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Longitudinal spread of bicomponent contaminant in wetland flow dominated by bank-wall effect

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SUMMARY

Presented in this paper is a theoretical analysis for longitudinal spread of bicomponent contaminant in a fully developed steady wetland flow dominated by bank-wall effect. Based on the general form of concentration transport equations adopted for wetland flows, an ecological risk assessment model is given for the decay of concentration under the combined action of reversible and irreversible reactions, as well as hydraulic dispersion. Through a combination of the method for solving linear parabolic system and an asymptotic analysis for hydraulic dispersion in the wetland flow, an analytical solution for long time evolution of bicomponent contaminant concentration is rigorously derived and illustrated. The solution is shown to be an extension of known solutions for single component contaminant transport due to an irreversible reaction and hydraulic dispersion, as well as biocomponent contaminant transport due to reversible reactions and hydraulic dispersion. It is found that the concentration ratio of binary components can approach an equilibrium status, with necessary time to obtain the status dependent on transfer and degradation rates of each component. The length and duration of influenced region with concentration of contaminant cloud beyond given environmental standard level are presented for a uniform instantaneous emission into the wetland flow. The result shows that the length increases with time to reach maximum and then decreases to zero, and the duration is sensitive to the variation of a dimensionless parameter to reflect the relative importance of an irreversible action and lateral mass dispersion.

1. Introduction

Wetlands have play a very important role in water quality improvement, groundwater recharge, flood storage, drought resistance, wildlife conservation, food supply, etc. (Mitsch and Gosselink, 1993; Costanza et al., 1997). For wastewater treatment engineering associated with constructed wetlands, and ecological risk assessment and ecological restoration related to natural wetlands (Carvalho et al., 2009; Hammer, 1989; Linder et al., 1994), a fundamental issue is to forecast the transport of contaminant cloud under the combined action of reversible and irreversible reactions, as well as hydraulic dispersion (Chen et al., 2010; Zeng and Chen, 2011).

Regarding contaminant transport in wetland flows due to hydraulic dispersion, some theoretical efforts have been made based on Taylor's analysis on dispersion (Taylor, 1953; Taylor, 1954), method of concentration moments (Aris, 1956; Aris, 1960), and method of multi-scale expansion (Mei et al., 1996). Lightbody and Nepf (2006a) and Lightbody and Nepf (2006b) established an expression of longitudinal dispersion coefficient for flow through a salt marsh controlled by emergent vegetation. Zeng et al. (2011) and Chen et al. (2010) predicted the decay of mean concentration in two-dimensional and three-dimensional wetland channels, respectively. Murphy et al. (2007) and Nepf et al. (2007) explored the characteristics of longitudinal dispersion by turbulence at different scales. Zeng et al. (2012a) analyzed the effect of wind on contaminant dispersion in a free-surface wetland flow. Chen et al. (2011) and Wu et al. (2011a) derived the analytical solution of environmental dispersivities for a two-zone wetland flow and a two-layer wetland flow, respectively. Zeng et al. (2012b) and Wu et al. (2012) examined the behavior of contaminant dispersion in typical tidal wetland flows with magnitude and direction changing periodically. However, these studies only examined the effect of pure physical processes associated with advection and mass dispersion at the phase average scale on contaminant transport, and they cannot reflect the effect of reversible or irreversible reactions.

Contaminant transport in wetland flows is quite complex, closely associated with physical, chemical and biological processes wherein (US EPA, 1988; US EPA, 1993; US EPA, 1999a; US EPA, 1999b). A reliable prediction for contaminant concentration in the wetland flow requires a reasonable understanding of the behavior of solutes transport under the combined action of reactions and hydraulic dispersion. By use of an exponential transformation, Zeng and Chen (2011) explored the evolution of

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depth-averaged concentration of single component contaminant due to an irreversible reaction and hydraulic dispersion. In contrast to the transport of single contaminant, that of bicomponent contaminant is quite complicated due to competitive absorption (Sağ et al., 2000; Gonnella and Lamura, 2007; Ziagova et al., 2007; Fereidouni et al., 2009; Chiban et al., 2011).Recently, an analytical endeavor was made to reveal the characteristic of long-time evolution of bicomponent contaminant in free-surface wetland flow (Chen et al., 2012). However, the analytical solution only takes the effect of reversible reactions on contaminant concentration into account, and up to now, no analytical solution has been presented to predict the evolution of bicomponent contaminant under the combined action of reversible and irreversible reactions, as well as hydraulic dispersion.

