The water environmental governance for tidal lakes based on water ecology model

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Abstract: The problem of water eutrophication is one of the most serious environmental pollution problems in the Pearl River Delta tidal region. According to the water environmental governance for tidal lakes, a water ecology numerical model is developed based on the two-dimensional shallow water equations and the convection-diffusion equation. The proposed model considers eight water quality indices, and their interactions are modeled by four subsystems. The proposed model is applied to a tidal lake in the Pearl River Delta, and the spatial and temporal distribution of the chlorophyll-a under different scheme of water replacement is simulated, which gives the data support for water replacement scheme optimization. Results show that the proposed method can provide evidence for the control of water eutrophication in tidal lakes.
Keywords: water environmental governance; water ecology model; tidal lakes; numerical simulation

1. Introduction

The problem of water eutrophication is one of the most serious environmental pollution problems in the Pearl River Delta tidal region. From the aspect of environmental water area, the hydraulic control technology which transforms the natural reciprocating flow to the unidirectional flow by sluice-operation is a very useful tool for water environmental governance, and this technology have been widely used in the complex urban river network of Pearl River Delta tidal region. Hydrodynamic models based on the two-dimensional shallow water equations (Canestrelli et al. 2010; Song et al. 2011(a, b); Xing et al. 2011) are traditional tools for the gate controlled flow modeling, which should provide support for the sluice scheduling. Moreover, various flow-transport models (Begnudelli and Sanders 2006; Cai et al. 2007; Zhou et al. 2015) could be used to predict the pollutant transport in flows. However, those models only simulate hydrodynamic states and single water quality index such as COD or NH_3-N, and the interactions among water quality indices are simply generalized by an empirical degradation coefficient. Since their interactions are very complex and highly nonlinear, the empirical degradation coefficient would produce much numerical errors, and a water ecology numerical model which adopts the eutrophication theory should be developed for high-precision predicting.

This paper develops a water ecology numerical model based on the two-dimensional shallow water equations and convection-diffusion equation. The proposed model considers eight water quality indices, including dissolved oxygen (DO), ammonia nitrogen (NH_3-N), nitrate nitrogen (NO_3-N), organic nitrogen (ON), inorganic phosphorus (OPO_4), organic phosphorus (OP), carbon biochemical oxygen demand (CBOD), and chlorophyll-a. The interactions of the eight water quality indices are modeled by four subsystems of the dissolved oxygen balance, nitrogen cycle, phosphorus cycle, and phytoplankton dynamics. The proposed model is applied to a tidal lake in the Pearl River Delta, and the spatial and temporal distribution of the chlorophyll-a under different scheme of water replacement is simulated, which gives the data support for water replacement scheme optimization. Results show that the proposed method can provide evidence for the control of eutrophication in tidal lakes.

2. Numerical Model

2.1 Governing equations

The two-dimensional shallow water equations and convection-diffusion equation are given by,

$$\frac{\partial \mathbf{U}}{\partial t}+\frac{\partial \mathbf{E}}{\partial x}+\frac{\partial \mathbf{G}}{\partial y}=\mathbf{S} \tag{1}$$

in which,

$$\mathbf{U}=\begin{bmatrix} h \\ hu \\ hv \\ hc \end{bmatrix} \qquad \mathbf{E}=\begin{bmatrix} hu \\ hu^2+g(h^2-b^2)/2 \\ huv \\ huc \end{bmatrix} \qquad \mathbf{G}=\begin{bmatrix} hv \\ huv \\ hv^2+g(h^2-b^2)/2 \\ hvc \end{bmatrix}$$

$$\mathbf{S}=\begin{bmatrix} q_{in} \\ g(h+b)S_{0x}-ghS_{fx} \\ g(h+b)S_{0y}-ghS_{fy} \\ \frac{\partial}{\partial x}(D_x h\frac{\partial c}{\partial x})+\frac{\partial}{\partial y}(D_y h\frac{\partial c}{\partial y})-khc+q_{in}c_{in} \end{bmatrix}$$

where h is the water depth; u and v are velocities; c is the concentration; b is the bottom elevation; q_{in} is the discharge of point source; $S_{0x}= -\partial b/\partial x$ and $S_{0y}= -\partial b/\partial y$ are bed slopes; S_{fx} and S_{fy} are bottom friction terms, $S_{fx}= n^2u(u^2+v^2)^{1/2}h^{-4/3}$ and $S_{fy}= n^2v(u^2+v^2)^{1/2}h^{-4/3}$; D_x and D_y are the coefficients of diffusion; t is the time; g is the gravity acceleration.

