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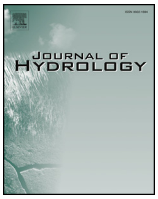

Research papers

A method for determining steady velocity of shallow water flow on hill-slope and the distance when water flow reaches stability

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ABSTRACT

Understanding the velocity distribution of shallow water flow along hill-slope is of great significance in soil erosion studies. This study proposes a method to estimate the steady flow velocity and the distance when water flow reaches stability, using hill-slope flow velocity distribution data along a simulated rill measured by the electrolyte tracer pulse method. Laboratory experiments were performed using a flume of 12 m long, 0.1 m wide and 0.3 m height under five slope gradients (5°, 10°, 15°, 20° and 25°) and four flow discharges (2, 4, 8 and 16 L min^{-1}). The electrolyte tracer pulse method was employed to measure the flow velocities at locations of 1, 2, 3, 4, 6, 8, 10 and 12 m from the inlet of the flowing water. The flow velocities measured by the dye tracer method served as a control. The results showed that the flow velocities measured by the electrolyte tracer pulse method initially accelerated and then reached a steady value. An equation for estimating flow velocity on the basis of the measurement distance was established. The flow velocities calculated by the equation agreed well with those measured by the electrolyte tracer pulse method. The determination (R^2) and the Nash-Sutcliffe model efficiency (NSE) were greater than 0.800, except for a few cases. In addition, the equation established in this study was shown to successfully predict flow velocities measured in other studies. The steady flow velocities and the distances when water flow reached stability under different slope gradients and flow discharges were determined by this equation. When the differences between the measured flow velocity and the steady flow velocity were very small, that is, 5% and 10%, the steady distances ranged from 2.239 m to 4.772 m and from 2.843 m to 6.059 m, respectively. By comparing the steady flow velocities with the flow velocities measured by the dye tracer method, the results indicated that the steady flow velocities were 0.702–0.735 times that of the flow velocities measured by the dye tracer method at various slope gradients and flow discharges. A linear function existed between the two, and the regressed parameter k (i.e., 0.718) could be used as the correction factor between the two. In general, the equation established in this study can facilitate the prediction of the steady flow velocity.

1. Introduction

The velocity of shallow water flow on hill-slope is an important hydraulic parameter for soil erosion and overland flow studies (Zhang et al., 2009; Guo et al., 2013; Qian et al., 2016; Zhang and Wang, 2017). The flow velocity is not only the driving force of soil water erosion (Lei et al., 2005) but also the basis for establishing the process-based soil erosion models, since it is directly related to sediment transport, soil detachment and deposition (Zhang et al., 2008; Rahma et al., 2013; Yang et al., 2018). Accurate measurement of hill-slope shallow water flow velocity remains an important issue to be solved because the depth of shallow water flow is very shallow, usually in mm or cm, and influenced by the slope gradient, flow discharge, topography and surface conditions (Zhang et al., 2003; Lei et al., 2010; Dong et al., 2014; Huang et al., 2018).

The traditional velocity meter suitable for channel flow measurement is too large to be used for shallow overland flow. Moreover, several other meters used in flow velocity measurements for soil erosion studies are based on optics and automated measurement technologies, including acoustic Doppler velocimeters, hot film anemometers, and

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particle imaging velocimeters (Rice et al., 1988; Lu et al., 1998; Raffel et al., 1998; Gimenez et al., 2004; Hyun et al., 2003; Robinson and Cook, 1998; Sidorchuk et al., 2008). However, most of the meters have certain limitations, particularly in sophisticated field conditions.

At present, the measurement of shallow water flow velocity on hill-slope often includes the tracer method (Luk and Merz, 1992; Li et al., 1996; Nearing et al., 1999; Zhang et al., 2003, 2010). Commonly used tracers include different materials, such as dyes of various colours (Abrahams et al., 1986; Zhang et al., 2010), electrolytes (Lei et al., 2005; Lei et al., 2010; Planchon et al., 2005), heat pulses (Angermann et al., 2012), radioactive isotopes (Gardner and Dunn, 1964), natural water isotopes (Berman et al., 2009), floating objects (Tauro et al., 2010, 2012) and magnetic materials (Ventura et al., 2001). The flow velocity is determined by measuring the time interval for the tracers to travel a given distance. However, the flow velocities measured by the tracer method must be corrected or recalibrated to obtain the average flow velocity. Using the dye tracer method as an example, the flow velocity measured by this method is regarded as the surface velocity of the flow due to dye diffusion (Luk and Merz 1992; Planchon et al., 2005; Zhang et al., 2010). To make the correction, a correction factor is then used to convert surface velocity to average flow velocity. The commonly used correction factor α is the ratio of mean flow velocity to surface velocity. Many scholars have obtained different correction factors in their respective experiments. Researchers found that the correction factor α was not a constant (Luk and Merz 1992; Emmett 1970; Zhang et al., 2010). The factor was affected by different factors, such as bed roughness, slope gradient, flow discharge and flow velocity (Phelps 1975; King and Norton, 1992). Therefore, the tracer method has certain limitations in determining the average flow velocity.