This work is to investigate the behavior of longitudinal spread of bicomponent contaminant under the combined action of reversible and irreversible reactions, as well as hydraulic dispersion. The specific objects are: (I) to formulate the typical case of concentration evolution of bicomponent contaminant in the wetland flow dominated by bank-wall effect, (II) to find the concrete expression for long-time decay of components concentration, and (III) to determine the length and duration of influenced region in which contaminant concentration is beyond given environmental standard level.

2. Formulation

For a typical wetland flow, governing equations for mass transport of bicomponent contaminant can be adopted at the phase average scale as (Liu and Masliyah, 2005; Chen et al., 2010; Zeng, 2010; Chen, 2013)

$$\phi\frac{\partial C_A}{\partial t}+\frac{\partial(u_iC_A)}{\partial x_i}=\frac{\partial}{\partial x_i}\left(\kappa\lambda\phi\frac{\partial C_A}{\partial x_i}\right)+\kappa\frac{\partial}{\partial x_i}\left(K_{ij}\frac{\partial C_A}{\partial x_j}\right) - \phi r_A(C_A-k_dC_B)-\phi k_AC_A \tag{1}$$

$$\phi\frac{\partial C_B}{\partial t}+\frac{\partial(u_iC_B)}{\partial x_i}=\frac{\partial}{\partial x_i}\left(\kappa\lambda\phi\frac{\partial C_B}{\partial x_i}\right)+\kappa\frac{\partial}{\partial x_i}\left(K_{ij}\frac{\partial C_B}{\partial x_j}\right) + \phi\frac{r_B}{k_d}(C_A-k_dC_B)-\phi k_BC_B \tag{2}$$

where ϕ (dimensionless) is porosity, C_A (kg m^{-3}) the concentration of component A, t (s) time, x_i and x_j (m) spacial coordinates ($i,j=1,2,3$), u_i (ms^{-1}) velocity component, κ (dimensionless) tortuosity, λ (m^2 s^{-1}) mass diffusivity, K_{ij} (m^2 s^{-1}) the component of mass dispersivity tensor, r_A (s^{-1}) the transfer rate of component A, k_d (dimensionless) distribution coefficient, C_B (kg m^{-3}) the concentration of component B, k_A (s^{-1}) the degradation rate of component A, r_B (s^{-1}) the transfer rate of component B, and k_B (s^{-1}) the degradation rate of component B. Eqs. (1) and (2) are out of a combination of an convective–diffusive equation for pure fluid flow and a mass dispersion term on the phase average scale due to vegetation.

Consider biocomponent transport in a steady, fully developed, bank-wall dominated wetland flow with constant ϕ,κ and K_{ij}, in a Cartesian coordinate system with coordinate axes coinciding with the principle axes of mass dispersivity tensor with longitudinal x-axis along flow direction and lateral y-axis with origin at one of the channel banks, as illustrated in Fig. 1. The solution of velocity profile for the wetland flow on the phase average scale can be expressed as (Zeng, 2010)

$$u(y)=U_m\alpha\frac{\sinh\alpha+\sinh[\alpha(y/W-1)]-\sinh(\alpha y/W)}{2-2\cosh\alpha+\alpha\sinh\alpha} \tag{3}$$

where U_m (ms^{-1}) is the width-averaged velocity, α is a dimensionless parameter representing the combined action of width, lateral momentum dispersion, microscopic curvature of flow passage and friction of vegetation, and W (m) is the width of the channel (Zeng, 2010).

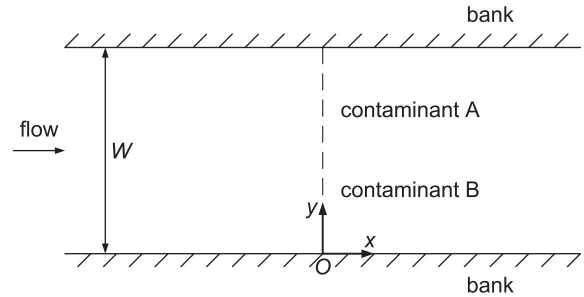

Fig. 1. Sketch for a wetland flow dominated by bank-wall effect.

