Application of EFDC model to grading the eutrophic state of reservoir: case study in Tianjin Erwangzhuang Reservoir, China

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ABSTRACT
Reservoirs are major sources of water supply in many densely populated areas. Eutrophic state plays an important role in reflecting the health status of reservoir ecosystem and it is a key field of water environment study. In this paper the method of grading the eutrophic state of reservoir based on the results of Environmental Fluid Dynamics Code (EFDC) model was proposed in order to obtain the spatial and temporal evaluation of eutrophic state in reservoir. Taking Tianjin Erwangzhuang reservoir as an example, the temporal and spatial trends of hydrodynamic and water quality of the reservoir were studied. The eutrophic state and the limited factor of eutrophication were predicted for Tianjin Erwangzhuang reservoir. This study provides a useful tool for understanding of the eutrophic state grade in a reservoir and surface water environment.

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1. Introduction
Reservoir as an important water resource is of increasing importance for worldwide economic and social sustainable development. In recent years, instead of flood control and irrigation, the drinking water supplement has become the primary purpose of reservoirs. However, many shallow reservoirs are confronted with severe eutrophication in China (Lv, Jiang, & Liu, 2013).

Eutrophication is a major water quality problem which may result in turbid water with high algal biomass. The level evaluation of eutrophication is very important to the water quality management and ecological protection. At present, the evaluation methods of eutrophication are mainly eutrophic state index (Elzbieta et al., 2014), grey clustering (Heung & Hu, 2013, 2014), fuzzy mathematics (Ju & Yoo, 2014; Liou & Lo, 2005; Pecher & Esther, 2012) and matter element analysis (Chen, Wu, Blanckaert, Ma, & Huang, 2012). However, these methods are based on the field data monitored and collected traditionally at limited locations. It is often disputed whether the limited field data represent the overall trophic state of water body. Numerical models play an important role in decision support for the management of surface water systems. They can simulate and predict the overall water quality of water body. In this sense, they are superior to the traditional field monitoring methods.

Numerical methods have been widely applied to hydrodynamics, sediment transport, water quality and ecology. In the past decades, the hydrodynamic and water quality models have been evolved from one-dimensional to three-dimensional models. Chau and Jiang (2001, 2004) developed a three-dimensional numerical model for the Pearl River estuary. Wu and Chau (2006) studied the model of water quality rehabilitation with the rainwater utilization. Haun, Olsen, and Feurich (2011) developed the numerical modeling of flow over a trapezoidal broad-crested weir. Lai and Khan (2012) studied the discontinuous Galerkin method for shallow water flows in natural rivers. All these studies are in agreement with the experimental results, and the results of water flow and water quality in the whole study area are presented, which make up for the deficiency of the experimental monitoring points.

In addition to the achievements listed above, some general-purpose models for simulating three-dimensional flow, transport and biogeochemical process in surface water systems have been developed, such as Environmental Fluid Dynamics Code (EFDC) (Hamrick, 1992; Zhang, Gao, Wang, & Chen, 2013). The hydrodynamics, sediment transport, toxic contaminant transport and water quality are always included in these three-dimensional models. Furthermore, the model of EFDC even considers multiple factors such as vegetative
resistances, hydraulic structures and meteorological conditions. It has been successfully used in the simulation of hydrodynamic processes (Ji, Hu, Shen, & Wan, 2007; Sinha, Liu, & Garcia, 2012), water age analysis (Gao, Chen, & Zhang, 2013; Li et al., 2013), sediment transport (Lv, Zhang, Liu, Hao, & Wu, 2013; Wang et al., 2013), salinity spreading (Gong, Wang, & Jia, 2012; Zhou, Wang, & Luo, 2012), dissolved oxygen distribution (Xia et al., 2011), algae growth prediction (James & Boriah, 2010; James, Janardhanam, & Hanson, 2013; Wu & Xu, 2011) and so on.

