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Research paper

A hybrid inverse-modeling technique to estimate circulation in a steady wind driven open channel flow

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Abstract

A pollutant transport model for small water bodies is proposed in this paper. This novel model uses kriging and a simple neural network in combination with limited physics to model transport of pollutants in water body instead of trying to model all natural hydrodynamic processes. This technique helps to keep the unknown parameters in the model to fewer numbers compared to models with similar spatial resolution. As such, the model is suitable for 'inverse modeling' and predicting the pollutant distribution in water bodies. The model is validated with extensive simulated data and lab scale experiments.

Keywords: Transport of pollutants; Box model; Tracer studies; Kriging; Inverse modeling

1. Introduction

Long-term protection and sustainable industrial development around water bodies require an understanding of the distribution and transport of pollutants within the water bodies. In addition to theoretical analysis based on transport equations, tracer studies have proved to be very powerful in following pollutants inside the water bodies. In general, the tracer fields represent a time-averaged picture of these processes over a long period (Garcon and Minster, 1988). Given a set of observations of tracer concentration distributed over an interior domain and on the boundaries, the use of an optimization technique enables some of the fluid flow parameters of a model to be estimated in a way that best explains the concentration profile (Wunsch, 1985, 1988). In applied mathematics, this is known as 'identification', whereas in water resources it is often referred to as 'inverse modeling' (Ljung, 2009). Inverse modeling is feasible if unknown parameters requiring calibration are few in number. As the number of unknown parameters increases, the optimization algorithm will have difficulty in converging to a true solution and the estimated parameters may lose the physical significance (Imtiaz and Baheri, 2003). Due to this limitation in estimation, model parameters are usually restricted to a small number when the parameters need calibration. Taking this into consideration, box models were typically used in tracer studies to model water bodies. For example, steady state and unsteady state box models were used to model ocean flow directions and to investigate the heat balance of world's oceans and lakes (Bolin et al., 1983; Wunsch, 1985; Garcon and Minster, 1988). A box model is an extremely coarse grid model that represents the time averaged properties of a water body. The model gives important information on the circulation of a system. However, a box model is not suitable for predicting pollutant distribution in a system when higher spatial resolution is desired. Better spatial resolution can be achieved by resolving the system into finer grids and solving convection diffusion

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equations. Reaching a solution for the convection diffusion equation requires the velocity vectors at each grid point. Due to the large number of grid points, the number of unknown parameters will be large, resulting in a large set of linear equations. System noise and measurement noise may make these linear set of equations ill-conditioned, which prohibits solution of these linear equations by matrix inversion. In those cases, velocity profiles are calculated by solving the momentum balance equation considering various forces acting on the system combined with the boundary conditions coming from the geometry of the system (Tsanis and Saied, 2007). These analytical expressions are complex, and add computational burden to the model. Also, the simplifying assumptions used to develop the physics-based model can limit the applicability of the model. In order to address these issues, we propose and test an alternative modeling approach which is simple to calibrate and, at the same time, provides spatially varying information with high resolution. In this research we put forward the hypothesis that empirical statistical modeling technique, such as ‘kriging’, can be used for modeling velocity profiles in a hydrodynamic system. The proposed model subdivides the domain into fine grids. It uses kriging and a simple neural network in combination with limited physics to model water circulation instead of trying to model all natural hydrodynamic processes. The model can be easily calibrated using ‘inverse modeling’ as it has fewer unknown parameters compared to models with a similar spatial resolution. The proposed model is validated by extensive simulation studies and experimental studies carried out in a laboratory scale setup.

