

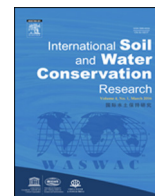
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Original Research Article

Determination and impact factor analysis of hydrodynamic dispersion coefficient within a gravel layer using an electrolyte tracer method

Xiaonan Shi^{a,b,*}, Tingwu Lei^c, Yan Yan^d, Fan Zhang^b^a State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Water and Soil Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, 712100 Shaanxi, PR China^b Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, PR China^c College of Water Resources and Civil Engineering, China Agricultural University, Beijing 100083, PR China^d HydroChina Kunming Engineering Corporation, LTD, Kunming 650000, Yunnan, PR China

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ABSTRACT

Hydrodynamic dispersion is a measure for describing the process of solute transport in porous media. Characterizing the dispersion of water flow within gravel is essential for the prediction of solute transport especially nonpoint source pollutants migration in alpine watersheds where the land surface is typically covered with gravel. In this study, an integrated model and experimental method using an electrolyte tracer is proposed for determination of the hydrodynamic dispersion coefficient. Two experimental scenarios were designed to measure electrolyte tracer transport processes in both free water flow and gravel layer flow under different slope gradients and transport distances. Subsequently, the measured data were used to simultaneously calculate both the hydrodynamic dispersion coefficient and flow velocity by fitting the experimental data with the mathematical model. Dispersivity, as a critical feature of hydrodynamic dispersion, was determined as well under the two specified scenarios. Finally, the impact mechanisms of the gravel layer and factors related to the dispersion processes were comprehensively analyzed. The results indicate that the presence of a gravel layer significantly reduces flow velocity and the hydrodynamic dispersion coefficient, but increases solute dispersivity. For the flow within gravel layers, with much lower velocity, the positive effect of the gravel layer on dispersivity may be neutralized or even surpassed by the negative effect of flow velocity. The results should be helpful in characterizing the dispersion processes of water flow within gravel layer and hence in predicting solute transport, especially in nonpoint source pollutants migration in alpine watersheds where the land surface is richly covered with gravel.

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1. Introduction

Hydrodynamic dispersion is a measure for describing the mixing processes of solutes in porous media/aquifers. The dispersion coefficient is dependent on the flow rate and the dispersivity factor, which can be determined by the structure and the texture of the medium. Theoretically, there are both molecular and mechanical dispersion functions in solute transfer processes, but it is difficult to distinguish them, so the hydrodynamic dispersion coefficient is the sum of the molecular diffusion coefficient and mechanical dispersion coefficient. The molecular diffusivity is

correlated with the diffusion coefficient of the solute in water and the tortuosity factor of the medium. This component is negligible under two conditions. One is when the flow rate is quite high and the effect of the mechanical dispersion greatly exceeds that of the molecular diffusion. The other one is when the molecular diffusivity is small enough to be neglected for many non-aggregated media with very small intraparticle porosities such as sandy/gravel flow or aquifer materials. Under these conditions, only the mechanical dispersion needs to be considered in hydrodynamic dispersion as a function of mechanical dispersivity and average flow velocity. A great deal of research spanning many decades has

* Corresponding author at: Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, PR China.

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E-mail address: shixiaonan@itpcas.ac.cn (X. Shi).

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Nomenclature

C	Electrolyte concentration (M L^{-3})
C_0	Integral of electrolyte concentration with time (M L^{-3})
D_H	Hydrodynamic dispersion coefficient ($\text{L}^2 \text{T}^{-1}$)
D_0	Diffusion coefficient of solute in water ($\text{L}^2 \text{T}^{-1}$)

