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Calculation of water environmental capacity of large shallow lakes – a case study of Taihu Lake

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Abstract

Lake currents have an important impact on distribution of pollutant concentrations in large shallow lakes. Taking Taihu Lake as an example, in view of the characteristics of wind-driven water flow in the lake, this paper puts forward a water environmental capacity calculation method that uses wind direction and wind speed combined frequency to provide joint correction and pollution zone control for the designed hydrological conditions. In the study, the total length of the pollution belt was controlled to be 10% of the length of the study area, and a mathematical model of two-dimensional unsteady water quantity and quality in Taihu Lake was established. By analyzing the hydrological water quality characteristics and measured data of Taihu Lake in recent years, the flow field and concentration field were simulated and verified, the mathematical model and the plausibility of the parameters were calibrated. The water environmental capacity of Taihu Lake basin was calculated by this method. The calculated results showed that the water environmental capacity of chemical oxygen demand (COD), total phosphorus (TP), and total nitrogen (TN) in Taihu Lake were 113,331 $t{\cdot}a^{-1}$, 479 $t{\cdot}a^{-1}$ and 6,521 $t{\cdot}a^{-1}$. By providing a technical basis for total pollutant control and management in Taihu Lake basin, this study is conducive to the planning and management of water environment.

Keywords: Joint frequency; Pollution belt; Pollution zone; Taihu Lake; Water environmental capacity; Wind-driven current

Introduction

Large shallow lakes, especially those located in highly developed areas, provide multifunctional services for industry, agriculture, navigation, and recreation (Liu *et al.*, 2018a, 2018b). However, due to the continuous development of industrial and agricultural production and the growth of population

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along the lake area, the increasing amount of pollutants and the deteriorating lake water environment are causing a variety of water environmental problems. Shallow lakes, as one of the most prone eutrophic water bodies, have low pollution load capacity. Water quality issues such as eutrophication have impacted industrial, agricultural, and domestic water consumption around the lake and restricted the development of the regional economy (Paerl *et al.*, 2011; Ma *et al.*, 2015).

The water environmental capacity (WEC) refers to the maximum amount of pollutants that the water can accommodate under the designed hydrological conditions and the specified environmental objectives without destroying its own function (Zhao *et al.*, 2018). The calculation of the WEC can provide a scientific basis for water pollution control. Accurate data of environmental capacity are most important in research of the actual amount of contaminant discharge into a water system (Pan *et al.*, 2013). In this paper, taking Taihu Lake as an example, we considered the wind directions and wind speeds' combined frequency to jointly correct the designed hydrological conditions and used the pollution zone control to calculate the WEC of Taihu Lake. This provides an important basis for Taihu Lake water resources planning and water environmental protection. The concept of 'water environmental capacity' in China was first introduced from Japan's 'environmental capacity' (Dong *et al.*, 2014). The concept is a synonym of 'assimilation capacity' and 'total maximum daily load' which are normally used in the United States (Kim *et al.*, 2012; Fakhraei *et al.*, 2014; Gulati *et al.*, 2014), Canada (Elshorbagy *et al.*, 2005), and other countries (Leandri, 2009; Lee *et al.*, 2013). The calculation methods of assimilation capacity (Gupta *et al.*, 2004) and total maximum daily load (Camacho *et al.*, 2018) also provided some reference for the study of the water environment in China. Previous studies have focused on the exploration of WEC calculation methods. Many Chinese researchers have developed different WEC calculation methods for different water bodies such as rivers, reservoirs, lakes, and coastal waters (Li *et al.*, 2010, 2015; Bao *et al.*, 2011; Gao, 2011; Liu *et al.*, 2012, 2018a, 2018b; Wang *et al.*, 2012a, 2012b; Xie *et al.*, 2012; Zhang *et al.*, 2012; Han *et al.*, 2013; Zhou *et al.*, 2014; Yang *et al.*, 2015; Zhao *et al.*, 2018). For example, Wang *et al.* (2012a) used a one-dimensional steady-state water quality model to study the WEC of the middle section of the Weihe River. Zhao *et al.* (2018) coupled the environmental fluid dynamics code (EFDC) model and the one-dimensional river water quality model to calculate the WEC of the river-reservoir composite system. The result can be used to quantify the pollution in tributaries, and therefore can provide references for local water quality management. According to the characteristics of the river network, Xie *et al.* (2014) established 19 control units and used the zero-dimensional mathematical model to calculate the WEC in the western part of Taihu Lake and explored its temporal and spatial distribution characteristics.

