# IMPACT OF VEGETATION ON CONTAMINANT TRANSPORT IN PARTLY-VEGETATED OPEN-CHANNEL FLOWS

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**Abstract:** This paper investigates the impact of vegetation on contaminant transport in partly-vegetated open-channel flows. For this, the one-dimensional advection-diffusion equation with the longitudinal dispersion coefficient is considered. The longitudinal dispersion coefficient can be estimated by the triple integral, where the velocity distribution and lateral mixing coefficient play important roles. The lateral distribution method is used to predict the depth-averaged velocity over the width of the channel with the uniform flow assumption. First, the non-dimensional eddy viscosity is sought for flows through emergent vegetation. Best fit values of non-dimensional eddy viscosity are obtained by comparing predicted flow conditions with measured data in laboratory experiments in the literature. Then, impacts of vegetation density and vegetated width on longitudinal dispersion coefficient are given and discussed.

**Keywords:** vegetation, contaminant transport, longitudinal dispersion coefficient, lateral distribution method, turbulent viscosity

## 1 INTODUCTION

In water quality modeling, due to many reasons, one –dimensional approach is most frequently used. In such modeling, the longitudinal dispersion coefficient plays a key role. That is, accurate estimation of this coefficient is essential not only to water quality dynamics in rivers but also to design of water intakes or outfalls.

The conventional method of estimating the one-dimensional dispersion coefficient is based on Taylor's theory. The method uses the lateral distribution of depth-averaged velocity profile with turbulent diffusion coefficient. Thus, such factors as channel shape, in-stream vegetation, and stream meandering, can affect the transport of the contaminant to a large extent.

In this study, the impact of vegetation on the contaminant transport in the partly-vegetated open-channel flow is investigated numerically. The presence of vegetation in the watercourse changes the flow structure significantly. That is, vegetation tends to reduce the mean velocity in the vegetated region, resulting in a strong gradient in the depth-averaged velocity profile in the lateral direction. This, of course, modifies the transport mechanism of contaminant in the longitudinal direction, which necessitates to assess the impact of vegetation quantitatively.

For this aim, the longitudinal dispersion coefficient of the partly-vegetated open-channel flow is estimated. The lateral distribution method is used to obtain the depth-averaged velocity over the width. The relationship by Smeithlov (1990) is used for the lateral dispersion coefficient, and calibration is carried out for lateral eddy viscosity for partly-vegetated flows. The impact of vegetation density and vegetated width on the longitudinal dispersion coefficient are given and discussed.

## 2 GOVERNING EQUATIONS

In order to investigate the characteristics of solute transport in partly-vegetated open-channels, the one-dimensional advection-diffusion equation is considered. For flow analysis, the lateral distribution method is used. The presence of vegetation in the watercourse modifies the flow structure, which affects the feature of solute transport in such flow.

### 2.1 Lateral distribution method

In the present study, in order to obtain the depth-averaged velocity in a channel cross section, the lateral distribution method introduced by Wark et al. (1990) and Knight and Shiono (1990) is used. In a channel cross section, the lateral distribution of the depth-averaged longitudinal velocity u can be obtained by solving the following equation:

$$\rho g h S_x = \frac{\rho g n^2}{h^{1/3}} B_g u^2 + F_v - \rho h \frac{\partial}{\partial y}\left( \varepsilon_y \frac{\partial u}{\partial y} \right) \tag{1}$$

where *x* and *y* denote the longitudinal and lateral directions, respectively, ρ is water density, *g* is the gravity, *h* is the local flow depth, $S_x$ is the longitudinal bed slope (= tanα, here, α is the angle of inclination of the bed in the *x*-direction), $B_g$ is the geometrical factor ($= \sqrt{1+S_x^2+S_y^2}$ , here, $S_y$ is the lateral bed slope), n is the roughness coefficient, and $\varepsilon_y$ is the *y*-component depth-averaged eddy viscosity. The lateral turbulent diffusion coefficient or viscosity is given by following relationship:

$$\varepsilon_y = \chi_y U_* h \tag{2}$$

where $\chi_y$ is the non-dimensional lateral turbulent viscosity coefficient and $U_*$ is the shear velocity. In Eq.(1), $F_v$ is the drag force due to vegetation per unit bed area, which is given by

$$F_v = \frac{\rho}{2} C_D a h_p u^2 \tag{3}$$

where $C_D$ is the bulk drag coefficient of vegetation, *a* is the vegetation density [$L^{-1}$], and $h_p$ is the vegetation height. Since Eq.(1) provides the lateral distribution of the depth-averaged velocity along the width of the channel, the impact of the secondary currents cannot be considered in the present study.

### 2.2 Solute transport

In a river, the propagation of any substance discharged can be described by the following advection diffusion equation:

$$\frac{\partial C}{\partial t} + U \frac{\partial C}{\partial x} = K \frac{\partial^2 C}{\partial x^2} \tag{4}$$

which describes the dispersion process mainly by two major mechanisms such as longitudinal advection and lateral diffusion. In Eq.(4), t and x are time and longitudinal distance, respectively, C is the mean concentration, U is the mean velocity, and K is the longitudinal dispersion coefficient. Here, C and U are section-averaged variables. Due to Fischer et al. (1975), the longitudinal dispersion coefficient K can be estimated by

$$K = -\frac{1}{A}\int_{-W/2}^{W/2} h(y)u'(y)\int_{-y}^{y}\frac{1}{\varepsilon_t(y)h(y)}\int_{-y}^{y} h(y)u'(y)dydydy \qquad (5)$$

where $u'(y)$ is the deviation of local mean velocity from the cross sectional mean velocity and $\varepsilon_t(y)$ is the lateral mixing coefficient. Deng et al. (2001) presented the local lateral mixing coefficient as

$$\varepsilon_t = K_y + \varepsilon_y \qquad (6)$$

where $K_y$ is the lateral dispersion coefficient. In a wide channel where two-dimensional flow is formed, the effect of lateral dispersion can be ignored. However, for large rivers, the following relationship can be used for the lateral dispersion coefficient

$$\frac{K_y}{HU_*} = \frac{1}{3,520}\left(\frac{U}{U_*}\right)\left(\frac{B}{H}\right)^{1.38} \qquad (7)$$

which was proposed by Smeithlov (1990) from data sets measured in eleven rivers in the US. In Eq.(7), B and H denote the water surface width and mean flow depth, respectively. Eq.(7) was also used to estimate the lateral dispersion coefficient in vegetated open-channel flows at laboratory-scale in Perucca et al. (2009). Thus, the lateral mixing coefficient normalized by is given by

$$\frac{\varepsilon_t}{U_* H} = \chi_y + \frac{1}{3,520}\left(\frac{U}{U_*}\right)\left(\frac{B}{H}\right)^{1.38} \qquad (8)$$

## 3 CALIBRATION OF NON-DIMENSIONAL EDDY VISCOSITY

For plain channel flows, Fischer et al. (1979) presented non-dimensional turbulent viscosities of 0.067, 0.15, and 0.15 in vertical, lateral, and longitudinal directions, respectively. Darby and Thorne (1996) obtained lateral non-dimensional turbulent viscosity of 0.16 through fitting computed results from the lateral distribution model to measured data. Herein, the lateral component of the non-dimensional eddy viscosity for flows through emergent vegetation is sought through numerical experiments.

In order to obtain non-dimensional eddy viscosity for vegetated flows, the flow model is applied to laboratory experiments of Jordanova and James (2003). In fact, Jordanova and James (2003) studied the effect of emergent vegetation on bedload transport through laboratory experiments. Two series of experiments were carried out. In A Series, flow depths changed for a fixed discharge, while both flow depth and discharge changed in B Series. Reynolds number ranges between 3,400 – 19,000. In all cases, the bed shear stress never exceeds 22% of the total resisting force, indicating that vegetation drag absorbs most of momentum of the flow.