T	Time (T)
u	Flow velocity (L T^{-1})
x	Transport distance (L)
τ	Tortuosity factor
α	Dispersivity factor (L)

focused on the hydrodynamic dispersion in soil or aquifer materials, and the research has covered numerous aspects involving theoretical (Gelhar, Welty, & Rehfeldt, 1992; Jaiswal, Kumar, Kumar, & Singh, 2011; Smiles, Gardner, & Schulz, 1995), experimental (Bond, 1986; Chou, Wu, Zeng, & Chang, 2012; Gandolfi, Facchi, & Whelan, 2001; Lafolie, Hayot, & Schweich, 1997), and modeling approaches (Auset & Keller, 2004; Deng & Jung, 2009; Haga, Nii-bori, & Chida, 1999; Nützmänn, Maciejewski, & Joswig, 2002; Wilson & Gelhar, 1981). However, for water flow within a gravel layer, a typical land surface type, studies on the hydrodynamic dispersion coefficient are relatively scarce (Conca & Wright, 1990; Lei, Yan, & Shi, 2013). Characterizing the dispersion in gravel flow is of great interest for the prediction of solute transport and nonpoint source pollution, especially in alpine watersheds where the land surface is richly covered with gravel (Geissen, Mol, & Klumpp, 2015; Peiretti & Dumanski, 2014).

In the study, two experimental scenarios for solute transport are considered, free water flow (control) and gravel layer flow, to comparatively understand the impacts of a gravel layer on the dispersion processes. A new method using an electrolyte tracer was introduced to obtain the hydrodynamic dispersion coefficient and flow velocity. The impact mechanisms of the gravel layer on the dispersion processes were comprehensively analyzed by focusing on the responses of separate independent or dependent variables involved.

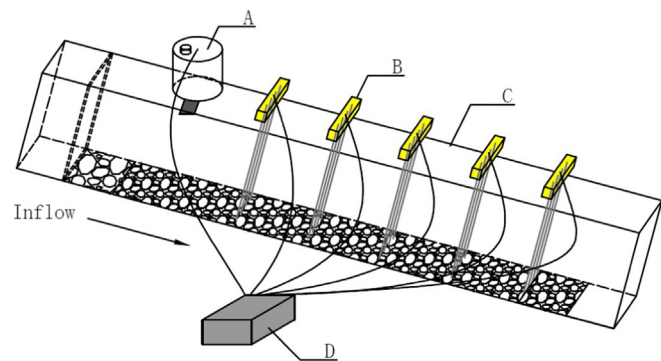


Fig. 1. The experimental equipment system: A is electrolyte injector; B is electric conductivity sensor; C is water flume; D is data logger and auto-controller of electrolyte injection; a water-supply tank with 1 m^3 volume is not shown in the figure.

Table 1
Descriptive statistical result of dispersion factors and flow velocity.

	Mean	N	Std. deviation
$D_{H_control}$ ($\text{m}^2 \text{ s}$)	0.010	12	3.61E-3
D_{H_gravel} ($\text{m}^2 \text{ s}$)	0.002	12	9.66E-4
$u_control$ (m s^{-1})	0.441	12	5.44E-2
u_gravel (m s^{-1})	0.051	12	1.53E-2
$\alpha_control$ (m)	0.023	12	6.44E-3
α_gravel (m)	0.046	12	2.51E-2

2. Theoretical backgrounds

An integrated modeling and experimental method with an electrolyte tracer (Lei, Chuo, & Zhao, 2010; Shi, Zhang, & Lei, 2012) was employed to obtain the hydrodynamic dispersion coefficient and water flow velocity within a gravel layer. Both the hydrodynamic dispersion coefficient and water flow velocity are model parameters in the convection dispersion equation for solute transport. The integrated method is implemented by fitting the solution curve of the one-dimensional convection dispersion equation with experimentally measured electrolyte tracer transport data to derive the two parameters.

Assuming the flow in a flume is one-dimensional steady flow with constant flow velocity, the convection and dispersion processes of an electrolyte are described as:

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

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

The upper boundary condition is given as a function defining the input signal of the upstream injector, which is:

$$C(x, t) = f(t) \quad x = 0 \quad (2)$$

The lower boundary condition and initial condition are given respectively as:

$$C(x, t) = 0 \quad x = \infty \quad (3)$$

$$C(x, t) = 0 \quad t = 0 \quad (4)$$

Substituting the boundary conditions (Eqs. (2) and (3)) and initial condition (Eq. (4)) into the convection and dispersion equation (Eq. (1)), the solution is obtained as follows:

$$C(x, t)/C_0 = \int_0^t \frac{x}{2\tau\sqrt{\pi D_H \tau}} \exp\left(-\frac{(x-u\tau)^2}{4D_H \tau}\right) f(t-\tau) d\tau \quad (5)$$

where C_0 is the integral of the observed electrolyte transport curve with time, as $\int_0^\infty C(x, t) dt$, to normalize the observed electrolyte concentration.

