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FLUCTUATION OF RIVER NETWORK WATER ENVIRONMENTAL CARRYING CAPACITY IN A COMPLICATED RIVER-LAKE SYSTEM

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Abstract

Aiming at river network in a complicated river-lake system, a new water environmental carrying capacity (WECC) calculation method was presented based on multi-objectives including water quality objectives for rivers, water quality objectives for control sections, pollution zones length at the sewage outlets and pollution zones area at the external lake inlets. The river network to the northwest of Lake Taihu was selected as the study area. Based on this new method, the WECC fluctuation was analyzed by 1-2D coupled numerical model which had been validated against the field data. Results showed that WECC changes obviously among different hydrological years, and the WECC for COD is 68938.8 metric tons in high flow year, which is 15.4% and 35.0% higher than that in normal flow year and low flow year. The WECC variation with time in different hydrological years is basically similar that the WECC in flood (May-October) season is markedly larger than that in dry season. While the fluctuation range of the WECC varies with hydrological conditions, which is higher in high flow year than that in normal flow year and low flow year.

Key words: water environmental carrying capacity, fluctuation, coupled model, river network, river-lake system

1. Introduction

Water environmental carrying capacity (WECC) is the ability to accommodate pollutants for a certain water unit with some given environmental goals, which is tightly connected with water quality objective, water feature and pollutant characteristics (Kang et al., 2011; Xu et al., 2000). The calculation methods of WECC for different water bodies, such as rivers and lakes, vary with water feature. It is difficult to calculate the river network WECC for its criss-crossed rivers and streams, and the complicated processes of water flow and water quality (Chang et al., 1997; Ye et al., 2010). To date, several studies have proposed a certain preliminary calculation methods on WECC and gained some fruits (Pang et al., 2003; Luo et al., 2004). However, these previous work mainly

focused on a separate river network or lake, and the river network WECC was only estimated based on water environmental functional zone (WEFZ). WEFZ is used to determine the water quality objectives and identify the zone boundary for each river or reach (Han et al., 2011). For river network in a complicated river-lake system, both the water quality objectives of internal rivers and external lakes should be considered (Li et al., 2011; Zhang et al., 2011), on which there is still a lack of study. Here, we laid particular emphasis on the entire river-lake system to investigate the river network WECC. Taking water quality objectives of the external lakes into consideration, we put forward a new calculation method on the basis of four objectives that few studies have simultaneously considered, including water quality objectives of WEFZ for rivers, water quality objectives for control sections, the

pollution zones length at the sewage outlets and the pollution zones area at the external lake inlets. The complicated river-lake system located to the northwest of Lake Taihu was selected as an example to study WECC. A one-dimensional numerical model for river network coupled with a two-dimensional numerical model for lakes was established and validated against the field investigated data. By the numerical model and the calculation method, the fluctuation processes of the river network WECC in different hydrological years were analyzed. This paper was of great significance for pollutant total amount control and water environmental protection in the study area, and more importantly, provided a new calculation method for the river network WECC in the river-lake system.

2. Case studies

2.1. Study area

The study area located to the northwest of Lake Taihu in China is a typical river-lake system, involving three cities of Yixing, Wuxi, and Wujin (Fig. 1a). It covers an area of approximately 5272 km^2, 14% of the total area of Taihu basin. There are 12 main rivers in this area (Fig. 1b). Seven rivers, Taige River, Caoqiao River, Taige South River, Guandu River, Chendong River, Zhihu River, and Wujin River, flow into Lake Taihu, among which the former 5 rivers flow into Zhushan Bay and the latter 2 into Meiliang Bay. With the rapid development of industry and agriculture, the continuous increase of population and the constant expansion of urbanization, pollutants discharged into the rivers are increasing gradually in recent years, and these 7 rivers transport lots of pollutants from the river network to Lake Taihu directly. There are 5 lakes including Gehu, Dongjiu, Xijiu, Zhushan Bay, and Meiliang Bay in the river-lake system (Fig. 1b). Lake Gehu, located to the west of Lake Taihu, is a very important flood regulating lake in the region. Lake Gehu keeps a good water quantity balance, its water

retention time is relatively short and the water exchange period is 7.03 times per year. The Lake Dongjiu and Lake Xijiu, located to the west of Lake Taihu and to the south of Lake Gehu, are very important receiving water bodies for many rivers within the river network before they flow into Lake Taihu.

Zhushan Bay and Meiliang Bay are two important semi-close lacustrine bays in the north of Lake Taihu, which respectively account for 2.4% and 5.2% of the total area of Lake Taihu. The two bays are undertaking a large number of pollutants from the river network, and facing series of environmental problems such as water quality deterioration, transparency decrease, algal bloom, and ecological damage. With the aim of protecting the water environment of Lake Taihu, it is dramatic significant to reasonably estimate the river network WECC and control the pollutant load from the rivers to the two receiving bays. Detailed information of the rivers and lakes are shown in Tables 1, 2.

