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Modeling of pollutant removal by powdered activated carbon in a raw water aqueduct

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Abstract

This study provides new parameters for the use of powdered activated carbon (PAC) in a raw water aqueduct under emergency response. Here, we developed a coupled model that dynamically predicts simultaneous PAC transport and pollutant removal in the water aqueduct. To calibrate the model, we have performed a Particle Image Velocimetry (PIV) settling experiment to determine the dynamic settling velocity, PAC deposition experiments in a rotating flume to quantify the bottom shearing effects, and jar tests to determine the dynamic pollutant adsorption rate. The model was validated against a field chemical oxygen demand experiment in a water aqueduct in Shanghai (China) and a laboratory nitrobenzene flume test. Then, given a certain pollution concentration arising from an accidental pollution event, the model could be used to predict the optimal flow rate and PAC dosage for the establishment of mitigation measures.

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1. Introduction

Powdered activated carbon (PAC) treatment is a widely used and effective method of removing water pollutants, especially dissolved micro-organic contaminants (Loo et al., 2012). Its use for emergency responses in drinking water treatment plants (DWTPs), however, may be less efficient, because DWTPs usually offer a low hydraulic retention time (HRT) during which the PAC can adsorb the pollutants from the water column. To enhance the efficiency, it has been proposed that the PAC can be fed into the water aqueduct that connects the water source with the DWTP. These aqueducts are usually several kilometers long and there is a prolonged contact time during which the PAC can treat the pollutants. This idea has been implemented in some projects. For example, PAC was added to a raw water aqueduct as an emergency measure to treat the pollution released from the explosion of Jilin Petrochemical Plant in 2005, which resulted in a high nitrobenzene concentration, 3.5 times higher than the drinking water standard (Chen et al., 2006). Dedicated PAC feeding facilities were also built in Beijing and Shanghai in 2008 and 2009. The Beijing facility is located at the south-to-north diversion project of the Yangtze River and the Shanghai project is on the Huangpu River. These facilities will play an important role in treating future potential environmental pollution accidents.

For the effective operation of a PAC feeding facility, it is necessary to understand the interactions between the transport processes of PAC and the simultaneous pollutant removal in the water aqueduct. These interactive processes comprise PAC transport by advection and turbulent diffusion, sediment deposition, and PAC adsorption of pollutants. Although there is extensive literature on the PAC removal rates of a wide range of organic compounds using jar tests or pilot-scale experimental setups (e.g., Baeta et al., 2013; Ho et al., 2011; Kumar et al., 2010), little information is available on the dynamic behavior of organic pollutant removal along an aqueduct while the water is flowing and PAC is distributed into the aqueduct by a controlled method. A computational fluid dynamics (CFD) model can offer a better representation of the water flow and PAC transport along with pollutant removal in a long-distance water aqueduct. Results from the CFD studies will provide information and guidance on

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PAC transport and settling as well as on feeding rates, making it possible to provide effective treatment under various conditions developed by water resource managers and engineers.

It is known that various aspects of sediment–pollutant transport modeling in a water environment have been studied. These studies concerned the modeling of sediment dynamics in water systems (Chen et al., 2014; Choi and Lee, 2015; Kiat et al., 2008; Liu and Huang, 2009; Spencer et al., 2011; Sun et al., 2015; Wang et al., 2014; Xiao et al., 2014) and the association of pollutants with suspended sediments and erosion of pollutants in association with bed sediments (Cheng et al., 2014; Droppo et al., 2011; Liang et al., 2013; Lick, 2009; Wang et al., 2013; Yin et al., 2011). Software for the assessment of regional exposure (e.g., GREAT-ER) has also been developed to predict the spatially explicit exposure concentration of typical down-the-drain chemicals in river basins (Kehrein et al., 2015). However, these models are basically limited to uniform sediment deposition parameters as the sediments are transported from upstream to downstream reach rather than accounting for the dynamic nature of deposition related to sediment characteristics, local hydrodynamics, and so on. From this perspective, these modeling methods may be insufficient in the present problem, mainly because of potential variation in the PAC settling rate as well as the PAC adsorption rate through the water aqueduct. Therefore, a coupled PAC–pollutant removal model that incorporates dynamic PAC deposition and pollution adsorption rates is still needed to fully describe the relevant conditions and processes. In addition, dynamic transport and deposition differ from sediment to sediment, being influenced by the general properties of sediments, fluid shear stress, and so on; hence, experimental data are also required to support the model to be developed.

