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Concentration distribution of contaminant transport in wetland flows

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SUMMARY

Study on contaminant transport in wetland flows is of fundamental importance. Recent investigation on scalar transport in laminar tube flows (Wu and Chen, 2014. J. Fluid Mech., 740: 196-213.) indicates that the vertical concentration difference in wetland flows may be remarkable for a very long time, which cannot be captured by the extensively applied one-dimensional Taylor dispersion model. To understand detailed information for the vertical distribution of contaminant in wetland flows, for the first time, the present paper deduces an analytical solution for the multi-dimensional concentration distribution by the method of mean concentration expansion. The solution is verified by both our analytical and numerical results. Representing the effects of vegetation in wetlands, the unique dimensionless parameter α can cause the longitudinal contraction of the contaminant cloud and the change of the shape of the concentration contours. By these complicated effects, it is shown unexpectedly that the maximum vertical concentration difference remains nearly unaffected, although its longitudinal position may change. Thus the slow-decaying transient effect (Wu and Chen, 2014. J. Hydrol., 519: 1974-1984.) is shown also apply to the process of contaminant transport in wetland flows.

1. Introduction

Study on contaminant transport in wetland flows is of fundamental importance for applications such as environmental risk assessment, wastewater treatment and ecological restoration engineering (Chen, 2013; Chen et al., 2012; Fischer, 1976; Fischer et al., 1979; Guerrero and Skaggs, 2010; Logan, 1996; Shao and Chen, 2013; Shao et al., 2013; Wu et al., 2011a, 2012; Zeng et al., 2012). For describing the evolution of the contaminant cloud as essential in environmental risk assessment, the longitudinal distributed mean concentration under long-time evolution is concerned when trying to figure out some characteristic parameters including the duration and the critical length of the contaminant cloud (Zeng et al., 2014).

Generally, at present it is well understood on the asymptotic contaminant transport process based on the cross-sectional mean concentration (Chen et al., 2010; Wu et al., 2011b): after an initial stage of the release of the contaminant, the mean concentration of the contaminant cloud longitudinally forms a Gaussian distribution and can be described accurately by the classical Taylor dispersion model, which is an extensively applied one-dimensional approximation. For the mean concentration the initial stage is of the order of H^2/D, which can be determined by the approach to longitudinal normality of the real distribution (Chatwin, 1970; Wu and Chen, 2014b); Here H is the depth of the wetland and D is the effective vertical diffusion coefficient.

However, some new physical insight has been revealed by the recent exploration on scalar transport in laminar tube flows (Wu, 2014; Wu and Chen, 2014b): it is shown by the analytical solution that the time period required for the concentration to approach transverse uniformity is at least an order of magnitude longer than the approach to longitudinal normality. The conclusion was confirmed for contaminant transport in laminar open channel flow and termed as the slow-decaying transient effect (Wu and Chen, 2014a). In other words for wetland flows, it is quite possible that when the mean concentration can be described by the Taylor dispersion model, the vertical concentration difference may still remain remarkable for quite a long time, which is distinct from the traditional understandings of a uniform distribution. Thus a detailed discussion on the vertical concentration distribution and its evolution in wetland flows would be essential in providing scientific basis and technique support for related applications.

Great endeavors have been made recently on the study of contaminant dispersion in wetland flows, with different approaches implemented including laboratory and field measurements (Nepf, 2012; Nepf and Ghisalberti, 2008), numerical simulations (Zhang et al., 2010), and theoretical explorations (Chen et al., 2012; Wang and Chen, 2015; Wu et al., 2011b). Among the analytical techniques, the concentration moment method (Aris, 1956) is one that most extensively applied. Related progresses include: contaminant

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dispersion in the single-zone wetland flows was explored, with homogeneous vegetation or granular media packed in the flow region (Zeng et al., 2011); this work was then extended to analyze the dispersion processes with a multi-zone structure, which is caused by the distinct media packed in each zone (Wang et al., 2013; Wu et al., 2011a). As pointed out by some researchers (Chen and Wu, 2012; Phillips and Kaye, 1996), concentration moments at different orders can reveal different statistic properties for the contaminant cloud in the transport processes (Barton, 1983; Zeng, 2010), but not to give a direct concentration distribution: neither for the mean concentration nor for the vertical distribution.

Extending the homogenization technique (Mei et al., 1996; Ng and Yip, 2001; Wu and Chen, 2014b) developed a two-scale perturbation analysis framework for dealing with the scalar transport process. Since flow velocity distribution and contaminant dispersion in wetlands are much more complicated than that in pure fluid flows, this approach may not be feasible enough for determining the required analytical solutions. For a different analytical approach determining a first-estimation, the mean concentration expansion method by Gill is straightforward and illustrative (Gill, 1972, 1967; Gill and Sankaras, 1970). This method has been applied for scalar transport in packed media flows (Wu and Chen, 2012). Recently, the combined effects of ecological degradation and environmental dispersion in a two-zone wetland is also addressed by the method, and the longitudinal dispersion of the mean concentration was analyzed (Chen, 2013). Actually, it is possible to describe the longitudinal as well as the vertical concentration evolution under Gill's framework, though a related exploration on the vertical distribution for contaminant transport in wetland flows has never been touched.

