Ecological Indicators xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Original Articles

A simplified method for estimating the longitudinal dispersion coefficient in ecological channels with vegetation

Wenxin Huai[a,*], Haoran Shi[a], Suwen Song[a], Shaoqiang Ni[b]

[a] State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China
[b] Center for Earth System Science, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Keywords:
Longitudinal dispersion coefficient
Emergent vegetation
Partially vegetated rivers
N-zone model

ABSTRACT

The longitudinal dispersion coefficient is an important parameter for describing the transport processes in rivers. Riparian vegetation significantly influences the velocity profile and transport processes. This paper examines the longitudinal dispersion coefficient under the condition that rigid emergent vegetation grows symmetrically along the river bank. We build a three-zone model by extending the N-zone models of *Chickwendu* and *Boxall & Guymer*. We also analyze the velocity profiles that are significantly affected by vegetation to estimate the parameters in our model. Our tests using the experimental data from a series of experiments validate the acceptable accuracy of our three-zone model.

1. Introduction

The transport of contaminants is crucial to the chemical and biological processes that regulate the river environments (Perucca et al., 2009). The contaminants in water can be transported in various ways, including molecular diffusion, advection, turbulent diffusion, dispersion, and convection, among which dispersion is the most dominant in natural rivers. To determine the transport condition of contaminants in rivers, many theoretical and experimental studies have proposed and investigated the longitudinal dispersion coefficient. However, these studies have mostly ignored the influence of riparian vegetation on flow structure and transport of contaminants, but instead advocated for the removal of such vegetation to improve the conveyance of channels (López and García, 1998; Murphy et al., 2007). Nonetheless, recent studies have realized that vegetation directly improves the quality of water and ecology along the river (Kadlec and Knight, 1996). Other studies show that riparian vegetation significantly influences the transport of contaminants (Perucca et al., 2009; Murphy et al., 2007).

Taylor (Taylor, 1954) introduced the longitudinal dispersion concept using the following advection–diffusion differential equation in pipe flow:

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} = K_x\frac{\partial^2 C}{\partial x^2}, \tag{1}$$

where C is the cross-section averaged concentration, t is the time, u is the time-averaged velocity, x is the longitudinal coordinate oriented to the flow, and K_x is the longitudinal dispersion coefficient.

Many studies have investigated longitudinal dispersion based on the theory of Taylor (1954). For instance, Fischer (1967) proposed the following equation to predict the longitudinal dispersion in open channel flows caused by the velocity gradient in the transverse direction:

$$K_x = -\frac{1}{A}\int_0^B h(y)u'(y)\int_0^y \frac{1}{e(y)h(y)}\int_0^y h(y)u'(y)dydydy, \tag{2}$$

where A is the cross-sectional area, B is the width of the channel, $h(y)$ is the local flow depth, $u'(y) = \bar{u}(y) - V$ is the deviation of the depth-averaged velocity, $\bar{u}(y) = \int_0^{h(y)} u(y, z)dz$ is the local-depth-averaged longitudinal velocity, $u(y, z)$ is the local longitudinal velocity, V is the cross-section averaged velocity, and $e(y)$ is the local transverse mixing coefficient. Despite having a strong theoretical basis, this integral method has a complicated format. To obtain the integral result of Eq. (2), Seo and Baek (2004) used the beta density function to describe the transverse velocity distribution of natural rivers. Despite favorably describing the velocity distribution, the parameters of this function must be obtained using some measurements, which suggests that the maximum velocity and its location must be specified to estimate the parameters (Seo and Baek, 2004). In 1991, Shiono and Wellington (1991) proposed the SKM (Shiono and Knight Method) from the momentum equation to solve the lateral distribution of depth-averaged longitudinal velocity. Wang and Huai (2016) applied Fourier transformation into the SKM results to simplify the computation process of longitudinal dispersion.

