Modeling the effects of gate-controlled on water quality improvement in river network

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Abstract

Suzhou River in Shanghai is one of the largest tributaries of Huangpu River and also the main contact waterways of Taihu Lake and Huangpu River, characterized by the indirect effects of the tide of the Yangtze River, belongs to the plain tidal river network. Hydrodynamic model was established with node level method to solve the discrete form of Saint-Venant equation. Finite-volume was also applied to solve the one-dimensional convection-dispersion equation. The reaction terms in the pollutant mass transport equation are illustrated via the principle of eco-chemical cycling processes of nitrogen, phosphorus, dissolved oxygen and phytoplankton. The results showed that the concentration calculation errors of Ammonia and COD in the model were in the ranges of -15%–13% and -14%–17%, respectively, which met the requirement of practical needs. Therefore, the coupled model can be applied to the simulation of water quality for Suzhou river network and similar river networks as well.

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Keywords: Suzhou River network; hydrodynamic model; water quality model; finite volume method.

1 Introduction

The Suzhou River in Shanghai is classified as a typical plain tidal river network, with a high density of population and rapid development of its economy leading to a significant change in the hydrological environment. It has been polluted seriously because of numerous and concentrated sewage emissions.

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Meanwhile, more than 20 gates are constructed in the inner Suzhou River to control the water exchange, which further aggravated the water environmental pollution [1].

Phytoplankton is the basic component of the river food chain and river ecosystem, representing the primary productivity of the river [2]. As one of the important indicators for biological monitoring and water quality monitoring, phytoplankton concentration has traditionally been used as a direct metric of water pollution level [3, 4]. This paper aims to establish a hydrological model, incorporating the phytoplankton factors into the mass transportation equation. The hydrological scenarios, such as flow by the gate switch, change in the adverse hydrodynamic conditions and variation of the water quality of the tidal river gating, are then set and analyzed.

2 Methodology

2.1 Hydrodynamic model

The tidal rivers mixed with each other due to the dynamic interactions. The water flow pattern was complex, with the diffusion and transportation non-directional. We simplified the calculation by considering the reciprocation of rivers and echoed effect of the tide and then applied the one-dimensional dynamic model of water quantity and quality cross-section to average the calculation of the tidal river.

The governing equations were based on the one dimensional unsteady flow Saint-Venant equation:

\[
\frac{\partial Z}{\partial t} + \frac{1}{B} \frac{\partial Q}{\partial x} = 0
\]

\[
\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{\alpha Q^2}{A} + gA \frac{\partial Z}{\partial x} + \frac{Q}{K^2} \right) = 0
\]

where \( Q \) is the flow (m³/s); \( B \) is the river surface width (m); \( Z \) is the water level(tidal level) (m); \( A \) is the cross section in the water area (m²); \( g \) is the gravity acceleration; \( K \) is the unit discharge; \( x \) is the space coordinates; \( t \) is the time coordinates; and \( \alpha \) is the momentum correction factor.

The Saint-Venant equation was discretized by Preissmann four-point implicit finite difference scheme to obtain the one-dimensional nonlinear equations. The external boundary condition of the calculated river was given by the water level hydrograph \( h(t) \), discharge hydrograph \( Q(t) \) or the water level, and flow process lines \( Q(h) \). The internal boundary condition was the hydraulic structures, such as dam, gate, bridge, pump station and lateral inflow. The boundary condition is given according to the features of the structures in line with the compatibility condition when the Saint-Venant equation is not effective due to the mutant of hydraulic characteristics [5].

2.2 Water quality model

The water quality model is based on the nitrogen and phosphorus circulation mechanism, considering the water quality index, point pollution source and surface pollution sources. The water quality parameters cover the ammonia, nitrate, organic nitrate, phosphorous, etc.

The one-dimensional convection and diffusion equation was used for a water quality simulation as below:
\[ \frac{\partial}{\partial t} (AC) = \frac{\partial}{\partial x} \left[ -U_x AC + E_x A \frac{\partial C}{\partial x} \right] + A(S_L + S_B) + AS_K \]  

(3)

where \( C \) is the water quality component density; \( t \) is the time; \( U_x \) is the longitudinal counter-flow speed; \( E_x \) is the longitudinal divergence coefficient; \( S_L \) is the point pollution load and non-point pollution load; \( S_B \) is the Boundary load; \( S_k \) is the source or sink term (source is positive; sink is negative); and \( A \) is the cross-sectional area.