Moreover, the hydrodynamic dispersion coefficient D_H is usually defined as (cf. Freeze, & Cherry, 1979):

$$D_H = D_0/\tau + \alpha u \quad (6)$$

where D_0 is the diffusion coefficient of the solute in water ($\text{L}^2 \text{T}^{-1}$), τ is the tortuosity factor (greater than 1), and α is the dispersivity factor (L). As discussed above, the contribution of diffusion (first term on the right-hand side of Eq. (6)) is usually negligible in gravel flow (cf. Klotz, Seiler, Moser, & Neumaier, 1980; Roberts, Reinhard, Hopkins, & Summers, 1985), and Eq. (6) is reduced to:

$$D_H = \alpha u \quad (7)$$

The parameters u and D_H can be derived by fitting the model

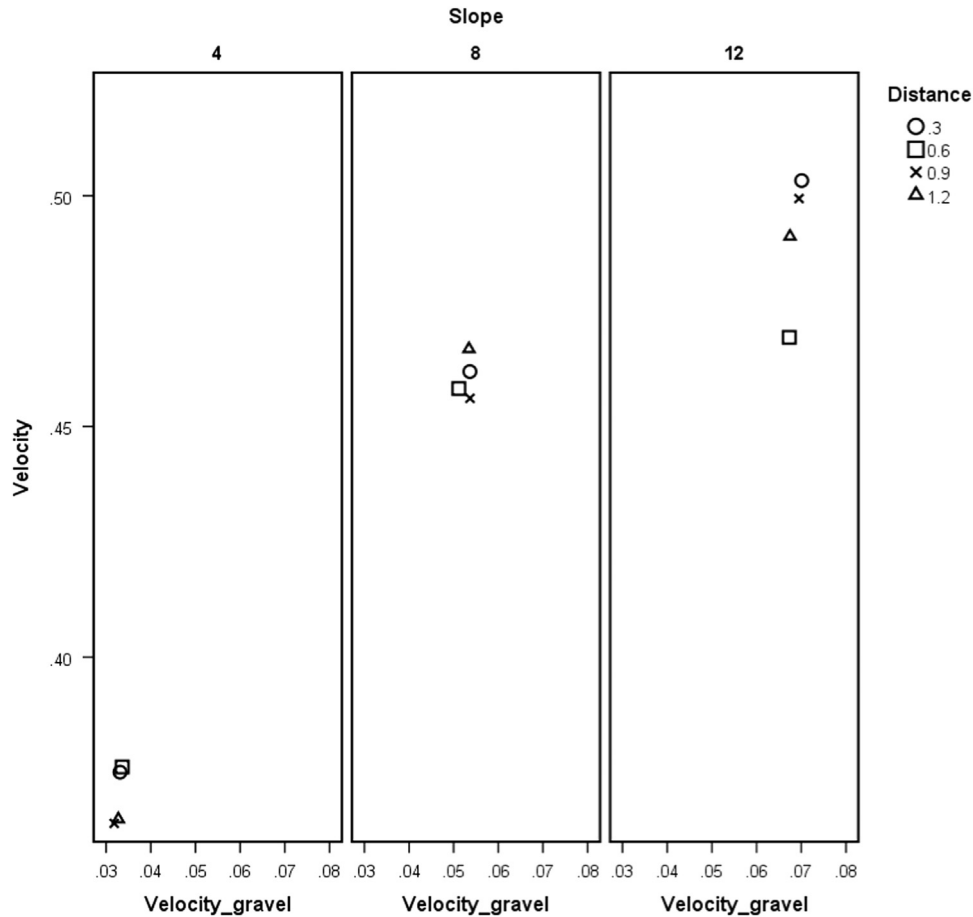


Fig. 2. Comparison of hydrodynamic dispersion coefficients ($\text{m}^2 \text{s}^{-1}$) in gravel flow and free water flow.

solution (Eq. (5)) with experimentally obtained data using the least squares method. The dispersivity can then be determined as $\alpha = D_H/u$.