2.2 Numerical methods

The Godunov-type, well-balanced, unstructured finite volume method is adopted for the numerical solution of the two-dimensional shallow water equations and convection-diffusion equation. See Song et al. (2011a, b) and Zhou et al. (2015) for the details of the method. It should be noted that the numerical model is second-order accurate in space and time, and various test cases with exact or theoretical solutions are used for model validation, see Song et al. (2014).

2.3 The eutrophication model

The eutrophication model of WASP (Water Quality Analysis Simulation Program) is adopted in this paper. The model considers eight water quality indices, including dissolved oxygen (DO), ammonia nitrogen (NH3-N), nitrate nitrogen (NO3-N), organic nitrogen (ON), inorganic phosphorus (OPO4), organic phosphorus (OP), carbon biochemical oxygen demand (CBOD), and chlorophyll-a. The interactions of the eight water quality indices are modeled by four subsystems of the dissolved oxygen balance, nitrogen cycle, phosphorus cycle, and phytoplankton dynamics. See Wool et al. (2001) for the details of the eutrophication model.

The transfer of chlorophyll-a is governed by phytoplankton dynamics, and the growth rate is given by,

$$G_p = k_{gr}\theta_{gr}^{(T-20)} F_{RI} F_{RN} \tag{2}$$

in which, k_{gr} is the best growth rate in the water temperature of 20°; θ_{gr} is the adjust coefficient of temperature; T is the water temperature. F_{RI} is the limiting factor of lights, which is given by,

$$F_{RI} = \frac{ef}{K_e h}\left[\exp[-\frac{I_a}{I_s}\exp(-K_e h)] - \exp(-\frac{I_a}{I_s}) \right] \tag{3}$$

in which, f is the sunshine ratio; K_e is the extinction coefficient; I_a is the light intensity at water surface; I_s is the saturated light intensity.

and the F_{RN} is the limiting factor of nutrients, which is given by,

$$F_{RN} = \min\left(\frac{C_{\mathrm{NH_3\text{-}N}} + C_{\mathrm{NO_3-N}}}{C_{\mathrm{NH_3\text{-}N}} + C_{\mathrm{NO_3-N}} + K_{mN}}, \frac{C_{\mathrm{OPO_4}}}{C_{\mathrm{OPO_4}} + K_{mP}} \right) \tag{4}$$

in which, C is the concentration; K_{mN} is the half-saturated concentration of Nitrogen intake; K_{mP} is the half-saturated concentration of Phosphorus intake.

The death rate of phytoplankton is given by,

$$D_p = k_{par} + k_{grz} + k_{r2}\theta_{r2}^{(T-20)} \tag{5}$$

in which, k_{par}+k_{grz} is the non-predation death rate of phytoplankton; k_{r2} is the endogenous respiration rate of phytoplankton; θ_{r2} is the adjust coefficient of temperature.

3. Application

3.1 Overview

The study area is an artificial lake in the complex urban river network of Pearl River Delta tidal region. The area of the artificial lake is about 0.4 km^2. This eco-hydraulic engineering have two main functions, i.e. flood control and drainage, and ecological environment construction. To maintain the water quality and scenery of the lake, especially to control the blue-green algae blooms, the hydraulic control technology which transforms the natural reciprocating flow to the unidirectional flow by sluice-operation is used. To optimize the water replacement scheme, the proposed water ecology model is used for chlorophyll-a simulation.

The normal water level of the lake is 0.9 m, and the average bottom elevation is -2.1 m. The water storage is about 120 million cubic meters. The inlet and outlet is controlled by gates with the same size, which is of 24m width and 4.5m height. Fig.1 is the diagram of the lake.

