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Measuring flow velocity under straw mulch using the improved electrolyte tracer method

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SUMMARY

Most conventional methods cannot measure flow velocities under a canopy without disturbing it. Use of mulch that reduces runoff and soil losses is a common land management practice. It is useful to study flow velocity beneath the mulch canopy to understand the processes involved. An improved method to measure flow velocity that uses an electrolyte tracer was proposed by Lei et al. (2010, J. Hydrology 390, 45–56). This study was designed to illustrate the application of that method by measuring flow velocity under wheat straw mulch. Tap water at flow rates of 2, 4 or 8 L min^{-1} entered the upper end of flumes (1 m long, 0.25 m wide) set at three slope gradients (5°, 10° or 15°), which contained soil with or without a mulch cover (0.4 kg m^{-2}). Flow velocity was measured at three different distances from the electrolyte injector. The results obtained were qualitatively as expected. In all cases, the mean flow velocity was significantly lower under the mulch than over the bare soil. The flow velocity over the bare soil was found to be on average 23% higher than that under the mulch regardless of the slope gradient or the flow rate. However, flow velocity was significantly affected by the slope gradient and flow rate. The diameter of the sensors (about 4 mm) meant that flow velocity could be measured with minimal disturbance of the mulch, thereby reducing edge effects that can affect the water flow. Therefore, the improved electrolyte tracer method was found to be suitable for conditions where overland flow cannot be observed directly. Thus, the method can be applied in the field to study flow velocity distributions under canopies.

1. Introduction

Flow velocity is an important parameter in the study of overland flow and soil erosion. The mean flow velocity of shallow overland flow is important in soil erosion modeling since it is directly related to soil detachment and the sediment carrying capacity of the water flow, and determines the fates of sediments and pollutants. Flow velocity is also related to flow discharge, slope gradient, topography, and surface conditions (Lei et al., 2010; Zhang et al., 2003).

The measurement of shallow water flow often involves the use of a tracer. Tracers used have included dyes (Abrahams et al., 1986; Zhang et al., 2010), salts (electrolytes) (Lei et al., 2005; Planchon et al., 2005), magnetic materials (Ventura et al., 2001), natural water isotopes (Berman et al., 2009), radioisotopes (Gardner and Dunn, 1964), and floating objects (Tauro et al., 2010, 2012). Most of these methods necessarily involve the use of instrumentation to detect the tracer movement. Since reducing human error is desirable, even the movement of dyes and floating objects may be detected by instruments rather than by direct observation. Fluorometers can detect dyes (Gilley and Finkner, 1991) while optical tachometers (Dunkerley, 2003) and automatic imaging systems (Tauro et al., 2012) can track floating objects. Other methods have used hot film anemometers (Robinson and Cook, 1998), miniaturized acoustic Doppler velocimeters (Giménez et al., 2004), particle imaging velocimeters (Hyun et al., 2003), etc. Electrical conductivity sensors (Lei et al., 2005; Planchon et al., 2005) or ion-selective electrodes (Barros and Colello, 2001) detect the movement of electrolyte tracers.

Many of these methods require unobstructed access to the overland flow and a flow path that is clear of obstructions. For example, the use of dyes as tracers generally requires visual observation so that a material that covers the overland flow, such as a plant canopy or mulch, must be removed at the point of observation. Such disturbance may induce an edge effect that affects the flow velocity. When physical barriers such as plant stems are

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present, floating objects used as tracers may be obstructed leading to errors in flow velocity determinations. Other limitations involved with alterative methods mean that the use of dyes or electrolyte tracers is often the only practical means with which to measure flow velocity (Planchon et al., 2005).

Both Planchon et al. (2005) and Lei et al. (2005) described the use of electrolyte tracers to determine shallow water flow velocity. Lei et al. (2010) described an improved electrolyte tracer method based on the mathematical solution of solute transport in water flow under actual measured boundary conditions. The method accurately determines shallow water flow velocity by detecting the electrolyte boundary injected into the flow path as it passes a sensor at a known distance from the input signal. The mathematical solution determines the process of the solute transport. The transport processes at the measurement position are fitted with the mathematical solution to get the flow velocity. Since the sensors are thin (<4 mm in diameter), they can be inserted through plant or mulch covers, for example, thereby greatly reducing the need to disturb the cover, although this is still an invasive procedure (Planchon et al., 2005).

Flow velocities are reduced by the presence of mulch as compared with the bare soil situation (Foster and Meyer, 1975). More tortuous flow paths beneath mulch result in a more complex pattern in the way eroded sediment is detached, transported or deposited, which affects the fate of the sediment itself and of potential pollutants carried with it. The importance of the use of mulch in reducing soil and water losses means that overland flow beneath the mulch canopy should be studied in more detail to more fully understand the processes that are occurring.

