Science of the Total Environment 643 (2018) 610–622

Contents lists available at ScienceDirect

Science of the Total Environment

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

Incorporating vegetation dynamics noticeably improved performance of hydrological model under vegetation greening

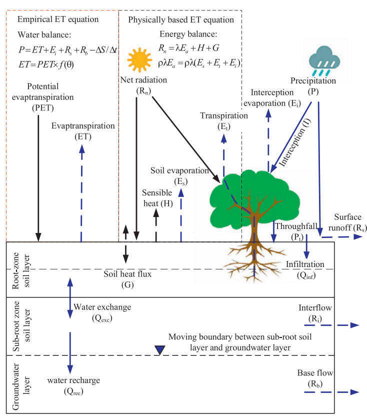
Peng Bai [a], Xiaomang Liu [a,*], Yongqiang Zhang [b], Changming Liu [a]

[a] *Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, 100101 Beijing, China*
[b] *CSIRO Land and Water, GPO Box 1700, Canberra ACT 2601, Australia*

HIGHLIGHTS

- A grid-based hydrological model was modified by incorporating a physically based evaporation equation.
- The original and modified models were compared in a catchment undergoing rapid vegetation greening.
- The modified model improved hydrological simulations under vegetation greening.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 6 April 2018
Received in revised form 9 May 2018
Accepted 19 June 2018
Available online xxxx

Editor: Ouyang Wei

Keywords:
Hydrological model
Evaporation estimates
Vegetation dynamics
Penman-Monteith

ABSTRACT

Numerous hydrological models calculate actual evaporation as a function of potential evaporation (*PET*) and soil moisture stress. There are some limitations for such empirical equations since they do not consider vegetation changes, and therefore cannot account for the different responses of soil evaporation and plant transpiration to changes in environmental factors and cannot be used for evaluating the impacts of vegetation changes. Here, we investigated whether incorporating a physically based evaporation scheme into a grid-based hydrological model can improve the accuracy of hydrological simulations. The original and modified hydrological models were evaluated in a basin which has experienced rapid vegetation greening. The model evaluations were performed using streamflow observations, soil moisture observations and water balance-based evaporation estimates. Results indicated that the modified model can provide better evaporation simulations than the original model during the period of vegetation greening. The streamflow and soil moisture simulations by the modified model over the same period benefitted significantly from the improvement in evaporation simulations and exhibited better consistency with in situ observations than the original model. This study underscores the importance of including vegetation change information in evaporation estimates and demonstrated that the physically based evaporation equation can be used in hydrological models to improve the hydrological simulations under vegetation greening conditions.

1. Introduction

Land surface evaporation (E_a) is a major component of the land water balance since approximately 60% of land precipitation is returned

* Corresponding author.
E-mail address: liuxm@igsnrr.ac.cn (X. Liu).

https://doi.org/10.1016/j.scitotenv.2018.06.233
0048-9697/© 2018 Published by Elsevier B.V.

to the atmosphere via E_a (Oki and Kanae, 2006; Trenberth et al., 2007; Jung et al., 2010). It is also a nexus that links the land surface water and energy balances and exerts a key role in controlling land surface water and energy exchanges between terrestrial ecosystems and the atmosphere (Roderick and Farquhar, 2004; Yang et al., 2007; Mueller et al., 2011; Wang et al., 2015). E_a can be estimated by several tools and techniques at the point or field scales, such as the weighting lysimeter, the eddy covariance technique and the Bowen ratio energy balance system (Wang and Dickinson, 2012). However, these techniques have difficulties in quantifying large-scale E_a fluxes (e.g., at continental or global scales) due to the heterogeneity of the land surface and the limited number of monitoring stations (Wang et al., 2007; Liu et al., 2017; Wu et al., 2017). In practice, large-scale E_a can be estimated from remote-sensing retrievals and numerical models (e.g., ecological models, land surface models, and hydrological models). These approaches can provide large-scale E_a simulations with high temporal resolution and are therefore useful for E_a-related applications such as drought monitoring and assessment, irrigation planning and water resources management. The advantages and disadvantages of large-scale E_a estimation methods have been well documented by several previous studies (e.g., Courault et al., 2005; Kalma et al., 2008; Wang and Dickinson, 2012; McMahon et al., 2013; Long et al., 2014).

Hydrological models, which represent a type of numerical models, provide a simple way to simulate large-scale E_a values at various time scales. The traditional hydrological models have generally focused on reproducing runoff characteristics, with less scrutiny on E_a process simulations (Guo et al., 2016; Bai et al., 2018). A common approach to simulating E_a in traditional hydrological models is to multiply potential evaporation (PET) by a function of soil moisture, i.e., $E_a = PET \times f(\theta)$ (hereafter called $PET - f(\theta)$ based equation). Some commonly used $PET - f(\theta)$ based equations have been summarized by Dyck (1985), Maidment (1992) and Zhao et al. (2013). These empirical evaporation equations seem plausible in terms of their mathematical expressions, in which both water-limiting and energy-limiting factors affecting E_a are considered. However, large uncertainties in E_a simulations have been reported for hydrological models using these empirical equations, even though good fits between simulated and observed runoff have been achieved (e.g., Rientjes et al., 2013; Bai et al., 2016; Rakovec et al., 2016). The actual processes underlying E_a are far more complicated than such empirical equations described and are controlled by many interacting factors. These factors involve complex plant physiological characteristics such as photosynthesis rates, root water uptake rates and stomatal conductance (Green et al., 2006; Wang and Dickinson, 2012; Brutsaert, 2013).

