Evaluation of water environmental capacity using a total optimized method — A case study of the guan river estuary in Jiangsu, China

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Received 7 August 2013; revised 13 September 2013

Two pollution-creating sources adjacent to the Guan River Estuary (i.e., Guan River and Xinyi River, that fed into Guan River at its mouth) were investigated in this work. A mathematical model is established for simulation analysis of the water environment of Guan River Estuary. Simulation results are verified with measured data experimentally from 12 monitoring stations in July 2007. Annual pollutant discharge of the two rivers were calculated, and the environmental capacity of Guan River Estuary was also evaluated. The dynamic relations of pollution-creating sources of the two rivers can result in the maximum amount and optimal layout of pollution discharge of Guan River and Xinyi River. Present study reveals that amounts of N and P discharged into the two rivers were substantially excessive, and adjacent water quality was below the third- and fourth-class water standard of China.

[Keywords: Environmental capacity, Numerical simulation, Water quality standard, Maximum pollutant load, Optimal pollution load allocation]

Introduction

Guan River Estuary, situated in the south part of Haizhou Bay, features complex underwater topography, and it discharges into wide areas of sea water. The estuarine water flow of Guan River converges a variety of flows such as tidal current, runoff, coastal current, and wave, whereas the Xinyi River and the Nanchao River feed into the main channel of Guan River at its mouth, resulting in a crisscrossed river network.

A number of works have traced the pollutants discharged into the Guan River Estuary. For example, Li¹ monitored the water quality at the mouths of coastal rivers in Jiangsu Province, indicating that the levels of major nutrient salts and petroleum in the Guan river exceeded the water quality standard. Dou² analysed the water-quality conditions of the Guan River adjacent area, denoting that the levels of major nutrient salts containing nitrogen (N) and phosphate (P) exceeded the water quality standards. More recently, Ma et al.³ surveyed the water quality conditions of the Guan River Estuary and the Sheyang River Estuary and estimated the annual discharge of the main pollutants into the nearby sea water. They found that the pollution index of the Guan River water quality increased year by year without limitation to these cases, these findings indicate that the water environment of Guan River Estuary has been subjected to substantial pollution. To a large extent, there is lacking of research methodologies for a total control of pollutant discharge through the Guan River.

Present study consists a mathematical model is established for dealing with this issue, from simulation analysis of the water environment of Guan River Estuary to verification of simulation results of water quality with measured data. Considering the complex environmental dynamics of the Guan River, the maximum pollutant load and the optimal pollutant load allocation of each pollutant source in the Guan River and the Xinyi River would be obtained based on the verified numerical simulation results using a total optimized method. This method comprehensively takes into account the dynamic relations of the pollutant sources.
Materials and Methods

The Guan River is situated in the north of Jiangsu Province, China. It is the largest tidal river that discharges into the sea in the northern Jiangsu area. The main stream of Guan River is 74.5 km in full-length. The river is generally 350 m in width and 7–11 m in depth. The drainage area is 8000 km$^2$. The annual runoff is approximately 15×10$^8$ m$^3$. The measured maximum velocity is 2.34 m/s.

Internally, the river is connected to the Yangtze River and the Huai River through the Yan River and the Beijing-Hangzhou Grand Canal. Externally, it is connected to Japan and Korea through the Yellow Sea, East Sea, Bo Sea, and South Sea. Overall, the Guan River has excellent collection and distribution conditions, and it is a idea researching model among sea-river, river-river, and river-land connection.

According to simulation proceedings, the mesh generation in the Guan River Estuary study area is shown in Fig. 1. The step length of the calculating space is set as 20–2000m. They account to a total of 5267 grid cells and 11016 grid nodes. Grids in the marine space adjacent to the estuary have been refined as well. The distribution of water quality monitoring stations in the study area is shown in Fig. 2.

Evaluation methods for the environmental capacity

Previously, a large body of work was conducted on the evaluation of marine environmental capacity$^{4-6}$. Due to the complex marine environmental conditions and dynamic pollutant discharge, it is difficult to accurately calculate the environmental capacity within a certain region. Comparably, we have undertaken comparative collections (manmade collections of raw marine data measured from survey boat and references by literatures$^{7,8}$

The total optimization method, which introduces optimal thoughts into the calculation of the environmental capacity, can deduce the maximum pollutant discharge and the optimal pollutant-discharge layout by calculating linear norms specified by the restrictive condition of the environmental quality. The significant advantage of this method is integrally taking into account the dynamic relations of various pollutant sources inside the marine area (water bodies), so as to obtain the optimal pollutant-discharge layout and the maximum pollutant discharge. To date, the total optimization method has been widely used in research of the environmental capacity$^{7,8}$.