3. Experimental materials and methods

Sets of experiments were conducted to evaluate the impact of gravel layer flow on the hydrodynamic dispersion coefficient by comparison with a control of free water flow. The experimental system was designed to capture the electrolyte tracer transport process in water flow (see Fig. 1). The experiment flume is 4 m length by 15 cm width by 50 cm height, in which the electrolyte is transported. For the scenario of gravel layer flow, the bottom of the flume was filled with uniformly-mixed gravels with two types of diameters (2 cm and 4 cm) to a depth of 5 cm. A group of sensors for electric conductivity (EC) measurements were set up along the downstream of the flume at different distances from the injection point. When a set of experiments started, water flow from a water-supply tank was introduced into the flume from the upper end. Once the thin layer flow (< 5 cm depth) was stabilized, the computer initiated the salt solute injector to release highly saturated KCl solution into the water flow at the upper end of the flume and carried out data logging to register electrolyte concentrations through EC sensors. The experiments involved 12 combinations with 1 discharge (12 L min^{-1}), 3 slope gradients (4° , 8° , 12°), and 4 distances (0.3, 0.6, 0.9, and 1.2 m) individually under the flow condition in free water and within the gravel layer.

4. Results and discussions

The features of hydrodynamic dispersion, flow velocity and dispersivity were compared individually under the conditions of water flow and gravel layer flow.

Table 1 lists the basic statistical descriptions of the hydrodynamic dispersion coefficient, flow velocity, and dispersivity obtained under the two scenarios respectively.

On average, the hydrodynamic dispersion coefficient in water flow ($0.010 \text{ m}^2 \text{ s}^{-1}$) is nearly five times the value in gravel layer flow ($0.002 \text{ m}^2 \text{ s}^{-1}$). On one hand, the velocity in water flow (0.441 m s^{-1}) is far higher than the flow velocity within the gravel layer (0.051 m s^{-1}), illustrating that the gravel layer significantly decreases flow velocity. On the other hand, the dispersivity of solute transport in gravel flow (0.046 m) is higher than that in the water flow (0.023 m), indicating that the flow state within porous media is more turbulent compared with free water.

The hydrodynamic dispersion coefficients in gravel layer flow ($D_{H\text{-gravel}}$) are compared with the control values in free water flow ($D_{H\text{-control}}$) under different slope gradient and transport distance conditions (see Fig. 2).

As shown in Fig. 2, the $D_{H\text{-control}}$ values are higher than $D_{H\text{-gravel}}$ values under all the experimental conditions, which is consistent with the above conclusion deduced from the average values. The impact of distance seems not significant. As for the three slope gradients, the highest $D_{H\text{-control}}$ value occurs at 8° slope gradient and the lowest value appears at 4° for both experimental conditions. Subsequently, the responses of flow velocity and dispersivity factor to slope gradient were studied respectively to understand their contribution to the hydrodynamic dispersion coefficient.