2.2. Calculation method

Water quality objective, which is determined by WEFZ, is an important factor for WECC calculation. Different from an independent river system, WECC calculation for river network in a complicated river-lake system should consider water quality objective of rivers and lakes simultaneously. In addition to ensuring water quality reaching standard in the internal rivers, the impacts of river network on the external lakes should be taken into account. Therefore, we presented a new method on the basis of four objectives including water quality objectives for rivers, water quality objectives for control sections, the pollution zones length at the sewage outlets, and the pollution zones area at the external lake inlets. The calculation framework is composed of four modules, the input module, the numerical simulation module, the data processing module, and the output module.
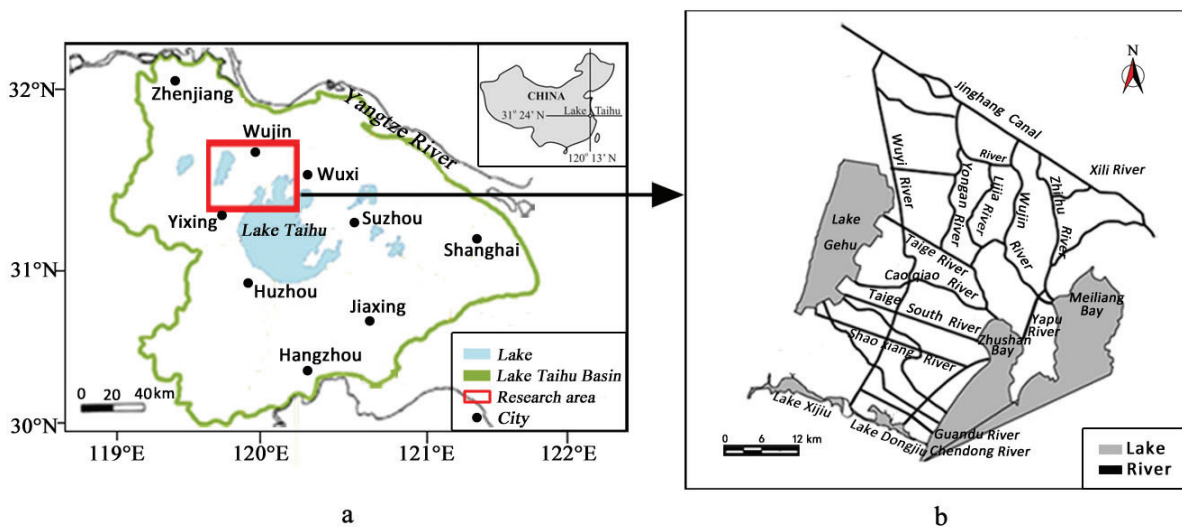

Fig. 1. (a) The location of study area and Lake Taihu; (b) The distribution of the rivers and lakes

Table 1. Basic characteristic of the rivers in the study area

Number	River	Length (km)	Width (m)	Flow rate (m³·s⁻¹)	Mean water depth (m)
1	Jinghang Canal	47.0	50-65	18.5	2.0
2	Taige River	22.5	20-50	10.81	3.2
3	Caoqiao River	21.5	25.6	7.1	3.3
4	Taige South River	20.3	45	14.3	3.7
5	Wuyi River	37.0	30	15.4	3.5
6	Xili River	36.8	50-70	10.5	3.6
7	Shaoxiang River	24.8	35-45	9.8	2.9
8	Wujin River	29.0	25-30	11.2	3.3
9	Zhihu River	20.1	30-40	10	3.4
10	Yapu River	7.0	50-60	11.2	2.6
11	Guandu River	6.9	25	2.2	1.4
12	Chendong River	2.1	70-80	49.0	4.2

Table 2. Basic characteristic of the lakes in the study area

Number	Lake	Surface area (km²)	Mean water depth (m)	Water volume (10⁶ m³)
1	Lake Gehu	160	1.27	215
2	Lake Dongjiu	8.0	1.85	21
3	Lake Xijiu	12.4	1.79	32
4	Zhushan Bay	56.7	1.90	118
5	Meiliang Bay	123.8	1.80	241

