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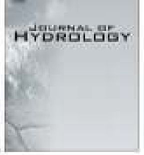

Measuring flow velocity under straw mulch using the improved electrolyte tracer method

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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:

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

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

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

or a Normal Distribution function:

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

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:

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

or

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

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_o, 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

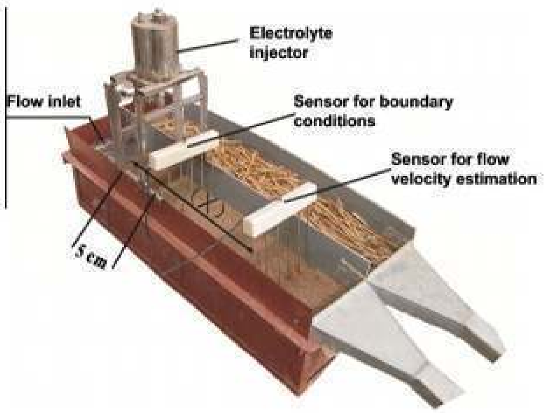

Fig. 1. Experimental equipment system used to measure flow velocity by the

0.4 kg m^{-2}) for three discharge rates (2, 4, and 8 L min^{-1}) and three slope gradients (5°, 10°, and 15°). For each experimental run, a clay loam soil was uniformly packed into the flume to give a bulk density of 1400 kg m^{-3}. Tap water was used to generate overland flow at constant discharge rates. The mulch was wheat straw cut to lengths of less than 30 cm. A computer installed with specially designed software (Lei et al., 2010) controlled the delivery of an electrolyte solute instantaneously via an injector and logged data produced by electrical conductivity sensors. The injector was positioned 50 cm from the top of the flume, to allow the establishment of steady flow for the solute. The sensor used to determine the boundary conditions was inserted into the soil 5 cm downslope of the injector. The second sensor was used to measure the flow velocity at three different locations (15, 25 and 40 cm) downslope from the injector in that sequence (see Fig. 2 for an example of the output fitted by Eqs. (3) and (4)).

Each experiment was carried out in the same timed, set sequence to mitigate the effects of infiltration rate changes and of scouring, which occurred around the sensors, on the flow velocity (Planchon et al., 2005). The regulated water flow was first stabilized (within 1 L min^{-1} fluctuation) outside of the flume and was then directed into the flume at the upper end. The overland flow was allowed to reach the end of the flume and a further 45 s passed before the first injection of 6 mL of a saturated electrolyte solution of KCl. It was assumed that changes in infiltration would be relatively small once the upper soil layer was saturated, which was achieved by this procedure. Data from the upper (5 cm) and lower (40 cm) sensors were recorded. Two more measurements were made for electrolyte solute injections made at intervals of 1 min. The lower sensor was then moved upslope to the next position (25 cm) and the sequence of measurements was repeated; and this was repeated again for the final lower sensor position (15 cm). Each experimental run was repeated three times for each set of flow rate, slope gradient and mulch rate conditions.

The data were fitted by the models presented in Section 2 and the derived flow velocity data was tested for normality before being analyzed using one-way ANOVA. Means were separated using a post hoc least significant difference test with a probability level of 0.05.

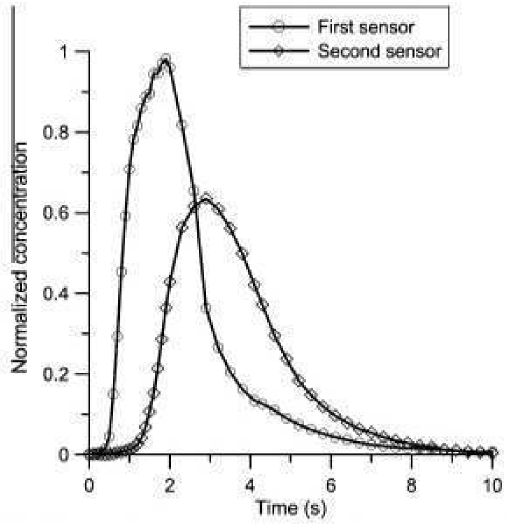

Fig. 2. Example of output signal curves from an actual experiment where the first sensor is used to determine the boundary conditions and the second sensor is used

4. Results and discussion

Values of the flow velocities for overland flow, determined at three slope positions for different hydraulic conditions produced by three slope gradients and three flow rates, over a soil surface with and without mulch are presented in Tables 1 and 2, respectively. The flow velocity data were normally distributed (kurtosis = −0.812, skewness value = 0.392). The results of the one-way ANOVA of the flow velocities under the various conditions and their interactions are presented in Table 3.