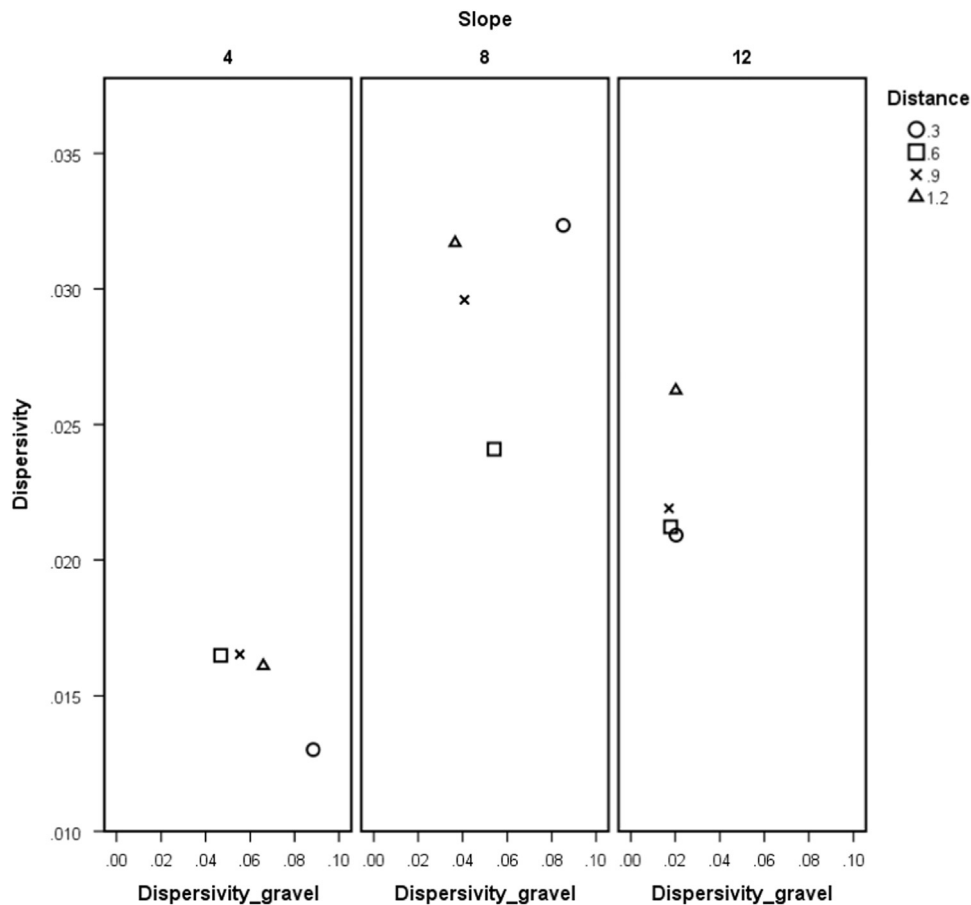


Fig. 3. Comparison of velocity values (m s^{-1}) in gravel flow and free water flow.

Fig. 3 compares the velocity values in gravel flow and in free water surface flow under the impact of slope gradient and transport distance. The velocities in water flow are larger than those within the gravel layer under all experimental treatments. As the slope gradient increases from 4° , 8° , to 12° , the ratio of $u_{\text{control}}:u_{\text{gravel}}$ decreases from 11.3, 8.7, to 7.2 on average, whereas the distance shows no significant effect on the velocity values. Under the same discharge and slope conditions, the presence of the gravel layer greatly lowered the flow velocity.

The dispersivity under the two flow conditions is compared in Fig. 4. The dispersivity values for both gravel flow and free water flow under different slope gradient and transport distance conditions first increase with slope gradient from 4° to 8° and then decrease at the 12° slope. This is consistent with the response of the hydrodynamic dispersion coefficient to the slope, which illustrates the fact that variation of dispersivity can be partly attributed to the hydrodynamic dispersion coefficient, and the flow velocity is not the only factor. Both the flow velocity and the dispersivity variables reflect the complex mechanism of hydrodynamic dispersion response to given impact factors.