The rest of the paper is organized as follows: the wind tunnel water tank experimental setup and the experiments carried out in the system are described in Section 2. The mathematical development of the transport model and circulation model are presented in Section 3. The circulation model uses a geostatistical method called kriging to interpolate the velocities. A brief introduction to kriging and the application steps of kriging to predict velocity profiles is described in this section. The inverse modeling technique is presented in Section 4. In this study we used neural network to recover key velocities in the system from concentration data. Since neural networks are not commonly used in hydrodynamic study, an introduction to neural networks is also presented in this section. In Section 5, we describe the numerical solution technique used for the solution of the mathematical model. In Section 6, the mathematical model presented in Section 3 is validated using extensive simulation and experimental data. Finally, in Section 7, the major contributions of the work are highlighted and future research needs are identified.

2. System description

The laboratory scale wind tunnel water tank system is shown in Fig. 1. The water tank with a wind tunnel is a scaled down model for water bodies with wind induced current in water. In order to account for the irregular boundaries in natural water bodies the water tank was made to be L-shaped.

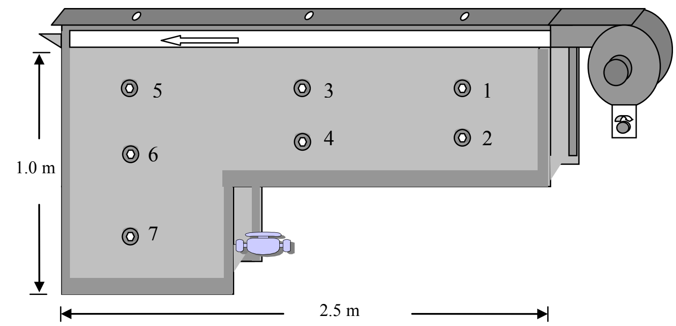

Fig. 1. Experimental setup with marked sampling ports.

Considering the fact that natural water bodies have large horizontal dimensions relative to the vertical dimension the water tank was constructed 2.5 m long and 0.7 m deep at the shallow-side, and 1 m deep at the deep-side of the tank. The width of the tank is 20 cm. Above the water surface there is a 400 cm^2 wind tunnel duct. A blower is attached to the wind tunnel via a wind box. The wind box eliminates the entrance effect of air into the wind tunnel and the perforated plate inside the wind box distributes wind evenly into the wind tunnel. The blower has a maximum capacity of 20 m^3/min of air at standard temperature and pressure. A solid-state controller attached to the setup can manipulate the rpm of the blower. The wind velocities were measured inside the wind tunnel at a distance 1 m from the entrance of the wind tunnel at different heights above the water surface with an Extech hot wire thermo-anemometer (Model M407123). Velocity profile of the wind inside the wind tunnel is shown in Fig. 2.

The circulation inside the water is driven by the wind from the blower. The water tank has seven injection ports, as shown in Fig. 1. Each port is sealed with rubber septa to facilitate the injection of dye into the system using a hypodermic syringe. Several sets of tracer experiments were carried out in the system with different combinations of wind velocity and dye injection points. The tank was filled with water and the blower was turned on, keeping the rpm at the desired set point. The blower was kept running for 2 h to allow sufficient time to stabilize the system and develop a steady circulation of water within the tank. Once steady circulation pattern has been established, Rhodamine WT dye was injected into the system.

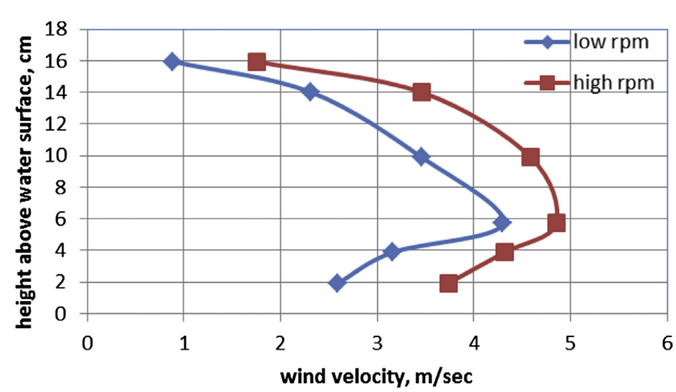

Fig. 2. Measured wind velocity profile inside wind tunnel.