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Prediction of longitudinal dispersion coefficient in natural streams by prediction map

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Abstract

Longitudinal dispersion coefficient can be determined by experimental procedures in natural streams. Many theoretical and empirical equations that are based on hydraulic and geometric characteristics have been developed from the field experiments of longitudinal dispersion coefficient. Regression analysis, which carries some restrictive assumptions such as linearity, normality and homoscedasticity, was used to derive some of these equations. Generally speaking, results obtained from regression analyses are not that accurate as these assumptions are often not satisfied completely. In this study, a method called Prediction Map (PM) is developed based on geostatistics to predict longitudinal dispersion coefficient from measured discharge values, shear velocities, and other conventional parameters of the hydraulic variables and normalized velocity with the objective of overcoming the drawbacks indicated above. As part of this method, a new procedure called Iterative Error Training Procedure (IETP) was developed to minimize prediction error. The prediction error level was reduced after implementing the IETP. PM was compared with various regression models by taking analyzed errors (average relative error percentage and root mean square error), coefficient of efficiency, coefficient of determination and Scatter Index as performance evaluation criteria. The results of the study indicate that the PM approach can perform very well in predicting longitudinal dispersion coefficient by applying IETP. The presented approach yielded lower average relative error percentage, root mean square error and Scatter Indices, and higher coefficient of efficiency and coefficient of determination values compared to the regression models. One of the important advantages of the PM method is that valuable interpretations and a prediction map can be extracted from the resulting contour maps, and as a result, more accurate predictions can be obtained compared to regression analysis.

Keywords: Longitudinal dispersion coefficient; Optimum interpolation technique; Stream; Water pollution

1. Introduction

Monitoring of soluble pollutants is a very important issue in managing river environment. Longitudinal dispersion is a term that refers to the spreading of soluble pollutants along the longitudinal axis of a flow. This process results in changes in the mixing characteristics of the soluble pollutants. For instance, the concentration of the soluble pollutants changes from a state of high concentration and low spatial variance at upstream, to a state of lower concentration and higher spatial variance at downstream. Longitudinal dispersion coefficient is a coefficient that describes the change in the characteristics of soluble pollutants as they travel along the longitudinal axis of a flow. It relates the mass transfer inside the liquid to concentration gradients and it is important in predicting the evolution of accidental discharge of soluble pollutants to a river (Palancar et al., 2003). It is also the fundamental parameter to control water quality in natural streams as it is the primary parameter in quantifying the diffusive capacity of a steam. In addition, it has been the main parameter of the models currently used to describe longitudinal dispersion. An appropriate longitudinal dispersion coefficient is critical to the modeling of 1-D dispersion while assessing the variation of the pollutant concentration along a river. According to Zeng and Huai (2014), longitudinal dispersion coefficient is a crucial parameter for 1-D water quality analysis in natural rivers. According to Fischer (1966), lateral variations in velocity are the dominant mechanisms for dispersion in streams. Both diffusive and advective effects play a major role in the dispersion of solute down a river (Hassan, 1993). A number of researchers have tried to understand the mechanisms of longitudinal dispersion in rivers, and theoretical

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and empirical formulations have been proposed to determine the longitudinal dispersion coefficient (Ahsan, 2008). Longitudinal dispersion coefficient can be predicted by employing the physically based Fickian model. Due to the nature of flowing rivers, the prevailing velocity can be generally obtained by solving the one-dimensional (1-D) equation of motion (Kashefipour and Falconer, 2002). Taylor (1954) proposed the following 1-D Fickian-type dispersion equation.

$$A\frac{\partial C}{\partial t}+UA\frac{\partial C}{\partial X}=\frac{\partial}{\partial X}\left(K_x A\frac{\partial C}{\partial X}\right) \tag{1}$$

where A is the cross-sectional area, C is the cross-sectional average concentration, U is the cross-sectional average velocity, K_x is the longitudinal dispersion coefficient, t is time and X is the direction of mean flow. The 1-D dispersion equation is valid at locations where a balance exists between advection (left-hand side) and diffusion (right-hand side). However, Eq. (1) is valid for solute transport in impermeable channels. Fischer et al. (1979) suggested that, during the early phase of the transportation, the advective transport is dominant because of the velocity distribution. Taylor's analysis cannot be applied at the time of initial phase due to the off balance between advection and diffusion. Therefore, the 1-D dispersion equation is applicable only for the late time (Fickian) period.

