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Indicators for contaminant transport in wetlands

L. Shao[a,b,1], Z. Jiang[a,1], Z. Li[a,*], B. Chen[c,d], T. Hayat[d,e], B. Ahmad[d], A. Alsaedi[d,**]

[a] *College of Engineering, Peking University, Beijing 100871, China*
[b] *School of Humanities and Economic Management, China University of Geosciences, Beijing 100083, China*
[c] *State Key Laboratory of Water Environment Simulation, School of Environment, Beijing Normal University, Beijing 100875, China*
[d] *NAAM Group, Faculty of Science, King Abdulaziz University, Jeddah, Saudi Arabia*
[e] *Department of Mathematics, Quaid-i-Azam University, Islamabad, Pakistan*

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ABSTRACT

Wetlands provide significant ecological services for urban regions in terms of water supply, wastewater treatment, flood storage, drought resistance, etc. For wetland flows, it is crucial to understand the process of contaminant transport as it provides scientific support for applications associated with various urban services. Two indicators respectively as the critical length and duration are frequently adopted for risk assessment of incidental release of toxic or contaminant cloud. This paper presents a review on recent progresses in the analytical study of contaminant transport in wetland flows by Taylor dispersion at the phase-average scale. The method of concentration moments is introduced. Analytical procedures for determining the key quantity of Taylor dispersivity are given for typical wetlands with free water surface, respectively as the steady flow wetlands, tidal flow wetlands, and the two-layer flow wetlands. As an example of applications, critical length and duration of the contaminant cloud in the steady flow wetlands are analyzed based on the obtained Taylor dispersivity. Results show that in contrast to the temporary, localized influence of COD on water quality, the heavy metal Pb can give rise to more severe damage.

1. Introduction

For cities as superorganisms there are numerous urban metabolism processes, including fluxes of water, materials, energy, nutrient, and wastes flowing in and out of an urban region (Kennedy et al., 2007; Shao and Chen, 2013; Zhang et al., 2009). Analyses of urban metabolism can offer indicators for urban sustainability, and the measures of energy consumption, material flows, natural resources and wastes are also necessary to quantify environmental impacts for cities (Chen and Chen, 2012; Chen et al., 2009d; Guo and Chen, 2013; Jiang et al., 2009; Kennedy et al., 2011; Meng et al., 2013; Zhou et al., 2010). As an essential ecological endowment for urban metabolism, substantial water resources are explored, consumed and then discharged as wastewater (Kennedy et al., 2007). Cumulative efforts have been made to investigate urban water metabolism in terms of water resource conservation, urban water supply assurance, flood storage, drought resistance, municipal wastewater treatment devise, intrinsic ecological values of natural water systems and so on (Chen et al., 2009a, 2010a,b, 2008, 2009d; Chen and Ji, 2007; Costanza et al., 1997; Fischer et al., 1979; Huang et al., 2007; Mitsch and Gosselink, 1993; Yuan et al., 2008; Zhou et al., 2009).

As a promising approach to treat municipal wastewater, and a primary means to maintain ecological balance, wetlands have been comprehensively studied (Chen et al., 2010a, 2013, 2008; Costanza et al., 1997; Zeng and Chen, 2009). Typical types of wetlands, such as rivers, lakes and coastal zones, provide ecological services (Chen et al., 2009a,b,c; Tilley and Brown, 2006; Wu et al., 2008; Wu and Chen, 2012). The applications of wetlands for municipal wastewater treatment and ecological restoration are associated with a number of important ecological benefits, such as coping with urban water crisis, improving effluent water quality, increasing vegetation productivity, expanding green areas, and beautifying cities (Chen et al., 2011b; Day et al., 2004). Both monetary saving and environmental benefits could be attained when a traditional wastewater treatment system was complemented by a wetland (Tilley and Brown, 2006). Nowadays, the ecological engineering of constructed wetland has been emerging for wastewater treatment due to its low cost, high efficiency, minimal operation and maintenance, and favorable environmental performance (Chen et al., 2009a,b, 2011a,b; EPA, 1999; Han et al., 2013; Kivaisi, 2001; Shao et al., 2013a,b; Vymazal, 2005; Zhou et al., 2009).

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[*] Corresponding author. Tel.: +86 1062754280.
[**] Corresponding author.
E-mail addresses: pkulizhi@163.com (Z. Li), aalsaedi@hotmail.com (A. Alsaedi).
[1] The authors contributed equally to this work.

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Contaminant transport in wetland flows is directly involved in urban water supply, water quality control and environmental risk assessment and management (Chen et al., 2010a, 2012a, 2008, 2012b; Fischer et al., 1979; Wu et al., 2011b, 2012; Zeng, 2010; Zeng et al., 2011). Understanding the transport process forms the scientific basis for associated applications. Wetlands with aquatic vegetation exhibit complicated flow behavior, leading to difficulty in assessing the fate of soluble pollutants (Shucksmith et al., 2011).

The most crucial and interesting part of the problem is that the dispersion of contaminant cloud in the fluid flows appears to be much different from the process by the mechanism of molecular diffusion (Chatwin and Allen, 1985; Fischer et al., 1979; Taylor, 1953; Wu and Chen, 2014a,b). Due to the vertical flow velocity difference in a river, for example, the apparent expansion of the contaminant cloud would be much faster than that in calm water, usually by orders of magnitude (Fischer et al., 1979; Wu and Chen, 2014a). The evolving of the size of contaminant cloud is thus of significant importance for practical purpose (Chen et al., 2010a; Wu and Chen, 2014a; Zeng et al., 2011).