In fact, the larger the environmental capacity is, the more pollutants can be loaded; and vice versa. If merely specifying the allowable pollutant concentrations of each pollutant source but taking no account the maximum workload of the environment, the total pollutants discharged into the sea would exceed the water quality standard and cause pollution damage even though the pollutant discharge in each pollution area probably meets the water quality standard$^9$. If the total pollutants that enter the sea are confined within the permissible carrying capacity and the pollutant load capacity of each pollutant source is simultaneously restrained within the total pollutants, then, the water environmental quality of the sea areas will maintain a good state$^{10,11}$.
The total optimal method derives the environmental capacity using the linear programming technique with water quality target as the constraint condition and the maximum load of pollutant sources as the target function. Based on the calculation of the response coefficient field of each pollutant source at unit load, the linear program used for calculating the water environmental capacity of pollutant is listed as follows:\cite{12, 13}:

$$\max L = \sum_{j=1}^{n} Q_j$$  \hspace{1cm} (1.1)

The constraint condition is:

$$C_{0j} + \alpha Q_j \leq C_{si}, \quad i = 1, \ldots, m$$
$$Q_j \geq 0, \quad j = 1, \ldots, n$$  \hspace{1cm} (1.2)

In the Formula (1.1), $i$ is the serial number of water-quality control point; $j$ is the serial number of pollutant source; $m$ is the quantity of water quality control points; $n$ is the quantity of pollution-creating sources; $Q_j$ is the pollutant discharge of the $i$-th pollution source; $C_{0j}$ is the background concentration of water-quality control point; $\alpha_i$ is the response coefficient for the $j$-th source of pollution at the $i$-th water-quality control point; and $C_o$ is the standard concentration of water quality at the $i$-th water-quality control point.

In the Formula (1.2), it is actually the concentration of the water-quality control point on the left side. Because of the linear diffusion model of water quality, the concentration has additivity. Thus, it is practicable to calculate the concentration of a certain point using the linear superposition method.

**Establishment of the water quality model**

The control equation of water quality is given as follows:

$$\frac{\partial c}{\partial t} + u \frac{\partial c}{\partial x} + v \frac{\partial c}{\partial y} - D_x \frac{\partial^2 c}{\partial x^2} - D_y \frac{\partial^2 c}{\partial y^2} - \sigma + k c = 0$$  \hspace{1cm} (1.3)

where $h$ is the depth of water; $c$ is the concentration of pollutant; $t$ is the time; $u$ and $v$ are the velocity in $x$- and $y$-direction, respectively; $D_x$ and $D_y$ are the diffusion coefficient in $x$- and $y$-direction; $\sigma$ is the source sink term; and $k$ is the attenuation coefficient of pollutant.

The open boundary conditions are shown as below:

$$\left\{ \begin{array}{l}
\left( \frac{\partial c}{\partial x} \right)_{x = \Gamma} = 0 \\
\left( \frac{\partial c}{\partial y} \right)_{y = \Gamma} = 0 \\
\end{array} \right. $$  \hspace{1cm} (1.4)

Where $\Gamma$ is the open boundary of water area, and $c^*(x, y, t)$ is the concentration of known pollutant.

During the calculation of the hydrodynamic coefficient, Manning settings have great influence on the calculation results. Considering the Manning value is a comprehensive index to measure the boundary shape of bed (irregular or not) and to detect the surface roughness of bed, in our calculation, the Manning coefficient in our river model is set as 0.031, coastal and estuarine being at 0.024 and off the coast of 0.018. In addition, calculation of pollutant diffusion was primarily dependent on the diffusion coefficient and degradation coefficient.

According to the empirical formula\cite{14}:

$$(D_x, D_y) = 5.93h\eta^2n\eta^{-6}(u, v)$$

where $\eta$ is the Manning coefficient. In such model, the degradation coefficient is pertinent to flow characteristics, marine species and quantity, the gas transferring velocity, concentration and hydrological conditions and other factors, and degradation coefficient will be around 0.02~0.07d\(^{-1}\) when the hydrology in 10~28 °C\cite{14}.

According to the actual situation of irrigation estuary, when the temperature approach 15 °C, then, the degradation coefficient region is 0.047 d\(^{-1}\).

**Results and Discussion**

Look the pollution-creating sources of Guan River and Xinyi River as the research objectives, a water quality model is then established for numerical simulation of pollutant diffusion in the Guan River. Monitoring data are those of N, P, and chemical oxygen demand (COD) collected from 12 adjacent monitoring sites in July 2007. The calculation results of the water quality model and the measured data obtained in field are compared in Fig. 3. It can be seen that the two sets of data have small relative errors (e.g., <40%), except for those of N level at the sites 1 (40.2%) and 4 (56.7%) and that of P level at the site 9 (39.6%). These results indicate the calculated data are generally accurate and the established water quality
model can very well reflect the situation of pollutant discharge of the Guan River and the Xinyi River.