* Corresponding author.
E-mail address: wxhuai@whu.edu.cn (W. Huai).

http://dx.doi.org/10.1016/j.ecolind.2017.05.015
Received 31 December 2016; Received in revised form 29 April 2017; Accepted 5 May 2017

To avoid complicated integration, Fischer (1975) proposed the following empirical formula:

$$K_x = 0.011\left(\frac{V}{u*}\right)^2\left(\frac{B}{H}\right)^2 Hu*, \tag{3}$$

where $u*$ is the friction velocity and H is the mean water depth.

Many researchers have adopted this formula and proposed a large number of similar formulae. Deng and Chu (2001) assumed a parabolic equation to describe the cross-section shape and obtained the following:

$$K_x = \frac{0.043}{8e(y)_0}\left(\frac{V}{u*}\right)^2\left(\frac{B}{H}\right)^2 Hu*, \tag{4}$$

where $e(y)_0$ can be obtained as follows:

$$e(y)_0 = \left[0.145 + \frac{1}{3520}\left(\frac{V}{u_*}\right)\left(\frac{B}{H}\right)^{1.38}\right]. \tag{5}$$

By analyzing 116 data sets from different rivers, Zeng and Huai (2013) replaced the friction velocity $u*$ with the cross-sectional averaged velocity V to fit the datasets, that is,

$$K_x = 5.4\left(\frac{B}{H}\right)^{0.7}\left(\frac{V}{u_*}\right)^{0.13} HV. \tag{6}$$

Through a regression analysis, Wang and Huai (2016) proposed the following empirical formula in rectangular flumes that will be used in this paper:

$$K_x = 0.0798\left(\frac{B}{H}\right)^{0.6239}\left(\frac{V}{u_*}\right)^2 Hu_*. \tag{7}$$

Unlike the methods above, a zoning method was constructed by dividing flow into zones (Chikwendu and Ojiakor, 1985; Chikwendu, 1986a). The starting point of this method was the slow zone model dividing the flow into two zones (Chikwendu and Ojiakor, 1985). The resulting coupled dispersion equations were then obtained and solved (Chikwendu, 1986a). Chikwendu (1986a) proposed an N-zone model for calculating the longitudinal dispersion coefficient on the basis of the slow-zone model. Given that dispersion is caused by the non-uniformity of time-averaged velocity, Chikwendu (1986a) considered the non-uniformity of longitudinal velocity in the vertical direction; next, he outlined a mathematical approach for predicting overall dispersion coefficients in a system with N distinct velocity zones over the vertical plane. If N is sufficiently large, then each zone is assumed to have the same time-averaged velocity. Chikwendu (1986a) then proposed the following N-zone model:

$$K_x = \sum_{j=1}^{N-1}\frac{(\alpha_1+\alpha_2+...+\alpha_j)^2[1-(\alpha_1+\alpha_2+...+\alpha_j)]^2\times[V_{1,j}-V_{(j+1),N}]^2}{b_{j(j+1)}} + \sum_{j=1}^{N}\alpha_j K_{xj}, \tag{8}$$

where $\alpha_j = h_j/H$, H is the depth of the water, h_j is the thickness of the j zone, $V_{a,b} = \left(\sum_{j=a}^{b}\alpha_j V_j\right)\Big/\left(\sum_{j=a}^{b}\alpha_j\right)$, V_j is the cross-section averaged velocity of the j zone, and K_{xj} is the longitudinal dispersion in the j zone. $b_{j(j+1)}$ is the transverse exchange coefficient between the j zone and the $j+1$ zone. This model (Eq. (8)) was applied in the pipe and plate flow (Chikwendu, 1986a; Chikwendu, 1986b). An example of the use of the N-zone model in an open channel flow is available in the work of Pearson et al. (2002). Boxall and Guymer (2007) extended the method to natural rivers, in which case the transverse profile of depth-averaged velocity dominates the longitudinal dispersion. Boxall and Guymer (2007) changed some parameters in Eq. (8), as discussed in Section 2.2, and then proved that this method could be used to calculate the longitudinal dispersion in meandering channels.