The EFDC has been also applied in the simulation of hydrodynamic process, temperature stratification, sediment transport, pollutant load estimation and water quality prediction in reservoirs. Caliskan and Elci (2009) investigated the effect of selective withdrawal from four outlets located along the water intake structure of the Tahtali reservoir in Turkey. The water withdrawal at the bottom outlet was found to be most effective to mix the water column and reduce anoxia. Yang, Li, and Li (2012) predicted the water temperature in Xiahushan reservoir and determined the influence range of low-temperature water. Elci, Asli, and Caliskan (2009) applied the sediment transport module on Tahtali Reservoir to describe sediment deposition pattern and the erosion of soils. The results could be used for further water quality studies and long term management plans. Guo and Jia (2012) proposed an approach on allowable pollutant load and allocation and their methodology was demonstrated to be efficient and appropriate by a case study of the Chaihe Reservoir. He et al. (2011) developed a three-dimensional water quality model for Beijing Guanting reservoir. The influence of the background level of nutrients, external loading of nutrients, and meteorological conditions on water quality was analyzed. The short-term effects of applying the management scenarios were revealed. However, the influence of nutrient and temperature on algal growth was not taken into consideration. Furthermore, the temporal and spatial grading of eutrophic state and the determination of the limitation factors of eutrophication were not studied.

The purpose of the present paper was to investigate the feasibility of the EFDC model to predict trends of trophic status in reservoirs. In this approach, a temporal and spatial grading method of eutrophic state of reservoir was proposed based on the EFDC model. After the EFDC model was calibrated and validated, a series of numerical simulations were conducted to explore the effects of vegetation and wind on flow, water exchange and water quality in the Erwangzhuang reservoir. The influence of nutrient salts and temperature on algal growth was also analyzed to grade the temporal and spatial variation of eutrophic state of the Erwangzhuang reservoir.

2. Numerical methods

The EFDC model uses horizontal Cartesian and vertical sigma coordinates. The data of horizontal coordinates were obtained by converting the geographic coordinate system into Beijing 54 geodetic coordinate systems. The vertical coordinate was determined by the Huanghai elevation system. The formulation of the governing equations for ambient environmental flows was characterized by horizontal-length scales which the orders of magnitude were greater than the vertical-length. To accommodate realistic horizontal boundaries, it was convenient to formulate the control equations with the curvilinear orthogonal coordinates, $x$ and $y$. Time-variable mapping and stretching transformation given by Hamrick (1992) were used to provide uniform resolution in the vertical direction. After applying the Boussinesq approximation and hydrostatic assumption and ignoring the Coriolis force for the small study areas, the resultant continuity and momentum equations could be found in Hamrick (1992) and Zhang, You, and Zhao (2014). The 2.5 level Mellor–Yamada turbulence closure was used to provide the turbulent viscosity and diffusivity (Hamrick, 1992; Zhang et al., 2014). In the water quality module, the governing mass-balance equation for each water quality state variable and the temperature of water was expressed as (Park & Kuo, 1995):

$$\frac{\partial C}{\partial t} + \frac{\partial (uC)}{\partial x} + \frac{\partial (vC)}{\partial y} = \frac{\partial}{\partial x} \left( K_x \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_y \frac{\partial C}{\partial y} \right) + S_C$$

where, $C$ is either the concentration of a water quality state variable or the temperature of water; $u$, $v$ and $w$ are velocity components in the $x$- and $y$-directions, respectively; $K_x$ and $K_y$ are turbulent diffusivity coefficients in the $x$-, $y$- and $z$-directions, respectively; $S_C$ is internal and external sources and sinks per unit volume.

Algae as a central role in water quality model were grouped into three state variables: cyanobacteria, diatoms and green algae. The subscript $\tau$ (c for cyanobacteria, $d$ for diatoms, $g$ for green algae) was used to denote three algal groups. The source and sink considered are production, basal metabolism, predation, settling and external loads. The kinetic equation describing these processes was (Park & Kuo, 1995):

$$\frac{\partial B_\tau}{\partial t} = (P_\tau - BM_\tau - PR_\tau)B_\tau + \frac{\partial}{\partial z} (WS_\tau \cdot B_\tau) + \frac{WB_\tau}{V}$$

where, $t$ is time (day), $V$ is the cell volume ($m^3$). $B_\tau$, $P_\tau$, $BM_\tau$, $PR_\tau$, $WS_\tau$ and $WB_\tau$ are the algal biomass ($gC/m^3$),
the production rate (day\(^{-1}\)), the basal metabolism rate (day\(^{-1}\)), the predation rate (day\(^{-1}\)), the settling velocity (m/day) and the external loads (gC/day).

