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Environmental dispersion in a tidal wetland with sorption by vegetation

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ABSTRACT

Understanding of the solute transport mechanism under the effect of sorption by vegetation in tidal wetland gains its significance for environmental and ecological management. Presented in this paper is a theoretical analysis of effective environmental dispersion in a depth-dominated tidal wetland. Based on the transport in porous media, a linear sorption isotherm model is adopted to account for the sorption by vegetation, and two models for momentum and concentration transport in wetlands are given, respectively. The velocity of flow forced by oscillating pressure is derived, and the effect of dimensionless parameters on velocity pulsation is analyzed. The velocity direction may reverse in the case of pulsation amplitude larger than the mean velocity. Using Aris's method of concentration moments, we investigate the effective environmental dispersivity and concentration distribution. The effective environmental dispersivity increases over time at the initial stage to attain a steady oscillating status, the growth rate of which depends on the distribution coefficient K_D. The variations of concentration distribution with typical dimensionless parameters are determined, which turn out to be consistent with those of dispersivity. The sorption by vegetation leads to lowered concentration and delayed contaminant cloud, contributing to the dispersion.

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1. Introduction

Tidal wetlands ranging from unvegetated tidal flats to salt marshes or mangroves are ubiquitously scattered along the world's coastlines [1,2]. Intensive investigations have been carried out on tidal wetlands due to their various ecological services in water supply, drought resistance, flood storage, groundwater recharge and wastewater treatment, etc. [3–10]. As buffers between upstream ecosystems and the estuary, tidal wetlands display high aquatic vegetation diversity [11]. Dominated aquatic vegetation exert control on flow modification, as well as mass transport by accumulating and trapping solute such as organic matter, pesticides and ions, consequently contributing to the agriculture and marine matter cycles [12–18]. Differing from the steady wetlands, tidal flow pattern introduces complexity in hydrodynamics and transport process to tidal wetlands. A major concern in tidal wetlands goes to the mass transport process characterized by environmental dispersion under the combined action of tidal flow and aquatic vegetation.

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Numerous works have come out on the mechanisms of solute dispersion in water bodies since the canonical work of Taylor. The concept of Taylor dispersion refers to the process that dissolved solute disperses towards longitudinal direction under the combination of lateral solute diffusion and the transverse non-uniformity of the longitudinal velocity [19]. It has been applied to a variety of environmental flows including those in wetlands, rivers and estuaries [20–24]. In pure flow, Holley et al. explored the variation of dispersion with transverse variations of velocity in oscillatory, estuary flow [21]. His results demonstrated that the dispersion coefficient depends on the ratio of the tidal period and characteristic time for turbulent diffusion. Fischer et al. analyzed the mechanisms of transporting the solute in estuary flow, and found that the dispersion coefficient can sometimes be negative [22]. However, the negative dispersion coefficient is not reasonable in our intuition. Yasuda analytically elucidated the time-dependence of the vertically averaged dispersion coefficient $\overline{D}$ in both the steady and oscillatory flows, $\overline{D}$ is by no means negative [25]. Mondal and Mazumder numerically analyzed the solute dispersion in a tidal channel flow, revealing that for all cases the dispersion coefficient asymptotically reaches a stationary positive state [26]. Wu and Chen recently provided new physical insight into Taylor dispersion in the investigation of approach toward transverse uniformity of concentration distribution [27]. Some other existing researches on dispersion in tidal flows have also been reported [28–31]. However, all these researches were conducted for pure fluid tidal flows without the emergence of aquatic vegetation, the flow pattern and mass transport process will be complicated under the influence of aquatic vegetation.

Further endeavors have been contributed to understanding the dispersion process in tidal flows with aquatic vegetation. In tidal meadow, vegetation reduced oscillatory velocities about 30%, manifesting as damping factor to the flow [32]. To explore the dispersion in oscillating flows, Patil et al. recently conducted a laboratory experiment to quantify the wave-current-vegetation longitudinal dispersion coefficient by routing method, indicating that the shear effect increases the value of dispersion coefficient [33]. These above experimental and analytical researches focused on the micro-dispersion in terms of phase average based superficial diffusion as Taylor dispersion in the micro-flow in the porous media, belonging to hydraulics in the micro scale area. Nevertheless, the most concerned topic in the environmental area is the environmental dispersivity, concentration distribution and critical length of the contaminant cloud. It is an application of Taylor dispersion at the environmental scale, i.e. the environmental dispersion. Environmental dispersion serves as a kind of macro-dispersion, revealing the apparent results of dispersion in the concerned environmental scale. In context of mechanics of porous media flows, the mathematical dispersion models were proposed by Zeng et al. [34] and Wu et al. [35] to analyze the environmental dispersion in tidal wetlands in which the existence of vegetation is considered as porous media. However, the presence of vegetation introduces complexity not just in physical process of the environmental dispersion, but the chemical and biological reactions also need to be considered wherein [36].

A precise prediction of environmental dispersion in tidal wetlands requires a reasonable understanding of the behavior of solutes transport under the influence of hydraulic dispersion and reactions. Environmental dispersion with the effect of reaction or sorption into consideration can be defined as effective environmental dispersion, referring to the apparent solute transport in the macro scale. In wetland, vegetation as the solid phase absorbs the solute. Crum et al. experimentally studied the sorption of nine pesticides to aquatic vegetation, the results of which showed almost linear sorption isotherms [37]. The distribution coefficient K_D mainly depends on vegetation morphology, vegetation with a greater surface area had greater K_D. Rogers and Stringfellow conducted a series experiments to determine chlorpyrifos sorption to emergent vegetation, suggesting that the linear sorption isotherm dominated for all practical purposes [13]. Chang et al. further conducted a kinetic experiment to examine the sorption equilibrium model between vegetation and water, suggesting linearity of the sorption isotherm [38]. The linear equilibrium isotherm model was adopted by Chrysikopoulos et al. to characterize the macroscopic behavior of sorbing solute transport in porous media using Aris's moment analysis [39]. The results of which were in good agreement with numerical computations. For bicomponent contaminant released instantaneously in wetland flows, Zeng et al. theoretically analyzed the environmental dispersion under the combined action of reversible and irreversible reactions [40]. These researches were mainly in the case of steady wetlands. The effective environmental dispersion in the tidal wetlands under the effect of sorption remains to be characterized.

Presented in this paper is an analytical study on the effective environmental dispersion for a depth-dominated tidal wetland with free-water-surface considering the effect of sorption. The specific objectives of this paper are: (a) to present a longitudinal transport model for effective environmental dispersion in a depth-dominated tidal wetland under the combined action of hydraulic dispersion and sorption; (b) to give and illustrate the flow velocity profile; (c) to analyze the effects of dimensionless characteristic parameters on the velocity profile and effective environmental dispersivity; (d) to determine the longitudinal concentration distribution.

2. Formulation for momentum and concentration transport

For a typical wetland, the basic equation for momentum transport can be adopted generally at the phase average scale as [41–43]

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

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