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Modeling non-Fickian pollutant mixing in open channel flows using two-dimensional particle dispersion model

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ABSTRACT

The non-Fickian particle dispersion model was developed in this study to model two-dimensional pollutant mixing in open channel flows. The proposed model represents shear dispersion using step-by-step arithmetic calculations, which consist of horizontal transport and vertical mixing steps, instead of using Fick's law. In the sequential calculations, the model directly applied the effect of vertical variations of both longitudinal and transverse velocities, whereas the Fickian dispersion model incorporates the effect of shear flow in the dispersion coefficients. Furthermore, in order to avoid the numerical diffusion errors induced by the grid tracking method of previously developed non-Fickian dispersion models, this model adopted the particle tracking technique to trace each particle. The simulation results in the straight channel show that the proposed model reproduced the anomalous mixing, which shows a non-linear increase of variance with time and large skewness coefficient in the initial period. However, in the Taylor period, the variance and skewness of the concentration curves approached the Fickian mixing. The simulation results in the meandering channel reveal that the proposed model adequately reproduced the skewed concentration–time curves of the experimental results whereas the Fickian dispersion model, CTM-2D, generated symmetrical curves. Further comparison between the simulation results and the tracer test results conducted in the Hongcheon River shows that the proposed model properly demonstrated the two-dimensional mixing without adopting Fick's law.

1. Introduction

In streams and rivers, in the intermediate mixing region after the completion of vertical mixing, pollutant mixing can be modeled by adopting the two-dimensional (2D) dispersion theory, as shown in Fig. 1. This mixing process is called 'shear flow dispersion', in which, for 2D shear flow shown in Fig. 1b) and c), the pollutant column is stretched due to the different velocities over the depth in both the longitudinal (s) and transverse (n) directions. The stretched pollutant column is then well mixed due to the turbulent diffusion in the vertical direction after time, t. Finally, the pollutant cloud is widely dispersed, and the depth-averaged concentration curves spread wider with time, as shown in Fig. 1d. Among the various mixing mechanisms affecting the mixing of pollutant slugs that are introduced into the streams and rivers, the dispersion of the pollutant cloud by the shear flow is regarded as the most important because the shear flow is the largest fluctuation that controls the motion of water parcels over the whole flow field of the river (Daily and Harleman, 1966; Schwab and Rehmann, 2015). In order to model the aforementioned dispersion mechanism using a 2D approach, a 2D advection-dispersion equation has previously been used (Fischer et al., 1979; Rutherford, 1994). This equation can be derived by averaging the three-dimensional (3D) diffusion equation for turbulent flows over the depth (Rutherford, 1994) in the natural coordinate system as

$$\frac{\partial(hC)}{\partial t}+\frac{\partial(h\bar{u}_sC)}{\partial s}+\frac{\partial(h\bar{u}_nC)}{\partial n}-\frac{\partial}{\partial s}\left(h\varepsilon_L\frac{\partial C}{\partial s}\right)-\frac{\partial}{\partial n}\left(h\varepsilon_T\frac{\partial C}{\partial n}\right)=\frac{\partial}{\partial s}\left(-\int_0^h u'_sc'\,dz\right)+\frac{\partial}{\partial n}\left(-\int_0^h u'_nc'\,dz\right) \quad (1)$$

where z is the vertical direction; h is the water depth; ε_L and ε_T are the longitudinal and transverse turbulent diffusion coefficients, respectively; $\bar{u}_s$ and $\bar{u}_n$ are the depth-averaged velocity components corresponding to the s- and n-directions, respectively; $u'_s=u_s-\bar{u}_s$; u_s and u_n are the time-averaged velocity components which vary over depth; C is the depth-averaged concentration; $c'=c-C$; and c is the time-averaged concentration. As aforementioned, the effect of the shear flow on the 2D mixing is incorporated into the correlation term on the right-