3. Study area

The water shortage of Tianjin is solved by the water diversion project from the Luanhe River to Tianjin City. The comprehensive urban water supply system composes of multiple components, such as water diversion, storage, purification and distribution. The Erwangzhuang reservoir was built in 1983 as backup water storage. It covers an area of 13.03 km\(^2\). The total capacity of reservoir is 4.5 \(\times\) 10\(^7\) m\(^3\). It is facing the eutrophication problem due to its small capacity and the weak self-purification ability. At present, monitoring the water quality and salvaging the aquatic plants are the main measures to control the eutrophication of the reservoir. The prediction of a developing trend of trophic status is lacking and the influence of nutrient and temperature on the algal growth is also not well understood. In the present study, EFDC was used to simulate the hydrodynamic process and water quality in the Erwangzhuang reservoir. Based on the simulation results, the prediction method for the temporal and spatial trend of trophic state was developed.

The locations of the Yinluan Open Channel and Erwangzhuang reservoir were shown in Figure 1a. The 64.2 km-length Yinluan Open Channel is the dedicated channel for a water diversion project from the Luanhe River to Tianjin City. Yinluan Open Channel is divided into two parts based on the design flow. The first part is from Jiuwangzhuang to Erwangzhuang whose length is 47.2 km and design flow is 50 m\(^3\)/s. The second part is from Erwangzhuang to Dazhangzhuang whose length is 17 km and design flow is 30 m\(^3\)/s.

The Erwangzhuang reservoir was selected as the study area. The shape of the reservoir is approximately rectangular being 4.4 km in length and 3 km in width. There are two sluice gates named Sluice Gate 1 and Sluice Gate 2. Sluice Gate 1 is commonly used in the water exchange between the Erwangzhuang reservoir and Yinluan Open Channel. Sluice Gate 2 is closed in most cases. There is a small island named Huanghuadian in the reservoir. The geometry of Erwangzhuang reservoir is shown in Figure 1b.

4. Model setup

The grid independent study shows that 27,846 grid cells are good for simulation. The grid resolution is 20 m \(\times\) 20 m in the horizontal plane. The roughness is 0.02, based on the engineering report. One water layer was used for the shallow study area. The study area and the position of six monitoring points C1 to C6 are shown in Figure 2.

The Huanghai elevation system was adopted in the vertical coordinate. The average bottom elevation of the Erwangzhuang reservoir is 1.40 m and the average water level is 5.32 m. Aquatic plant is predominant in the reservoir and it is assumed completely covered by this at the bottom of the reservoir.

Figure 2. Flow field and the position of monitoring points.

Figure 1. Location and geometry of the Erwangzhuang reservoir.
The time step for hydrodynamic and water quality model is 3 s. This time step ensures the accuracy of the results and the stability of the calculation process.

The monitoring volume flow at Sluice Gate 1 was applied to analyze the water exchange process of the Erwangzhuang reservoir and is shown in Figure 3. The positive number (Q > 0) means that the water flows into the reservoir.

The measurement data at Sluice Gate 1 in 2012 were adopted as the boundary conditions for the water quality model. The initial concentrations (monitoring) of dissolved oxygen (DO), chemical oxygen demand (COD), ammonia nitrogen (NH4-N), nitrate nitrogen (NO3-N), total nitrogen (TN) and total phosphorus (TP) are 12.8, 3.7, 0.1, 1.07, 1.7 and 0.03 mg/L, respectively. The major coefficients and constants of water quality model are shown in Table 1.