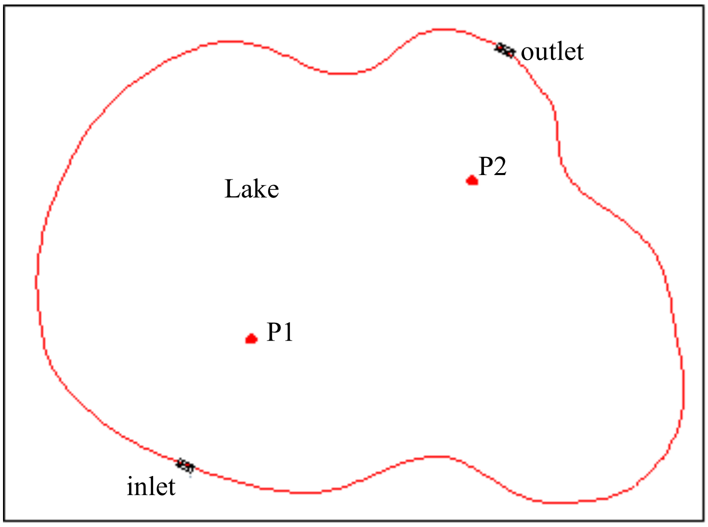


Fig.1 Layout schematic diagram of the lake

Through the field survey, investigation and water monitoring analysis to the channel near the inlet, the average concentration of TN, NH_3-N, NO_3-N, TP, COD and Chl-a is about 4.06 mg/L, 0.60 mg/L, 3.28 mg/L, 0.11 mg/L, 32.08 mg/L, and 6.04 μg/L, respectively, which belongs to the national standards poor five kind of water quality. Moreover, the comprehensive trophic level index of the lake is 64.43, which belongs to the moderately eutrophic state. As the new artificial lake has no original ecosystem through long-term natural selection, it has a poor self-purification capacity, and the pollutant such as Nitrogen and Phosphorus would be accumulated easily in the lake, inducing further the blue-green algae blooms. So the water eutrophication and the blue-green algae blooms is the most severe ecological environment problem in the lake.

3.2 The growth rate of blue-green algae

The growth rate of blue-green algae is a very important parameter of water ecology model. To obtain the growth rate data, a series of laboratory experiment are carried out using the microcystis aeruginosa, which is the dominant species of cyanobacteria in the Pearl River Delta tidal region. The experimental condition are: light intensity 5000 lux; relative humidity 40%-60%; the ratio of light to dark 12h:12h; the temperature 27-30.5°C; the PH 7.6; the concentration of TN 4.0 mg/L; the concentration of TP 0.10 mg/L. The nitrogen and phosphorus is supplied daily to maintain the concentration of nutrient.

The absorbance (OD) is measured daily (see Fig. 2), and the algal density is equal to $6561.3\times e^{1.2203\times OD}$ (number of algae / mL). Using the measured data, the maximum growth rate of blue-green algae is computed to 1.85/d, and the average death rate is 0.32/d. Those parameter values will be further modified by model according to the water temperature, light intensity, the concentration of nitrogen and phosphorus, and so on (Salacinska, 2010).

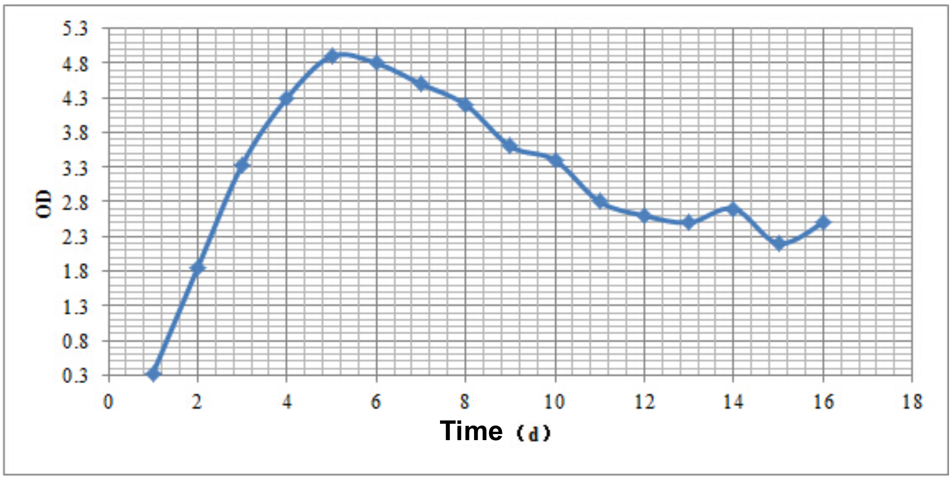


Fig.2 Growth curve of cyanobacteria

3.3 Parameter calibration

As the concentrations of inorganic nitrogen and inorganic phosphorus are relatively high, with very low limiting effect on algae growth, so the limiting factor of nutrients F_{RN} was set to 1.0. Other parameters were set as: k_{gr} = 1.85; θ_{gr} = 1.068; f = 0.6; K_e = 2.5; I_a = 650; I_s = 350; k_{par}+k_{grz} = 0.32; k_{r2} = 0.125; θ_{r2} = 1.028.