The input module is used to give the initial conditions such as the hydrological boundary, water quality objective and pollutant load. The output module shows final results. The numerical simulation module aims at expressing the processes of water flow and water quality in the river-lake system by the coupled model. The data processing module is a very important analysis part including river network constraint unit and lake constraint unit. Detailed calculating procedures are shown in Fig. 2. Three factors, which are river water quality, control section water quality, and pollution zone length at sewage outlets, are selected as the constrained conditions in the river network constraint unit. The pollution zone area at the external lake inlet is selected as the constrained conditions in the lake constraint unit.
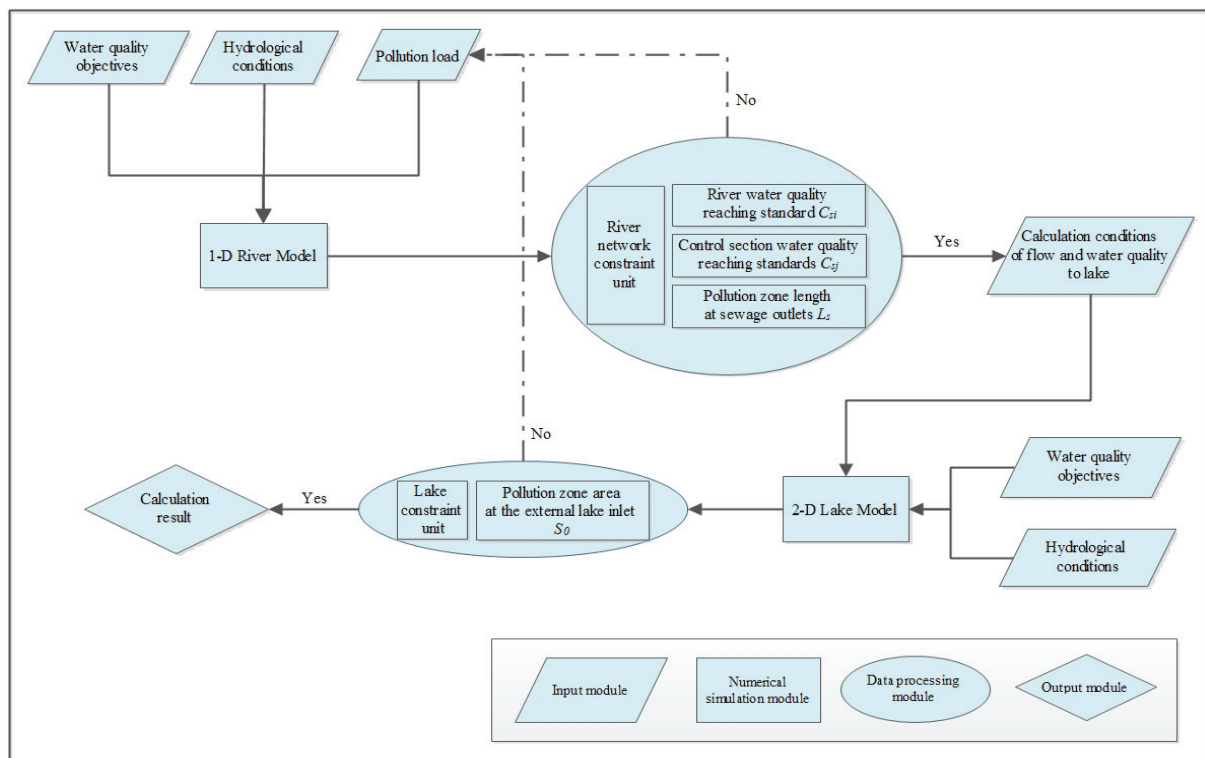
Fig. 2. Calculation framework for the river network WECC in a complicated river-lake system

Based on the constraint units, four control objectives, including water quality objectives C_{si} for rivers of WEFZ, water quality objectives C_{sj} for control sections, pollution zone length L_s at sewage outlets and pollution zone area S_0, are set up accordingly. The mathematical equations can be expressed by Eqs. (1):

$$\begin{cases} C_i = f(Q_i, W_i) \le C_{si}, i = 1, \cdots, m \\ C_j = g(Q_j, W_j) \le C_{sj}, j = 1, \cdots, n \\ L_k = r(Q_k, W_k) \le L_s, k = 1, \cdots, h \\ S_t = p(Q_t, C_t) \le S_0, t = 1, \cdots, e \end{cases} \quad (1)$$

where C_i and C_j are respectively the water concentration of WEFZ i and control section j, mg·L⁻¹; C_{si} and C_{sj} are the corresponding water quality objectives, mg·L⁻¹; W_i and W_j are the pollutant load of WEFZ i and control section j, metric ton; L_k is the length of the pollutant zone at the sewage outlet k, m; L_s is the constraint length, m. W_k is the discharged pollutant volume at the sewage outlet k, metric ton; S_t is the pollution zone area at the external lake inlet of river t, km²; S_0 is the constraint area, km²; C_t is the water concentration of the inflowing river t, mg·L⁻¹. Q_i, Q_j, Q_k and Q_t are the river flow rate of the river i, j, k, m³·s⁻¹; f, g, r, and p express the correlation function; m, n, h, and e are respectively the number of WEFZ, control section, internal sewage outlet, and inflowing river.

The water environmental processes under different calculation boundaries will be simulated by the numerical model. With the aim of determining the most appropriate WECC, which can meet the requirements of the four constraint equations, different pollutant combination including point source and non-point source will be inputted for trial calculation. After the result optimization, the optimal value can be found. During calculation, the internal constraint length was selected as 800-1000 m, and the external constraint area was fixed to 1.5-2.0 km², according to the "Water Environmental Carrying Capacity Calculation Report of Jiangsu Province (approved by the government in August 2004)".