In recent years, research of the calculation method of the WEC of lakes has attracted more attention (Lu *et al.*, 2004; Li & Hong, 2005; Wang *et al.*, 2005, 2015; Bao *et al.*, 2011; Yan *et al.*, 2011; Li & Zou, 2015). Lu *et al.* (2004) calculated the WEC of Dongting Lake using a fully mixed model, but only for a certain given designed condition. Li & Hong (2005) used the blind number theory to establish a lake WEC calculation model under blind information, and explored the lake water environment system under uncertain conditions. Taking Bosten Lake as an example, Wang *et al.* (2005) proposed the superposition addition of WEC. The method first divided the lake into various grids, calculated the WEC of each grid, and then obtained the WEC of the lake by superposition. Even with accurate division, the model cannot solve the inhomogeneous and uncertain spatio-temporal effects caused by water quality and lake hydrologic and hydraulic conditions.

Although governments of different levels have attached great importance to the Taihu's water environmental problems and a series of measures was taken to address them, the general trend of water deterioration has not been effectively curbed. The excess of WEC caused by the pollution load from the major inflows of Taihu Lake is one of the prime reasons leading to deterioration of water quality. In the existing works (Hu *et al.*, 2011; Zhang *et al.*, 2012; Xie *et al.*, 2014; Li & Zou, 2015; Huang *et al.*, 2019), the calculations of lake WEC have greatly improved, but none of them could well reflect the actual hydrodynamic conditions of Taihu Lake. Therefore, it is difficult to accurately determine the maximum pollution-carrying capacity of Taihu Lake. Several problems and assumptions are worth discussion. First, the use of a fully hybrid model would be biased. The pollutants in Taihu Lake are mainly from the inflows of the lake. After entering the lake, the pollutants will form a pollution zone in the lake. Due to the large width/depth ratio, it is difficult to achieve full-section homogeneous mixing after the pollutants discharge into the water body. Hence, a two-dimensional unsteady water quantity and quality mathematical model will be an advanced choice. Second, the hydrological conditions considered in the models were limited to several specific cases. The dominant wind direction of large shallow lakes has obvious interannual variations, and different wind fields will form different lake flows, while the concentration and boundary of the contaminated areas are strongly influenced by the wind field. Models that are limited to a particular wind field therefore do not have broad applicability (Wu & Hua, 2014; Zhang *et al.*, 2015; Huang *et al.*, 2016; Wang *et al.*, 2016; Li *et al.*, 2017; Ding *et al.*, 2018). Third, control of the pollution zone is not considered. Containing the source of pollution, the pollution zone area is also an important factor with huge uncertainty. The deterioration process cannot be effectively controlled without taking it into consideration. According to the designed water quantity of the river and the water quality target values of the corresponding functional areas, Wang *et al.* (2015) used a two-dimensional unsteady water mathematical model to calculate the allowable emissions of different winds forming the pollution zone. The calculation result is significant. It shows that this research method is feasible. This paper is a new attempt to calculate the WEC of Taihu Lake.