Taylor (1954) first introduced a theoretical model for the determination of longitudinal dispersion coefficient and, then, Elder (1959) extended that model and proposed the equation given as follows by assuming a logarithmic velocity profile for a wide channel and uniform flow.

$$K_x = 5.93HU^* \tag{2}$$

where H is the depth of flow and U^* is the shear velocity. Elder's equation has been widely used in environmental studies because of its theoretical and simple foundation. Fischer (1966, 1968) developed the following integral relation for the determination of longitudinal dispersion coefficient in natural streams.

$$K_x = -\frac{1}{A}\int_0^W h\cdot u'\int_0^y \frac{1}{\varepsilon_t h}\int_0^y h\cdot u' dy dy dy \tag{3}$$

where h is the local flow depth, u' is the deviation of the velocity from the cross-sectional mean velocity, W is the channel width, y is the Cartesian coordinate in the lateral direction and $\mathcal{E}_t$ is the local transverse turbulent diffusion coefficient. A simplified version of the above equation was proposed by Fischer (1975) and is given as follows.

$$K_x = 0.011\frac{U^2W^2}{HU^*} \tag{4}$$

According to Eq. (4), the longitudinal dispersion coefficient can be determined by using only cross-sectional variables. However, Fischer et al. (1979) stated that Eq. (2) does not reflect the real conditions in natural streams. Many researchers have proposed numerous empirical and semi-empirical equations meant for determining longitudinal dispersion coefficient (Abd El-Hadi and Daver, 1976; Iwasa and Aya, 1991; Liu, 1977; Magazine et al., 1988; McQuivey and Keefer, 1976; Sooky, 1969).

Seo and Cheong (1998) derived a new longitudinal dispersion coefficient equation using the one-step Huber method, which is one of the nonlinear multi-regression methods. They presented the following equation and compared the new equation with other existing equations.

$$\frac{K_x}{HU^*} = 5.915\left(\frac{W}{H}\right)^{0.620}\left(\frac{U}{U^*}\right)^{1.428} \tag{5}$$

In regression analysis (as in Eq. (5), restrictive assumptions such as the presence of normal distribution and constant variance should be met for the model to obtain accurate prediction results (Sen et al., 2003). Moreover, because of its sensitivity to outliers, regression analysis based longitudinal dispersion coefficient prediction models cannot be taken as reliable methods. Therefore, the development of a technique that is not based on such assumptions and does not include limitations is of paramount importance for the reliable determination of longitudinal dispersion coefficient.

Deng et al. (2001) proposed a theoretical expression given below based on Eq. (3) for predicting longitudinal dispersion coefficient.

$$\frac{K_x}{HU^*} = \frac{0.15}{8\varepsilon_t}\left(\frac{W}{H}\right)^{5/3}\left(\frac{U}{U^*}\right)^{2} \tag{6}$$

where

$$\varepsilon_t = 0.145 + \frac{1}{3520}\left(\frac{W}{H}\right)^{1.38}\left(\frac{U}{U^*}\right).$$

This model involves the conventional parameters of the hydraulic variables, W/H, and the normalized velocity, U/U^*, and also reveals the effect of nonuniformity.

Kashefipour and Falconer (2002) derived an equation for predicting longitudinal dispersion coefficient using 81 sets of data measured in 30 rivers in the USA. The equation is given as:

$$K_x = \left[7.428 + 1.775\left(\frac{W}{H}\right)^{0.620}\left(\frac{U^*}{U}\right)^{0.572}\right]HU\left(\frac{U}{U^*}\right). \tag{7}$$

Rowinski et al. (2005) estimated longitudinal dispersion coefficient using artificial neural networks and evaluated different configurations of inputs. They stated that, although results of the artificial neural networks are not fully satisfactory, they are more accurate and far less costly than physically-based models. Kim (2012) provided algorithms to be used in calculating longitudinal dispersion coefficients using Acoustic Doppler Current Profilers (ADCP) data driven by either vertical or transverse velocity gradients in large rivers. The study compared longitudinal dispersion coefficients obtained with the theoretical formula using ADCP with those from the other available alternative empirical formulas, and found that the empirical formula overestimated the longitudinal dispersion coefficient in large rivers.