Herein, best matching values of non-dimensional eddy viscosity were obtained by fitting computed flow depth to measured data under each flow condition. Resulting values of non-dimensional eddy viscosity are listed in Table 1. It can be seen that lateral component of eddy viscosity lies in the range of 0.016 – 0.164 except for B1 case. The average value of non-dimensional eddy viscosity is 0.062, which is apparently smaller than 0.15 or 0.16 for plain channel flows.

Figure 1 shows the lateral component of eddy viscosity with Reynolds number. The figure shows a clear tendency that the eddy viscosity decreases with Reynolds number except for Case B5.

## 4 SOLUTE TRANSPORT IN PARTLY-VEGETATED FLOWS

In order to investigate the characteristics of solute transport in vegetated open-channel flows, the rectangular channel a part of which is vegetated as shown in Figure 2 is considered. The channel width and slope are assumed to be 1.0 m and 0.0005, respectively. Manning's roughness coefficient of 0.02 is used for the bottom resistance. For the lateral dispersion coefficient, Eq.(7) is used. Values of 0.15 and 0.06 are used for turbulent diffusion coefficient $\chi_y$ for plain and vegetated zones, respectively.

Figure 3 shows the lateral distribution of depth-averaged velocity for different vegetation densities when the vegetated width is 0.3 m. It can be seen that the depth-averaged velocity decreases and increases in the vegetated and non-vegetated regions, respectively, as vegetation density increases in the vegetated region. The higher the vegetation density is, the steeper the velocity gradient is. However, as the vegetation density increases, the velocity gradient at the left hand side wall becomes lower, but that at the right hand side wall becomes higher. This change in velocity structure will affect the solute transport in the channel.

The change of longitudinal dispersion coefficient, estimated from Eq.(5), with vegetation density is given in Figure 4. The longitudinal dispersion coefficient of the plain channel (a = 0 $m^{-1}$) is estimated to be 0.010 $m^2/s$. To see the impact, vegetation densities were varied from 0 to 5.0 $m^{-1}$. If 30% of the channel bottom is vegetated from the plain to vegetation density of 1.0 $m^{-1}$, the longitudinal dispersion coefficient changes dramatically, up to nearly forty times. Then, the longitudinal dispersion coefficient increases slowly with further increase of vegetation density.

Now, the impact of vegetated width on the longitudinal dispersion coefficient is examined for a fixed vegetation density of 0.5 $m^{-1}$. It can be seen that the longitudinal dispersion coefficient increases gradually with the vegetated width unlike the case where vegetation density increases. That is, if the vegetated width is 10% of the total width, the longitudinal dispersion coefficient increases up to 5 times, and up to 27 times increase if the vegetated width is half of the total width.

## 5 CONCLUSIONS

This paper investigated numerically the impact of vegetation on solute transport in the partly-vegetated open-channel flow. For this, one-dimensional advection-diffusion equation with the longitudinal dispersion coefficient is considered. The longitudinal dispersion coefficient was estimated by the triple integral including velocity distribution and lateral mixing coefficient.

The lateral distribution of depth-averaged velocity was obtained using the lateral distribution method. The relationship by Smeithlov (1990) was used for the lateral dispersion coefficient and non-dimensional turbulent viscosity for partly-vegetated flows was obtained through calibration. The impact of vegetation on the longitudinal dispersion coefficient was studied by varying the vegetation density for a fixed vegetation width and the vegetation width for a fixed vegetation density.

Vegetation on the channel bottom changes flow structure by increasing the velocity in the non-vegetated zone and thus decreasing the velocity in the vegetated zone. Resulting flow pattern has a shear layer at the interface between the two zones. This increases the longitudinal dispersion coefficient dramatically. The impact of vegetation density and vegetation width is given quantitatively.

