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Indicators for environmental dispersion in a three-layer wetland: Extension of Taylor's classical analysis

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ABSTRACT

The rapid growth of population in cities places great pressure on urban ecosystem health and management, especially on urban water supply and disposal of wastewater. To cope with urban water degradation, indicators are needed for predicting and evaluating anthropogenic impacts on wetlands. Presented in this paper is a analytical study of the environmental dispersion in a three-layer wetland in terms of the longitudinal evolution of the lateral mean concentration. An environmental dispersion model for the mean concentration in the three-layer wetland is devised as an extension of Taylor's classical formulation. The analytical results illustrate the effect of dimensionless parameters on the environmental dispersivity. Other related indicators for urban water quality assessment in three-layer wetlands, i.e., the critical length and duration of the contaminant cloud of typical contaminant constituents are illustrated and characterized.

1. Introduction

Cities are characterized as complex dynamic systems (United Nations, 2008). According to the projections of the United Nations (UN) Population Division, by 2050 two-thirds of inhabitants of the developing world are likely to live in urban areas (United Nations, 2005). Current estimates indicate that the trend toward an urbanized world will continue well into the twenty-first century as that in the past century (Brockerhoff, 2000). While the rapid growth of anthropogenic activity has led to urban sprawl and increase of urban conurbations, the ongoing urbanization consequentially consumes large amounts of resources and causes severe waste discharge, putting increasing pressures on ecosystem management to cope with ecological degradation within urban environments. A survey by the US Department of Agriculture indicated that urbanization resulted in wetland loss in nearly all surveyed watersheds (96%) and may comprise as much as 58% of the total wetland loss (United States, 1997; Opheim, 1997). Constrained by water resources shortage, the green-space coverage rate will be limited in urban area (Yuan et al., 2008). Anthropogenic and ubiquitous ecological and environmental problems, such as pollution, congestion, noise annoyance, shortages of fresh water and energy, ecological degradation, contribute to a serious threat to urban ecosystem health and development (Van Dijk and Mingshun, 2005; Jiang, 2008; Moussiopoulos et al., 2010; Han et al., 2014b). Emphasis should be, therefore, given to developing indicator systems for 'health' assessment of urban ecosystems.

Considering the different aspects of urban ecosystem health as well as various priorities and objectives, various indicators and systems modelling approaches have been developed. Among these indicators, environment or environmental quality is absolutely indispensable since it is a significant component of urban ecosystem health assessment. Environment indicator represents the effect of human activity on urban environment and vice versa the sustainment of urban environment to city life. Environment indicator was employed to compare urban and rural health by Harpham (1996). Takano and Nakamura (1998) established 459 indicators of a healthy urban ecosystem involved environmental quality. Urban fresh water supply and wastewater disposal determine the urban environment quality and further urban ecosystem health to a large extent. Water scarcity and water pollution are serious urban problems, particularly in arid and semi-arid

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countries (Galea and Vlahov, 2005). Inadequate disposal of solid waste and wastewater frequently leads to water contamination, which presents a substantial risk for city dwellers' health (Chanthikul et al., 2004). Coupled with rapid population growth, urban water quality has to burden huge pressures (Chen and Ji, 2007; Ji, 2008).

Wetlands, as important ecological infrastructures for urban sustainable development, provide numerous ecological services, for example, effective wastewater treatment, environmental and ecological restoration (Costanza et al., 1997; United States, 1999; Carvalho et al., 2009; Chen, 2013; Chen et al., 2010b; Chen and Wu, 2012; Wu et al., 2011b,c, 2012; Zeng et al., 2012a). In terms of environmental economics for wetland construction, restoration and preservation, the constructed wetland has the largest net services value in a reasonable discount rate (Chen et al., 2009b). Based on cosmic exergy as a unified thermodynamic indicator in context of ecological thermodynamics, a holistic methodology has been proposed to assess the wetland ecosystem (Chen et al., 2011b). The results suggest that the wetland ecosystem is a more environmentally friendly and sustainable approach for water treatment. In the economic aspect, a comparison between a constructed urban wetland and some conventional treatment systems was conducted, implying that constructed wetland involves more local renewable resources and less ecological cost, thus promoting the economic benefit (Chen et al., 2009a; Zhou et al., 2009). Breaux et al. (2005) conducted a study to assess compensatory wetland mitigation projects in San Francisco Bay Region for both permit compliance and habitat function. Survey results imply that economies of scale could be achieved with large scale regional wetland restoration sites. In the low-carbon assessment for urban sustainable development, the constructed wetland is considered to be favorable for achieving the low-carbon goal (Zhou et al., 2010; Chen et al., 2011a; Guo and Chen, 2013; Han et al., 2014a).

Due to the ecological importance of wetlands to cities, rapid urbanization brings about growing urban health concern on wetlands, especially on urban water, resulting in an increased demand for the knowledge of contaminant transport to accurately predict the fate of contaminants (Huang et al., 2007; Shucksmith et al., 2011; Wu et al., 2011a, 2012; Wang et al., 2013; Zeng et al., 2012b; Shao et al., 2012). To successfully combat urban wetland degradation, indicator systems for better assessment of the impact of urban development on wetlands are necessary.

