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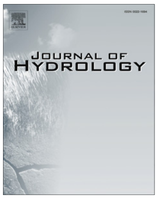

Research papers

Contaminant transport in wetland flows with bulk degradation and bed absorption

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ABSTRACT

Ecological degradation and absorption are ubiquitous and exert considerable influence on the contaminant transport in natural and constructed wetland flows. It creates an increased demand on models to accurately characterize the spatial concentration distribution of the transport process. This work extends a method of spatial concentration moments by considering the non-uniform longitudinal solute displacements along the vertical direction, and analytically determines the spatial concentration distribution in the very initial stage since source release with effects of bulk degradation and bed absorption. The present method is demonstrated to bear a more accurate prediction especially in the initial stage through convergence analysis of Hermite polynomials. Results reveal that contaminant cloud shows to be more contracted and reformed by bed absorption with increasing damping factor of wetland flows. Tremendous vertical concentration variation especially in the downstream of the contaminant cloud remains great even at asymptotic large times. Spatial concentration evolution by the extended method other than the mean by previous studies is potential for various implements associated with contaminant transport with strict environmental standards.

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1. Introduction

Prediction of the contaminant transport in wetland flows plays an essential role in the field of environmental science and engineering including environment risk assessment, wastewater treatment engineering and ecological restoration (Fischer, 1972; Fischer et al., 1979; Nepf, 2012; Rubol et al., 2016; Zeng et al., 2011; Chen, 2013; Wu et al., 2015; Wang and Chen, 2016b,c). Contaminant transport in natural and constructed wetland flows is widely subjected to various ecological effects, for example, the bulk degradation induced by biophysical or biochemical processes, the absorption or adsorption to the substrate and vegetation, etc. (Berkowitz, 2002; Ziagova et al., 2007; Fereidouni et al., 2009; Langergraber et al., 2009; Chiban et al., 2011; Mburu et al., 2013). Mostly concerned therein is the spatial concentration evolution especially in its initial stage under the effects of hydraulic dispersion and ecological effects (Mburu et al., 2013; Wu and Chen, 2014a,b; Wu et al., 2015; Wang and Chen, 2016c, 2017).

Contaminant transport in flows is extensively termed as Taylor dispersion, originally proposed by Taylor (1953) in studying the solute transport in a pipe flow. Taylor dispersion refers to the mechanism that solute spreads under the combined action of flow velocity non-uniformity and diffusion effect. Actually, in dispersion process especially in the initial stage concentration over cross-sections greatly deviates from the mean (Gill, 1967; Chatwin, 1970; Smith, 1986; Wu and Chen, 2014a,b; Wang and Chen, 2016b,c). Recently, Wu and Chen (2014a) explored transverse concentration distribution in a pure dispersion process through an extended two-scale perturbation analysis, the result of which is further verified and extended by Wang and Chen (2016a) by the developed Aris-Gill expansion. It has been established that transverse concentration distribution shows tremendous nonuniformity even when mean concentration distribution reaches its longitudinal normality, and it remains remarkable in a long dispersion stage. Wall absorption further reshapes concentration distribution over cross-sections to form larger transverse concentration nonuniformity (Sankarasubramanian and Gill, 1973; Wang and Chen, 2016c). Complexity and difficulty is as well introduced by reactions to the theoretical analysis for accurately characterizing the transport process.

Intensive theoretical and experimental works have been conducted on the contaminant transport in wetland flows to figure

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out the mechanism (Nepf, 1999; Henrichs et al., 2007; Langergraber et al., 2009; Mburu et al., 2013). Nepf's group comprehensively explored the longitudinal dispersion process through wetland flows with submerged or emergent vegetation (Lightbody and Nepf, 2006; Nepf and Ghisalberti, 2008; Nepf, 2012) and in turbulent wetland flows (Nepf, 1999; Murphy et al., 2007), etc. To illustrate the mechanism of transport in wetland flows from Taylor's classical analysis of dispersion, Zeng and Chen (2009) and Chen et al. (2010) characterized the transport process, termed as environmental dispersion, based on the phase average technique by smearing out the discontinuity between the two phases of water and vegetation. Chen (2013) further explored the environmental dispersion process in wetland flows with distinctive zones. Nevertheless, previous studies only focused on the longitudinal mean concentration evolution, regardless of the extremely non-uniform vertical concentration distribution, as well as the ubiquitous effects of bulk degradation and bed absorption in wetlands.

On Taylor dispersion model, extensively applied is Aris's method of concentration moments, which accurately reveals the statistical properties for mean concentration in the transport process (Aris, 1956; Barton, 1983; Andersson and Berglin, 1981; Mazumder and Das, 1992). Great endeavors have applied the concentration moments in studying the mean concentration distribution in the initial and asymptotic stages of dispersion, and obtaining the accurate based characteristics for related analyses (Chatwin, 1970; Wu and Chen, 2014a,b; Wang and Chen, 2016c, 2017). Consider deviations in the vertical direction, Yasuda (1984) introduced spatially distributed concentration moments and derived nonnegative dispersivity in a tidal flow. This approach is a more generalized and integrated method without assumptions, but the potential of this method to pursue the spatial concentration distribution in the initial stage has not been realized.