A finite volume method is employed to solve the convection and diffusion equation. The item \( S_k \) indicates the chemical processes and the biotransformation. Ammonia, nitrate, phytoplankton, dissolved oxygen, phosphorous, organic nitrogen are considered together. \( S_k \) is described through the corresponding equation. The water quality indicators \( C_i(t) \) are chosen as the boundary condition of the single inflow river section [6-10].

3 Case study

3.1 Layout the river network

The simulated river network is located in Shanghai. The river layout is shown in Fig. 1. There are totally 120 rivers in the simplified Suzhou River network with 71 river nodes, and 20 boundary nodes, among which there are 3 water level nodes and 17 discharge nodes. The total cross section is 662. Boundary condition of the hydraulic calculation is the Huangdu water level in the upstream Suzhou River, water level in Huangpu Park and water level in Wusongkou. Simplified the given boundary conditions and consider the exchange of the water between rivers, \( C_i(t) \) was considered as the water quality index for boundary condition during the water quality simulation.

3.2 Hydrological data

The model is rated by the observation data synchronization of the hydrological data from April 1-11, 2000, at 23:00, by calculating and debugging. With the roughness of the Suzhou River being 0.020-0.030, the observation points of water level boundary are Huangdu, Huangpu Park and Wusongkou. It was rainy on April 1-16. Monitoring data from the rainfall station in Qingpu and Songjiang district were used in the runoff calculations. During the simulation, 25 gates were operated during the water transfer process, such as Wenxi gate, Yantietang gate, Fengbang gate, Xinchapu gate, and Pengyuepu gate, among others.

3.3 Water quality monitoring section data

During the water transfer process, we choose 17 water quality observation sections. The main observation index includes water temperature, COD, BOD, ammonia, DO, water color, etc. The observation sections layout is shown in Fig 1.
3.4 Pollution sources

According to the survey, industrial emissions, enterprise discharge, living water discharge, livestock emission and the catchment of the surface runoff pollution are included in the Suzhou River network in Shanghai. Based on the resources census data in Shanghai, the model concentrated the pollution source into 17 point sources within the catchment that were discharged into the corresponding rivers.

3.5 Water quality parameters

The model checks the values of ammonia, COD, BOD₅ and DO. The values of water quality parameters are [11]: diffusion coefficient $D_0=150$–$450 \text{m}^2/\text{d}$, aerobic coefficient in $20^\circ\text{C}$ $k_d=0.15$–$0.35 \text{d}^{-1}$, the temperature coefficient $\theta_d=1.05$, COD half-saturation coefficient $k_{COD}=0.4 \text{mg/L}$, $20^\circ\text{C}$ nitrification coefficient $k_{12}=0.09$–$0.13 \text{d}^{-1}$, temperature coefficient $\theta_{12}=1.08$, half-saturation coefficient $k_{NIT}=0.5 \text{mg/L}$, reaeration coefficient $k_2=4.1$–$4.7 \text{d}^{-1}$, and temperature coefficient $\theta_2=1.02826$.

3.6 Validation

The real-time monitoring data in Pengyuepu gate, Beixinjing gate, and Zhejiang Road Bridge and the calculation of the water level and water flow were consistent. The comparisons between the measured water flow and the calculated one are shown in Fig.2. The average error is less than 24% due to potential monitoring error and over simplified of the cross section.
3.7 Water quality results

The comparisons between the simulated ammonia and COD concentration are shown in Figs. 3-4. The calculated and the measured values had an overall good agreement.
By comparing the calculated results of water quality and water flow of the Pengyupu gate, Beixinjing gate, Zhejiang road bridge, Yantietang gate, and when cited, the diversion of water in the Yantietang gate, the concentrations of ammonia and COD reduced, and the water quality was justified. In addition, the water quality in the monitoring sections of Zhejiang Road Bridge had clear differences due to the water quality sampling taken near the gate due to the water level fluctuation.

4. Conclusions
Some major restoration projects for the Suzhou River were ongoing during the investigation period, such as closure, interception, water transfer, artificial aeration, dredge and coastal landscape transformation, etc., which would make the disturbances of phytoplankton inevitable. Meanwhile, the high nutrient level was one of the basic reasons for the composition and volume change level of the phytoplankton. Considering the nutrient factor, when TN and TP concentrations reached 0.02mg/L and 0.2mg/L, respectively, phytoplankton bloomed [12-14]. During the simulation period, phytoplankton concentration in the Suzhou River network increased rapidly.

The calculation errors of ammonia and COD were in the range of -15%-13% and -14-17%, respectively. Considering the measurement error, the precision of the water quality model can meet the engineering requirement. The coupled model can be used to simulate the water quality of similar river network that is influenced by tidal, which could be regarded as a first step towards the hydrological scenario analysis covering flow velocity and its effects on phytoplankton.

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