2.3. One-two dimensional coupled numerical model

In order to simulate the water environmental process in the river-lake system, a 1-D water quality model for river network coupled with a 2-D numerical model for lakes was developed. The 1-D model simulates the water flow and water quality processes of the internal rivers and streams, and provides some calculation boundaries for the 2-D model of which the emphasis is to reflect the impacts of the internal rivers on the external lakes.

(a) One-dimensional river model

The conservation forms of 1-D shallow water equations and the convection-diffusion equations can be written as given by Eqs. (2):

$$\begin{cases} \dfrac{\partial Q}{\partial x} + B_W \dfrac{\partial Z}{\partial t} = q \\ \dfrac{\partial Q}{\partial t} + 2U\dfrac{\partial Q}{\partial x} - U^2 \dfrac{\partial A}{\partial x}\Big|_z + (gA - U^2 B)\dfrac{\partial Z}{\partial x} + g\dfrac{n^2 Q|Q|}{AR^{1.33}} = 0 \\ \dfrac{\partial(AC)}{\partial t} + \dfrac{\partial(AUC)}{\partial x} = \dfrac{\partial}{\partial x}\left(AE_x \dfrac{\partial C}{\partial x}\right) - KAC + S \end{cases}$$

$$(2)$$

where t is the time, s; x is the distance coordinate in the river direction, m; Q is the river flow rate, m³·s⁻¹; Z is the water level, m; U is the averaged velocity of cross section, m·s⁻¹; n is the roughness; A is the flow section area, m²; B is the flow section wide, m; B_W is the water surface wide, m; R is the hydraulic radius, m; g is the acceleration of gravity, m·s⁻²; q is the franking inflow rate, m³·s⁻¹; C is the average section pollutant concentration, mg·L⁻¹; E_x is the longitudinal dispersion coefficient, m²·s⁻¹; S is the source-sink vector of pollutant; K is the degradation coefficient, d⁻¹.

(b) Two-dimensional lake model

The conservation forms of 2-D shallow water equations and the convection-diffusion equations are written as follows (Wang et al., 2014):

$$\begin{cases} \dfrac{\partial h}{\partial t} + \dfrac{\partial(hu)}{\partial x} + \dfrac{\partial(hv)}{\partial y} = 0 \\ \dfrac{\partial(hu)}{\partial t} + \dfrac{\partial(hu^2 + gh^2/2)}{\partial x} + \dfrac{\partial(huv)}{\partial y} = gh(s_{0x} - s_{fx}) \\ \dfrac{\partial(hv)}{\partial t} + \dfrac{\partial(huv)}{\partial x} + \dfrac{\partial(hv^2 + gh^2/2)}{\partial y} = gh(s_{0y} - s_{fy}) \\ \dfrac{\partial(hC)}{\partial t} + \dfrac{\partial(huC)}{\partial x} + \dfrac{\partial(hvC)}{\partial y} = \dfrac{\partial}{\partial x}\left(D_x h\dfrac{\partial C}{\partial x}\right) + \dfrac{\partial}{\partial y}\left(D_y h\dfrac{\partial C}{\partial y}\right) - KhC + S \end{cases}$$

$$(3)$$

where h is the water depth, m; t is time, s; u *and* v are respectively the depth-averaged velocity components in x and y directions, m·s⁻¹; g is the acceleration of gravity, m·s⁻²; s_{0x} and s_{fx} are the bed slope and friction slope in the x direction; s_{0y} and s_{fy} are the bed slope and friction slope in the y direction; E_x and E_y are the dispersion coefficient of pollutants in the x and y directions under dynamic condition, m²·s⁻¹; K is the degradation coefficient, d⁻¹; C is the depth-averaged pollutant concentration, mg·L⁻¹; S is the source-sink vector of pollutant.

(c) Model coupling

The key point in coupling different dimensional numerical models is how to accurately determine the calculation parameters at the connection point. For the coupling of the 1-D and 2-D model, we use mass conservation principle to handle the water level, flow rate, and pollutant concentration at the public sections. The following junction conditions (Eqs. 4) should be satisfied for the transitional simulation from 1-D model to 2-D model:

$$\begin{cases} \text{water level: } Z_1 = Z_2 \\ \text{water volume: } Q_1 = \int U_\varepsilon h_\varepsilon \, d\varepsilon \\ \text{water quality: } C_1 = C_2 \end{cases} \quad (4)$$

where Z_1 and Z_2 are respectively the water levels of the 1-D and 2-D models at the junction section, m; C_1 and C_2 are respectively the water qualities of the 1-D and 2-D models at the junction section, mg·L^{-1}; Q_1 is the flow rate of the 1-D model at the junction section, m^3·s^{-1}; U_ε is the water velocity in the normal direction at the junction section, mg·s^{-1}; h is the water depth, m; ε is the coordinate of the junction section.

