Journal of Hydrology 524 (2015) 549–561

Contents lists available at ScienceDirect

Journal of Hydrology

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

Impacts of different types of measurements on estimating unsaturated flow parameters

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ARTICLE INFO

Article history:
Received 29 June 2014
Received in revised form 27 January 2015
Accepted 30 January 2015
Available online 9 February 2015
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Felipe de Barros, Associate Editor

Keywords:
Data assimilation
Ensemble Kalman filter
Unsaturated flow
Data worth

SUMMARY

This paper assesses the value of different types of measurements for estimating soil hydraulic parameters. A numerical method based on ensemble Kalman filter (EnKF) is presented to solely or jointly assimilate point-scale soil water head data, point-scale soil water content data, surface soil water content data and groundwater level data. This study investigates the performance of EnKF under different types of data, the potential worth contained in these data, and the factors that may affect estimation accuracy. Results show that for all types of data, smaller measurements errors lead to faster convergence to the true values. Higher accuracy measurements are required to improve the parameter estimation if a large number of unknown parameters need to be identified simultaneously. The data worth implied by the surface soil water content data and groundwater level data is prone to corruption by a deviated initial guess. Surface soil moisture data are capable of identifying soil hydraulic parameters for the top layers, but exert less or no influence on deeper layers especially when estimating multiple parameters simultaneously. Groundwater level is one type of valuable information to infer the soil hydraulic parameters. However, based on the approach used in this study, the estimates from groundwater level data may suffer severe degradation if a large number of parameters must be identified. Combined use of two or more types of data is helpful to improve the parameter estimation.

1. Introduction

Unsaturated zone is the link between the land surface and the top of the phreatic zone. It is of great importance in providing water and nutrients to the groundwater environment. In agriculture, the unsaturated zone is essential for optimum water resources management, irrigation and drainage scheduling, fertilizer application, and crop production. Obtaining accurate soil hydraulic parameters is very important but not an easy task. These parameters are usually determined by laboratory experiments with repacked or intact soil cores. However, parameter estimates obtained from laboratory experiments may be considerably different from real parameters due to unavoidable disturbance to soil. There are also many in situ methods for direct estimation of the soil hydraulic parameters, including the crust method, the instantaneous method, and the unit gradient internal drainage (Lazarovitch et al., 2007). The main limitation of in situ methods is that they are time consuming due to the need of adhering to relatively strict initial and boundary conditions (Šimůnek and van Genuchten, 1996). Thus, many parameter estimation methods have been introduced to identify soil and aquifer hydraulic parameters. Overviews on inverse methods in hydrogeology are presented by Carrera et al. (2005), and recently by Zhou et al. (2014).

Different types of observations are adopted for parameter inference, including the outflow flux in soil column experiments (Kool et al., 1985; van Dam et al., 1992, 1994; Toorman et al., 1992), soil water content (Zijlstra and Dane, 1996; Wang et al., 2003; Ritter et al., 2003; Yeh et al., 2005), soil water pressure head (Kool and Parker, 1988; Yeh and Zhang, 1996; Wöhling et al., 2008; Li and Ren, 2011), tracer test data (Mishra and Parker, 1989), cumulative infiltration data (Šimůnek and van Genuchten, 1996), and water evapotranspiration flux (Jhorar et al., 2002). In recent years, hydrogeophysical measurement methods, such as electrical resistivity tomography (ERT) and ground penetrating radar (GPR), are also widely used to collect information (Yeh et al., 2002; Kowalsky et al., 2005; Jadoon et al., 2012; Scholer et al., 2013). Furthermore, remote sensing is able to provide data for parameters estimation at larger scale (Vereecken et al., 2008; Montzka et al., 2011).

Soil water pressure or soil matric potential is very sensitive to the alternation of soil wetting and drying. Matric potential data, often combined with measurements of flux data (e.g. outflow and

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http://dx.doi.org/10.1016/j.jhydrol.2015.01.078

evaporation), are the common data to estimate unsaturated parameters at the column scale (Kool et al., 1987; Toorman et al., 1992; Nutzmann et al., 1998). Šimůnek et al. (1998) used measured pressure head to estimate unsaturated flow parameters, and Marquardt–Levenberg optimization scheme was used in their study. They found that pressure heads measured near the soil surface are more valuable to parameter estimation than those measured at lower locations. Li and Ren (2011) showed that soil water pressure data can lead to satisfactory parameter estimates, especially for K_s and α in van Genuchten model. In practice, a major obstacle of estimating soil hydraulic parameters with soil water pressure data is the higher measurement error of pressure head. In addition, conventional matric potential measurement only covers the wet part of the moisture retention characteristic (Vereecken et al., 2008). For example, MPS-2 sensor produced by Decagon measures the range of soil water potentials between −9 and −100,000 kPa, with relative accuracy of 25% in the range of −9 kPa to −100 kPa (Decagon Devices Inc., 2014). Furthermore, soil matric potential can only be measured at the point scale, since current techniques do not allow to obtain spatially averaged measurement of matric potential.