![Figure 3. Water volume flow at Sluice Gate 1 in 2012 (1st day refers to 1 January 2012).](image)

### Table 1. Major coefficients and constants of water quality model.

| Parameter                                | Value                  |
|------------------------------------------|------------------------|
| COD decay rate                           | 0.02 day⁻¹             |
| Maximum nitrification rate               | 0.2 g N m⁻³ day⁻¹      |
| Minimum hydrolysis rate of refractory particulate organic phosphorus | 0.001 day⁻¹             |
| Minimum hydrolysis rate of labile particulate organic phosphorus | 0.002 day⁻¹             |
| Minimum hydrolysis rate of dissolved organic phosphorus | 0.005 day⁻¹             |
| Minimum hydrolysis rate of refractory particulate organic nitrogen | 0.005 day⁻¹             |
| Minimum hydrolysis rate of labile particulate organic nitrogen | 0.05 day⁻¹              |
| Minimum hydrolysis rate of dissolved organic nitrogen | 0.05 day⁻¹              |
| Maximum growth rate for algae            | 2.0 day⁻¹              |
| Basal metabolism rate for algae          | 0.01 day⁻¹             |
| Nitrogen half-saturation for algae growth| 0.01 g N/m³            |
| Phosphorus half-saturation for algae growth | 0.001 P/m³             |

### 5. Results and discussion

#### 5.1. Hydrodynamic results

##### 5.1.1. Model validation

The hydrodynamic model was validated by comparing the monitoring data with the simulation data of the Erwangzhuang reservoir between April and September 2012. The root mean square error (RMS) was used to measure the deviation between the monitoring data and simulation data. RMS was expressed as:

\[
RMS = \sqrt{\frac{\sum_{i=1}^{N} (M_i - S_i)^2}{N}}
\]

where, \(M_i\) and \(S_i\) are the monitoring and simulation data. \(N\) is the number of data sets.

Figure 4 shows the comparison of the simulation data and monitoring data. Table 2 lists the RMS value of the simulated data and monitoring data. The RMS of water level was less than 0.07 m except 0.22 m in July. It was found that the numerical results agree well with the monitoring data except in July. This is because a rainfall in July was not considered and it resulted in the rise of water level. The results showed that the present model was suitable for analyzing water exchange characteristics of the Erwangzhuang reservoir.

##### 5.1.2. Water exchange process

Residence Time (RT) is a significant parameter to evaluate the water exchange. RT was defined as the time required for the concentration of dye in water to reduce to \(e^{-1}\) times (0.37) of its initial concentration (Wang, Hsu, & Kuo, 2004). The initial concentration of dye in the reservoir was assumed as 1 mg/L. The average dye concentration of the Erwangzhuang reservoir is shown in Figure 5. On the 305th day, the average concentration of dye was the minimum (0.60 mg/L), but it was still not reduced to \(e^{-1}\) times (0.37) of the initial concentration. This result indicated that the water exchange of the Erwangzhuang reservoir was very weak.

Six segments of the Erwangzhuang reservoir shown in Figure 6 were used to analyze the water exchange of different parts. The water exchange of the segments was evaluated by Flushing Time (FT). FT is the time required to replace the existing water in a segment (Wang et al., 2004). The initial dye concentration in the object segment is 1 mg/L. Table 3 shows that the FT of Segment VI is the shortest (106 days) and it has the best water exchange compared with the other segments. The FT of Segment I, II, III and V is longer than 365 days. On the 366th day, the maximum dye concentration in the above four segments is 0.99 mg/L. The water exchange in these segments was
Figure 4. Comparison of simulation and monitoring data for hydrodynamic model. (a) Average water level in April 2012 (b) Average water level in May 2012 (c) Average water level in June 2012 (d) Average water level in July 2012 (e) Average water level in August 2012 (f) Average water level in September 2012.

Table 2. The root mean square error of the water level of the simulated data and monitoring data in 2012 (hydrodynamic module).

| Month | RMS (m) |
|-------|---------|
| 6     | 0.06    |
| 7     | 0.22    |
| 8     | 0.06    |
| 9     | 0.07    |

weak because they are far away from Sluice Gate 1 and the mobility of water body was low.

5.1.3. Effect of boundary conditions
Vegetation, wind and flow boundary as three important factors were selected to analyze their influence on the water exchange in the Erwangzhuang reservoir. The

Figure 5. Average dye concentration for the Erwangzhuang reservoir (1st day refers to 1 January 2012).
flow data measured in April 2012 was applied to analyze the influence of above three parameters on the water exchange process.