Both the numerical and experimental results of the chlorophyll-a concentration at two surveillance sites P1 and P2 (see Fig. 1) are presented in Fig. 3. Result comparison shows a well agreement between numerical result and experimental data, validating that the selected parameter values are reasonable for the artificial lake, and thus could be used for chlorophyll-a simulation under water replacement condition.

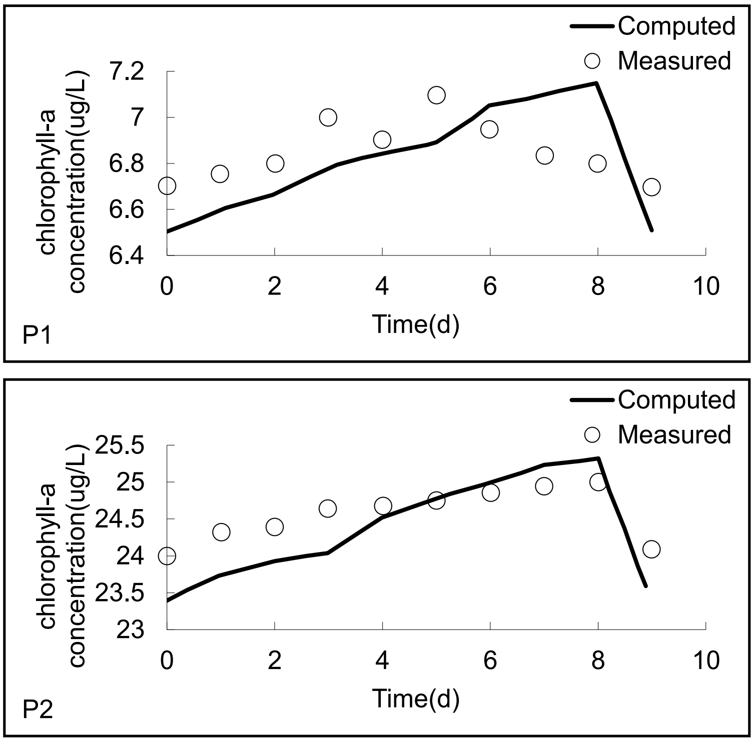


Fig.3 The comparison of numerical and measured results

3.4 Chlorophyll-a simulation

Take the summer, at when the blue-green algae outbreak often, as example, the distribution of Chlorophyll-a concentration is simulated under different water replacement schemes to evaluate the optimal scheme. Considering some limitation such as water abstraction and electricity consumption, the water replacement period is expected as long as possible. However, to maintain the water quality and scenery of the lake, especially to control the blue-green algae blooms, the water replacement period should not be too long. As the average bottom elevation of the lake is -2.1 m, and the lowest water level should be controlled to 0.6 m due to the scenery limitation, the ratio of exchanged water volume is about 10% for every cycle of water replacement. For a water replacement cycle, during the period of ebb-tide, the inlet gate is closed, the outlet gate is open, and then the water flows out from the lake until the water level of the lake reduced to 0.6m; during the period of flood-tide, the inlet gate is open, the outlet gate is closed, and then the water flows to the lake until the water level of the lake rise to 0.9m.

Three typical schemes are considered: the water exchange rate is 10%, and the water replacement period is 7d (case 1), 9d (case 2), and 11d (case 3), respectively. Fig. 4 presents the typical, combined velocity field during both the water diversion and drainage periods. Hydrodynamic results show that the flow direction is more or less same near the central line from the inlet gate to the outlet gate. Due to the lake boundary, local circumfluence occurs at both sides of the line.