According to the simulation results of the proposed model for water quality combined with the measured data from the 12 monitoring stations, the annual discharge of major pollutants of the Guan River and the Xinyi River are calculated (Table 1). Thus, the annual discharge of N is 44623 t in the Xinyi River and 5490 t in the Guan River. The annual discharge of P is 3270 t in the Xinyi River and 954 t in the Guan River. Furthermore, the annual discharge of COD is 48483 t in the Xinyi River and 16350 t in the Guan River. These results presented above are generally consistent with those previously reported by other studies in the Guan River estuarine area. In particular, Ma et al. have recently reported the water quality monitoring data of the annual discharge of COD in Guan River Estuary in 2007, i.e., 14604.6 t. Taken together, we can see that the numerical model proposed in the present study is accurate and reasonable for simulation analysis of water quality in the Guan River Estuary.

In this study, Guan River and Xinyi River are taken as the pollution-creating sources, and the sum of the maximum pollutant discharge of the two rivers are set as the pollutant discharge target. According to controlling target for water quality and the background pollutant concentrations of each control point, as well as the pollution contribution coefficients of each pollution-creating source per control point, we list the constraint conditions of linear programming. Further, the linear programming is undertaken according to the objective function. Thus, the optimal solutions, i.e., the maximum pollutant discharge of each pollution-creating source can be obtained accordingly.

The evaluation standards are referred to the Water Quality Evaluation Standards of China (GB3097-1997). The water quality evaluation standard for major control indices is summarized in Table 2.

The control condition can be summarized as: the seawater quality of the Guan River Estuary meets the second class of the Sea Water Quality Standard of China (Table 2). The annual pollutant discharge of Guan River and Xinyi River are calculated using the established model for water quality. Then, taking the

Table 1: The pollutant discharge of Guan River and Xinyi River that meets the second-class sea water quality standard (unit:t/a)

<table>
<thead>
<tr>
<th>Objective</th>
<th>Guan River</th>
<th>Xinyi River</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current discharge</td>
<td>Maximum permissible discharge</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>5490</td>
<td>3300</td>
</tr>
<tr>
<td>Phosphorous</td>
<td>954</td>
<td>954</td>
</tr>
<tr>
<td>Chemical oxygen demand</td>
<td>16350</td>
<td>16365</td>
</tr>
</tbody>
</table>
target of water quality as the constraint condition, the total pollutant discharge of the two pollution-creating sources would be obtained using the total optimization method. The water quality is evaluated according to the Sea Water Quality Standard of China (Table 2). The current (annual) discharge, permissible discharge and the residual capacity of N, P, and COD are shown in Table 2.

Results show that current discharge of inorganic N is twice the permissible discharge of N in the Guan River and far exceeds the permissible discharge of N in the Xinyi River. The current discharge of P approaches the permissible discharge of P in the Guan River, but exceeds twice the permissible discharge of P in the Xinyi River. The discharge of inorganic N and P has substantially exceeded the standard, and the corresponding pollutant concentrations even exceed the third and fourth classes of Water Quality Standard of China (Table 2), it means to remain a certain amount of COD in the Guan River and Xinyi River, but the current COD is still within the maximum permissible discharge of the second-class Water Quality Standard of China.

Conclusions

The established numerical model is used for simulation analysis of the estuarine water quality successfully. Results also agree with measured data from 12 monitoring stations. Additionally, the annual discharge of major pollutants and the optimal layout of pollutant discharge of Guan River and Xinyi River are obtained accordingly. Some key points are summarized as below:

The annual discharge of major pollutants in Guan River and Xinyi River in 2007 were obtained: The annual discharge of N in the two rivers is 5490 t and 44623 t, respectively; that of P is 954 t and 3270 t, respectively; and that of COD is 16350 t and 48483 t, respectively. The current discharge of COD falls within the maximum permissible amount and to meet the second-class water quality standard of China. Given that the estuarine area for Guan River meets the second-class Seawater Quality Standard of China, the discharge reduction of N in Guan River should be about 2190 t/a, whereas those of N and P in Xinyi River were 38711 t/a and 1758 t/a, respectively. Excessive amounts of N and P had been discharged into such two rivers, so the water quality has exceeded the third- and fourth-class water standard of China. With ever increasing complexity and particularity for the marine environmental dynamics, local government and community should enact policies to control the discharge of N and P in the areas to adjacent the Guan River Estuary.

Acknowledgment

This study was supported by the National Natural Science Foundation of China (No. 41276017), the Ocean Public Welfare Scientific Research Project of the State Oceanic Administration of China (No. 201205005-2) and the Project supported by the National Natural Science Foundation of China (Grant No. 41106014)

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