Flow velocity was significantly affected by the mulch cover rate, slope gradient, flow rate and the distance between the sensors and the injector, as well as by all of their interactions with the exception of the treatment ∗ flow rate ∗ distance interaction. Flow velocity significantly increased with increases in slope gradient ($P < 0.05$), due to the increases in the gravitational force component acting parallel to the soil surface. As expected, flow velocity also significantly increased with increases in the flow rate. For any given set of conditions and slope position, the flow velocity was higher without mulch than with mulch (Fig. 3). A linear relationship ($y = 1.23x$) was found between the flow velocities determined without mulch cover and those under a mulch with a coefficient of determination (R^2) of 0.998. These results agree qualitatively with those of earlier studies (Foster and Meyer, 1975).

The behavior of flow velocity with distance was complex (Tables 1 and 2). Some conditions resulted in increases in flow velocity as the distance from the injector increased, which generally occurred when the flow rate was 2 L min^{-1} on the steeper slopes (10° and 15°). Decreases in flow velocity with increasing distance tended to occur on the gentlest slope (5°) under the lower flow rates (2 and 4 L min^{-1}). When the flow rate was high (4 and 8 L min^{-1}) and the slope was steeper (10° and 15°), the behavior of the flow velocity with increasing distance tended to either increase and then decrease or to be constant. These differences may result from the acceleration of the flow due to gravity being dominant in the first case; deceleration due to frictional forces being dominant in the second case; and the changing balance between the two in the third case. The presence of mulch tended to result in the third case scenario occurring more often than it did for the bare soil (in seven as opposed to five of the nine treatment conditions) and in only one case each was the flow velocity increased (15°, 2 L min^{-1}) or decreased (5°, 2 L min^{-1}). It should be noted that the experimental design might have influenced these relationships to some degree since the time of measurement was directly related to the distance from the injector.

Table 1
Flow velocities estimated for shallow water flow over bare soil (m s^{-1}).

Q^a (L min^{-1})	X (m)		
	0.15	0.25	0.4
$S = 5°$			
2	0.152 (0.001)^b	0.143 (0.004)	0.138 (0.001)
4	0.236 (0.004)	0.221 (0.006)	0.219 (0.002)
8	0.359 (0.003)	0.367 (0.002)	0.356 (0.001)
$S = 10°$			
2	0.173 (0.005)	0.188 (0.005)	0.193 (0.006)
4	0.284 (0.058)	0.295 (0.000)	0.282 (0.000)
8	0.431 (0.004)	0.439 (0.0037)	0.428 (0.000)
$S = 15°$			
2	0.201 (0.005)	0.216 (0.006)	0. 235 (0.000)
4	0.302 (0.006)	0.318 (0.000)	0.307 (0.001)
8	0.456 (0.006)	0.464 (0.000)	0.453 (0.000)

[a] Q is the input flow rate; S is the slope gradient; X is the distance between the

Q[a] (L min^{-1})	X (m) 0.15	0.25	0.4
S = 5°			
2	0.120 (0.000)[b]	0.112 (0.001)	0.103 (0.0017)
4	0.186 (0.001)	0.191 (0.001)	0.179 (0.001)
8	0.288 (0.001)	0.291 (0.001)	0.289 (0.001)
S = 10°			
2	0.145 (0.001)	0.156 (0.009)	0.154 (0.001)
4	0.244 (0.001)	0.254 (0.001)	0.232 (0.006)
8	0.335 (0.001)	0.346 (0.001)	0.322 (0.0066)
S = 15°			
2	0.168 (0.004)	0.179 (0.005)	0. 182 (0.003)
4	0.258 (0.004)	0.263 (0.003)	0.247 (0.007)
8	0.391 (0.006)	0.395 (0.009)	0.378 (0.007)

[a] Q is the input flow rate; S is the slope gradient; X is the distance between the electrolyte injector and the sensors.

[b] Mean values are followed by standard deviations in parentheses.

Knowing the flow velocity allows an approximate flow depth to be determined, which can have important applications. Assuming flow occurred over the entire area of the flume and that there was no infiltration, the flow depth would be approximately equal to the flow rate divided by the product of the flow velocity and the width of the flume. In this study, this maximum potential depth ranged from 0.15 to 1.5 mm (data not shown) for the bare soil case. In this range, which is less than the maximum diameter of a raindrop (4 mm), the force of raindrop impacts would be increasingly diminished, reducing their capacity to breakdown and compact aggregates on the soil surface, while detachment due to raindrop splash would consistently increase (Ferreira and Singer, 1985). The maximum potential depth ranged from 0.73 to 1.9 mm under the mulch. In this range a blade of straw having a typical diameter of 4 mm, laying directly on the soil surface, would effectively dam and divert the flow path leading to potential flow concentrations under the mulch. Infiltration does in fact occur in this study and the flow depths would therefore have been shallower, although it can be reasonably assumed that at a given time the infiltration rate would be approximately the same for all treatment conditions.