The simplest dispersion of dissolved contaminants in laminar pipe flows was firstly analyzed in Taylor (1953). Taylor dispersion refers to the process that solutes disperse towards longitudinal direction under the combined action of lateral solute diffusion and longitudinal velocity non-uniformity, which results in the attenuation of peak concentrations (Fischer, 1973). It remains the most frequently used concept to describe contaminant transport in channel flows (Elder, 1959; Fischer et al., 1979; Holley, 1970; Chen, 2013; Chen and Wu, 2012; Wu et al., 2012). In the field of wetland science, the term of environmental dispersion refers to the Taylor dispersion in porous media at the environmental scale that contaminant cloud disperses towards longitudinal direction under combined action of molecular diffusion plus cross-sectional microscopic dispersion of concentration and non-uniformity of longitudinal superficial velocity (Wu et al., 2011b; Wu and Chen, 2012, 2014; Zeng et al., 2012a,b; Wang et al., 2014).

Several researchers have studied the environmental dispersion in wetlands analytically and experimentally. Based on Taylor's analysis, Elder (1959) analyzed the dispersion in an open channel, the theoretical work indicates that in such channels the dispersion coefficient varies parabolically with depth, and depends on both depth and shear velocity. Holley (1970) investigated the effects of the transverse variations of velocity on dispersion in oscillatory, estuary flow. The results indicate that both the ratio of the tidal period and the characteristic time for the turbulent diffusion affect the dispersion coefficient. Fischer (1967) developed an integral expression of the time-independent portion of the resultant conservation of mass equation over the depth. The former studies were carried out in the channel flow without vegetation. Considering the vegetation occupied in wetlands, the flow behavior and hydraulic condition were changed and became more complex (Nepf, 1999; Shucksmith et al., 2011). In wetlands that aquatic and semiaquatic vegetation occupied in the flow, the flow passage could be modeled as porous media. Nepf and her group investigated the dispersion of the contaminant in wetlands, aquatic vegetation significantly alters the mean and turbulent flow field (Nepf, 1999; Lightbody and Nepf, 2006). Chen and his fellows first rigorously derived the velocity profiles in the depth- and width-dominated wetlands, based on fluid dynamics for porous media (Zeng and Chen, 2011; Chen et al., 2010a; Zeng et al., 2011). For the wetlands with two-layer vegetation, the lower layer with submerged vegetation and the higher layer with emergent vegetation, the environmental dispersion was studied through the method of concentration moments by Chen et al. (2012).

Regarding to the more complex forms associated with natural and constructed wetlands, a three-layer wetland is typical (i.e., gravels or roots in the bottom layer, submerged plants in the internal layer and stems of emergent plants in the top layer) (Wang et al., 2013). Manes et al. (2009) explored velocity profile in layered channel flow, finding out that characteristics of velocity and turbulent are different due to the porous structure in subsurface layer, transition layer and surface layer. Velocity profile in an open channel flow with submerged vegetation has been investigated by Huai et al. (2009) using a proposed three-layer model. The submerged vegetation can be regarded as a 'new layer of channel bed', and the effects of channel bed roughness have been shielded by the submerged vegetation. Above the new layer, the flow can be sketched as two layers: the lower one within the vegetation and the upper one above the vegetation (Righetti and Armanini, 2002; Huai et al., 2009). The results revealed that the velocity profile consists of three hydrodynamic regimes, namely the upper non-vegetated layer, the outer and bottom layer with vegetation (Huai et al., 2009). Based on the velocity profile in two-layer vegetation flow, Liu et al. (2010) predicted the velocity profile in three-layer vegetation flow with free surface. Nepf (2012) described the mean and turbulent flow and mass transport flow with aquatic vegetation, indicating that the characteristics of velocity and turbulent are different due to the vegetation structures in three layers. Wang et al. (2013) applied the method of concentration moment to analyze the environmental dispersion in the three-layer wetland, and gave the prediction of the time duration and critical length of the contaminant discharged into wetlands beyond the given environmental standard level.

For the case of contaminant transport in fully developed flow in a three-layer wetland, the method of extended Taylor's classical formulation remains to be applied to analyze the environmental dispersivity. Indicators need to be set up for predicting and evaluating the critical length of contaminant cloud.

Presented in this paper is for the three-layer wetland an analytically study based on Taylor's classical work for the longitudinal dispersion of cross-sectional mean concentration under Taylor dispersion. The specific objectives of this paper are: (a) to present a formulation for the dispersion by extending Taylor's classical analysis; (b) to determine the dispersivity in the three-layer wetland; (c) to characterize the enhancement of the dispersivity by relevant dimensionless parameters; (d) to illustrate the evolution of contaminant cloud in terms of critical length and duration of an influenced region with contaminant concentration beyond given environmental standard level, which is essential in ecological impact assessment and environmental management.