Calculation methods

The study area

Taihu Lake is the third largest freshwater lake in China. The area of Taihu Lake is 2,338 km^2 and it has the shape of an ellipse (Figure 1). The length from north to south is 68.5 km while the length from west to east is 34 km. The maximum width is 56 km. The lake shoreline is about 405 km. The terrain is very flat with an average gradient of about 0°0′19.66″. The average water depth is 1.9 m and the maximum water depth is 3.3 m. Most of the water depth is between 1.5 and 2.5 m and accounts for 72.3% of the total area. Taihu Lake has no deep groove or hollow, and there is no large-scale beach. It is situated in a plain depression. Taihu Lake is a typical large shallow lake. With the rapid development of the economy, the lake has shouldered a large amount of pollution load and unreasonable utilization. The activities of turning lake into field and intensive fishing have led to a decline in the diversity of lakes, an imbalance in ecological structure, and destruction of primary functions. On the other hand, over-utilization leads to a gradual degradation of the ecosystem, a decline in the self-purification capacity of water, and an increase in the contents of pollutant and nutrient in water and sediment. As a result, the water quality of Taihu Lake has deteriorated and the phenomenon of eutrophication has become more serious. All these problems have greatly affected people's quality of life and restricted economic development. The problem of water pollution in Taihu Lake has long been an important issue for researchers.

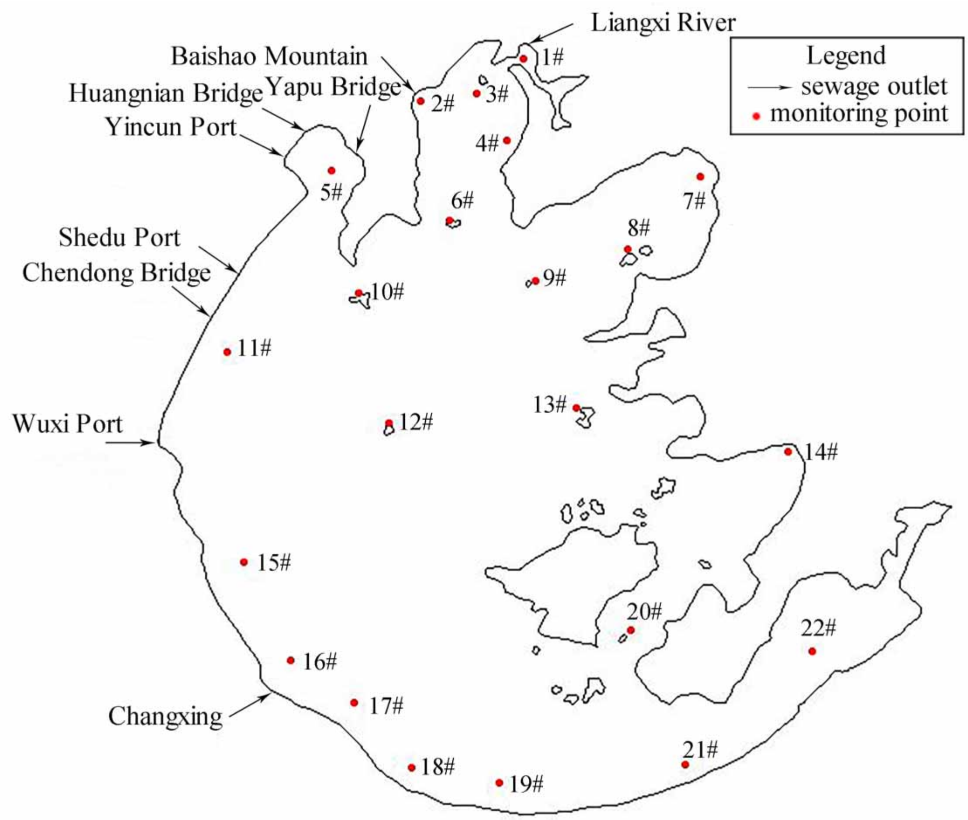


Fig. 1. General view of research area and water quality monitoring points.

