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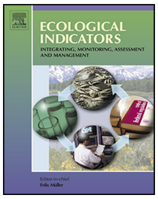

Indicators for environmental dispersion in a two-layer wetland flow with effect of wind

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ABSTRACT

For typical two-layer wetland flows where wind occurs frequently, indicators for flow and contaminant dispersion with wind effect are considered in this paper. Based on the general formulation for porous media flows, the velocity distribution of a fully developed flow through a wetland is illustrated, with that for a single-layer wetland flow under wind recovered as a special case. And the contrary wind of high speed might result in the appearance of an inverse-flow layer. For the more complex case of a two-layer wetland flow under wind, the more simplified method of asymptotic analysis is adopted instead of Aris's method of concentration moments to determine the dispersivity in terms of the longitudinal evolution of the depth-averaged concentration. And it is illustrated with the effect of dimensionless parameters. The velocity profile and environmental dispersivity for the two-layer wetland flow in the absence of wind can be included as a limiting case. Both the direction and the strength of the wind can affect the environmental dispersivity considerably under long-term evolution. Analytical solutions for the mean concentration and the region influenced by the contaminant cloud are derived. And for the instantaneous emission of typical contaminant constituents, the related indicators for water quality assessment, such as the critical length and duration of the influenced region are illustrated. The results show that the critical length and duration of the concentration cloud can change considerably because of the wind and vegetation heterogeneity.

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1. Introduction

Contaminant transport is a fundamental issue in ecological risk assessment, ecological restoration, and wastewater treatment of both natural and constructed wetlands (Carvalho et al., 2009; Costanza et al., 1998; US EPA, 1999; Chen et al., 2011). Specifically, when a hazardous pollutant is discharged into a wetland area, an affected region could develop in which the concentration of the pollutant exceeds the accepted environmental standard levels for water quality. During such an event, an essential indicator system is necessary for predicting and evaluating the extent of the affected region and the duration of influence, which can be based on a thorough understanding of contaminant transport characterized by environmental dispersion (Chen et al., 2010; Zeng and Chen, 2011).

Solute dispersion in wetland flows has attracted increasing attention since the publication of the seminal work by Taylor (1953). More recently, based on field tests, velocity profiles and mass transport have been explored in wetlands with emergent as well as submerged aquatic plants (Lightbody and Nepf, 2006; Nepf, 2012; Nepf and Ghisalberti, 2008). However, these studies were limited primarily to the complicated stem-scale processes. In the field of wetland science, one of the greatest concerns is the Taylor dispersion on the environmentally macroscopic scale (the phase-averaged scale), i.e., the longitudinal dispersion of concentration clouds in porous media (Wang et al., 2015). Mechanisms contributing to this process include cross-sectional diffusion, the non-uniformity of longitudinal velocity, and vertical concentration dispersion, which is attributed to complicated microscopic (complicated stem-scale) processes (Wang et al., 2013).

And contaminant transport in various single-channel wetlands has been investigated analytically on a phase-averaged scale based on Taylor's analysis on dispersion. For example, Zeng and Chen (2011) analyzed the hydraulic dispersion of a contaminant in single-layer wetlands dominated by the free-water-surface effect using the method of concentration moments (Aris, 1956), and taking the effects of ecological degradation into account. Moreover, Zeng et al. (2011) studied dispersion in wetland flows dominated by bank effect. Analytical

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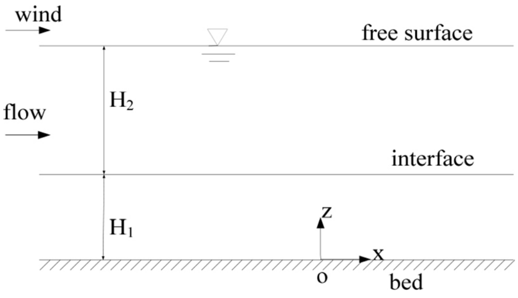

Fig. 1. Sketch of a two-layer wetland flow under wind.

solutions have also been explored for 3-D wetland flows (Chen et al., 2010). Some of these results have also been deduced by Wu et al. (2011b,c) using multi-scale analysis (Mei et al., 1996). In 2012, contaminant transport in tidal wetland flows was investigated analytically (Wu et al., 2012; Zeng et al., 2012a). And Chen et al. (2012a) even analyzed the transport of bicomponent contaminant in the wetland flow. To analyze the effects of media distribution heterogeneity, which could be caused by vegetation growth or the relative packing of granular material in two regions, velocity distributions and environmental dispersivities were explored analytically for two-zone and two-layer wetland flows by Wu et al. (2011a) and Chen et al. (2012b), respectively. Additionally, Chen (2013) first adopted the approach of asymptotic analysis to analyze the transport process of a contaminant in a fully developed unidirectional flow within a two-zone wetland considering both hydraulic and ecological effects. Wang et al. (2013, 2014) even addressed the analytical exploration of the velocity profile and environmental dispersion in three-layer wetland flows dominated by the free-surface effect, using the methods of concentration moments and asymptotic analysis, respectively.