Inaccurate simulations of E_a using $PET - f(\theta)$ based empirical equations mainly stems from two potential sources of uncertainty. First, such empirical equations treat the soil evaporation and plant transpiration as a whole instead of calculating them separately. In reality, the two evaporative processes have different sensitivities to environmental factors (Wang and Dickinson, 2012). For example, soil evaporation rate will significantly decrease under drought stress; Plant transpiration, on the other hand, can extract water from deep soil layers or from groundwater, and its response to drought stress is generally not as sensitive as that of soil evaporation. Consequently, E_a estimates from the hydrological models based on the empirical evaporation equations may have large uncertainties. Second, these empirical evaporation equations do not consider the effects of vegetation changes on E_a. Seasonal vegetation dynamics reallocate energy distribution between the canopy and the soil surface and then lead to changes in E_a and its components. Increasing evidences indicate that spatial and temporal dynamics of vegetation strongly affect terrestrial E_a fluxes via regulating plant transpiration (Gerten, 2013; Jasechko et al., 2013). Therefore, many hydrologists have highlighted the importance of incorporating the vegetation change information into hydrological models to achieve better hydrological simulations (e.g., Donohue et al., 2010; Thompson et al., 2011; Gerten, 2013).

Inaccurate estimation of E_a in hydrological models could also weaken the capacity of the models to simulate other hydrological variables such as soil moisture and groundwater level. These hydrological variables are also crucial for our understanding of hydrological responses to environmental changes. The physically based Penman-Monteith (PM) equation (Penman, 1948; Monteith, 1964) provides a promising option which better describes large-scale E_a process than the empirical equations. The PM equation has long been regarded as the most physically based and reliable method for E_a estimation (McMahon et al., 2013; Zhang et al., 2016). The challenge for the applications of the PM equation over the large scale is how to efficiently parameterize the surface conductance (G_s, the inverse of the surface resistance), which is a sensitive parameter in the PM equation (Mu et al., 2007; Leuning et al., 2008; Mallick et al., 2016). Due to the lack of temporal-continuous observations of soil moisture globally, these PM based equations generally do not directly incorporate soil moisture to regulate G_s, but use VPD to indirectly reflect soil water stress for G_s (e.g., Cleugh et al., 2007; Mu et al., 2011; Leuning et al., 2008). However, it is questionable whether the soil moisture controls near-surface VPD in regions where advection occurs frequently (Morillas et al., 2013; Bai et al., 2017). The poorly estimated water stress in the PM-based models may result in a large uncertainty in E_a estimates.

In this study, a modified version of the PM equation by Leuning et al. (2008) (that is, the PML equation) is employed. The PML equation is incorporated into a grid-based hydrological model by replacing the empirical evaporation equation in the model. In turn, the model provides the water stress estimates for the G_s in the PML equation (that will be described in Section 2.2). The objective is to investigate whether the incorporation of the physically based PML equation into the hydrological model can improve the model's accuracy in simulating hydrological variables. To fulfill this objective, the original and modified hydrological models are compared in a basin where rapid vegetation greening occurred in the past decades. The model evaluations focus on streamflow simulations, as well as the simulations of E_a and soil moisture.

2. Model descriptions

2.1. Hydro-informatic modeling system (HIMS) model

The HIMS model is a grid-based hydrological model that incorporates key hydrological processes in both the vertical and horizontal directions (Liu et al., 2008; Liu et al., 2017). The model runs on a daily scale with a $0.05° \times 0.05°$ resolution (~5 km × 5 km) and consists of two fundamental components that (1) simulate the water balance across all cells within a river basin and (2) route the runoff produced in each cell to the basin outlet. The water balance modeling of the HIMS model within each cell includes the following processes (Fig. 1): canopy interception loss (E_i), evaporation from soil and plants (ET, and $ET + E_i = E_a$), infiltration (Q_{inf}) and surface runoff (R_s), interflow (R_i), water exchange between soil layers (Q_{exc}), groundwater recharge (Q_{rec}) and base flow (R_b) (Liu et al., 2008; Jiang et al., 2015; Liu et al., 2017). Canopy interception is simulated based on a simple "bucket" model, in which the precipitation can reach the ground only when the precipitation exceeds the canopy storage capacity. ET is calculated based on a $PET - f(\theta)$ based nonlinear empirical equation (Fig. 2). Total water storage in the HIMS model is divided into unsaturated and saturated storage zones. The interactions between the unsaturated and saturated zones are described by a moving boundary between the two storages in response to groundwater storage dynamics. The model assumes that the sum of the unsaturated and saturated storage capacity is constant. The unsaturated storage capacity decreases when the saturated storage increases and vice versa. The model uses two soil layers to describe the soil moisture dynamics. The upper layer represents the root-zone soil, where the soil moisture is supplied via infiltration and lost via ET. The lower layer stands for the transition zone soil between the root-zone soil and the groundwater level (here called the sub-root soil layer), which acts as an adjustor that exchanges water with the upper soil and recharges groundwater when