Some essential indicators for the contaminant transport, namely the critical length and duration, have been suggested to address the aforementioned issue. Fig. 1 is a sketch for the indicators. After the release of the contaminant at the very beginning, the contaminant cloud will be carried downstream by the flow, and at the same time extend itself longitudinally. An initial period later, the depth-average concentration of the cloud will form a Gaussian distribution in the flow direction. Under some environment standard level, or the safe upper limit as shown in the figure, a longitudinal length of the contaminant cloud appears, with the depth-averaged concentration higher than the given value. This is the critical length for the contaminant cloud. Obviously, the critical length is a function of time that always increases from zero to a maximum and then decreases to zero again (Wu et al., 2011a; Zeng et al., 2011). And the time period for the critical length to be greater than zero is the duration of the contaminant cloud.

For pure fluid flows, the concept of Taylor dispersion has been widely applied for describing long time evolution of the concentration cloud (Elder, 1959; Fischer, 1972, 1973; Fischer et al., 1979; Ng, 2004; Smith, 1981; Wu and Chen, 2014a). This concept was first introduced by Taylor (1953) in his well-known research on soluble matter in solvent flowing slowly through a long and thin tube, and refers to the process that solutes disperse towards longitudinal direction under the combined action of lateral solute diffusion and non-uniformity of longitudinal velocity. The process is characterized as: after an initial stage of the transport, the concentration distribution across the cross-section tends to be the transverse mean concentration; if observed in a coordinate moving with the mean velocity of the cross-section, the transport process can be described by a one-dimensional diffusion equation, with a virtual coefficient known as Taylor dispersivity, far exceeding the molecular diffusivity in magnitude.

As a result of the existence of vegetation in the flow region, contaminant transport in wetland flows is much more complicated than that in pure fluid flows. Multiple spatial scales are involved: the microscopic scale characterized by the space among the stems or canopies of the vegetation, the intermediate scale as the phase-average scale, and the macroscopic scale characterized by the geometry of the configurations under concern, such as the depth or the width of the wetland channel (Zeng, 2010). Some numerical simulations (Maier et al., 2003, 1998; Zhang et al., 2013) and experimental studies (Lightbody and Nepf, 2006b; Nepf, 2012) have been implemented focusing on the microscopic scale processes. For analytical explorations, results of previous studies on the concentration transport in pure fluid flows can hardly be applied to investigate contaminant transport in wetland flows directly, as it is nearly impossible to obtain the velocity and concentration distributions at the microscopic scale owing to the irregular or even unknown geometry of the interfaces between the solid and fluid phase. Fortunately, in applications as environmental risk assessment and ecological restoration associated with wetlands, what mostly concerned is the effective concentration distribution and its temporal evolution at the intermediate scale by the phase-average operation, smearing out the microscopic concentration fluctuations and the discontinuity in space caused by the vegetation or the granular material (Zeng, 2010). Thus based on the phase-average theory, Taylor dispersion at the phase-average scale is appropriate for exploring contaminant transport in wetland flows (Chen and Wu, 2012; Chen et al., 2012a, 2010a; Wu and Chen, 2012; Wu et al., 2011a,b,c; Zeng et al., 2012).

During this paper, Section 2 introduces the general equations for momentum and concentration transport for wetland flows on the basis of phase average, the analytical approach of concentration moment method, as well as the indicators of critical length and duration of the contaminant cloud. The progresses in studying the most typical wetlands with free water surface are presented in Section 3, including the steady flow wetlands, the tidal flow wetlands, and the two-layer flow wetlands. The application of the proposed indicators for predicting the evolution of the contaminant cloud is illustrated in the last section.

2. Formulation

Once there is an instantaneous release of contaminant by the initial time over the depth of the wetlands, the evolution of the contaminant cloud can be described by two stages. At the very beginning, there is a large longitudinal gradient of the mean concentration over the depth, and the vertical concentration difference caused by the vertical variance of the longitudinal velocity is not to be balanced by the vertical diffusion driven by the vertical concentration gradient in turn, resulting in a skewed longitudinal distribution of mean concentration. As time goes by, the longitudinal gradient of mean concentration decreases, and gradually the vertical diffusion becomes capable of smearing out the vertical concentration difference, and the mean concentration tends to be in a normal distribution. Under such circumstances, the centroid of the contaminant cloud moves at the mean velocity of the flow, and the mean concentration disperses in the longitudinal direction by a virtual diffusion coefficient called Taylor dispersivity (Fischer et al., 1979; Zeng, 2010).

2.1. General equations for momentum and concentration transport

For a typical wetland flow, general equations for momentum and concentration transport can be adopted at the phase average scale as (Liu and Masliyah, 2005; Rajagopal and Tao, 1995)

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

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

where ρ is the density [kg m^{-3}], $\mathbf{U}$ velocity [m s^{-1}], t time [s], ϕ porosity, P pressure [kg m^{-1} s^{-2}], μ dynamic viscosity [kg m^{-1} s^{-1}], F shear factor [m^{-2}], κ tortuosity to account for the spatial structure of aquatic plants, $\mathbf{L}$ momentum dispersivity tensor [kg m^{-1} s^{-1}], C concentration [kg m^{-3}], λ concentration diffusivity [m^2 s^{-1}], and $\mathbf{K}$ concentration dispersivity tensor [m^2 s^{-1}]. Like viscosity for momentum transfer and diffusivity for concentration transfer valid for the description of the single phase clear water flow at the microscopic passage scale, momentum and concentration dispersivities are properties valid for the description of superficial flow at the