Since flow paths could be more tortuous under the mulch due to flow concentration, it was hypothesized that the spatial distribution of the measured flow velocities under mulch would demonstrate higher degrees of variability than those for the bare soil. Accordingly, the coefficient of variation values were tested for the two treatments. However, no significant differences were detected. It is likely this was due to the small area enclosed by the flumes and the hypothesis should be tested either in larger flumes or in the field.

Table 3
One-way analysis of variance of the flow velocity data measured under various conditions of mulch cover, slope gradient, flow rate, and distance from the electrolyte injector.

Sources	DF[a]	Sum of squares	F-value	Significance
Mulch	1	0.133	11588.773	0.000
Slope	2	0.170	7432.463	0.000
Flow rate	2	1.228	53548.773	0.000
Distance	2	0.002	78.088	0.000
Mulch * slope	2	0.001	32.747	0.000
Mulch * flow rate	2	0.014	614.734	0.000
Mulch * distance	2	0.000	20.446	0.000
Slope * flow rate	4	0.005	113.946	0.000
Slope * distance	4	0.001	11588.757	0.000
Distance * flow rate	4	0.002	40.959	0.000
Mulch * slope * flow rate	4	0.002	39.412	0.000
Mulch * slope * distance	4	0.000	10.143	0.000
Mulch * distance * flow rate	4	68.25	1.488	0.211
Slope * distance * flow rate	8	0.002	22.577	0.000
Mulch * slope * distance * flow rate	8	0.000	5.122	0.000

[a] DF, degrees of freedom.

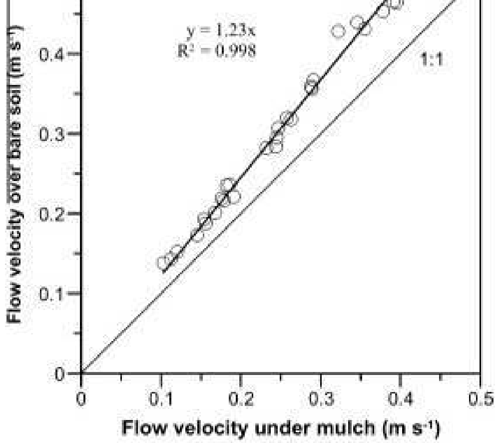

Fig. 3. Comparison of the flow velocities determined over bare soil and under mulch (0.1 kg m^{-2}) for the same conditions of slope gradient, input flow rate and distance from the electrolyte injector.

The equipment used in the improved electrolyte tracer method of Lei et al. (2010) is user friendly, easy to operate and is portable so that it can be used in the field. Multiple measurements can be made in short periods of time. The disadvantage of most flow velocity measurement methods is the invasive nature of the sensors required to detect the tracers or to sample the flow (Planchon et al., 2005). The sensors used in this study resulted in scouring, which would have affected the flow paths downstream of them in the narrow flume. This dictated one aspect of the experimental design, namely the decision to use only one set of sensors that would always be moved upstream when making measurements. The system is capable of using multiple sensors in practice. The set of sensors used to measure the actual boundary conditions also caused scouring and there was little that could be done to prevent this in this study. However, the further development of this methodology, where a virtual boundary condition is used, now removes the need for those sensors (Shi et al., 2012). In this study, the thinness of the sensors allowed them to be inserted between the straws to make measurements with minimal disturbance of the mulch thereby reducing edge effects.

5. Conclusion

This study was undertaken to demonstrate the applicability of the improved electrolyte tracer method of Lei et al. (2010) to measure shallow water flow velocity under a mulch canopy. The experiments were carried out in a laboratory flume and examined the effects of three flow rates and three slope gradients on the determined flow velocities of overland flow over a bare soil surface and under a mulch cover of 0.4 kg m^{-2}. As expected, flow velocities increased with the flow rate and with slope gradient. Mulch reduced flow velocities by a factor of 0.81 on average as compared with the flow over bare soil for any given set of experimental conditions. The results suggested that the improved electrolyte tracer method for the determination of shallow water flow velocity was reasonable. Although invasive, the insertion of the sensors through the mulch canopy caused little disturbance of the mulch cover, although scouring of the soil surface around them did occur. The method is ideal for the study of shallow flow under canopies of plants and mulches in the field.

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