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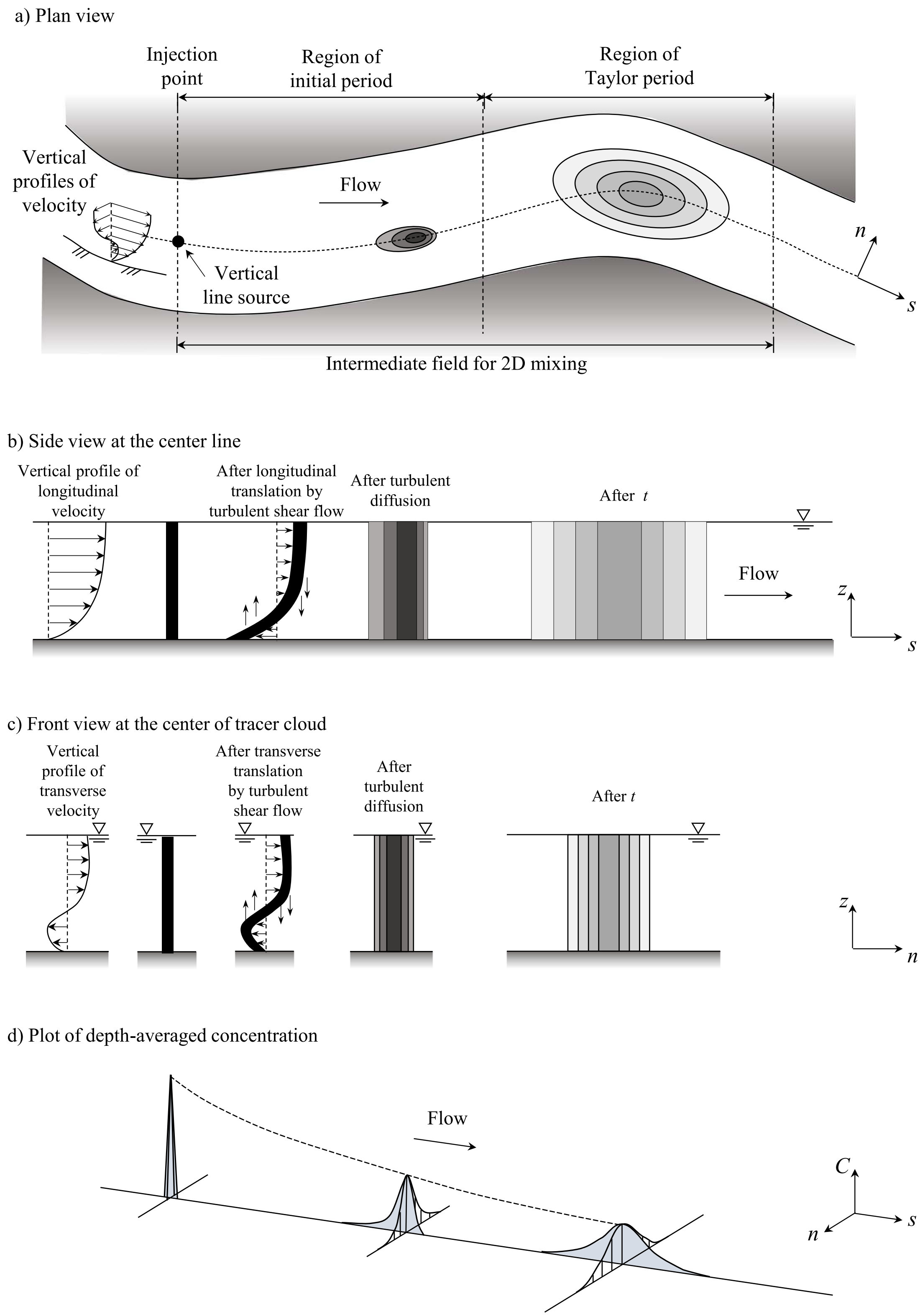

Fig. 1. Schematic diagram of the dispersion mechanism in two-dimensional shear flows.

hand side of Eq. (1), and this dispersive mass flux is due to the combined effect of shear transport and vertical diffusion as shown in Fig. 1.

To model the mass flux term on the right hand side of Eq. (1), Fischer (1978) obtained the analytical solution of $c'(z)$ by simply expanding the one-dimensional (1D) dispersion theory originally introduced by Taylor (1954) to 2D mixing, then found the relation as follows:

$$\int_0^h u'_s c'\, dz = -hD_L \frac{\partial C}{\partial s} \tag{2a}$$

$$\int_0^h u'_n c'\, dz = -hD_T \frac{\partial C}{\partial n} \tag{2b}$$

where D_L and D_T are the longitudinal and transverse dispersion coefficients, respectively. This result concurs with the Fickian diffusion for