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Application of isotopic information for estimating parameters in Philip infiltration model

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Abstract

Minimizing parameter uncertainty is crucial in the application of hydrologic models. Isotopic information in various hydrologic components of the water cycle can expand our knowledge of the dynamics of water flow in the system, provide additional information for parameter estimation, and improve parameter identifiability. This study combined the Philip infiltration model with an isotopic mixing model using an isotopic mass balance approach for estimating parameters in the Philip infiltration model. Two approaches to parameter estimation were compared: (a) using isotopic information to determine the soil water transmission and then hydrologic information to estimate the soil sorptivity, and (b) using hydrologic information to determine the soil water transmission and the soil sorptivity. Results of parameter estimation were verified through a rainfall infiltration experiment in a laboratory under rainfall with constant isotopic compositions and uniform initial soil water content conditions. Experimental results showed that approach (a), using isotopic and hydrologic information, estimated the soil water transmission in the Philip infiltration model in a manner that matched measured values well. The results of parameter estimation of approach (a) were better than those of approach (b). It was also found that the analytical precision of hydrogen and oxygen stable isotopes had a significant effect on parameter estimation using isotopic information.

Keywords: Isotopic information; Hydrologic information; Parameter estimation; Philip infiltration model; Rainfall infiltration experiment

1. Introduction

The successful application of a catchment model depends on the accuracy of hydrologic and hydraulic parameters used for the simulations and structures of the model. Model structures are based on the catchment characteristics and conceptualization of a realistic study system (Fenicia et al., 2008). Because some model parameters are difficult or impossible to measure in the natural world, model parameters are often estimated from secondary information sources (Fonseca et al., 2014). In fact, only some available data are used in model calculation because of the limitation of data (Wagener, 2003). Abundance of data is the foundation of understanding model structures and parameter estimation. Data mining and other auxiliary data are two important methods, apart from the traditional measurement method, for collecting information in a given catchment. The data mining method primarily extracts useful information from collected data using mathematical techniques (e.g., the clustering method), while auxiliary data means an increasing quantity of data independent of stream discharge and other hydrologic data. Hydrogen and oxygen isotopes are good auxiliary data tools and often used to trace water movement in the water cycle in order to provide orthogonal information on the catchment behavior (Fenicia et al., 2008). The combination of isotopic information and hydrologic information can provide plenty of available

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information for model calculation and reduce uncertainty in parameter estimation. The ways isotopic information is used in a hydrologic model for parameter estimation should be further developed. Dunn et al. (2008) studied the mixing processes and mean residence time in a set of nested sub-catchments in northeast Scotland as determined from isotopic data, which could reduce parameter uncertainty in a rainfall-runoff model. Sprenger et al. (2015) used the stable isotope composition of the soil pore water depth profile as a single or additional optimization target, and estimated flow and transport parameters in the unsaturated zone. They found that using both the isotope profiles and the soil moisture time series resulted in good simulation results and strong parameter identifiability. When only data from isotope profiles in combination with textural information were available, the results were still satisfactory (Sprenger et al., 2015). Klaus et al. (2015) studied temporal dynamics of catchment transit times from stable isotope data. They extracted information on catchment mixing from the stable isotope time series instead of prior assumptions of mixing or the shape of transit time distribution, and demonstrated proof of the concepts of the approach with artificial data. This indicated that the Nash-Sutcliffe efficiencies in tracer and instantaneous transit times were higher than 0.9.

The complexities of model structures and number of parameters have a significant effect on parameter estimation using isotopic information. The two-parameter Philip infiltration model with a simple model structure has a specific physical foundation and is widely used to simulate rainfall infiltration. However, because of limitations in observed hydrologic data, parameter estimation in a Philip infiltration model may be difficult. The objective of this study was to combine isotopic information with hydrologic information to estimate the parameters of a Philip infiltration model through a rainfall-infiltration experiment in a laboratory, and compare them with the results of parameter estimation using only hydrologic information.

2. Methods

2.1. Philip infiltration equation

The Philip infiltration equation (Philip, 1957a, 1957b) was derived from Richard's equation with water vertically infiltrating into the unsaturated and semi-infinite homogeneous soil under constant initial water content conditions (Prevedello et al., 2009). The infiltration rate with time, $i(t)$ in $\mathrm{cm \cdot h^{-1}}$, is defined as

$$i(t) = 0.5St^{-0.5} + A \tag{1}$$

where t is the infiltration time (h), S is the soil sorptivity ($\mathrm{cm \cdot h^{-0.5}}$), and A is the soil water transmission ($\mathrm{cm \cdot h^{-1}}$). The parameters S and A are related to soil diffusivity and moisture retention characteristics (Mishra et al., 2003). In this paper, S is taken into account as the average soil sorptivity, and A equals the saturated hydraulic conductivity K_s, which does not lead to serious errors in model calculation (Swartzendruber and Youngs, 1974). The soil sorptivity S appears to be correlated with the soil water transmission A (Wang et al., 2006).

The cumulative infiltration with time, $I(t)$ in cm, can be expressed as

$$I(t) = St^{0.5} + At \tag{2}$$

In reality, Eqs. (1) and (2) are applicable to a limited time span (Prevedello et al., 2009). However, the classical Philip infiltration equation is still widely used for a constant head boundary neglecting the effect of a limited time span.

2.2. Model parameter estimation using hydrologic information

Two parameters of the Philip infiltration model need to be estimated: the soil sorptivity S and soil water transmission A. There are also two major methods for parameter estimation using hydrologic information, namely, the linear graphic method and the least squares method (Bristow and Savage, 1987). In the linear graphic method, data of cumulative infiltration with time are plotted on a figure with $t^{0.5}$ as the abscissa and $I(t)t^{-0.5}$ as the ordinate. Then, the parameters S and A can be respectively obtained from the intercept and slope of the figure. The least squares method is used to optimize S and A through fitting observed data and Eq. (1) or (2). Notwithstanding that the linear graphic method can easily obtain the model parameters, it is highly arbitrary due to $t^{0.5}$ existing on both axes in order to introduce self-correlation and limitation of data at time $t = 0$ (Bonell and Williams, 1986). The least squares method shows objective characteristics and is widely used to estimate parameters of a model. In this study, S and A were estimated from observed data of cumulative infiltration calculated with Eq. (2) using the least square method, and the calculated results were regarded as parameters obtained from hydrologic information. Effects of limited time on model calculation were neglected or considered errors in the parameter estimation process using hydrologic information due to the deficiency of available data.

2.3. Model parameter estimation using isotopic information

Model parameter estimation using isotopic information is implemented with the isotopic mixing model based on isotope mass balance. The isotopic mixing model combines isotopic information with hydrologic information, and can be expressed as

$$C_j = \frac{\Delta V C_{\mathrm{p},j-1} + V_0 C_{j-1}}{\Delta V + V_0} \tag{3}$$

where C_{j-1} and C_j are the isotopic compositions of mixing water in the mixing tank at time t_{j-1} and t_j, respectively, and j indicates the time sequence; $C_{\mathrm{p},j-1}$ is the isotopic composition of input water (e.g., rainfall) at time t_{j-1}; ΔV is the volume of water infiltrating into soil from time t_{j-1} to t_j; and V_0 represents the initial soil water volume, which is equal to the