In general, the gravel layer plays a role in increasing solute dispersivity. This is true at the 4° and 8° slope where the ratios of α_{gravel} to α_{control} are 4.3 and 1.9 on average. When the slope gradient rises to 12° , the dispersivity factors in free water flow are slightly higher than in the gravel layer. A related study by Brusseau (1993) has reported that dispersivity will decrease to a constant value as water velocity increases for non-aggregated media at a macroscopic level. Therefore, the relationship between dispersivity and velocity is plotted in Fig. 5 by coupling the data of the control and the gravel treatment. As shown in Fig. 5, as gravel flow velocity increases, the values of dispersivity decrease quickly at

lower velocity and remain at a relatively constant value as velocity ranges from 0.07 to 0.55 m s^{-1} . The result is consistent with Brusseau's conclusions. It is also rational that the dispersivity is almost invariant with velocity for a large interval of water flow velocity, ranging from 4.2 m to 33 m per minute. As for the lower velocity under gravel flow conditions, the variation of dispersivity with velocity may be attributed to the effect of axial diffusion. This explanation has been verified in Brusseau's study (1993) for sandy material conditions. Meanwhile, the result could also explain the phenomenon that the gravel layer 'fails to' increase the dispersivity at 12° slope. The effect of flow velocity decrease on the dispersivity may neutralize or even surpass the effect of the dispersivity increase introduced by the gravel layer.

5. Conclusions

The hydrodynamic dispersion coefficient is an important variable in the description of solute transport processes in porous material. In this study, an electrolyte tracer method was effectively employed to obtain the hydrodynamic dispersion coefficient in gravel flow. The impact of the gravel layer on the dispersion coefficient and related variables (flow velocity and dispersivity) were studied by comparing with the results for free water flow as control. The results indicate that the presence of a gravel layer greatly decreased flow velocity as well as the dispersion function of the solute in the study case. As the slope gradients varied from 4° , 8° , to 12° , the ratios of the velocity in water flow to the velocity in gravel decreased from 11.3, 8.7, to 7.2 on average. The hydrodynamic dispersion coefficient in water flow is on average five times the value in gravel layer flow. Flow velocity is not the only factor affecting the hydrodynamic dispersion coefficient,