(1) Bed vegetation effect

The influence of the vegetation was analyzed by comparing the water exchange under the conditions of vegetation existing and no vegetation and the result is shown in Figure 7. It was found that the dye concentration under the condition of vegetation existing was higher than that under the condition of no vegetation in the same period. The average dye concentration in the reservoir was 0.77 mg/L and 0.73 mg/L under the conditions of vegetation existing and no vegetation after 30 days, respectively. It was shown that the resistance of the vegetation decreased the water exchange rate of the reservoir by about 5.5% because the flow velocity and solute transport near the reservoir bed was reduced. The improvement of the local intricate food web, such as grass carp's introduction every year, was proposed to prevent the overgrowth of aquatic plants. The operation is beneficial and important to keep a good water quality in the reservoir.

(2) Surface wind effect

According to the meteorological statistical data, the average wind speed was 3.3 m/s (equivalent to wind
level 2) and prevailing wind direction was southwest (WS) in April in the study area. C1, C3 and C4 were selected to analyze the influence of wind on water exchange of reservoir. The dye concentration at the above three monitoring points under different wind conditions are shown in Figure 8. The dye concentration at the above three points reduced in wind condition. The time for the dye concentration down to 0 at C1 was 8.0 and 7.5 days under the conditions of no wind and wind speed 3.3 m/s, respectively. The corresponding time for the dye concentration dispersion at C3 was 13.7 and 11.3 days. The dye concentration at C4 kept constant under the condition of no wind and it reduced to 0.91 mg/L under the wind condition on the 30th day.

The simulation results indicated that the reduction of the dye concentrations was mainly determined by the distance between the monitoring point and Sluice Gate 1. The closer the distance was, the faster reduction of dye concentration was. For the same monitoring point, the dye concentration was higher under the condition of no wind than that under the wind condition. The WS wind speeds up the water exchange in the reservoir.

5.2. Water quality model validation

5.2.1. Model validation

The water quality model was validated by using monitoring data at Sluice Gate 1 between April and September 2012. The comparison of simulation and monitoring data is shown in Figure 9. It is illustrated that the temporal variations of water quality constituents agreed well with the measured data at Sluice Gate 1. Table 4 listed the root mean square error (RMS) of the simulation data and monitoring data. The RMS of COD, ammonia nitrogen and total phosphorus (TP) was less than 0.08, in addition to that DO was 0.22. The large difference of DO was in April. It was found that the numerical results agreed well with the monitoring data except that of DO.

5.2.2. Prediction of water quality

The water quality of the Erwangzhuang reservoir at Sluice Gate 1 in 2012 is shown in Figure 10. The concentration of COD, TN, TP and Chla had increased significantly in the reservoir between July and August in 2012. The peak concentrations of COD and TP were 5.8 mg/L and 0.05 mg/L, respectively, and they satisfied with the standard of Class III (National Standard of Surface Water of

Figure 8. Dye concentration under different wind conditions (1st day refers to 1 April 2012). (a) C1, no wind (b) C1, wind level 2 and WS (c) C3, no wind (d) C3, wind level 2 and WS (e) C4, no wind (f) C4, wind level 2 and WS.
Table 4. The root mean square error of water quality parameters of the simulated data and monitoring data at Sluice Gate 1 between April and September 2012 (water quality module).

| Parameters | RMS (mg/L) |
|------------|------------|
| DO         | 0.22       |
| COD        | 0.08       |
| NH₄-N      | 0.01       |
| TP         | 0.01       |

China, GB3838–2002). The peak concentration of TN was 3.17 mg/L, which was above the standard of Class V. A deterioration of water quality between July and August was apparent because of the water quality upstream. According to the reference date (Zhang et al., 2013), the upstream water quality was not good between July and August due to the rainfall runoff influenced by agricultural pollution. In addition, the algae that was growing abundantly in the reservoir also resulted in the decline of water quality. Moreover, the effect of vegetation and wind on the water quality was studied. The measured flow data in April 2012 was applied to study the influences on water quality.