(d) Equations solution

The 1-D hydrodynamic differential equations are solved by the four-point implicit method, and the implicit and upwind scheme is selected to solve the water quality equation (Joo and Oh, 2007; Szymkiewicz and Gasiorowski, 2012). The 2-D water flow and quality equations are combined to be calculated, and the Eqs. 3 can be written in the following unified form (Eq. 5) (Zhao et al., 2000; Ding et al., 2004):

$$\frac{\partial q}{\partial t} + \frac{\partial f(q)}{\partial x} + \frac{\partial g(q)}{\partial y} = b(q) \quad (5)$$

where q is the vector of the conserved physical quantities; $f(q)$ and $g(q)$ are respectively the flux vectors in the x and y directions; $b(q)$ is the source-sink vector. The detailed expressions are as follows:

$$\begin{cases} q = (h, hu, hv, hC)^T \\ f(q) = (hu, hu^2 + gh^2/2, huv, huC)^T \\ g(q) = (hv, huv, hv^2 + gh^2/2, hvC)^T \\ b(q) = (0, gh(s_{0x} - s_{fx}), gh(s_{0y} - s_{fy}), \nabla \bullet (D_i \nabla(hC)) - khC + S)^T \end{cases} \quad (6)$$

Developed in the framework of finite volume method (FVM) on an unstructured grid, the flux vector splitting (FVS) scheme is employed to calculate the numerical normal flux of variables across the interface between grids. Detailed steps were documented in references (Hou et al., 2013; Zhao et al., 2002).

(e) Model calibration and verification

The coupled numerical model was calibrated and validate against the measured data in January and July 2012. 24 investigated points were arranged in the river-lake system (shown in Fig. 3). Water sample collection, storage and test refer to Water and Exhausted Water Monitoring Analysis Method (fourth edition) (China State Environmental Protection Administration, 2002). The water samples were collected at half of water depth, and then stored in a volume of 500mL polyethylene plastic bottle. And 1mL sulfuric acid was added to make pH less than 2. All water samples were stored in 2~5°C. COD was tested by potassium dichromate method; NH$_3$-N was tested by Nessler's reagent spectrophotometric method (GB11893-89).

Calculated region was the whole system. The lake area was divided into quadrilateral grids by the Gambit software. The field measured water flow rate and pollutant concentration in Lake Gehu (in the west) and Jinghang Canal (in the north) were selected as the calculation boundaries. To guarantee the stability and precision of the model the calculation time step was taken as 0.1s. It was found that the calculated results were close to the measured data and the relative errors were between 11.9% and 16%.

The established coupled model could accurately reflect the pollutant migration and transformation processes under different hydrodynamic conditions. Verification results of Site 7, 8 and 14 were shown in Fig. 4 and Fig. 5 as examples.

2.4. Calculation conditions

Four calculating conditions need to be inputted into the established model. (a) Hydrological boundary. To investigate the river network WECC in different hydrological conditions, the years of 2009, 2011, and 2003 were respectively selected as the high flow year, normal flow year, and low flow year according to the regional rainfall frequency analysis in recent years. (b) Water quality objective. The water quality objectives of internal rivers and external lakes were acquired from the "Water Environmental Function Zoning Report of Jiangsu Province", which had been approved by the people's government of Jiangsu Province on March 18 2003. (c) Control section.

In light of the assessment requirements of the country and Jiangsu province, 14 water quality control sections were selected in the study area. (d) Sewage outlet. It is necessary to generalize the sewage outlets for simplifying the calculation process. Based on the locations and discharge intensities of the present sewage outlets, 60 generalized outlets were identified. Detailed information was shown in Fig. 6.