Lei et al. (2005) described an electrolyte tracer pulse method to determine shallow water flow velocity. This method is based on the mathematical solution of solute transportation in steady water flow under a pulse boundary condition. The method accurately determines shallow water flow velocity by detecting the transport process of electrolyte in the flow as it passes a sensor at a known distance from the input signal and using the analytical solution to analyse the partial differential equation of solute transportation in shallow water flow. This method can directly measure the shallow water flow velocity without correcting or calibrating the empirical parameters and shows high stability and accuracy. At present, this method has been widely used on gravel layer slope (Lei et al., 2013), rill slope (Dong et al., 2014; Zhuang et al., 2018) and frozen and thawed slopes (Ban et al., 2016, 2017a, 2017b), and the measurements have achieved desired results. Therefore, the electrolyte tracer pulse method is a satisfactory method for measuring shallow water flow velocity on hill-slope.

Early studies mainly focused on the average flow velocity models on hill-slope. These studies indicated that flow discharge and slope gradient were better predictors of average flow velocity (Govers, 1992; Abrahams et al., 1996; Nearing et al., 1997, 1999; Foster et al., 1984; She et al., 2014). However, very few studies have been designed to investigate the relationship between shallow water flow velocity on hill-slope and measurement distance. In the process of water running down-slope, flow velocity gradually increases because potential energy has been converted to kinetic energy. The hydraulic features of water flow are directly related to the processes of soil detachment, sediment transport and deposition. The flow velocity determines how many soil particles are separated and transported, and how much sediment is delivered and deposited down the hillside and through the stream system. In the process of water running down-slope, water flow will experience a period of acceleration. In previous studies, this acceleration process was ignored in the measurement of shallow water flow velocity on hill-slope, or the length of the reserved accelerating section was so short that the flow velocity could not reach the stable value during measurement. This situation resulted in a lower accuracy in the measured velocity. Therefore, additional work is necessary to determine the steady flow velocities and the distances when water flow reaches stability. It is a better guidance and reference for further research and application of the electrolyte tracer pulse method and the dye tracer method to measure the velocity of shallow water flow on hill-slope. When the electrolyte tracer pulse method and the dye tracer method are used to measure the velocity of shallow water flow, the instrument should be placed after the steady distance.

The objectives of this study were to measure the velocities of shallow water flow on hill-slope by the electrolyte tracer pulse method to determine the steady flow velocities and the distances when water flow reached stability and to develop a flow velocity equation based on the measurement distance.

2. Materials and methods

2.1. Solute transport model

A solute, such as a salt solution, is transported in water flow through convection and dispersion mechanisms. The transportation process is affected by many factors, such as flow velocity, sediment concentration, flow discharge and water quality. To effectively quantify the transportation process, the following assumptions were made:

a) The flow is a one-dimensional (1D) and steady flow, and it is not influenced by infiltration or raindrops.
b) The time for injection of solute is short and can be treated as an electrolyte pulse input. The transportation of a solute in a steady state water flow is well quantified and defined by a partial differential equation (PDE).

According to the Fick's law, mass conservation law and assumptions outlined above, the convectional and dispersion processes of salt (chemical) in a steady and uniform water flow can be given by partial differential equation for the one-D solute transport as:

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} = \frac{\partial}{\partial x}\left(D_H \frac{\partial C}{\partial x}\right) \tag{1}$$

where C is the electrolyte concentration[kg m^{-3}], a function of distance x and time t, proportional to the electrical conductivity; u is the flow velocity[m s^{-1}]; x is the coordinate along the slope[m]; D_H is the hydrodynamic dispersion coefficient [m^2 s^{-1}]; and t is the time[s].

When the upper boundary condition is assumed to be a pulse, the lower boundary condition and initial condition for Eq. (1) are given as:

$$C(x, t) = \begin{cases} C_0\delta(t) & x = 0 \\ 0 & x = \infty \\ 0 & t = 0 \end{cases} \tag{2}$$

The solution to Eq. (1) is a time-dependent function and is given by Lei et al. (2005) as:

$$C(x, t) = C_0 \frac{x}{2t\sqrt{\pi D_H t}} \exp\left(-\frac{(x-ut)^2}{4D_H t}\right) \tag{3}$$

Eq. (3) is used to fit the experimentally obtained data of the solute transport process based on the least square method (Lei et al., 2005) to determine the parameters in Eq. (3), including the initial concentration (C_0), flow velocity (u) and hydrodynamic dispersion coefficient (D_H).

2.2. The measurement system

The experimental equipment system included a water-supply system, a flow velocity measurement system, a bucket, a buffering pit and an experimental flume with adjustable slope gradients from 0° to 35° (Fig. 1). The water-supply system consisted of a water pump and a water supply pipe, which was used to supply steady water flow into the buffering pit to ensure the water flow evenly distributed within the flume cross section. The experimental flume was 12 m long, 0.1 m wide

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