(1) Vegetation effect

The influence of the vegetation on DO was analyzed by comparing the concentration of DO under the conditions of vegetation and no vegetation. Figure 11 shows that the concentration of DO of vegetation case is lower than that of no vegetation. The existence of vegetation reduced the flow velocity at the bottom of the reservoir and reduced the exchange of water with high DO flowing into the internal part of reservoir. Meanwhile, the water exchange was lower for the case with vegetation and the low water exchange increased the DO consumption and reduced further the concentration of DO.

(2) Surface wind effect

The surface wind boundary condition was set up the same as that in Section 5.3. Three monitoring points, C1, C3 and C4, were selected to judge the influence of wind on water quality. The concentrations of DO and TP at the above three monitoring points under different wind conditions are shown in Figure 12. For the same monitoring point, the DO concentration was high while the TP concentration was low for the wind condition. The reason was that the WS wind speeds up the water exchange in the reservoir and promoted the water with the high DO concentration and low TP concentration flowing into the reservoir through Sluice Gate 1.

5.3. Eutrophic state evaluation

According to the recommendations of the State Environmental Protection Administration of China, the water eutrophication of the Erwangzhuang reservoir was evaluated by Trophic State Index. The formula was written as:

$$ TSI = \sum_{j=1}^{m} W_j \times TLI (j) $$  \hspace{1cm} (4)
Figure 10. Variations of water quality constituents at Sluice Gate 1 in 2012 (1st day refers to 1 January 2012).

\[ W_j = \frac{r_j^2}{\sum_{j=1}^{m} r_j^2} \]  

(5)

where, TSI is the trophic state index. TLI \((j)\) is the trophic level index for the parameter \(j\). \(W_j\) is the relative weight of trophic level index for the parameter \(j\). \(r_j\) is the correlation coefficient of the parameter \(j\) (Table 5) relative to basic parameter (Chla). \(m\) is the number of indexes.

TLI \((j)\) is calculated as:

\[
\begin{align*}
\text{TLI (Chla)} & = 10 \left( 2.5 + 1.086 \ln \text{Chla} \right) \\
\text{TLI (TP)} & = 10 \left( 9.436 + 1.624 \ln \text{TP} \right) \\
\text{TLI (TN)} & = 10 \left( 5.453 + 1.694 \ln \text{TN} \right) \\
\text{TLI (SD)} & = 10 \left( 5.118 - 1.94 \ln \text{SD} \right) \\
\text{TLI (COD)} & = 10 \left( 0.109 + 2.661 \ln \text{COD} \right)
\end{align*}
\]  

(6) (7) (8) (9) (10)

where, Chla is the Chlorophyll a. TP and TN are total phosphorus and total nitrogen. SD is the transparency. COD is the Chemical Oxygen Demand. The unit of Chla and SD is mg/m\(^3\) and m, respectively. The units of the others are mg/L.

The results of the grade of trophic state of reservoir are shown in Table 6. Due to the lack of data of SD, the parameter of SD was not involved in the TSI. Figure 13 shows the variation of average value of TSI in the Erwangzhuang reservoir. The value of TSI varied from 35.3 to 45.6, which indicated that the grade of trophic state of the reservoir was mesotropher according to Table 6. TSI was increased significantly in the reservoir between July and August in 2012. At this time, measures should be taken to ensure water quality of the reservoir.

Figure 14 shows the space distribution of TSI of the Erwangzhuang reservoir in April 2012. The value of TSI varied from 35.3 to 41.6, which means the trophic state of reservoir was mesotropher according to Table 6. From the 92nd day (1 April) to the 100th day (9 April), the TSI near Sluice Gate 1 was lower than that of the internal reservoir because the concentrations of Chla and TN of water flowing into the reservoir from Sluice Gate 1 were low. In the results are that the water quality near Sluice Gate 1 is better than that of the internal reservoir.