3. Results and discussion

Based on the given initial calculation items, the processes of water flow and water quality in the river-lake system under different hydrological conditions were simulated. In light of the multi-objectives in the river-lake system, the annual fluctuation processes of the river network WECC in the three typical years were studied. The results are as follows: (1) Due to the varied hydrological boundaries, the WECC fluctuated obviously among different hydrological years. The river network WECCs of COD and NH$_3$-N were respectively 68983.8 metric tons and 3511.9 metric tons in the high flow year, 59726.2 metric tons and 2866.9 metric tons in the normal flow year, and 51065.9 metric tons and 2269.6 metric tons in the low flow year. The high flow year had the highest WECC for its abundant water and strong hydrodynamic condition, and the WECCs of COD and NH$_3$-N were increased by 15.4% and 22.5% than that in the normal flow year.
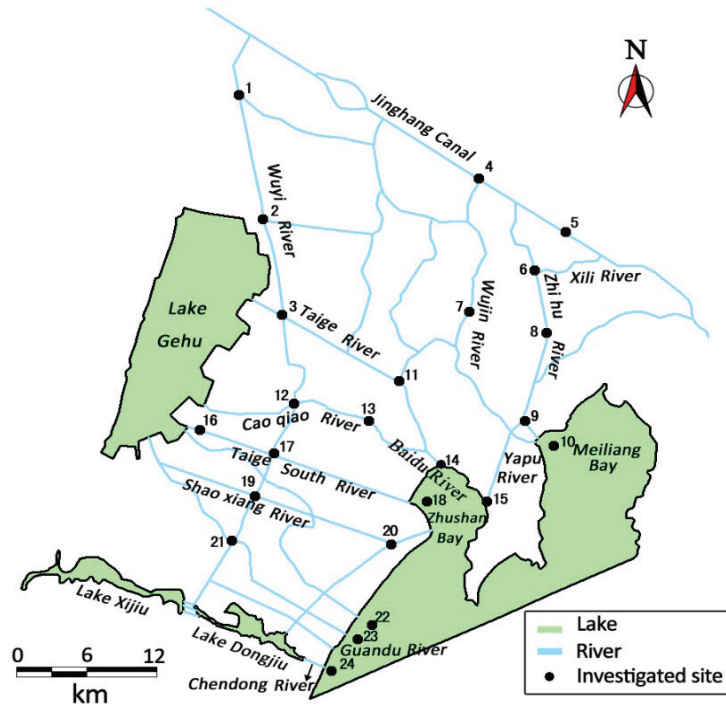
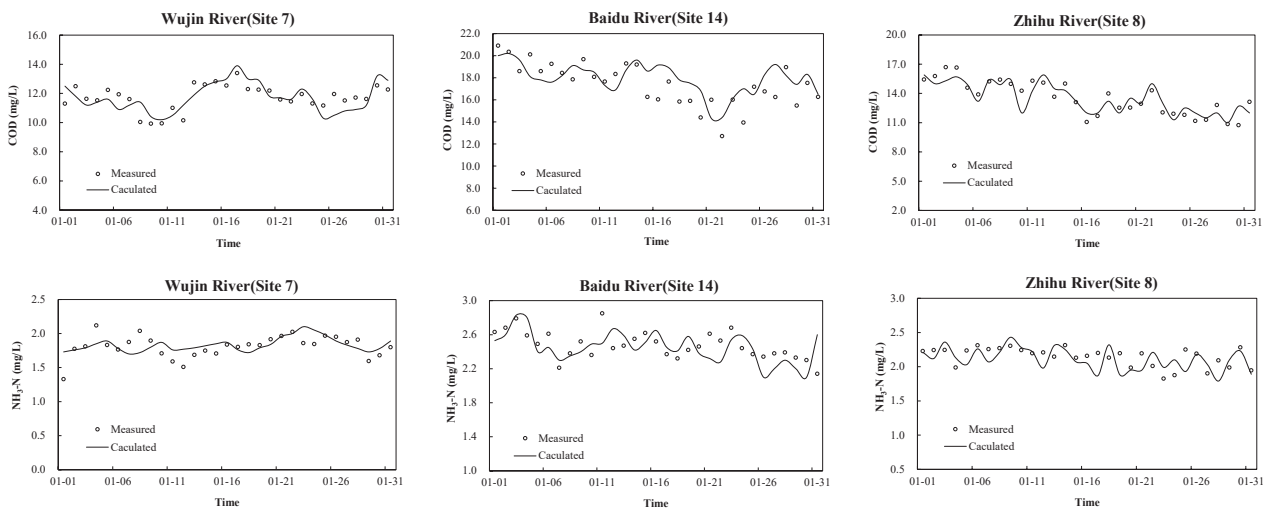**Fig. 3.** Field investigated site distribution in the river-lake system

Fig. 4. Verification of the numerical model in dry season (site 7, 8, 14)

Due to water shortage and stagnant water flow, the WECCs of COD and NH_3-N in the low flow year were the lowest, which were averagely decreased by 14.5% and 26.3% than that in the normal flow year. (2) The temporal distribution of WECC in different typical years was similar to each other. The flood (May-October) season has a remarkably higher WECC than the dry (December-April) season for its abundant water and strong hydrodynamic condition; for instance, in the flood season of the normal flow year, the WECCs of COD and NH_3-N were 39556.7 metric tons and 1837.2 metric tons, which respectively increased 96.1% and 78.4% compared with that in the dry season. However, due to the uneven water volume distribution in different typical years, the peak value and the valley value of WECC do not appear at the same time. For example, the peak values in the high flow year and normal flow year respectively appeared in August and June, while the valley values happened in January and November. (3) Despite the similarities in temporal distribution of the river network WECC, the fluctuation range of the WECC varies in the three typical years owing to different hydrological conditions. The high flow year, of which the annual variance was 0.10, has the maximum fluctuation range for its uneven water volume distribution.
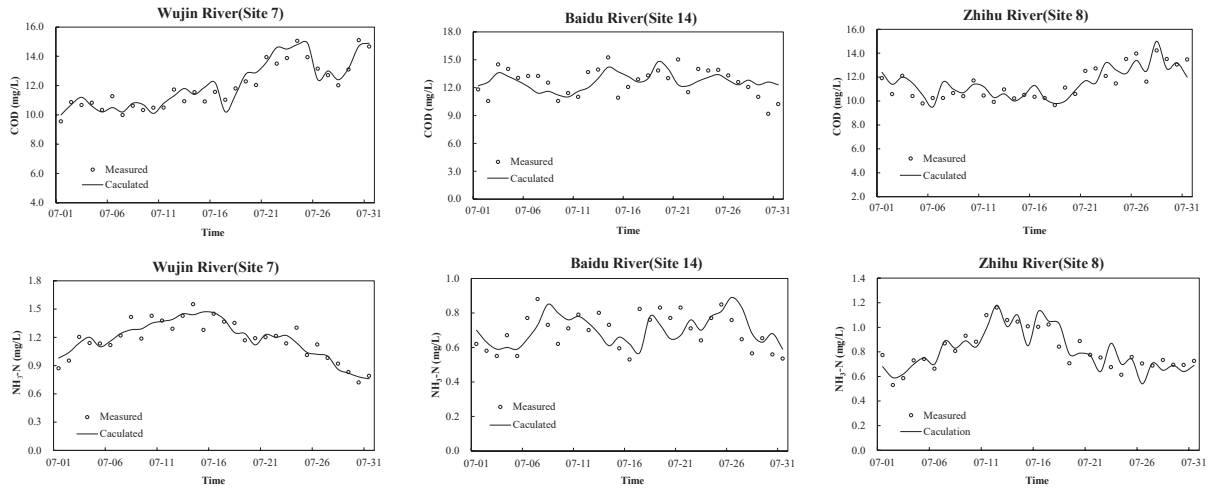
Fig. 5. Verification of the numerical model in flood season (site 7, 8, 14)