Basic formulas

The wind direction and speed of large shallow lakes have large spatial and temporal variability, and the important parameter reflecting the temporal and spatial variability of wind direction and speed is the joint frequency of wind direction and speed. The weight factor and frequency of wind are needed in the calculation of the WEC. Second, the WEC of large shallow lakes is different from a single channel. Due to the relatively large difference in the width and the depth, the pollutant in the lake will present significantly in the pollution belt near the sewage outlet. (*Note:* The pollution belt refers to the shore of water body that is polluted by the pollution zone. It is measured according to the result of the model.) Therefore, it is necessary to superimpose control of the area of a single pollution zone with the control of the ratio of the pollution zone length and the shoreline length. The area of single pollution is controlled within 1–3 km^2 (Guo *et al.*, 2006). The length of the pollution belt is controlled at 10% of the coastline's (in the study area) total length (Wang *et al.*, 2007). The calculation process is as follows: use a two-dimensional non-steady-state mathematical model of water quantity and quality (two-dimensional conservation model of unsteady flow in shallow water equations). Different pollution zones under different wind directions are calculated according to the designed water quantity of generated inflows and the water quality target values of corresponding functional areas.

The WEC of Taihu Lake is the formation of permitted discharge amounts of the pollution zone. Equations (1) and (2) are the formulas used in the calculation of the WEC of Taihu Lake:

$$W = \sum_{j=1}^{b}\left(\alpha_j \sum_{i=1}^{n} W_{ij}\right) + \Delta W \tag{1}$$

where W is the WEC (t·a^{-1}) that is controlled by the total length of coastline polluted belt length ratio; W_{ij} the WEC of one sewage outlet in a certain wind direction wind speed condition (t·a^{-1}), which is controlled by the pollution belt size; α_j the different wind direction and wind speed frequency (%); n the number of sewage outlets; b the number of wind speed frequency of different wind direction; ΔW the corrected value of WEC (t·a^{-1}) used for supplement of WEC of the sewage outlets which have not been generalized. (*Note:* It is used to supplement the WEC that exists but is not generalized to sewage outlet. It is calculated as follows. For the generalized sewage outlets, divide the total WEC with the total pollution belt length to get a WEC per pollution belt length value. If the total length of the pollution belt is over 10% of the study area's coastline length, ΔW equals the negative of the product of the excess part of the pollution belt length and the WEC per pollution belt length value. If less than 10%, take the positive.)

$$W_{ij} = \sum_{i=1}^{n} C_{ij} \cdot Q_{ij} \tag{2}$$

where C_{ij} is the water quality concentration value of the lake inflows (mg·L^{-1}); and Q_{ij} the designed water quantity value of the lake inflows; the data were from actual measurement (m^3·s^{-1}).

Model establishment and parameter selection

Basic equations

The two-dimensional shallow water equations and convection-diffusion equations (Wang *et al.*, 2008; Wang & Pang, 2009) can be expressed as the form in Equation (3):

$$\begin{aligned}
&\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0 \\
&\frac{\partial (hu)}{\partial t} + \frac{\partial (hu^2 + gh^2/2)}{\partial x} + \frac{\partial (huv)}{\partial y} = gh(s_{0x} - s_{fx}) \\
&\frac{\partial (hv)}{\partial t} + \frac{\partial (huv)}{\partial x} + \frac{\partial (hv^2 + gh^2/2)}{\partial y} = gh(s_{0y} - s_{fy}) \\
&\frac{\partial (hC_i)}{\partial t} + \frac{\partial (huC_i)}{\partial x} + \frac{\partial (hvC_i)}{\partial y} = \frac{\partial}{\partial x}\left(D_x^i h \frac{\partial C_i}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_y^i h \frac{\partial C_i}{\partial y}\right) - K_i h C_i + S_i
\end{aligned} \tag{3}$$

where h is the water depth; t the time; u and v the depth-averaged velocity components in the x and y directions; g the acceleration of gravity; s_{0x} and s_{fx} the bed slope and friction slope in x direction; s_{0y} and s_{fy} the bed slope and friction slope in y direction; C_i the depth-averaged pollutants' concentration (COD_{Mn}, TP, and TN); D_x^i and D_y^i the dispersion coefficient of pollutants in the x and y directions under dynamic condition; K_i the degradation coefficient of pollutants; S_i the source-sink vector of pollutants. According to the habitat characteristics of large shallow lakes, the source-sink vector of pollutants is primarily a bottom up suspension caused by pollutants' release (Li *et al.*, 2004).