From 101st day (10 April) to 121st day (30 April), the overall level of TSI in the reservoir starts falling.
This is because during this period algae begin to grow and consume a large amount of nutrients, which reduces the concentrations of TN, TP in the reservoir. Moreover, algae do not grow excessively to cause a rapid increase of Chla and COD. For the above reasons, the overall level of TSI is lower in the reservoir. However, the TSI near Sluice Gate 1 is higher than that of the internal reservoir. This is because the concentrations of TN, TP and COD in the water flowing into the reservoir from Sluice Gate 1 are increased during this period. It means that the water quality near the internal reservoir is better.

5.4. Limitation factors on algal growth

The growth of algal mainly depends on the nutrient availability, ambient light and temperature. For cyanobacteria in freshwater, it requires additional consideration of salinity. The effects of limitation factors were expressed as follows (Park & Kuo, 1995):

\[ P = P_M \times f(N) \times f(I) \times f(T) \times f(S) \]  

where \( P \) is the production rate of algal group (day\(^{-1}\)), \( P_M \) is the maximum growth rate under optimal conditions.
Figure 12. Concentration of water quality parameters under different wind conditions (95th day refers to 1 April 2012). (a) C1, DO (b) C1, TP. (c) C3, DO (d) C3, TP. (e) C4, DO (f) C4, TP.

Table 5. Correlation coefficient of parameters relative to basic parameter (Chla).

| Parameters | Chla | TP  | TN  | SD  | COD |
|------------|------|-----|-----|-----|-----|
| $r_1$      | 1    | 0.84| 0.82| −0.83| 0.83|
| $r_2$      | 1    | 0.7056 | 0.6724 | 0.6889 | 0.6889|

Table 6. Grades of trophic state for lakes (reservoirs).

| TSI         | Grade          |
|-------------|----------------|
| TSI < 30    | Oligotropher   |
| 30 ≤ TSI ≤ 50 | Mesotropher   |
| 50 < TSI ≤ 60 | Light eutropher|
| 60 < TSI ≤ 70 | Middle eutropher|
| TSI > 70    | Hyper eutropher|

for algal group (day$^{-1}$), $f(N)$ is the effect of suboptimal nutrient concentration on the algal group, $f(I)$ is the effect of suboptimal light intensity on algal group, $f(T)$ is the effect of suboptimal temperature on algal group, $f(S)$ is the effect of salinity on cyanobacteria growth.

The growth limitation factor varies from 0 to 1. A value of 1 indicates the factor does not limit growth, and a value of 0 means the factor is too severe to stop growth entirely.
Figure 14. Space distribution of TSI for the Erwangzhuang reservoir in April 2012 (95th day refers to 1 April 2012). (a) 95th day (b) 100th day (c) 105th day (d) 110th day (e) 115th day (f) 120th day.

(1) Nutrient limitation

The effect of nutrient limitation on algal growth was expressed as (Lin et al., 2008):

\[ f(N) = \min(f_N, f_P) \]  

\[ f_N = \frac{\text{NH}_4 + \text{NO}_3}{\text{KHN} + \text{NH}_4 + \text{NO}_3} \]  

\[ f_P = \frac{\text{PO}_{4d}}{\text{KHP} + \text{PO}_{4d}} \]

where \( f_N \) and \( f_P \) are the nitrogen and phosphorus limitation functions, respectively. \( \text{NH}_4 \) is the ammonium nitrogen concentration (gN/m³). \( \text{NO}_3 \) is the nitrate nitrogen concentration (gN/m³). \( \text{KHN} \) is the half-saturation constant for nitrogen uptake (0.01 gN/m³). \( \text{PO}_{4d} \) is the dissolved phosphate phosphorus concentration (gP/m³). \( \text{KHP} \) is the half-saturation constant for phosphorus uptake (0.001 gP/m³).

The variation of average value of \( f_N \) and \( f_P \) with respect to time in the Erwangzhuang reservoir is shown in Figure 15. \( f_N \) was close to 1 and the nitrogen did not limit the growth. \( f_P \) was in the range of 0.82–0.85. It indicated the limitation of phosphorus on the growth of algae and the reservoir was a phosphorus-limited environment.
Figure 15. The average $f_N$, $f_P$ and $f(N)$ with respect to time in the Erwangzhuang reservoir (95th day refers to 1 April 2012). (a) $f_N$ and $f_P$ (b) $f(N)$.

