with watershed hydrological processes influenced by changing environments. Distributed hydro-ecological models are effective tools to analyze the effects of flow variations on riverine ecosystems. Nevertheless, distributed hydro-ecological models are generally suffered from a poor simulation and prediction performance during low flow periods (Gebremariam et al., 2014), thus impede the using of these models to predict responses of the riverine ecosystems to the changes in environment, such as climate changes, land use changes, water and soil conservation managements (e.g., by installing the vegetation filter strip), agriculture managements (e.g., by changing the fertilizer applying quantities and manner) and regulations of the

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water conservancy facilities. Therefore, improving prediction abilities of these models for the low flow is necessary and has become a common concern for hydrological and hydro-ecological communities.

As one of the most representative distributed river-basin hydro-ecological models, Soil and Water Assessment Tool (SWAT) (Arnold et al., 1993, 1998; Arnold and Fohrer, 2005) has been applied in various fields such as assessment of the water-related ecosystem services (Psaris et al., 2012), hydrologic and water quality process simulations (Pisinaras et al., 2010), agricultural practices (Ullrich and Volk, 2009), land use and climate change impacts on water resources (Varanou et al., 2002), and identification of critical source areas (Panagopoulos et al., 2011). Although it has proved to be a powerful and adaptive tool, SWAT also suffers from the aforementioned deficiencies of hydro-ecological models (i.e., the disastrous model performance in dry periods and the fluctuated model efficiency between dry and wet seasons). This issue has largely impeded SWAT applications in simulating hydrologic processes, and also indirectly influenced its sediment and nutrient simulation efficiency.

The issue resulted mainly from two factors: the temporal variations in model parameters which exist in watersheds have not been considered or effectively accounted; the objective functions or performance indexes used to calibrate the model tend to rely on flood features, not taking dry flows into sufficient evaluation. As considerable differences exist between dry and wet periods, the model parameters should be varying accordingly. However the simplifications of model parameters between dry and wet periods made SWAT unable to describe the different behaviors between these two periods, especially for basins with notable seasonal difference of runoff fluxes. Muleta (2012) found that sensitivities of dominant parameters of SWAT were strikingly different between dry and wet periods. Model efficiency in the dry period was consistently lower than that in the wet period, as reported in studies using other hydrologic models (Li et al., 2012; Porretta-Brandyk et al., 2011).

Several researches were conducted to reflect seasonal hydrologic processes via a different set of SWAT parameters for the two periods. For example, Lévesque et al. (2008) used seasonal calibration scheme, in which winter and summer data were used to calibrate the model separately at two seasonally snow covered watersheds in southeastern Canada. An improved performance in summer (dry period) was obtained while using summer observations to calibrate the model; however, when winter (wet period) observations were used, no advantage was achieved compared with the traditional calibration method based on all available data. White et al. (2009) allowed SWAT to use a different curve number (CN) in growing and dormant seasons, slightly improved the daily model performance by increasing Nash-Sutcliffe efficiency (ENS) from 0.42 to 0.44. Muleta (2012) also adopted the seasonal calibration method to calibrate SWAT model for the Little River Experimental Watershed (116 km^2) in Georgia, USA, but the ENS values were small in general, and the ENS values of validation period were remarkably smaller than that of the calibration period which might be caused by an over-fitting. The seasonal calibration scheme was not elucidated in the report. Previous studies reveal that the seasonal calibration method needs to be further investigated and improved.

In addition, the choice of objective functions has a substantial effect on calibration results. As indicated by Legates and McCabe (1999), the commonly used criteria such as coefficient of determination (R^2), ENS and root mean square error (RMSE) are sensitive to larger or extreme values. These measures tend to sensitively reflect the characteristics of wet period or flood season, and a poor performance for the dry period can be expected while using the model calibrated by these objective functions. A lot of researches were conducted to improve the objective functions and try to give greater consideration to the dry period (Pushpalatha et al., 2012). Although these trials improved model's simulation for dry periods, the improvement is still limited. Sometimes the changed functions are too sensitive to dry periods to jeopardize the overall simulation effectiveness.

It is anticipated that a seasonal or separate calibration method should be an effective way to cope with the SWAT calibration issue for watersheds where a distinct difference of runoff fluxes exists for different periods within a year and an obvious contrast between performance of dry and wet periods is inevitable. This is also illustrated by the recently published study in which the seasonal calibration method was used to calibrate a concept model (Kim and Lee, 2014). Our study focuses on improving the SWAT model by extending the original SWAT (version 2009) with the seasonal calibration scheme, namely SWAT-SC, which calibrates and simulates the dry and wet periods separately. Jinjiang watershed dominated by a typical subtropical monsoon climate in southeastern China is used to evaluate and compare the performance of SWAT and SWAT-SC.

2. Methods and study area

2.1. SWAT

The soil and water assessment tool (SWAT) is a semi-distributed, watershed-scale hydrologic model which was developed by the Agricultural Research Service of United States Department of Agriculture (USDA-ARS) to simulate water quantity and quality of surface water and groundwater. In order to represent spatial heterogeneity, a watershed is initially divided into subbasins, and then each subbasin is subdivided into hydrologic response units (HRUs) based on the landuse and soil maps. The hydrologic cycle simulated by SWAT can be divided into two major phases: land phase and routing phase. The land phase first calculates loadings of water, sediment, nutrients and pesticide for each HRU, and for each subbasin the loading is calculated by aggregating the loadings of its HRUs and then entered to the main channel of the subbasin. Major hydrological processes of land phase include evaportranspiration, canopy storage, infiltration, surface runoff, sub-surface runoff and so on. The potential evaportranspiration is computed by one of three methods: Penman–Monteith, Priestley–Taylor and Hargreaves. Surface runoff is estimated either by modified SCS curve number method or Green-Ampt infiltration method. The amount of fluxes infiltrated into soil is calculated by a water balance equation. The routing phase controls the movement of water, sediment, etc. through the main channel to the subbasin outlet. Finally, estimated stream flow can be routed through river system, from subbasins to the basin outlet by using either the variable storage routing method or the Muskingum river routing method. More details of modeling information of SWAT can be found from SWAT documents (e.g. Neitsch et al., 2009).

2.2. SWAT-SC

Our proposed SWAT-SC model is an extension of the original SWAT (version 2009) by incorporating a seasonal calibration technique. SWAT-SC adopts a service-oriented architecture (SOA) and runs on a distributed computation environment. SWAT-SC calibrates model parameters and simulates hydrological process for the dry and wet periods separately, and combines the "optimal" simulation results of these two periods into a complete runoff series. The processes of calibration, simulation and combining simulated results are all automatic in SWAT-SC, no interferences are need.

SWAT-SC integrates several components via Java program language, including components specially built for it and other