Definite condition

1. The boundary conditions: flow and water level boundary condition: $Q = Q_0$, $Z = Z_0$; boundary conditions of concentration field: inlet boundary $C = C_0$, the outflow boundary $\partial c/\partial n = 0$.
2. The initial conditions: water level amplitude is 0 m, the initial rate of 0 m·s^{-1}, initial concentration is the average concentration of the previous month.

Parameter calibration verification

The simulation and analysis of lake body flow field. There are about 219 river channels around Taihu Lake which are affected by tides. Most of them are influent–effluent currents. However, compared with the 2,338 km^2 area of Taihu Lake and the 4.48×10^9 m^3 water storage volume, the influent–effluent currents around the lake have a relatively small impact on the overall lake flow movement. The lake movement is mainly affected by the wind flow. During the year, as the dominant wind direction changes in different seasons, the lake circulation affected by the wind field also presents different circulation directions and forms. The hydrological characteristics and measured data of Taihu Lake in recent years have been analyzed. The year 2000 was a typical low flow year (in 90% assurance rate) within the last 50 years. Therefore, the hydrological data of the year 2000 were selected for the determination and verification of the water flow model. Rainfall and evaporation are considered in the model using the information of Xishan Monitoring Station. The water level of Xishan is close to the average water level of Taihu Lake, and the average water level of Taihu Lake is replaced by the value of Xishan water level.

Taihu Lake is divided into 7,750 triangular grid elements with grid spacing of 220–500 m. The boundary conditions of the flow model are determined by the measured flow data in and out of Taihu Lake in May 2013. The calculation time step is taken as 1 second. Figures 2 and 3 show the simulated and measured flow field in Taihu Lake under the effect of north wind separately. The comparison between Figures 2 and 3 shows that the flow field simulated by the two-dimensional flow model is consistent with the actual monitored flow field from the Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences. It is consistent with the actual measurement stream and lake in the order of magnitude of value. It means that the Taihu Lake flow model can simulate the flow characteristics accurately in Taihu Lake.

The basic parameters of model calibration results for: Manning coefficient (bottom roughness): $n = 0.025$; wind stress coefficient: ${\gamma_\alpha}^2 = 0.0013$.

The simulation and analysis of the concentration field of the lake. Water quality monitoring data are needed to test all 22 monitoring stations in Taihu Lake each month in July and August 2013, and to

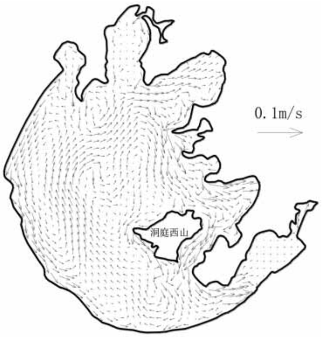


Fig. 2. Simulated flow field of Taihu Lake under the effect of north wind.

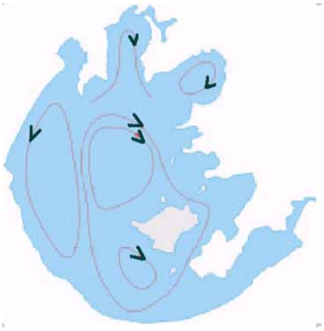


Fig. 3. Measured flow field of Taihu Lake under the effect of north wind.

simulate the water quality in the model. The 22 monitoring points are situated throughout the whole of Taihu Lake. They are located in areas all around the lake: highly polluted Meiliang Lake, West Taihu region with rapid flow, the middle region and light polluted East Taihu area. The specific distribution location is shown in Figure 1. The amount of pollution entering Taihu Lake and the main pollution emissions by the July 2013 export are used as the open boundary condition of the water quality model. The measured water quality data in August 2013 are used as the discrimination standard. Discrimination factors are COD_{Mn}, TP, and TN.

