

## Original Research Article

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



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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

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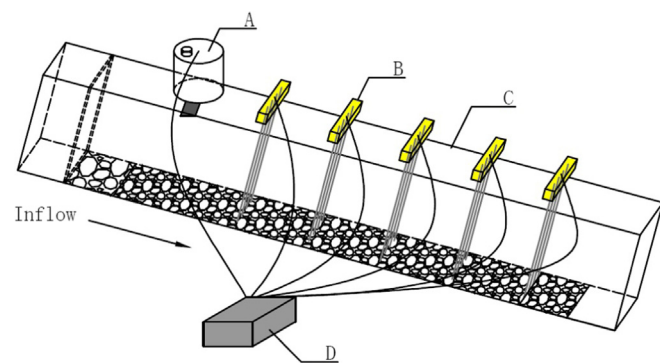
## Nomenclature

$C$	Electrolyte concentration ( $\text{M L}^{-3}$ )
$C_0$	Integral of electrolyte concentration with time ( $\text{M L}^{-3}$ )
$D_H$	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 ( $\text{L T}^{-1}$ )
$x$	Transport distance (L)
$\tau$	Tortuosity factor
$\alpha$	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; Nützmann, 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  $1 \text{ m}^3$  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
$u\_control$ ( $\text{m s}^{-1}$ )	0.441	12	5.44E-2
$u\_gravel$ ( $\text{m s}^{-1}$ )	0.051	12	1.53E-2
$\alpha\_control$ (m)	0.023	12	6.44E-3
$\alpha\_gravel$ (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  $C$  ( $\text{M L}^{-3}$ ) 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;  $u$  ( $\text{L T}^{-1}$ ) 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 ( $\text{L}^2 \text{T}^{-1}$ ),  $\tau$  is the tortuosity factor (greater than 1), and  $\alpha$  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

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