Therefore, in this study, Lei et al.'s (2010) method is used to: (1) demonstrate the effectiveness of the method in measuring flow velocity under a mulch cover; (2) determine and compare actual flow velocity values for various conditions with and without mulch; and (3) analyze the influences of slope gradient and flow rate on flow velocity.

2. The methodology

The improved electrolyte tracer method of Lei et al. (2010) uses a partial differential equation (PDE) for solute transport in a steady state water flow, formulated as a convective–dispersion process, with specified initial and boundary conditions. A sensor positioned about 5 cm from the electrolyte injection enables the practical boundary condition to be determined rather than by using an assumed pulse boundary function. Using the least squares method, either a normal or a sine model can be used to fit the measured boundary condition in order to obtain the parameters required for the boundary condition determination. The solute transport process, as measured by sensors other than the one used for the boundary determination, can be described by fitting the convective–dispersion process mathematical solution to the experimental data.

The analytical solution to the governing differential equation for the one-D solute transport under a pulse boundary condition is given as:

$$C(x,t) = C_o \frac{x}{2t\sqrt{\pi D_H t}} \exp\left(-\frac{(x-ut)^2}{4D_H t}\right) \quad (1)$$

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

The practically measured boundary may be fitted by either a Sine function, given by:

$$f(t) = \begin{cases} A\sin\left(\frac{2\pi t}{B} + D\right) & \left(1-\frac{D}{2\pi}\right)B \leqslant t \leqslant \left(\frac{3}{2}-\frac{D}{2\pi}\right)B \\ 0 & \text{Other} \end{cases} \quad (2a)$$

or a Normal Distribution function:

$$f(t) = \begin{cases} A\exp\left[-\frac{(t-D)^2}{2B^2}\right] & t \geqslant 0 \\ 0 & \text{Other} \end{cases} \quad (2b)$$

where $f(t)$ is the actual boundary function; and A, B, and D are constants used to specify the boundary conditions by the fitting procedure.

The solution to the PDE under a boundary condition other than a pulse function is given by Lei et al. (2010) as:

$$C_1(x,t) = \int_0^t C(x,t-\tau)A\sin\left(\frac{2\pi\tau}{B} + D\right)d\tau \quad (3)$$

or

$$C_1(x,t) = \int_0^t C(x,t-\tau)A\exp\left[-\frac{(\tau-D)^2}{2B^2}\right]d\tau \quad (4)$$

where C_1 is the solution function under the impact of the actual boundary condition; C is the response of the system to the pulse input function; and τ is time, s.

This is the analytical solution for the solute transport process in water flow, which quantifies the transient transport of solutes in the flowing water. Whereas Eq. (1) is the solution for an upper boundary condition of a pulse function, Eqs. (3) and (4) are the solutions under an upper boundary condition that is not a pulse but rather is a measured function of a Sine and Normal Distribution, respectively.

To obtain solutions to either Eq. (3) or Eq. (4), the boundary conditions as specified by either Eq. (2a) or Eq. (2b), respectively, need to be estimated by fitting the latter equations to the measured boundary data. Then, Eq. (3) or Eq. (4) is fitted to the data measured by sensors other than that used for the boundary condition determination to estimate the other three important parameters in Eq. (3) or Eq. (4), i.e. C_0, u, and D_H. See Lei et al. (2010) for full details.

3. Experimental materials and methods

The experiments were carried out in a flume (1 m long, 0. 25 m wide, 0.25 m deep) (Fig. 1). Flow velocity was measured over a bare soil surface under two different mulch cover rates (0 and

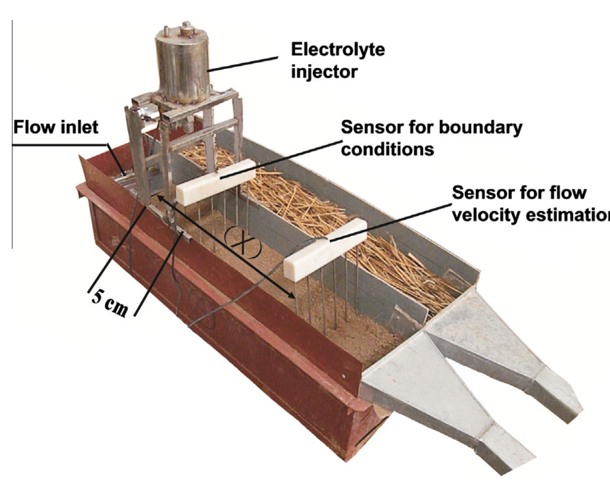

Fig. 1. Experimental equipment system used to measure flow velocity by the electrolyte tracer method.