The calibration results in Figure 4 show that: the calculated values are close to the measured values in the distribution trend and specific numerical value. This indicates that the mathematical model and the parameters obtained by the model are reasonable. It can be used to predict the effect of the sewage outlets' emission of Taihu Lake. The x, y direction dispersion coefficients are $2.0\ \mathrm{m{\cdot}s^{-2}}$. Degradation coefficients of COD_{Mn}, TP, and TN are $0.06\ \mathrm{d}^{-1}$, $0.02\ \mathrm{d}^{-1}$, and $0.04\ \mathrm{d}^{-1}$. In addition, the model was verified by the measured data of Zhushan Lake and the west district of Taihu Lake in June 2014, and the errors were all within 10%.

Calculation of water environmental capacity

Calculation conditions

Determination of designed hydrological conditions of Taihu Lake. Due to the great influence of the wind field on the pollution belt, even under the same pollution belt area control standard, the

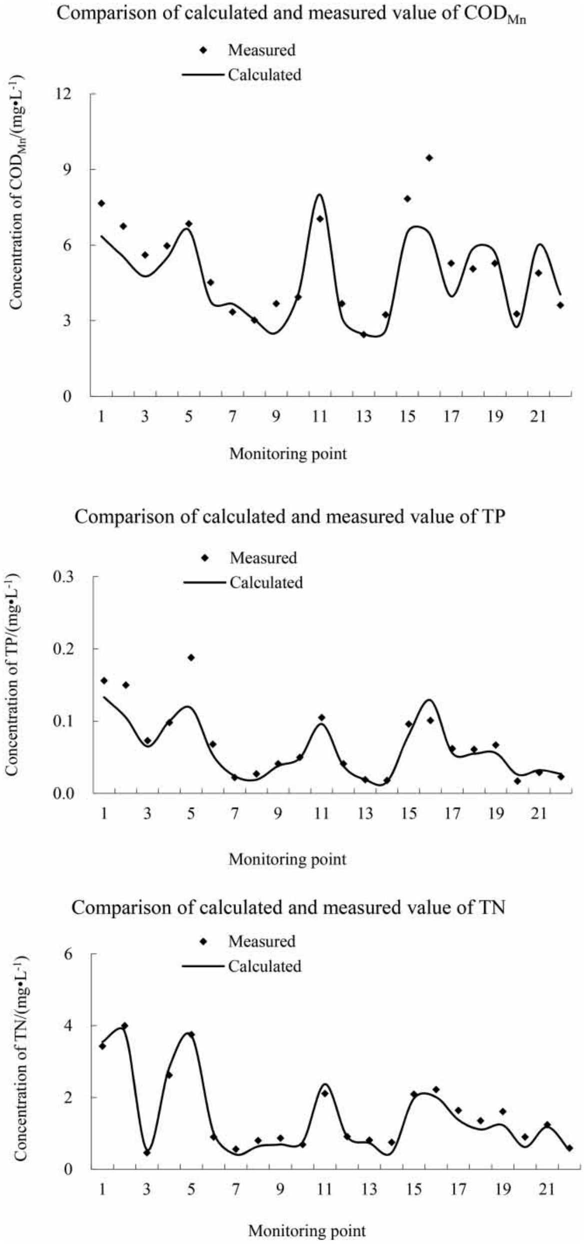


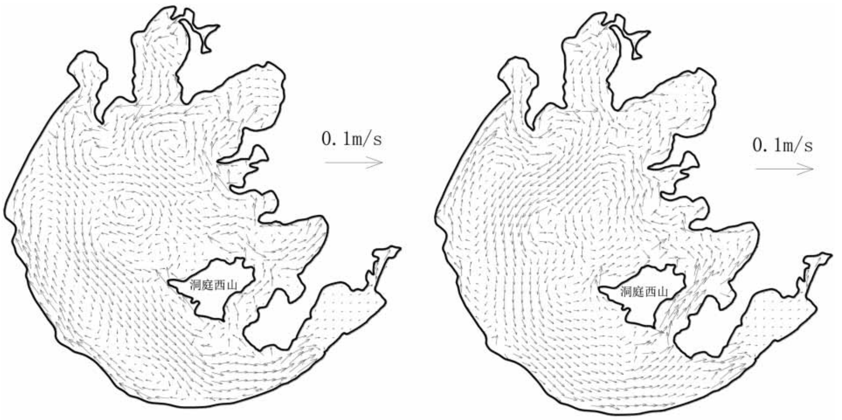
Fig. 4. Comparison of calculated and measured water quality concentration of each monitoring point.

environmental capacity of water body varies with the wind direction and speed. Therefore, it is necessary to consider the combined frequency of wind direction and speed to revise the designed hydrological conditions jointly. The wind direction frequency calculated by the Taihu Lake flow field is shown in Table 1. The average wind speed is 3.1 m·s^{-1}.