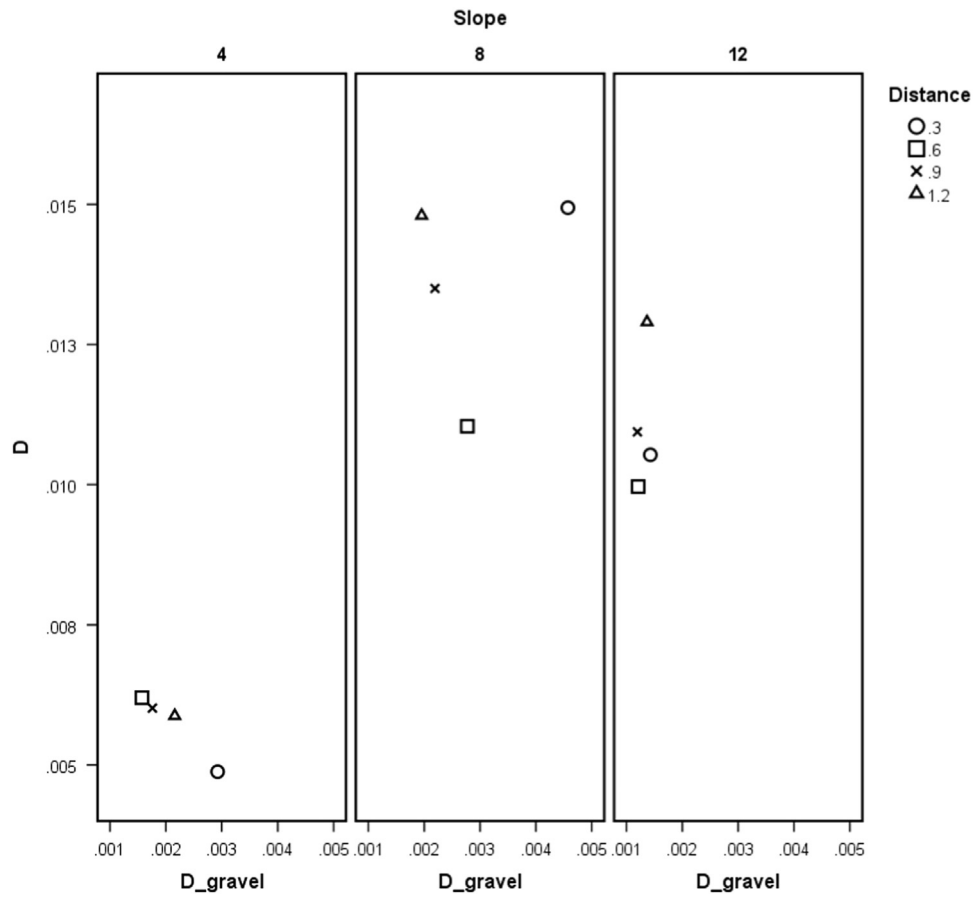


Fig. 4. Comparison of dispersivity factors (m) in gravel flow and free water flow.

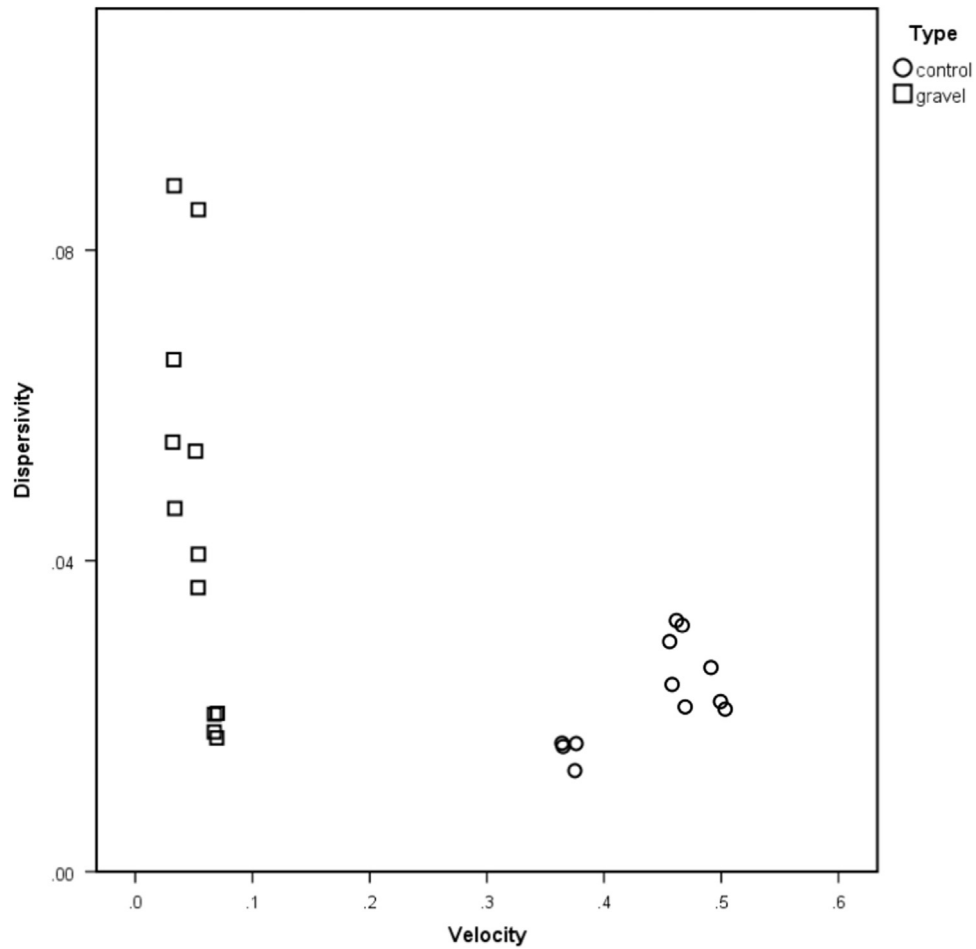


Fig. 5. The relationship between dispersivity and flow velocity under both gravel flow and free water flow conditions.

and the contribution of dispersivity cannot be ignored. The gravel layer plays a role of increasing solute dispersivity. But for gravel flow with much lower velocity, the negative effect of flow velocity on dispersivity may neutralize or even surpass the increase of dispersivity by the gravel layer.

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