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Effects of time step length and positioning location on ring-measured infiltration rate

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ABSTRACT

Soil infiltration, an important component of hillslope hydrology, is widely measured with ring infiltrometers. In the numerical algorithms used for soil infiltration measurement, the time step length (STL) for reading water level and positioning location (PL) of average infiltration rates within a time step considerably affect the measured infiltration rate curves. In this study, four TSLs (1, 2, 5 and 10 min) were used to record falling water depth and three PLs (initial, mid, and end points of the time step) were applied to position the measured average infiltration rate, to evaluate the effects of TSL and PL on the measurement accuracy of infiltration rate. For a specific TSL, three infiltration rate curves were obtained by positioning the average infiltration rate at initial point (f_i), midpoint (f_m), and end point (f_e), respectively. Results show that the infiltration rates of f_e increases with TSL increasing. A short TSL reduces measurement errors caused by the TSL. However, a short TSL produces high measurement errors caused by reading the Mariotte bottle scale and increases practical difficulties. The f_m of different TSL were the closest to the true soil infiltration process, regardless of the TSL (i.e. 2, 5 or 10 min), with a maximum error in cumulative infiltration of approximately 11.14%. The TSL could be reasonably long, such as 5 or 10 min, as long as the measured average infiltration rates are positioned at the midpoint of a TSL. This strategy can avoid short-time measurement errors and reduce operational difficulties.

1. Introduction

Infiltration is the process of water entering soil and generally referred to as the downward movement of water from the soil surface (Bouwer, 1986; Hillel, 1998). This process affects the transport route of chemicals, the water quality of agricultural drainage, and the uniformity and efficiency of surface irrigation (Berehe et al., 2013; Rashidi et al., 2014). Infiltration rates influence the timing of overland flow (Jury and Horton, 2004; Viessman and Lewis, 1995). In addition the actual soil infiltration and rainfall intensity determine the runoff volume (Philip and Wayne, 2002). Infiltration rate is an important component of any hydrologic model (Viessman and Lewis, 1995).

Among the numerous tools for soil infiltration measurement (Bouwer, 1986; Lei et al., 2006a,b; Ogden et al., 1997; Peterson and Bubenzer, 1986; Perroux and White, 1988), the double-ring infiltrometer described by Bouwer (1986) is the most commonly used method to determine soil infiltration and soil hydraulic properties (Bagarello and Sgroi, 2004; Iwanek, 2008; Neris et al., 2012; Verbist et al., 2013).

A complete infiltration curve measured with a ring infiltrometer is calculated using the average infiltration rate during a certain period before being positioned at the end point of the TSL. Therefore, determining the optimum TSL before measuring an infiltration curve is important to obtain accurate measurement results. ASTM (2003) suggests the use of a 15-min TSL for the first hour and 30 min for the second hour. Eijkelkamp Company (2012) also proposed that the decrease in water level in the inner ring must be determined using 1–2 min intervals in the initial infiltration stage and using with a 20–30 min intervals in the subsequent stages. Standards have not been unified regarding the optimum TSL required for ring infiltrometers used in different soils. Therefore, scientists use different TSL to measure soil infiltration rates. For example, Bagarello and Sgroi (2004) and Mao et al. (2008) used 2 min intervals by monitoring the decrease in water level in an infiltrometer reservoir. Peng et al. (2015) calculated the infiltration rate by using 2 min intervals for the first 10 min and 5 min intervals for 10–90 min to study the effect of urbanization on water retention. Woltemade (2010) also calculated the infiltration rate by using 15 min intervals to study the effect of residential soil disturbance

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on infiltration rate and storm water runoff. Carlier (2007) used a 3 min TSL to measure the soil infiltration. Anari et al. (2011), Adindu Ruth. et al. (2014), Champatiray (2014), Oshunsanya (2013), Rasaily et al. (2014) and Uloma et al. (2014), calculated infiltration rates by using 5 min intervals. In their studies, the average infiltration rates were all positioned at the end point of the TSL of measurement.

The infiltration rate curves of different soils follow the same trend, which is that soil infiltration is relatively high in the initial stage, rapidly decreases with time, and gradually settles to a steady infiltration rate. Soil infiltration rate curves continuously change over time (Jury and Horton, 2004) and can be described by Green and Ampt (1911), Kostiakov (1932), Horton (1941) and Philip (1954) models. Obtaining the average infiltration rate (the measured infiltration rate during a fixed interval), instead of the transient infiltration rate (the soil infiltration rate at a given moment within the interval), during a time period before positioning at the end of the TSL causes the measured infiltration curve to deviate from the actual curve and thus produces a system error in the infiltration rate measurement.

Scientists have adopted different strategies, such as a water level sensor or a water depth sensor, to improve the measurement accuracy of the supplied water flow (Constantz and Murphy, 1987; Prieksat et al., 1992; Maheshwari, 1996). These methods have not been widely adopted by the scientific community possibly because of their relative high cost and complexity. Therefore, the traditional method of reading a tape measure for the supplied water flow is still commonly used to determine soil infiltration by a ring infiltrometer (Bodhinayake et al., 2004; Bagarello et al., 2009; Bamutaze et al., 2010; Chowdary et al., 2006; Lai and Ren, 2007; Ries and Hirt, 2008; Ruggenthaler et al., 2015). In an attempt to reduce the measurement errors caused by the measurement TSL, scientists tried to use shorter intervals at the initial stage of infiltration. León et al. (2015) suggested that readings should be performed at a TSL of 0.5 min. The use of a short TSL may reduce the measurement errors and improve the calculation accuracy. However, this method causes observation difficulties to a certain extent, and introduces measurement errors resulting from the difficulties in accurately reading the scale of the water supply tank. The water level in the ring or Mariotte bottle minimally changes within a short time step. Thus, a short time step may not be ideal.

