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Research papers

Analysis of environmental dispersion in a wetland flow under the effect of wind: Extended solution

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A R T I C L E I N F O

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A B S T R A C T

The accurate analysis of the contaminant transport process in wetland flows is essential for environmental assessment. However, dispersivity assessment becomes complicated when the wind strength and direction are taken into consideration. Prior studies illustrating the wind effect on environmental dispersion in wetland flows simply focused on the mean longitudinal concentration distribution. Moreover, the results obtained by these analyses are not accurate when done on a smaller scale, namely, the initial stage of the contaminant transport process. By combining the concentration moments method (the Aris' method) and Gill's expansion theory, the previous researches on environmental dispersion in wetland flows with effect of wind have been extended. By adopting up to 4th-order moments, the wind effect—as illustrated by dimensionless parameters *Er* (wind force) and ω (wind direction)—on kurtosis and skewness is discussed, the up to 4th-order vertical concentration distribution is obtained, and the two-dimensional concentration distribution is illustrated. This work demonstrates that wind intensity and direction can significantly affect the contaminant dispersion. Moreover, the study presents a more accurate analytical solution of environmental dispersion in wetland flows under various wind conditions.

1. Introduction

Wetlands serve human society in many ways, such as through ecological restoration, water purification, irrigation, and so on (Costanza et al., 1989, 1997). Meanwhile, as a unique hydrological landscape, wetlands are considered ecologically sensitive and adaptive. Much attention has been given to the sustainable management of wetlands (Turner et al., 2000). As for wetland flows, analyzing the contaminant transport process is indispensable to wastewater treatment and environmental risk assessment associated with either natural or constructed wetlands (Carvalho et al., 2009; Costanza et al., 1997; US EPA, 1999).

Many studies on the environmental dispersion in wetland flows have been made. Nepf and Ghisalberti (2008) analyzed dispersivity in a wetland with emergent vegetation. As the wetland is considered a kind of porous media in the field of wetland science, based on Taylor's analysis on dispersivity (1953), the environmental dispersion in wetland flows focused on the macroscopic scale, and thus far, the contaminant transport process has been analyzed with the phase-average method (Rajagopal and Tao,1995; Liu and Masliyah, 2005) in many past studies (Chen et al., 2010; Wu et al., 2011a,b; Zeng and Chen, 2011, 2012; Chen, 2013). However, these studies only considered the velocity profile and contaminant dispersion with the absence of wind effect, which typically exists in natural wetland flows (Zeng et al., 2012).

Nevertheless, the effect of wind force on environmental dispersion should also be considered in analysis of environmental dispersion in wetland flows. Wind stress has been analyzed in the movement of water masses in the ocean (Smith, 1980; Munk, 1950). The wind is also found as an important factor for circulation in the estuary and plume (MacCready et al., 2009). Besides, wind effect has been considered in sediment dispersion pattern in a shallow lake by Sheng and Lick (1979). What's more, the wind can even lead to sediment resuspension when the wind velocity exceeds the critical value (Carper and Bachmann, 1984). Given that the wind can create a drag on the free-surface of wetland flows, the velocity profile and concentration distribution of the free-surface can be directly influenced by the wind force; the wind can even cause an inverse layer when the upstream wind force is big enough. Moreover, both wind force and wind direction can change the velocity structure and affect the environmental dispersion (Luo et al., 2017). Given that wind force and direction can indirectly influence environmental dispersion (Wu, 1969), understanding its effect is essential in environmental dispersion analysis.

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By considering wind force and direction, Zeng et al. (2012) analyzed the contaminant transport process in wetland flows under the effect of wind based on the concentration moments method proposed by Aris (1956, 1960). They obtained the mean longitudinal concentration distribution by adopting up to 2nd-order moments. On the basis of Gill's theory (Gill and Sankarasubramanian, 1970; Gill, 1967), Luo et al. (2017) analyzed environmental dispersion in wetland flows by considering wind effect via asymptotic analysis, in which they omitted the third- and higher-order derivative terms of the average concentration. However, the higher-order concentration moments, illustrating skewness (3rd concentration moment) and kurtosis (4th concentration moment) of the mean concentration distribution, the asymmetry and derivations occurring at the initial stage were not taken into account. Once the effect of wind is considered, the accuracy of approximation obtained by up to the 2nd Gill expansion cannot be satisfied. Considering the effect of wind, the dispersion model becomes too complicated when only the Taylor dispersion model is adopted; in this case, the higher-order expansion based on Gill's theory should be used to improve accuracy at the initial stage. In order to improve accuracy, Wang (2016) and Wang and Chen (2016) combined the concentration moments method proposed by Aris (1956) and Gill's expansion, resulting in an approach called the Aris–Gill method (Jiang et al., 2017).