In the present study, the relationship by Smeithlov (1990) is used to estimate the lateral dispersion coefficient for partly-vegetated streams. However, the relationship was obtained from many data sets in the field. So the relationship does not necessarily reflect the shear layer formed in the partly-vegetated stream. Further theoretical or experimental studies are needed for this parameter.

## ACKNOWLEDGMENTS

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Table 1. Jordanova and James' Experimental Conditions and Estimated Lateral Eddy Viscosity

| **Case** | **q** **($m^2$/s)** | **H** **(cm)** | **$S_x$** **(%)** | $\chi_y$ | **Re** |
|---|---|---|---|---|---|
| A1 | 0.0065 | 4.3 | 1.18 | 0.051 | 6885 |
| A2 | 0.0065 | 3.95 | 1.45 | 0.089 | 6096 |
| A3 | 0.0065 | 3.8 | 1.6 | 0.053 | 6228 |
| A4 | 0.0065 | 3.6 | 1.84 | 0.025 | 6398 |
| B1 | 0.0034 | 2.05 | 1.65 | 0.538 | 3443 |
| B2 | 0.0054 | 3.35 | 1.4 | 0.066 | 5621 |
| B3 | 0.0111 | 7.05 | 1.25 | 0.032 | 11200 |
| B4 | 0.0159 | 9.6 | 1.33 | 0.016 | 16503 |
| B5 | 0.0185 | 11.1 | 1.33 | 0.164 | 18639 |

