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Research papers

Estimation of root zone storage capacity at the catchment scale using improved Mass Curve Technique

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ABSTRACT

The root zone storage capacity (Sr) greatly influences runoff generation, soil water movement, and vegetation growth and is hence an important variable for ecological and hydrological modelling. However, due to the great heterogeneity in soil texture and structure, there seems to be no effective approach to monitor or estimate Sr at the catchment scale presently. To fill the gap, in this study the Mass Curve Technique (MCT) was improved by incorporating a snowmelt module for the estimation of Sr at the catchment scale in different climatic regions. The "range of perturbation" method was also used to generate different scenarios for determining the sensitivity of the improved MCT-derived Sr to its influencing factors after the evaluation of plausibility of Sr derived from the improved MCT. Results can be showed as: (i) Sr estimates of different catchments varied greatly from ~10 mm to ~200 mm with the changes of climatic conditions and underlying surface characteristics. (ii) The improved MCT is a simple but powerful tool for the Sr estimation in different climatic regions of China, and incorporation of more catchments into Sr comparisons can further improve our knowledge on the variability of Sr. (iii) Variation of Sr values is an integrated consequence of variations in rainfall, snowmelt water and evapotranspiration. Sr values are most sensitive to variations in evapotranspiration of ecosystems. Besides, Sr values with a longer return period are more stable than those with a shorter return period when affected by fluctuations in its influencing factors.

1. Introduction

The close linkage between water, climate and vegetation (like the vegetation-atmosphere interactions, the carbon cycle, the eco-hydrological processes and so on) has long been acknowledged (Milly, 1994) and a multitude of investigations have been carried out to study the two-way interactions (Eagleson, 1978; Farquhar, 1997; Bond and Midgley, 2000; Donohue et al., 2009, 2013; Hirota et al., 2011; Park et al., 2012). Though these studies have provided quite a good general understanding of how vegetation, water and climate are linked, our ability to explain in detail the mechanisms dominating the connections and the resulting interactions is less than satisfactory.

A better understanding of the root zone storage capacity (Sr) which is quite important in the water-climate-vegetation linkage may help us. Sr can be understood as a volume of water per unit area within reach of plants roots for plant uses. This variable directly determines the available water in the root zone that can be used by vegetation and thus controls the extent and type of vegetation (Tang et al., 2015). Besides, it affects evapotranspiration by controlling the maximum amount of water in root zone which is potentially available for vegetation transpiration (Hashemian et al., 2015). Further, it greatly influences the discharge and soil water storage, and thus the long-term water balance of a catchment (Zhang et al., 2001). So, a good understanding of Sr is not only essential to understand the hydrological processes of a catchment, but also important for the climate and ecological processes (de Boer-Euser et al., 2016).

Though great importance has been attached to Sr, this variable is very difficult to measure or estimate, especially at the large scales which are more suitable for hydrological or land surface modelling studies. Lack of soil and plant root observations restricts our ability to accurately understand the dynamics of Sr. Even if high-density observed data were available, it is still unknown whether site observations allow for representing the integrated estimates at the large scales due to high spatial heterogeneity of soil and plant root properties.

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Estimating Sr or relevant variables has been previously undertaken employing several approaches (which are summarized in Table 1): (1) the field observation approach gets rooting depth based on field measurements (Zeng, 2001). The measured results are solid and have relatively lower uncertainty. However, the spatial coverage of observation is limited. (2) Collecting rooting depth from previous studies is used in hydrological and land surface modelling (Wang-Erlandsson et al., 2014). This approach assumes that plants within the same vegetation functional type share the same rooting depth with little consideration for environmental adjustments. (3) Empirical models are used for estimating soil water retention parameters (Smith et al., 2011). These models always ignore the physical mechanism of soil-root interactions and are developed for some certain conditions. (4) Rooting distribution modelling approach predicts rooting depth based on detailed input data like soil, climatic and vegetation information (Collins and Bras, 2007). This approach is useful for describing root distribution. However its usage is limited by relatively higher data requirement. (5) Another approach quite often used in hydrological modelling is calibration (Werth and Güntner, 2010). However, this approach depends on the availability of hydrological records, which may be inaccessible in some regions. Also, parameter equifinality still remains a problem (Beven, 2006). Since the existing approaches are less than satisfactory and have limitations in several aspects like data requirement, scale dependence, model uncertainty and so on, the development of a new approach which is more practically useful and can be used to estimate Sr at the large scales is needed.