Figure 16. The space distribution of $f(N)$ in the Erwangzhuang reservoir in April 2012 (95th day refers to 1 April 2012). (a) 95th day (b) 100th day (c) 105th day (d) 110th day (e) 115th day (f) 120th day.
Figure 17. The limitation factor of temperature with respect to time in the Erwangzhuang reservoir (cyanobacteria).

Figure 16 shows the space distribution of $f(N)$ in the Erwangzhuang reservoir in April 2012. The $f(N)$ varied from 0.82 to 0.85. The result indicated that the nutrient limitation was not significant in this month. The $f(N)$ near Sluice Gate 1 was higher than that of the internal reservoir because the water with the high concentration PO$_{4d}$ was flowing into the reservoir from Sluice Gate 1. It means that the limitation of nutrient near Sluice Gate 1 was slightly lower than that of internal reservoir in April.

(2) Temperature dependence

A Gaussian probability curve was used to represent the temperature dependency of algal growth (Lin et al.,...
2008):

\[
f(T) = \begin{cases} 
\exp \left[ -KTG_1(T - T_M)^2 \right] & \text{if } T \leq T_M \\
\exp \left[ -KTG_2(T_M - T)^2 \right] & \text{if } T > T_M 
\end{cases}
\]

(15)

where \( T \) is the temperature (°C), \( T_M \) is the optimal temperature for algal growth (27.5°C for cyanobacteria), \( KTG_1 \) is the effect of temperature below \( T_M \) on algal growth (0.005°C\(^{-2}\) for cyanobacteria); \( KTG_2 \) is the effect of temperature above \( T_M \) on algal growth (0.004°C\(^{-2}\) for cyanobacteria).

The average value of \( f(T) \) in the Erwangzhuang reservoir is shown in Figure 17. The \( f(T) \) of cyanobacteria growth varied from 0.02 to 1.0. The near zero value of \( f(T) \) indicated the limitation of temperature from January (1st day) to April (92nd day). With the increase of temperature, the degree of restriction was reduced. The temperature was not the limiting factor for algae growth from June (153rd day) to September (245th day).

Figure 18 shows the space distribution of \( f(T) \) of cyanobacteria in the Erwangzhuang reservoir in April 2012. The \( f(T) \) varied from 0.23 to 0.51 in April, which showed the significant limitation of temperature. The \( f(T) \) near Sluice Gate 1 was higher than that of the internal reservoir because the temperature of water flowing into the reservoir was high. Moreover, the overall level of \( f(T) \) in the reservoir was increased from 92nd day (1 April) to 121st day (30 April) due to the increase of atmospheric temperature. The limitation of temperature was gradually reduced from the 92nd day to 121st day.

6. Conclusions

The method of grading the eutrophic state of reservoir based on the results of EFDC model was proposed in order to obtain the spatial and temporal evaluation of eutrophic state in reservoirs. The Erwangzhuang reservoir of Tianjin was taken as an example to show the performance of the proposed numerical model. After the hydrodynamic and water quality models were validated by the measured data, the water exchange, water quality and eutrophic state grading were studied. The main conclusions were as the following:

(1) The effect of wind and bed vegetation on the water exchange of reservoir is very strong. Suitable wind direction is favorable to the increase of water exchange. Bed vegetation always reduces the flow velocity near the reservoir bed and decreases the water exchange.

(2) The spatial and temporal distribution of eutrophic state in reservoirs was obtained and the grading of the eutrophic state of reservoir was predicted and evaluated.

(3) For the Erwangzhuang reservoir in 2012, the water exchange was low and the residence time (RT) was more than one year. The eutrophic state grade of reservoir varied from 35.3 to 45.6. TSI was increased significantly and the deterioration of water quality appeared between July and August. The reservoir was a phosphorus-limited environment. The temperature limitation was prominently for algae growth from January to April and it was not a limitation factor from June to September 2012.

The study was mainly focused on the water quality and eutrophic state grade of reservoir. Future research should take into account the sensitivity analysis of the parameters on the prediction of water quality and the ways of improvement of water quality in reservoirs.

Disclosure statement

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