Consider a uniform instantaneous emission of bicomponent contaminant at the cross-section of $x=0$ at time $t=0$, in terms of an initial condition as

$$C_A(x,y,t)|_{t=0}=\frac{Q}{\phi W}\delta(x) \tag{4}$$

$$C_B(x,y,t)|_{t=0}=\frac{Q}{\phi W}\delta(x) \tag{5}$$

where Q (kg m^{-1}) is mass per depth, and $\delta(x)$ is the Dirac delta function.

For the two-dimensional process, Eqs. (1) and (2) reduce to

$$\frac{\partial C_A}{\partial t}+\frac{u}{\phi}\frac{\partial C_A}{\partial x}=\kappa\left(\lambda+\frac{K_L}{\phi}\right)\frac{\partial^2C_A}{\partial x^2}+\kappa\left(\lambda+\frac{K_T}{\phi}\right)\frac{\partial^2C_A}{\partial y^2} - r_A(C_A-k_dC_B)-k_AC_A \tag{6}$$

$$\frac{\partial C_B}{\partial t}+\frac{u}{\phi}\frac{\partial C_B}{\partial x}=\kappa\left(\lambda+\frac{K_L}{\phi}\right)\frac{\partial^2C_B}{\partial x^2}+\kappa\left(\lambda+\frac{K_T}{\phi}\right)\frac{\partial^2C_B}{\partial y^2} + \frac{r_B}{k_d}(C_A-k_dC_B)-k_BC_B \tag{7}$$

where K_L (m^2 s^{-1}) and K_T (m^2 s^{-1}) are the longitudinal and lateral mass dispersivities, respectively. For the bank at $y=0$ and $y=W$, we have concentration boundary conditions as

$$\left.\frac{\partial C_A(x,y,t)}{\partial y}\right|_{y=0}=\left.\frac{\partial C_A(x,y,t)}{\partial y}\right|_{y=W}=0 \tag{8}$$

$$\left.\frac{\partial C_B(x,y,t)}{\partial y}\right|_{y=0}=\left.\frac{\partial C_B(x,y,t)}{\partial y}\right|_{y=W}=0 \tag{9}$$

Since the amount of discharged contaminant is finite, concentration boundary conditions at $x=\pm\infty$ read as

$$C_A(x,y,t)|_{x=\pm\infty}=0 \tag{10}$$

$$C_B(x,y,t)|_{x=\pm\infty}=0 \tag{11}$$

With dimensionless parameters of

$$\xi=\frac{x-U_mt/\phi}{W},\qquad \eta=\frac{y}{W},\qquad \tau=\frac{\kappa(\lambda+K_T/\phi)t}{W^2}$$

the governing equations, as well as boundary and initial conditions for concentration of components A and B can be rewritten as

$$\begin{cases}\frac{\partial\Omega_A}{\partial\tau}+\frac{Pe_xR_x^K}{\phi}\psi\frac{\partial\Omega_A}{\partial\xi}=R_x^K\frac{\partial^2\Omega_A}{\partial\xi^2}+\frac{\partial^2\Omega_A}{\partial\eta^2}-N_A(\Omega_A-k_d\Omega_B)-M_A\Omega_A\\ \Omega_A(\xi,\eta,\tau)|_{\xi=\pm\infty}=0\\ \left.\frac{\partial\Omega_A}{\partial\eta}\right|_{\eta=0}=\left.\frac{\partial\Omega_A}{\partial\eta}\right|_{\eta=1}=0\\ \Omega_A(\xi,\eta,\tau)|_{\tau=0}=W\delta(W\xi)\end{cases} \tag{12}$$

$$\begin{cases}\frac{\partial\Omega_B}{\partial\tau}+\frac{Pe_xR_x^K}{\phi}\psi\frac{\partial\Omega_B}{\partial\xi}=R_x^K\frac{\partial^2\Omega_B}{\partial\xi^2}+\frac{\partial^2\Omega_B}{\partial\eta^2}+\frac{N_B}{k_d}(\Omega_A-k_d\Omega_B)-M_B\Omega_B\\ \Omega_B(\xi,\eta,\tau)|_{\xi=\pm\infty}=0\\ \left.\frac{\partial\Omega_B}{\partial\eta}\right|_{\eta=0}=\left.\frac{\partial\Omega_B}{\partial\eta}\right|_{\eta=1}=0\\ \Omega_B(\xi,\eta,\tau)|_{\tau=0}=W\delta(W\xi)\end{cases} \tag{13}$$