In a recent study, Gao et al. (2014) estimated Sr at the catchment scale by employing the Mass Curve Technique (MCT), which is easy to use and has been shown to perform satisfactorily in some catchments in Thailand and the U.S. However, the original MCT is not suitable for cold regions where a large part of precipitation falls as snow, because it does not account for snow dynamics. Apart from this, no catchment in very dry climates (where aridity index was larger than 2) was included. Thus, it is still unknown how the Sr varies in the class of catchments which were not included in Gao's study and how Sr responds to the variations in its influencing factors.

To get a better understanding of the Sr at the catchment scale, we extend the work of Gao and estimated Sr using the improved MCT and analyzed its sensitivity in catchments in different climatic regions in China. By doing this, we can advance our understanding of how the Sr reacts to climate variability and its implications for water balance of catchments and ecological processes, and improve the status of hydrological, climate and ecological modelling. Specifically, the objectives of this paper were to: (1) develop an improved MCT and an improved FLEX hydrological model by incorporating a snowmelt module and thus extend the application of MCT technique for the Sr estimation; (2) apply the improved MCT to estimate Sr in several catchments selected from different climatic regions (including the cold ones) of China during the period of 1988–2010; (3) evaluate the plausibility of the improved MCT in Sr estimation by the Gumbel distribution and comparing with values obtained by the calibration approach; and (4) analyze response of Sr to the variations of its influencing factors.

2. Methods description

2.1. Mass Curve Technique (MCT) to estimate Sr

Like society, ecosystems need continuous water supply to maintain ecological functions, especially during dry seasons. Reservoirs are designed and constructed to store water and the stored water is used during the dry period. Analogously, ecosystems develop root zones. For reservoir design, the MCT technique is employed to determine the required reservoir storage capacity. In a similar vein, the concept of MCT can be employed to estimate Sr in certain ecosystems at the catchment scale.

To derive Sr by the MCT, only precipitation, streamflow and water demand data are needed and the following 3 steps can be taken:

(1) Determine the average daily catchment water demand (E_{ta}), which is known as the actual evapotranspiration, from water balance:

$$E_{ta} = \frac{P_E - R}{N} \quad (1)$$

Table 1
Overview of relevant literature on rooting depth or root zone storage capacity estimating approaches.

Study	Variable estimated	Approach	Spatial scale	Data required	Main advantages	Main limitations
Zeng (2001)	Rooting depth	Field observation	Site scale	Observe directly	1. Relatively lower uncertainty	1. Limited spatial coverage 2. Relatively higher fund-consuming
Wang-Erlandsson et al. (2014)	Rooting depth	Collecting data from results of previous studies	Site, regional and global scale	Data from relevant literature	1. Easy to carry out (no observation or computation is required)	1. Assuming that results of previous studies are valid in the target study area 2. Depending on the scientific quality of other studies
Smith et al. (2011)	Soil water retention parameters	Empirical models	Site scale	Soil moisture	1. Easy to carry out 2. Relative lower input data requirement	1. Limited consideration of physical mechanism 2. Limited applicable regions
Collins and Bras (2007)	Root profiles	Rooting distribution modelling	Site and regional scale	Detailed climate, soil and vegetation information	1. Physically based 2. Improving understanding of root depth and distribution	1. Detailed input data required 2. Model uncertainties
Werth and Güntner (2010)	(Hydrological) root zone storage capacity	Hydrological model calibrations	Catchment scale	Climatic and hydrological data	1. Suitable spatial scale for hydrological studies	1. Hydrological data required 2. Parameter equifinality
This study	Root zone storage capacity	Mass curve technique	Catchment scale	Runoff and/or evaporation demand and precipitation	1. Suitable spatial scale for hydrological studies 2. Observation based 3. No need for soil information 4. No need for models	1. Hydrological data required 2. Feasibility needed to be verified