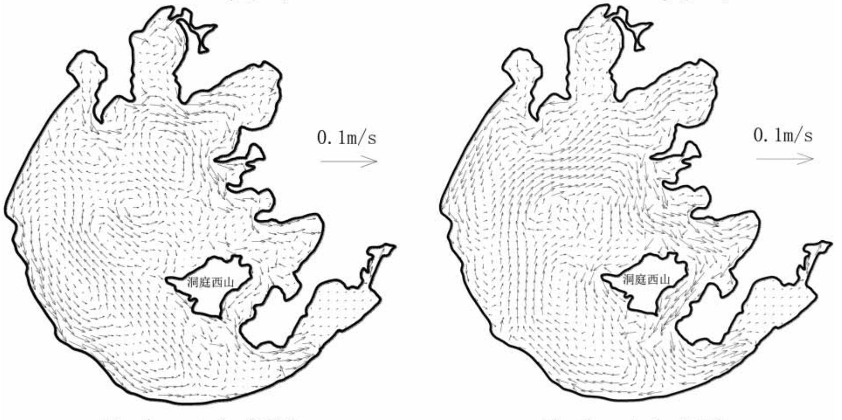
Table 1. Wind direction frequency of Taihu Lake.

Wind direction	N	NE	E	SE	S	SW	W	NW	Total
Frequency/(%)	7.085	13.930	23.240	17.850	13.815	9.495	7.790	6.795	100

The designed water flow condition is the comprehensive water flow condition under the combined frequency of different wind direction and wind speed. According to the water flow condition, the relationship between the amount of inflow pollution load and the area of the pollution belt is calculated, so as to calculate the WEC of the study area. To be specific, the flow field of Taihu Lake under different wind directions is calculated. On this basis, the distribution of the pollution belt is calculated. Taking the wind direction frequency of Taihu Lake as the weight, the pollution belt distribution after the joint frequency correction of wind direction and speed of Taihu Lake is obtained, so as to calculate the WEC of Taihu Lake body. Figure 5 shows the calculation results of the simulated flow field in Taihu Lake under typical wind directions.



Southeasterly (SE) Southwesterly (SW)



Northwesterly (NW) Northeasterly (NE)

Fig. 5. Simulated flow fields of Taihu Lake under the effect of typical wind directions.

Determination of designed hydrological conditions for inflows of Taihu Lake. According to the Taihu Lake river network model, calculation of the flow amount of the main inflows in high flow year, common flow year, and lower flow year was made, respectively (Zhang *et al.*, 2009). Since high flow year has more water quantity and better water quality, the common flow year and lower flow year, which are environmentally disadvantaged, were therefore chosen as the designed hydrologic condition. The average annual lower flow value of the main inflows was calculated as the designed flow amount, and the calculation results of the main inflows of Taihu Lake in the designed hydrological conditions are shown in Table 2.

The generalization of sewage outlets. The main inflows of Taihu Lake are generalized as follows: Liangxi River (Liangxi River), Zhihugang River (Baishao Mountain), Yapugang River (Yapu Bridge), Taige Canal (Huangnian Bridge), Taige South Canal (Yincun Port), Shedugang River (Shedu Port), Chendonggang River (Chendong Bridge), Wuxigang River (Wuxi Port), and Changxinggang River (Changxing). (*Note:* The name of the sewage outlet is in parentheses.) The location of the sewage outlet is shown in Figure 1.