With regard to longitudinal dispersion in vegetated flows, Lightbody and Nepf (2006) conducted an experimental and theoretical study on the longitudinal dispersion in emergent salt marsh vegetation with a focus on the dispersion process arising from stem-scale and depth-scale velocity heterogeneities. Nepf et al. (2007) found that canopy water retention affects longitudinal dispersion much through a transient storage process. Murphy et al. (2007) applied the N-zone model of Chikwendu (1986a) into open channel flows with submerged vegetation and then divided the flow into two zones ($N = 2$) to predict longitudinal dispersion. Shucksmith et al. (2010) studied the relationships between the longitudinal dispersion coefficient and $Hu*$ with a series of experiments conducted in emergent and submerged vegetated flows. Furthermore, Shucksmith et al. (2011) proposed an N-zone model ($N \to \infty$) to predict the longitudinal dispersion in a submerged vegetated flow. A uniform transversal distribution of vegetation was constantly assumed in the aforementioned studies.

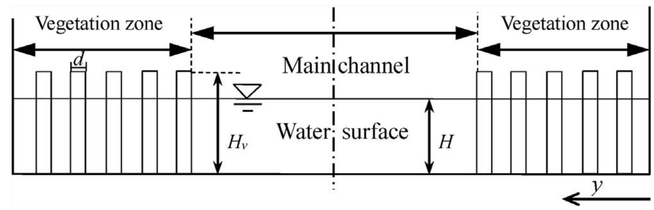

Fig. 1. Sketch of the cross section.

In the present study, we apply the N-zone model ($N = 3$) proposed by Boxall and Guymer (2007) to address the longitudinal dispersion in symmetric compound channels with emergent vegetation (Fig. 1).

To determine the dispersion process in symmetric compound channels with emergent vegetation, the unique flow structure under this condition must be considered. White and Nepf (2008) conducted several experiments and proposed an alternative vortex-based method to describe the lateral distribution of depth-averaged velocity in partially vegetated channels. Chen et al. (2010), Huai et al. (2009) and Liu et al. (2013) extended the SKM into this condition and built the following momentum equations:

$$gHS_0 - \frac{1}{8}f\bar{u}(y)^2 + \frac{\partial}{\partial y}\left[\lambda H^2\left(\frac{f}{8}\right)^{1/2}\bar{u}(y)\frac{\partial\bar{u}(y)}{\partial y}\right] - \frac{1}{2}C_d aH_v U_v^2 = \frac{\partial}{\partial y}[H(\overline{uv})_d] \tag{9}$$

and

$$gHS_0 - \frac{1}{8}f\bar{u}(y)^2 + \frac{\partial}{\partial y}\left[\lambda H^2\left(\frac{f}{8}\right)^{1/2}\bar{u}(y)\frac{\partial\bar{u}(y)}{\partial y}\right] = \frac{\partial}{\partial y}[H(\overline{uv})_d] \tag{10}$$

in the vegetation zone and main channel, respectively, where g is the gravitational acceleration, H is the flow depth, S_0 is the slope of the bed, λ is the lateral dimensionless eddy viscosity, u and v are the time-averaged local velocities in the longitudinal and lateral directions, and $(\overline{uv})_d = \int_0^H uvdz$,$C_d$ is the drag force coefficient ($C_d \approx 1.0$according to Li et al. (2015)). Moreover, a is the projected frontal area of the vegetation per unit volume, U_v is the depth-averaged velocity around the vegetation, H_v is the height of the vegetation when the vegetation is submerged, and equals to H when the vegetation is emergent.

Perucca et al. (2009) also used the SKM to determine the lateral distribution of depth-averaged velocity in partially vegetated channels. The result of $\bar{u}(y)$ was then taken into Eq. (2) to calculate the longitudinal dispersion coefficient. However, previous studies (Liu et al., 2013; Fernandes et al., 2014) reveal that the right-hand terms in Eqs. (9) and (10), which represents the secondary current is hard to calculate and might influence the accuracy a lot. On the other hand, the analytical solution of Eqs. (9) and (10), $\bar{u}(y) = {}^{1/2}$, is also difficult to integral (A_1, A_2, ω, γ_1, and γ_2 are all obtainable parameters).

This paper analyzes the lateral distribution of depth-averaged longitudinal velocity and extends the theories of Boxall and Guymer