The current work adopts up to 4th-order concentration moments and Gill expansions to analyze the environmental dispersion in wetland flows. This method not only significantly enhance the accuracy in the small time scale, it can also derive the vertical concentration distribution with the effect of wind. Although Zeng et al. (2012) and Luo et al. (2017) have analyzed the vertical concentration distribution in wetland flows under wind effect, they only gave the average-vertical concentration distribution. By adopting the 1st-order expansion of Gill's method (Gill and Sankarasubramanian, 1970; Gill, 1967), Wu et al. (2015) analyzed the multi-dimensional concentration distribution. In the present work, which aims to improve the order of solution, the two-dimensional (2D) concentration distribution is obtained. This work also examines the wind effect on the derivation of the local free-surface concentration dispersion and the local bed-surface concentration dispersion from mean contaminant dispersion.

Furthermore, this study analyzes the two-dimensional contaminant concentration distribution in wetland flows under wind effect. We extended the findings of a prior research (Wu et al., 2015) in order to investigate the wind effect on the complete contaminant process, especially at the initial time scale. We adopted the dimensionless parameters Er and ω to illustrate the wind force and wind direction, respectively. Through the Aris–Gill expansion method, the following objectives have been achieved: (a) to discuss the effect of wind on the skewness and kurtosis, (b) to obtain the wind effect on the mean concentration distribution at the initial stage by using up to fourth Hermite polynomials expansion, (c) to illustrate the complete vertical concentration distribution by adopting up to the fourth expansion of Gill's method, (d) to represent the derivation between the concentration distribution at the boundaries and the mean concentration distribution, and (e) to provide the two-dimensional concentration distribution.

2. Materials and methods

2.1. Formulation

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

In the equation above, C represents the concentration [kg m^{-3}], t is the time [s], Φ is the porosity [dimensionless], $\mathbf{U}$ is the velocity [m s^{-1}], κ is the tortuosity illustrating the spatial structure of the porous media [dimensionless], λ represents concentration diffusivity [m^{2}s^{-1}], and $\mathbf{K}$ is the concentration dispersivity tensor [m^{2}s^{-1}].

Considering that the flow is unidirectional and fully-developed in a wetland, as illustrated in Fig. 1, Eq. (1) can be simplified into

$$\frac{\partial C}{\partial t}+\frac{u}{\phi}\frac{\partial C}{\partial x}=\kappa\left(\lambda+\frac{K}{\phi}\right)\left(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2}\right),\quad -\infty<x<+\infty,\quad 0<y<H,\ t>0. \tag{2}$$

In Eq. (1), H represents the depth of the wetland.

The boundary conditions considering the non-penetrate bed and free-surface are given by

$$\left.\frac{\partial C}{\partial y}\right|_{y=0}=0,\left.\frac{\partial C}{\partial y}\right|_{y=H}=0. \tag{3}$$

As the finite amount release of contaminant, the upstream and downstream concentration condition can be written as

$$C|x=\pm\infty=0. \tag{4}$$

With the instantaneous and uniform release of contaminant, the initial contaminant condition in which mass Q is at t = 0 and at the cross-section x = 0, can be written as

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

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

Applying the dimensionless method to the parameters, we arrive at

$$\zeta=\frac{y}{H},\ \psi=\frac{u}{u_c},\ u_c=-\frac{\mathrm{dp}}{\mathrm{dx}}\frac{H^2}{\kappa(\mu+L_V)},$$
$$Pe=\frac{u_cH}{\phi\kappa(\lambda+K/\phi)},\ \tau=\frac{\kappa(\lambda+K/\phi)}{H^2}t,\ \Omega=\frac{\phi H^2}{Q}C,$$
$$\xi=\frac{x-u_c\bar{\psi}t/\phi}{H}=\frac{x-\bar{u}t/\phi}{H}.$$

The vertical-average operation is defined as

$$\bar{f}\equiv\int_0^1 f\,\mathrm{d}\zeta. \tag{6}$$

Thus, Eq. (1) turns into

$$\frac{\partial\Omega}{\partial\tau}+Pe\psi'\frac{\partial\Omega}{\partial\xi}=\frac{\partial^2\Omega}{\partial\xi^2}+\frac{\partial^2\Omega}{\partial\zeta^2},\quad -\infty<\xi<+\infty,\ 0<\zeta<1,\ \tau>0. \tag{7}$$

where $\psi'=\psi-\bar{\psi}$, and ψ' is the derivation of vertical velocity.

The boundary conditions can be rewritten as

$$\left.\frac{\partial\Omega}{\partial\zeta}\right|_{\zeta=0}=\left.\frac{\partial\Omega}{\partial\zeta}\right|_{\zeta=1}=0. \tag{8}$$

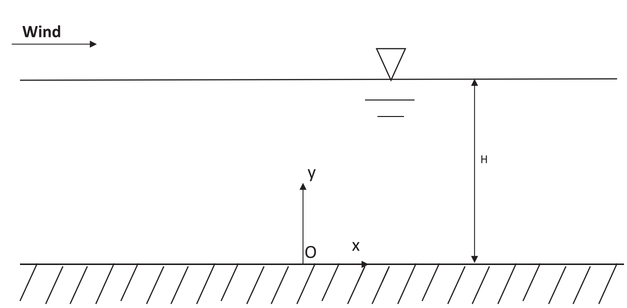

Fig. 1. Sketch for a wetland under the effect of wind.