Simulation results and analysis

The calculation formula of Taihu Lake water environmental capacity is shown in Equation (2). Taking C_{ij} as the water quality concentration of lake inflow functional zone was used in the 'Surface Water (Environmental) Functional Zone Planning of Jiangsu Province' to calculate the pollution zone area: (1) when the pollution zone area is less than 3 km^2, the pollutant discharge amount of the lake inflow is taken as W_{ij}; (2) when the pollution zone area is greater than 3 km^2, take the discharge amount of the zone when reducing the area to 3 km^2 as W_{ij}. Then calculate the WEC of the entire Taihu Lake based on the principle of pollution belt control that the total length of the pollution belt does not exceed 10% of the length of the entire Taihu coastline length.

According to the flow values of the main inflows into Taihu Lake in high flow year, common flow year, and lower flow year, nine generalized river channels are selected (including Liangxi River,

Table 2. Water environmental capacities of Taihu Lake.

River	Sewage outlet	Average designed flow values /(m^3·s^{-1})	The water quality target (in 2020)	Water environmental capacities/(t·a^{-1})		
				COD	TP	TN
Liangxi River	Liangxi River	3.58	III	2,659	12	204
Zhihugang River	Baishao Mountain	13.16	III	2,588	15	171
Yapugang River	Yapu Bridge	4.60	III	5,780	22	302
Taige Canal	Huangnian Bridge	33.12	III	6,233	25	351
Taige South Canal	Yincun Port	25.50	III	6,375	28	332
Shedugang River	Shedu Port	9.65	III	3,176	13	251
Chendonggang River	Chendong Bridge	21.21	III	3,924	21	276
Wuxigang River	Wuxi Port	7.01	III	5,852	26	325
Changxinggang River	Changxing	55.93	III	6,523	29	173
ΔW				70,221	288	4,136
The body of Taihu Lake				113,331	479	6,521

Zhihugang River, Yapugang River, Taige Canal, Taige South Canal, Shedugang River, Chendonggang River, Wuxigang River and Changxinggang River). For the nine generalized river channels, average annual lower flow value is used as the designed water quantity, and the WEC of the Taihu Lake body is calculated according to Equation (2). By using the principle of pollution belt control, the WEC of Taihu Lake body can be obtained. The calculation results are shown in Table 2.

It can be seen from Table 2 that the WEC of chemical oxygen demand (COD) in Taihu Lake was 113,331 $\mathrm{t{\cdot}a^{-1}}$, where the total phosphorus (TP) was 479 $\mathrm{t{\cdot}a^{-1}}$ and the total nitrogen (TN) 6,521 $\mathrm{t{\cdot}a^{-1}}$.

Conclusions

When calculating the WEC, a difficult issue is how to make the model simulation results accurately reflect the actual hydrological conditions of Taihu Lake. Taking Taihu Lake as an example, a combined WEC calculation method based on wind direction and speed joint frequency correction and pollution belt control are proposed in this paper. Considering the wind forming distributions of the pollution belts generated after inflows entering the lake, the method is aimed at large shallow lakes that are obviously affected by wind and current. The wind direction and speed combined frequency was used in the method. This reflects the influence of the seasonal change of dominant wind direction on the formation and flow regime of flows in large shallow lakes and its influence on WEC. It has good applicability and operability. Through the research above, we calculated the WEC of the main pollutants such as COD, TP, and TN, among others, in Taihu Lake. It provides the scientific evidence for environmental management departments to regulate total amounts of pollutants, a foundation also provided for total amount control of pollutants in the Taihu area. The two-dimensional unsteady water quantity and quality model can be applied to predict the water quality and environmental capacity of Taihu Lake. It can also be used for selection of suitable pollution load reduction projects to reach specific water quality targets, and for forecasting the effects of them. The model result is based on annual average data, water quantity, and quality data. The parameters and calculation results are the uncertainty sources of our study. The model can be improved by incorporating a longer period dataset for better interpretation of water quality changes and monthly data for seasonal variations. WEC could then be estimated on a seasonal scale or an even shorter period. Then, more detailed water quality management strategies can be made.

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