But these investigations only considered the velocity distribution and environmental dispersion for wetland flows in the absence of wind. Zeng et al. (2012b) stared to investigate the velocity distribution and environmental dispersivity analytically in singer-layer wetland flows under winds using Aris's method of concentration moments. Actually, wind is a frequent occurrence and it has wide effect on various areas relevant to wetland, shallow lake and estuary water bodies. For example, wind can significantly influence the sediment dispersion patterns in a shallow lake (Sheng and Lick, 1979). And Carper and Bachmann (1984) found that sediment can be resuspended when wind velocities surpassed critical velocities as computed from wave theory in a prairie lake. Wind forcing also could affect the dispersal of a freshwater plume as it enters the coastal ocean and influence the salinity structure, circulation and residence time in estuaries (Chao, 1988; Choi and Wilkin, 2007; Geyer, 1997). Meanwhile, wind is a widely available seed spread vector in wetlands and would transport seeds to reach more sites than water (Soons, 2006). And in real wetland flows, wind can alter the velocity profile considerably, leading to large variations in environmental dispersivity (Zeng et al., 2012b). Hence, it is necessary to explore the impact of wind on both the velocity structure and the environmental dispersion in wetland flows. Meanwhile, two-layer wetlands are typical of reality (i.e., gravels or roots or submerged plants in the lower layer and stems of emergent plants in the higher layer). However, currently, no analytical solution has been proposed to analyze the effects of wind on environmental dispersion for two-layer wetlands.

So we explore the effect of wind in a more complex two-layer system in this paper. And the simplified approach of asymptotic analysis is applied, which has greater flexibility for analytical solutions. This method avoids the complexity in the asymptotic variation before dispersivity becomes steady, and instead, it simply considers the steady status of dispersivity. This is important because the corresponding long-term evolution of transport after the initial stage of a contaminant release is the process of greatest concern when focusing on the extent and duration of the contaminant concentration cloud (Chen, 2013). And indicators need to be developed for predicting the critical length of contaminant cloud in the two-layer wetlands with wind effect.

As an extension to the analysis of the effect of wind on solute dispersion in singer-layer wetlands, contaminant dispersion in two-layer wetland flows under wind is investigated analytically in this paper, in terms of the longitudinal dispersion of the depth-averaged concentration. This paper has a number of specific goals: (a) to illustrate the velocity profile for steady two-layer wetland flows under wind; (b) to investigate the analytical solution of environmental dispersivity under wind using a simplified approach; and (c) to provide an application of the analytical results for predicting the critical length and duration of the concentration cloud.

2. Formulation for momentum and concentration transport

For typical wetland flows, the basic governing equations for momentum and mass transport can be adopted at the phase-average scale as (Chen and Wu, 2012; Liu and Masliyah, 2005; Wu and Chen, 2012; Wu et al., 2012; Zeng and Chen, 2011; Zeng et al., 2011):

$$\rho\left(\frac{\partial \mathbf{U}}{\partial t}+\nabla\cdot\frac{\mathbf{UU}}{\phi}\right)=-\nabla P-\mu F\mathbf{U}+\kappa\mu\nabla^2\mathbf{U}+\kappa\nabla\cdot(\mathbf{L}\cdot\nabla\mathbf{U}), \tag{1}$$

$$\phi\frac{\partial C}{\partial t}+\nabla\cdot(\mathbf{U}C)=\nabla\cdot(\kappa\lambda\phi\nabla C)+\kappa\nabla\cdot(\mathbf{K}\cdot\nabla C), \tag{2}$$

where ρ is the density of water [kg m^{-3}], $\mathbf{U}$ is velocity [m s^{-1}], t is time [s], ϕ is porosity, P is the effective pressure including gravitational effects [kg m^{-1} s^{-2}], μ is dynamic viscosity [kg m^{-1} s^{-1}], F is the shear factor [m^{-2}], κ is tortuosity for treating the spatial structure of the porous media, $\mathbf{L}$ is the momentum dispersivity tensor [kg m^{-1} s^{-1}], C is concentration [kg m^{-3}], λ is mass diffusivity [m^2 s^{-1}], and $\mathbf{K}$ is the mass dispersivity tensor [m^2 s^{-1}].

Consider a fully-developed steady flow with constant ϕ, F, κ, L, and K through a two-layer wetland with depth $H (H = H_1 + H_2)$ under wind, as illustrated in Fig. 1. Parameters H_1 and H_2 represent the depths of layers 1 and 2, respectively, in a Cartesian coordinate system that has the longitudinal x-axis along the flow direction, vertical z-axis for the z_1 and z_2 coordinates, and the origin at the bottom.

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