The amplitudes in the normal flow year and low flow year were relatively lower, and the average annual variance was 0.03. Detailed results were shown in Fig. 7 and Fig. 8.

4. Conclusions

A new method for calculating the river network WECC in a complicated river-lake system was proposed based on multi-objectives. The WECC of the river network in the northwest of Lake Taihu was calculated based on the presented method and 1-2D coupled model. The flood (May-October) season has a remarkably higher WECC than the dry (December-April) season. The WECC variation with time in different hydrological years is basically similar, while the fluctuation range of WECC varies with different hydrological conditions.
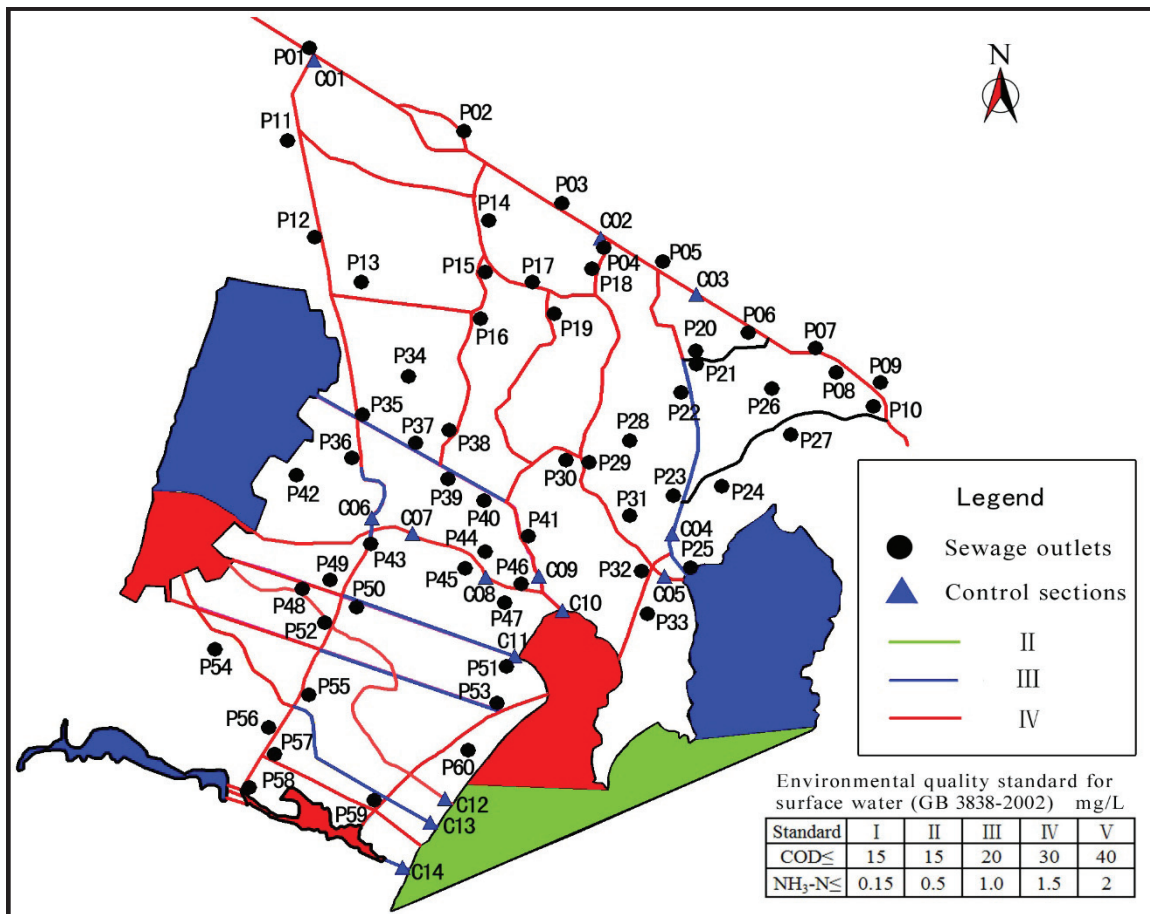