For the first time, the multi-dimensional concentration distribution for contaminant transport in wetland flows is analytically explored in this paper. The contents of the paper include: (1) to deduce Taylor dispersion model and the formal solutions for the concentration distribution, based on the basic equations for contaminant transport in wetland flows and the mean concentration expansion method; (2) to obtain analytical solutions for the first order vertical distribution function, the dispersion coefficient, as well as the multi-dimensional concentration distribution, and (3) to analyze the vertical concentration distribution by the obtained solution, and the effects of vegetation on the evolution.

2. Formulation

Contaminant transport in wetland flows is of great complexity for the existence of materials of a different phase other than water, for example the grown vegetation in the concerned region. This causes the discontinuity of flow and concentration in space, and the complicated additional boundary conditions at the surface of the vegetation changing the local flow and concentration distributions. Instead of studying the process at the micro-scale characterized by the typical scale of the flow path around the stem of the vegetation, for example, the problem has been explored at an intermediate phase-average scale, applying the phase average operation to smear out the spatial discontinuity (Chen, 2013; Liu and Masliyah, 2005; Wu and Chen, 2015; Wu et al., 2012; Zeng et al., 2014). Since the resulted flow and concentration distribution is continuous in space, the analysis we applied for the pure fluid flow can thus be directly extended for the present study. Such a framework has been applied extensively for studying contaminant transport in wetland flows (Chen, 2013; Chen et al., 2012, 2010; Wu et al., 2011b, 2012; Zeng, 2010; Zeng et al., 2014).

Under the framework of phase-average, the general mass transfer equation can be adopted for contaminant transport in wetland flows as (Liu and Masliyah, 2005; Rajagopal and Tao, 1995; Wu and Chen, 2015; Zeng et al., 2014)

$$\phi\frac{\partial C}{\partial t}+\nabla\cdot(\mathbf{U}C)=\nabla\cdot(\kappa\lambda\phi\nabla C)+\kappa\nabla\cdot(\mathbf{K}\cdot\nabla C), \tag{1}$$

where ϕ is the porosity (dimensionless), C the concentration ($\mathrm{kg\,m^{-3}}$), t the time (s), $\mathbf{U}$ the velocity ($\mathrm{m\,s^{-1}}$), κ the tortuosity (dimensionless), λ the concentration diffusivity ($\mathrm{m^2\,s^{-1}}$), and $\mathbf{K}$ the concentration dispersivity tensor ($\mathrm{m^2\,s^{-1}}$).

The purpose of an analytical exploration is to reveal some general information for the studied problem by some idealized case. Here for contaminant transport in wetland flows (as shown in Fig. 1), we consider the wetland channel of a depth H, in a Cartesian coordinate system with the longitudinal x-axis and vertical z-axis. The flow is fully-developed and longitudinally unidirectional. The origin is set at the wetland bed wall. For the most idealized case of homogeneous wetlands with constant parameters, Eq. (1) is simplified into (Chen, 2013; Zeng et al., 2014)

$$\frac{\partial C}{\partial t}+\frac{u}{\phi}\frac{\partial C}{\partial x}=\kappa\left(\lambda+\frac{K_x}{\phi}\right)\frac{\partial^2 C}{\partial x^2}+\kappa\left(\lambda+\frac{K_z}{\phi}\right)\frac{\partial^2 C}{\partial z^2}, \tag{2}$$

where u is the longitudinal velocity as a function of z; K_x and K_z are respectively the longitudinal and vertical dispersivities.

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

$$C(x,z,t)|_{t=0}=\frac{Q}{\phi}\delta\left(\frac{x}{H}\right), \tag{3}$$

where $\delta(x)$ is the Dirac delta function. The no flux conditions at the wetland bed wall of $z=0$ and the free-water-surface of $z=H$ are

$$\left.\frac{\partial C}{\partial z}\right|_{z=0}=\left.\frac{\partial C}{\partial z}\right|_{z=H}=0. \tag{4}$$

Since the amount of released contaminant is finite, we have boundary conditions for concentration at $x=\pm\infty$ as

$$C(x,z,t)|_{x=\pm\infty}=0. \tag{5}$$

With dimensionless parameters as

$$\tau=t\left/\frac{H^2}{\kappa\left(\lambda+\frac{K_z}{\phi}\right)}\right.,\quad \zeta=\frac{z}{H},\quad X=\frac{x}{H},$$
$$\mathrm{Pe}=\frac{Hu_m}{\kappa(\lambda\phi+K_z)},\quad R=\frac{\phi\lambda+K_x}{\phi\lambda+K_z},\quad \psi=\frac{u}{u_m}, \tag{6}$$

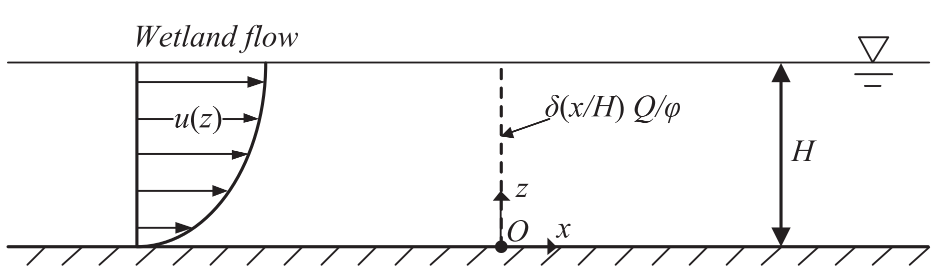

Fig. 1. Sketch for wetland flow with free-water surface.