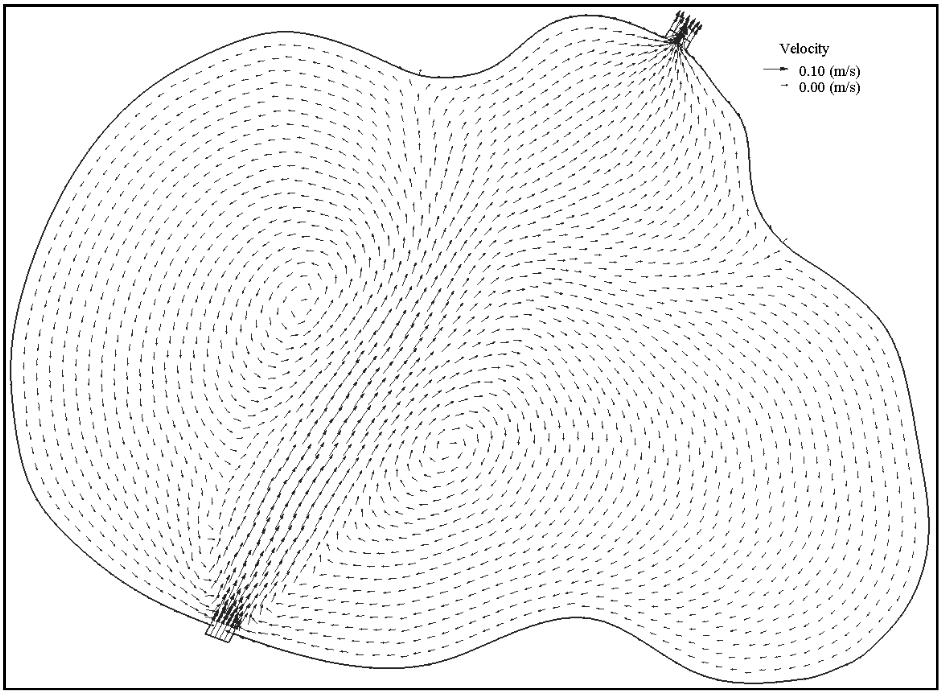
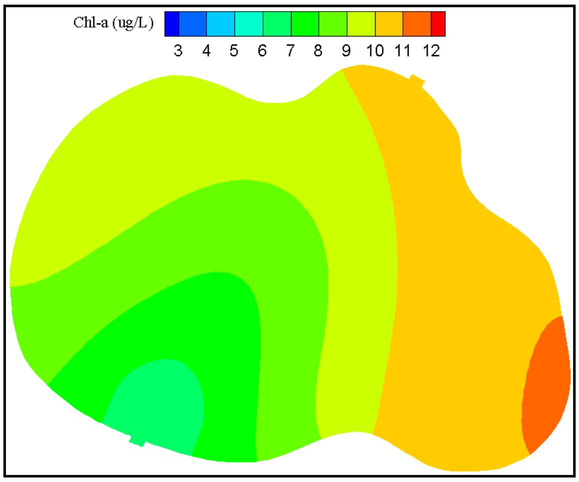
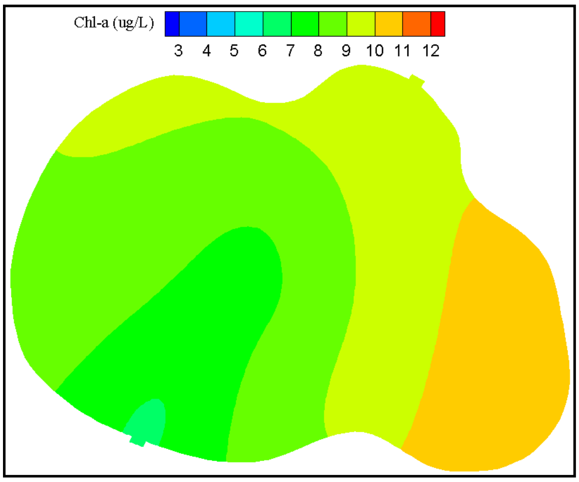


Fig.4 The typical, combined velocity field

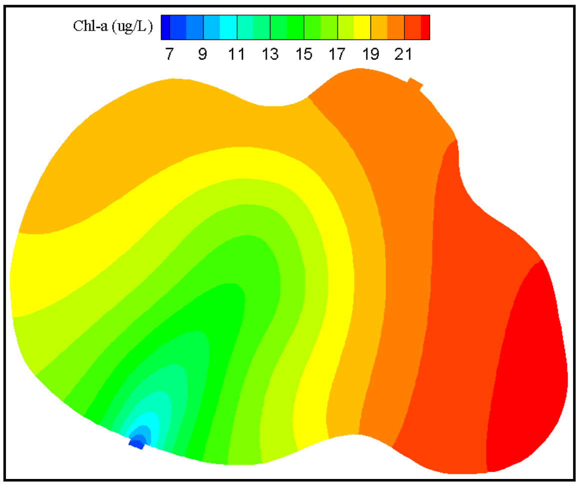
Fig. 5 presents the distribution of chlorophyll-a concentration at different case. Results show that cases 1 and 2 are satisfied the need for water quality improvement, while case 3 is not satisfied the need. In case 2, the chlorophyll-a concentration is about 6-10μg/L near the inlet gate, is about 13-19μg/L in the middle area of the lake, and is about 20-25μg/L in the southeast region. Overall the chlorophyll-a concentration is controlled to 20μg/L or lower. So case 2 is the optimal scheme, i.e. the water replacement period is relatively longer, and the need for water quality improvement is satisfied.