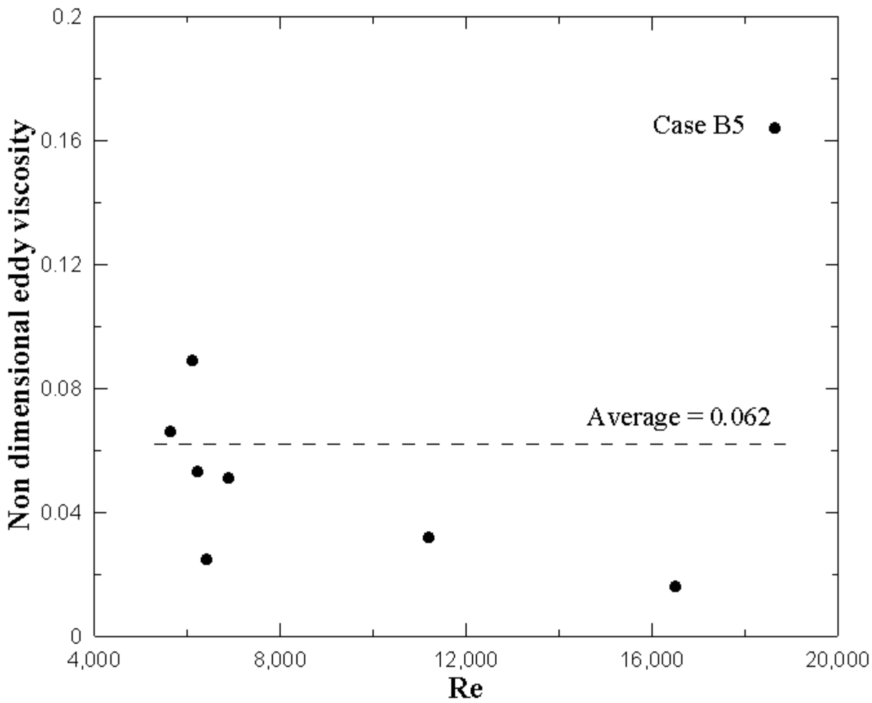

Figure 1. Lateral Eddy Viscosity versus Reynolds Number

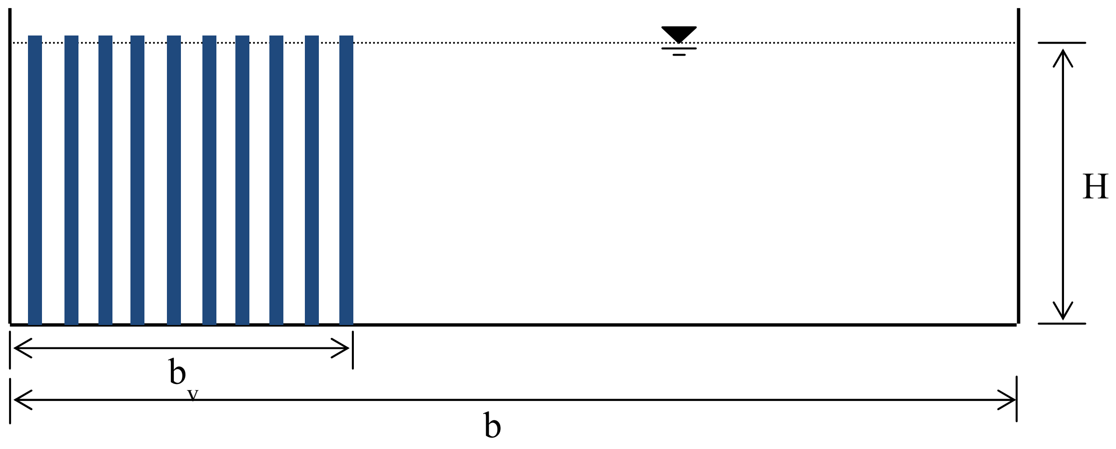


Figure 2. Schematic sketch of partly-vegetated open-channel flows

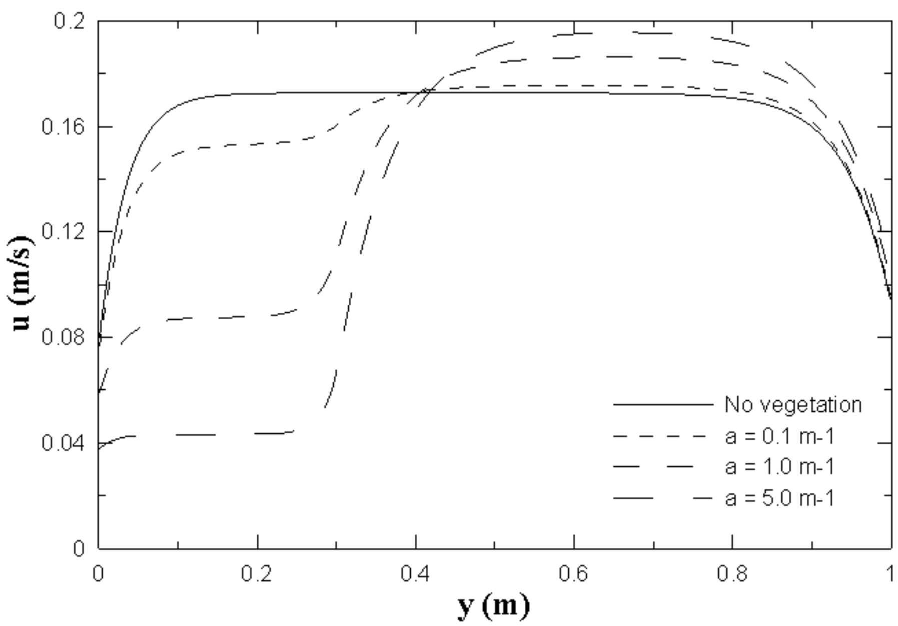


Figure 3. Lateral distribution of depth-averaged velocity for different vegetation densities