To date, no study has been published with respect to modeling PAC transport and its efficiency in removing pollutants in a raw water aqueduct. The purpose of this study is to develop a coupled PAC–pollutant removal model in conjunction with laboratory experiments and to provide a better understanding of how PAC works in a long-distance water aqueduct. The results of this study may reveal insights and indicate proper practice for PAC deployment in a water supply system for removal of water pollutants.

2. Methodology and numerical model

2.1. Site description

The study area is a raw water aqueduct located in Shanghai, China. As shown in Fig. 1, surface water from Songpu Bridge station of Huangpu River is conveyed to the DWTPs through four parallel closed underground aqueducts, each 16.3 km long, 3.75 m wide, and 3.25 m deep, to Caohang, where the water aqueduct system diverges into two routes. The first route extends more than 20 km from Caohang to Linjiang and then connects to five DWTPs: Yangshupu, Yangsi, Pudong, Jujiaqiao, and Nanshi; the second route guides water directly to the Changqiao DWTP. At Songpu, Linjiang, and Yanqiao, pumping stations and pressure surge tanks were installed to pressurize the flow within the long-distance trunk aqueduct. The peak flow rate of the raw water is 5.4×10^6 m^3/d.

2.2. Numerical model

To model the PAC transport in the aqueduct system, a numerical modeling system that includes a PAC transport model and a PAC adsorption model has been developed.

2.2.1. PAC transport model

A one-dimensional advection–diffusion model has been developed to describe the PAC transport within the aqueducts. The conservation of PAC mass can be described by:

$$\frac{\partial A\theta}{\partial t} + \frac{\partial Q\theta}{\partial x} = \frac{\partial}{\partial x}\left(AD\frac{\partial \theta}{\partial x}\right) - WF_d \tag{1}$$

where θ is the PAC concentration within the aqueduct, D is the dispersion coefficient in the longitudinal direction, W is the aqueduct width, and F_d is the deposition flux.

The deposition flux is given by the following equation (Krishnappan and Marsalek, 2002):

$$F_d = pw_s\theta \tag{2}$$

where w_s is the PAC settling velocity in still water and p is the probability that PAC particles will settle to the aqueduct bed, which can be given by (Krishnappan and Marsalek, 2002; Liu and Huang, 2009)

$$p = 1 - \frac{G}{G_{cr}} \tag{3}$$

where G_{cr} is the critical shear stress for PAC deposition, and G is the actual shear stressed defined by

$$G = \rho g \frac{U^2 n^2}{R^{1/3}} \tag{4}$$

where ρ is the water density, g is the acceleration of gravity, U is the cross-sectional averaged flow velocity, n is the bed roughness, and R is the hydraulic radius.

For each reach of the aqueduct, considering that the cross-sectional area of the aqueduct is constant along the longitudinal direction, Eq. (1) can be simplified to:

$$\frac{\partial \theta}{\partial t} + U\frac{\partial \theta}{\partial x} = \frac{\partial}{\partial x}\left(D\frac{\partial \theta}{\partial x}\right) - p\frac{w_s\theta}{h} \tag{5}$$

where h is water depth in the aqueduct.

For Eq.(5), its boundary condition is:

$$\theta(0,t) = \theta_0 \tag{6}$$

where θ_0 is PAC dose at the water aqueduct inlet. Assume the initial condition is zero everywhere.

Solving Eq. (6), one obtains:

$$\theta(x,t) = \frac{\theta_0}{2} f(x,t) \quad \text{for} \quad \theta \le \theta_s \tag{7}$$

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