Unlike the pressure head data, soil moisture content data covers the whole changing range of soil water status. Soil water content can be measured at different scales, depending on the equipment and method used. Point-scale measurement technique is most sophisticated in the real applications. It has been widely used to monitor the vertical soil moisture profile. Some measurement methods (e.g., time domain reflectometry) are able to provide spatially and temporally high resolution measurements at low cost. Vereecken et al. (2008) presented a comprehensive review on the value of soil moisture measurements in vadose zone hydrology at both field and catchment scales. In-situ measurements of point-scale water content at different depths and times during infiltration or drainage experiments are already long used for parameter estimation (Kool et al., 1987). Kool et al. showed that the parameters α and n (in Van Genuchten model) can be solve uniquely using only information on water content profiles during drainage, but simultaneous estimation of three or more parameters requires additional information. Ross (1993) found that besides the measured water content, at least one matric potential was required to obtain good parameter estimates. Ritter et al. (2003) used the measured time series of soil water content to estimate unsaturated flow parameters. An optimization algorithm, global multilevel coordinate search algorithm, was used in their study. The ill-posedness of their inverse problem was partially due to a large number of parameters to optimize and to insufficient information in the measured data. In other words, although soil moisture data at different depths and times alone can be easily measured, they may be not able to identify the unsaturated parameters.

Surface soil moisture is highly variable in space and time. It is defined as the moisture content averaged from the surface down to a given depth. Surface soil moisture can be easily captured over large regions with the rapid development of remote sensing technique. However, remote sensing technique characterizes soil moisture in the shallow soil, usually at a depth between 2 cm and 20 cm (Jackson et al., 1995). For example, the passive microwave L-band (1.4 GHz) sensor has a maximum penetration depth of 5 cm from the soil surface under minimal vegetation cover. Most studies focused on soil moisture profile retrieval by using near-surface soil moisture assimilation scheme (e.g., Walker et al., 2001; Walker and Houser, 2004; Dunne and Entekhabi, 2005). Several studies on estimating soil parameters with near-surface data have been reported in the literature. Ines and Mohanty (2008) employed a genetic algorithm to identify the soil water retention curve and the hydraulic conductivity function by using near-surface soil moisture (0–5 cm) data. For the case of layered soil systems, their approach was not quite successful and only certain parameters could be identified if only the near-surface soil moisture data were used. With continuous monitored surface soil moisture, Qin et al. (2009) employed particle filter method to retrieve soil moisture profiles and to estimate soil hydraulic parameters simultaneously. Montzka et al. (2011) further investigated the effectiveness of data assimilation in estimating the parameters for different soil types. Although surface soil moisture data are widely used, the measurement accuracy is still a critical issue and its ability to estimate deep soil hydraulic parameters remains challenging.

Measuring groundwater level is a common practice in field study. Groundwater level can be continuously measured by an automatic sensing device at a high accuracy and low cost. Groundwater level fluctuation indicates the groundwater recharge or discharge. Thus, it is a valuable data source for groundwater recharge estimation (Crosbie et al., 2005). It was widely used in traditional aquifer testing and parameter estimation in groundwater hydrology (McPherson, 1998). Cirkel et al. (2010) identified the seepage intensities from groundwater level data. However, the groundwater level data is not regarded as an important information source for studies on soil hydraulic parameter estimation.

Many studies evaluated the worth of different types of data on the estimation of spatially distributed unsaturated flow parameters. Yeh and Zhang (1996) and Zhang and Yeh (1997) showed usefulness of pressure head and moisture content measurements for estimating unsaturated hydraulic parameters. Li and Yeh (1999) investigated effects of head and tracer concentration measurements on unsaturated flow parameters estimation. More recently, Mao et al. (2013) conducted a rigorous cross-correlation analysis to show the importance of head measurements at different times for estimating unsaturated hydraulic parameters. These studies, however, have not comprehensively compared the data worth of

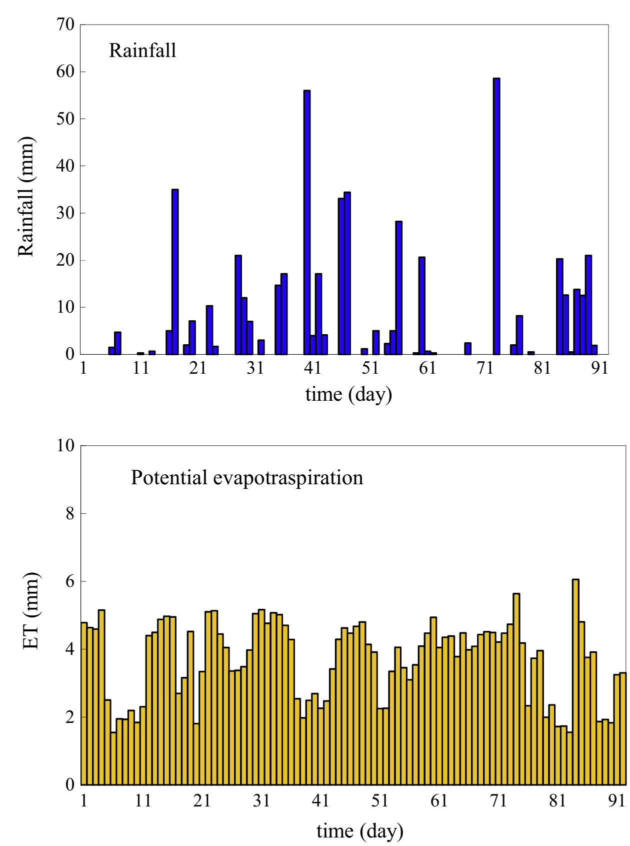

Fig. 1. Synthetic rainfall and potential evapotranspiration.