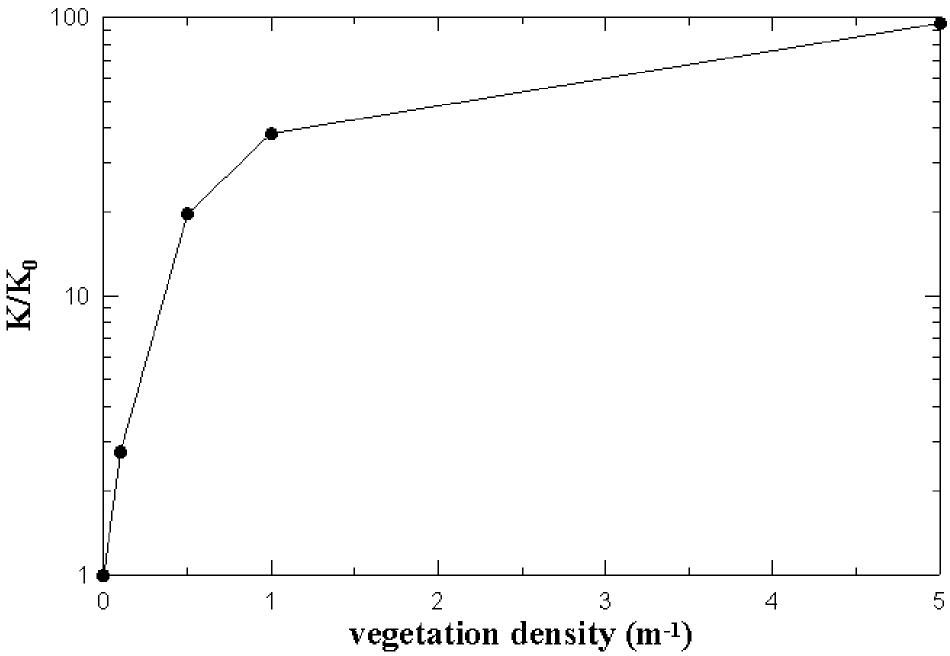


Figure 4. Change of longitudinal dispersion coefficient with vegetation density (bv/b = 0.3)

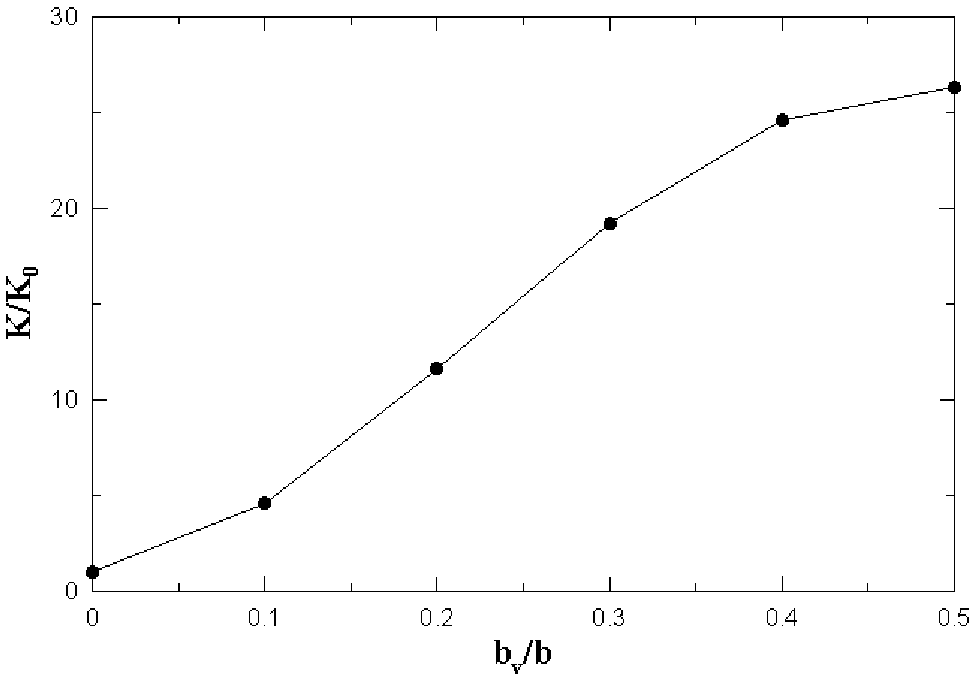


Figure 5. Change of longitudinal dispersion coefficient with width ratio (a = 0.5 $m^{-1}$)