To measure the infiltration accurately, the influence of different TSL and PL on measurement accuracy should be quantitatively evaluated. Accordingly, this study aimed to: 1) quantitatively estimate the effects of TSL and PL on measured soil infiltration curves, 2) estimate the measurement error under different TSLs and PLs on the basis of water balance, and 3) propose the optimal PL for measurements using ring infiltrometers.

2. Theory

A ring infiltrometer works based on the following assumption: the infiltration rate curves at different spatial locations follow the same decreasing function over time. The Mariotte bottle supplies water for ring infiltrometers at varied rates to maintain a constant water level in the ring. The infiltration water flow is calculated based on the changing water level in the Mariotte bottle. The infiltration rate is then calculated based on the changing water flow rates given by:

$$i(t) = q(t)/A \tag{1}$$

where $q(t)$ is the transient water flow rate of a Mariotte bottle, $L^3\ T^{-1}$; $i(t)$ is the infiltration rate, $L\ T^{-1}$; and A is the area of the ring, L^2.

2.1. Effect of TSL on infiltration curve

The instantaneous $q(t)$ in Eq. (1) is theoretical which is unachievable in actual water supply processes. Instead of the transient water flow rate, the average flow rate is used during practical measurement in a given time period:

$$\bar{q}_j = \frac{Q_j - Q_{j-1}}{\Delta t_j} = \frac{1}{t_j - t_{j-1}} \int_{t_{j-1}}^{t_j} q(t)dt \tag{2}$$

where $\bar{q}_j$ is the average flow rate during the period of $t_j - t_{j-1}$, $L^3\ T^{-1}$; Q_{j-1} and Q_j are the amounts of water in the Mariotte bottle at time moments t_{j-1} and t_j respectively, L^3; Δt_j is the TSL, T.

In consideration of the average flow rate at a specific TSL, the average infiltration rate is given as:

$$\bar{i}_j = \frac{\bar{q}_j}{A} = \frac{1}{A(t_j - t_{j-1})} \int_{t_{j-1}}^{t_j} q(t)dt \tag{3}$$

where $\bar{i}_j$ is the average infiltration rate in the period $t_j - t_{j-1}$, $L\ T^{-1}$; and A is the area of the infiltration ring, L^2.

According to the integral mean value theorem, Eq. (3) can be transformed into:

$$\bar{i}_j = i(t_\zeta) = \frac{\bar{q}_j}{A} = \frac{1}{A(t_j - t_{j-1})} \int_{t_{j-1}}^{t_j} q(t)dt = \frac{q(t_\zeta)}{A}\ \ (t_{j-1} < t_\zeta < t_j) \tag{4}$$

where t_ζ is the time at which the accurate infiltration rate is positioned (the true soil infiltration rate under ideal conditions compared with the measured values), T; and $\bar{i}_j$ located at a moment between t_{j-1} and t_j is reached.

In the literature (Kumar, 2014; Mao et al., 2008; Peng et al., 2015; Rasaily et al., 2014), the average infiltration rate ($\bar{i}_j$) is positioned at the end of the TSL (Conventional PL in Fig. 2). Hence, the coordinate of the infiltration curve at time t_j is (t_j, $\bar{i}_j$). The infiltration process $i(t)$ is the monotone function of time t; thus $i(t_j) < \bar{i}_j < i(t_{j-1})$. The measured infiltration curve is higher than the natural value when $\bar{i}_j$, instead of $i(t_j)$, is placed at the end moment of the TSL; hence, system measurement errors are produced.

Fig. 1 presents three infiltration curves: the first curve is the probable true infiltration curve (the probable correct value positioned at the right moment) and the two other curves are the infiltration curves measured at dt_1 and dt_2 TSL ($dt_2 > dt_1$). As shown in Fig. 1, the measured infiltration rate is higher than the actual value when positioned at the end point of time step. The infiltration curve measured at dt_2 TSL is higher than that measured at dt_1 ($dt_1 < dt_2$) TSL. In this case, $\bar{i}_1$ and $\bar{i}_2$ are the average infiltration rates measured at dt_1 and dt_2 TSL, respectively. Moreover, $\bar{i}_1$ is larger than $\bar{i}_2$, indicating that the measured average infiltration rate increases with decreasing TSL. The infiltration curve determined at dt_1 approximates the probably actual curve better than that determined at dt_2. The system measurement error decreases

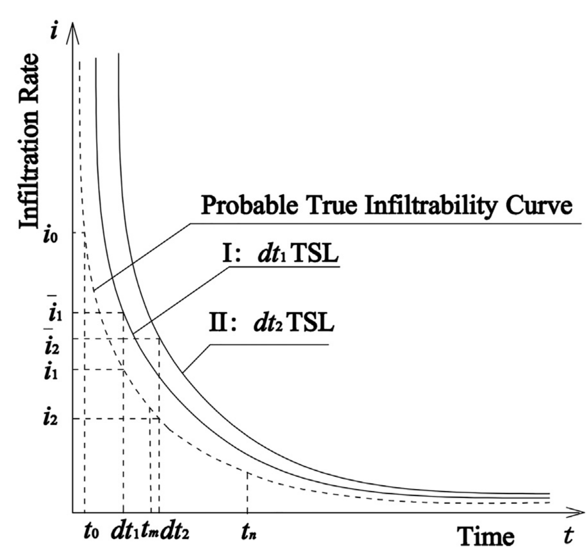

Fig. 1. Effect of different TSLs on the measured infiltration rates (note: I is the infiltration rate curve measured at dt_1; II is the infiltration rate curve measured at dt_2).