Fig. 6. The distribution of WEFZs, control sections and sewage outlets in the river-lake system
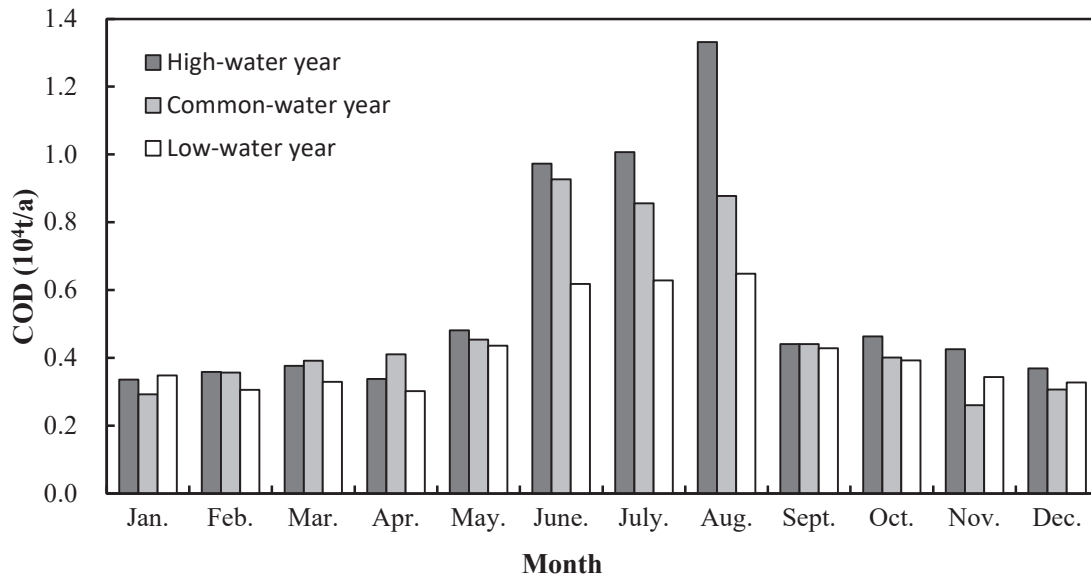
Fig.7. The fluctuation processes of the river network WECC in different typical years (COD)
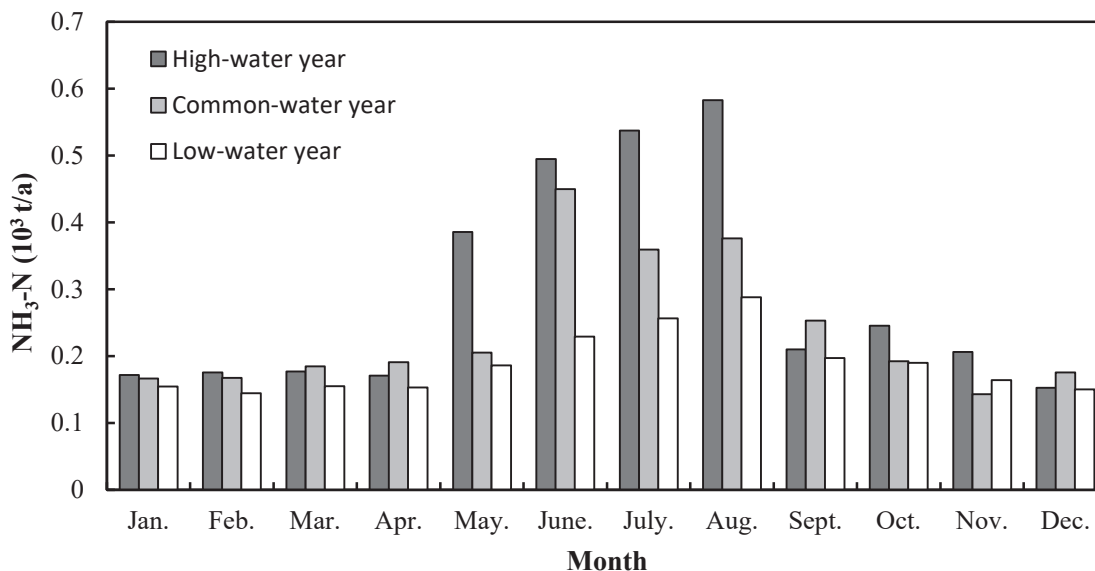

Fig. 8. The fluctuation processes of the river network WECC in different typical years (NH₃-N)

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