Presented in this work is an analytical study of contaminant dispersion in its initial stage in an open channel wetland flow with bulk degradation and bed absorption by extending the method of spatial concentration moments. The detailed contents of this paper are: (I) to present the phase-averaged transport equation in an ideal open channel wetland flow; (II) to analytically derive the zeroth to fourth order spatial concentration moments; (III) to determine the higher order convergence and compare the results of mean concentration deduced from two techniques of concentration moments; and (IV) to illustrate the spatial concentration evolution in the initial stage.

2. Method

2.1. Formulation for contaminant transport

Though the contaminant transport in wetland flows is extremely complex due to the existence of vegetation as a solid phase other than pure water, the details of the real flow and transport process in the domain of irregular vicinity around the vegetation stem scale are not concerned for practical applications at the environmental scale. What focused is the behaviour of the superficial transport process, treated as a continuous distribution in the entire domain of concern, out of the phase average technique to smear out the discontinuity between the water and vegetation and to get free of the microscopic fluctuations of flow (Chen and Zeng, 2009; Chen et al., 2010). The deduced equation for mass transfer is out of a combination of an advection-diffusive equation and a mass dispersion term. It is widely applied for studying contaminant transport process in wetland flows (Wu et al., 2015; Zeng et al., 2011; Chen, 2013).

For a typical wetland flow with constant density, viscosity and diffusivity bearing bulk degradation effect, the right-handed Cartesian coordinate system is set as shown in Fig. 1, where the water height is h. Then the governing equation for superficial contaminant transport can be adopted generally at the phase average scale as (Liu and Masliyah, 2005; Chen et al., 2010)

$$\frac{\partial C^*}{\partial t}+\frac{u}{\phi}\frac{\partial C^*}{\partial x}=\kappa\left(\lambda+\frac{K}{\phi}\right)\frac{\partial^2 C^*}{\partial x^2}+\kappa\left(\lambda+\frac{K}{\phi}\right)\frac{\partial^2 C^*}{\partial z^2}-k_a^* C^*, \tag{1}$$

where C^* is the concentration [kgm^{-3}], t the time [s], u the apparent longitudinal velocity as a function of z [ms^{-1}], ϕ the porosity [dimensionless], κ the tortuosity [dimensionless] to account for the spatial structure of aquatic plants, λ the concentration diffusivity [m^{2}s^{-1}], K the concentration dispersivity tensor [m^{2}s^{-1}], and k_a^* the apparent reaction rate [s^{-1}].

Consider a uniform and instantaneous release of contaminant with mass Q at the position of $x = 0$ at time $t = 0$, the initial condition can be set as

$$C^*(0,x,z)=\frac{Q}{\phi h}\delta(x), \tag{2}$$

where $\delta(x)$ is the Dirac delta function.

The non-penetration condition at the free surface read as

$$\left.\frac{\partial C^*(t,x,z)}{\partial z}\right|_{z=h}=0. \tag{3}$$

Consider the wetland bottom is well consolidated so that no scouring takes place, and the contaminant absorbed to the substrate is described by the linear first-order irreversible absorption, the boundary condition at the bottom gives

$$\kappa\left(\lambda+\frac{K}{\phi}\right)\left.\frac{\partial C^*(t,x,z)}{\partial z}\right|_{z=0}=\beta^* C^*(t,x,z)|_{z=0}. \tag{4}$$

Since the amount of released contaminant substance is finite, the upstream and downstream conditions are

$$C^*(t,\pm\infty,z)=0. \tag{5}$$

With dimensionless variables introduced as

$$\begin{gathered}\tau=\frac{\kappa\left(\lambda+\frac{K}{\phi}\right)t}{h^2},\quad \eta=\frac{x-(\bar{u}/\phi)t}{h},\quad \zeta=\frac{z}{h},\quad C_d=\frac{\phi h^2}{Q}C^*,\\ Pe=\frac{(\bar{u}/\phi)h}{\kappa\left(\lambda+\frac{K}{\phi}\right)},\quad \beta=\frac{\beta^* h}{\kappa\left(\lambda+\frac{K}{\phi}\right)},\quad k_a=\frac{k_a^* h^2}{\kappa\left(\lambda+\frac{K}{\phi}\right)},\end{gathered} \tag{6}$$

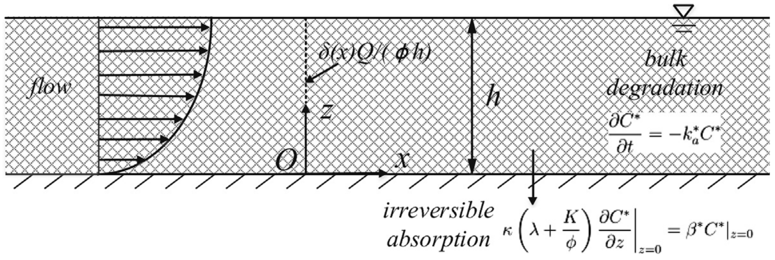

Fig. 1. Schematic of wetland flow and initial and boundary conditions for contaminant transport.

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