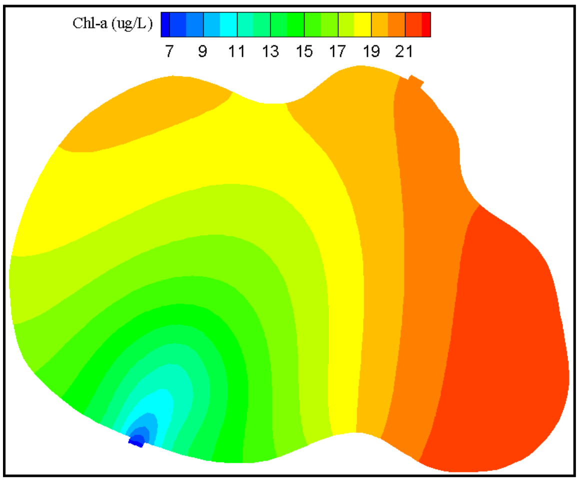
(a) 7days before water replacement (case 1)



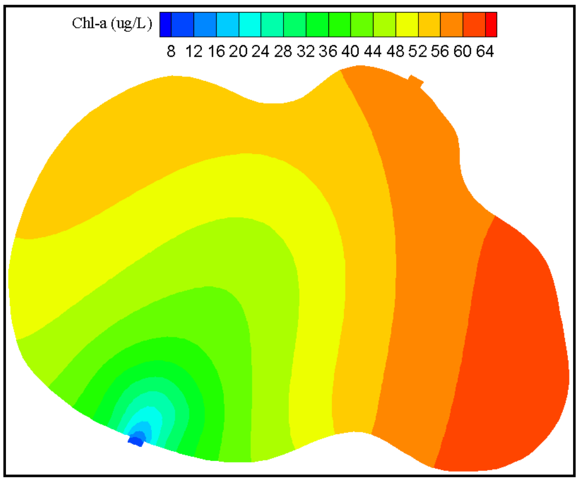
(b) after water replacement (case 1)



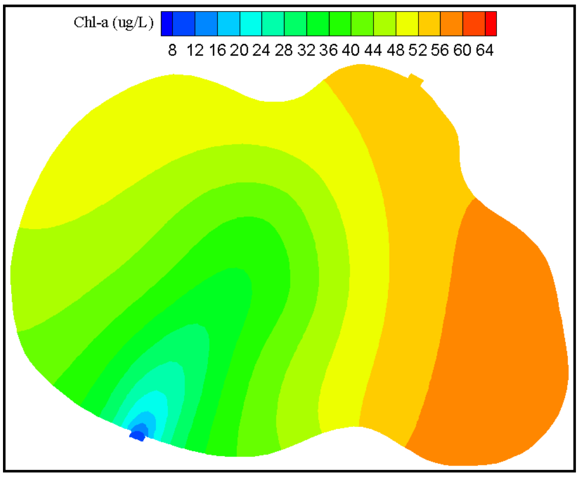
(c) 9days before water replacement (case 2)



(d) after water replacement (case 2)



(e) 11days before water replacement (case 3)



(f) after water replacement (case 3)

Fig.5 The distribution of chlorophyll-a concentration at different case

4. Conclusions

According to the water environmental governance for tidal lakes, a water ecology numerical model is developed based on the two-dimensional shallow water equations and convection-diffusion equation. The proposed model considers eight water quality indices, including dissolved oxygen (DO), ammonia nitrogen (NH_3-N), nitrate nitrogen (NO_3-N), organic nitrogen (ON), inorganic phosphorus (OPO_4), organic phosphorus (OP), carbon biochemical oxygen demand (CBOD), and chlorophyll-a. The interactions of the eight water quality indices are modeled by four subsystems of the dissolved oxygen balance, nitrogen cycle, phosphorus cycle, and phytoplankton dynamics. The proposed model is applied to a tidal lake in the Pearl River Delta, and the spatial and temporal distribution of the chlorophyll-a under different scheme of water replacement is simulated, which gives the data support for water replacement scheme optimization. Results show that the proposed method can provide evidence for the control of eutrophication in tidal lakes.

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