

Analysis of agricultural pollution by flood flow impact on water quality in a reservoir using a three-dimensional water quality model

Chen Zhang, Xueping Gao, Liyi Wang and Yuanyuan Chen

ABSTRACT

This study presents the Yuqiao Reservoir Water Quality Model (YRWQM), a three-dimensional hydrodynamic and water quality model of the Yuqiao reservoir, China. The YRWQM was developed under the environmental fluid dynamics code (EFDC) model and was calibrated and verified to hydrodynamic and water quality data, using two sets of observed data from January 1 to December 31, 2006 and from May 1 to October 31, 2007, respectively. The primary hydrodynamic and transport driving forces are inflows/outflows and surface wind stresses. Considering effects of water transfer and wind on the advection-dispersion processes, the model results showed better agreements with observed data in the reservoir. The YRWQM predicted the variations of water quality resulting from agricultural pollution which flowed into the reservoir with floods lasting for 12 days in 2009. The results indicated that the concentrations of chemical oxygen demand and total nitrogen were increased 225 and 314%, respectively. Considering the interactions between chlorophyll-*a* and nitrogen in the model, the results indicated the reservoir was not a nitrogen-limited environment. We suggest the management should focus on agricultural pollution strategies for the reservoir during the flood period. The YRWQM could be a useful tool for water sources management in the reservoir.

Key words | advection-dispersion process, agricultural pollution, EFDC, three-dimensional modeling, water quality, Yuqiao reservoir

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INTRODUCTION

Numerical models are important decision support tools for surface water systems management, such as rivers, lakes, reservoirs, estuaries and coastal waters. Models play a critical role in advancing hydrodynamics, sediment transport, water quality, ecology, and water resources management. In the past decades, hydrodynamic and water quality models have evolved from simplified one-dimensional models to complex three-dimensional (3D) models. Some of the most common examples are enhanced stream water quality model (QUAL2E) (Brown & Barnwell 1987), Princeton ocean model (POM) (Blumberg & Mellor 1987), estuarine, coastal and ocean model (ECOM) (HydroQual 1991) and Three-dimensional Generalized Water Quality Modeling Computer Code (RCA) (HydroQual 2004), environmental fluid

dynamics code (EFDC) (Hamrick 1992), CE-QUAL-W2 (Cole & Buchak 1995) and CE-QUAL-ICM (Cercio & Cole 1994), water quality analysis simulation program (WASP) (Wool *et al.* 2002), MIKE 3 (DHI 2001), and so on. These advanced models often include several coupled submodels for different physical, chemical, biological processes in surface waters.

In previous research, EFDC is one of the outstanding models and widely used for taking into environmental problems in varied types of surface water bodies. The model was used in the Blackstone River study (Ji *et al.* 2002), the Cape Fear River Estuary study (Xia *et al.* 2007), the Lake Okeechobee study (Jin & Ji 2004; James *et al.* 2005; Jin *et al.* 2007), the Tahtali reservoir study (Sebnem 2008), amongst others. EFDC has been

applied on many water bodies within USEPA Region 4 for total maximum daily load and supported by Tetra Tech. Subsequently, EFDC has also been applied in China.

In this paper, EFDC was used to simulate hydrodynamic and water quality in the Yuqiao reservoir in China. Although there have been many studies that have investigated water quality problems of the reservoir, Liu *et al.* (2008) used a two-dimensional coupled model to simulate the characteristics of hydrodynamic field and mass transport processes in the reservoir. Zhang *et al.* (2011) studied the impact on water quality of excessive growth of *Potamogeton crispus* for the reservoir. However, there is no study focusing on developing a water quality modeling for studying water quality and submerged aquatic vegetation processes in the reservoir. Are there significant differences in advection-dispersion processes due to the characteristic features of the Yuqiao reservoir?

The objectives of this study are the following: (1) to calibrate a hydrodynamic model with water surface elevation (WSE) and temperature; (2) to calibrate and verify a water quality model with water quality constituents; (3) to predict the variations of water quality resulting from agricultural pollution which flowed into the reservoir with flood; and (4) to discuss the differences in advection-dispersion

processes by water transfer and wind, and the relation between chlorophyll-*a* (Chl*a*) and nitrogen. The results reveal a successful model application for the Yuqiao reservoir based on EFDC in this study. The Yuqiao Reservoir Water Quality Model (YRWQM) could be a useful tool for water quality managers and scientists.

MATERIALS AND METHODS

Study area

Yuqiao reservoir (Figure 1) is located in Tianjin city in China, which has been the only source for water supply in Tianjin city (population, more than 10 million) since 1983. This shallow reservoir (maximum depth 12.16 m and mean depth 4.74 m) has a watershed area of 2,060 km², a storage capacity of 1.559 billion m³ and a surface area of 86.8 km² at an elevation of 19.97 m, according to the 1985 national elevation standard (China). The Lin, Sha and Li rivers are the contributing rivers of the reservoir. There is extensive agricultural land use, covering 721.8 km², 35% of the watershed area. The types of agricultural land are paddy field (154.1 km²), irrigable land (372.0 km²), dry land (184.8 km²) and vegetable field

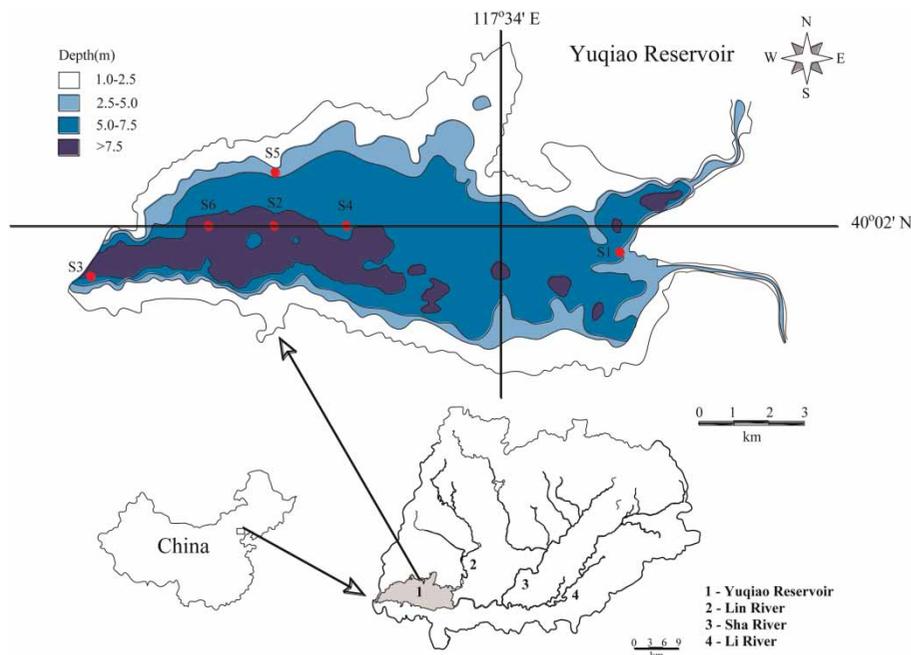


Figure 1 | Yuqiao reservoir (117° 34'E, 40° 02'N) bathymetry and monitoring stations (Stations S1–S6) used in this study.

(10.9 km²). The annual average water resource is 0.19 billion m³, with an evaporation is 0.06 billion m³ in the watershed. To deal with the serious shortage of water resources in Tianjin water supply, the water is transferred from the Luan watershed to the Yuqiao watershed through the Li River during the water diversion period (April–June and October–December). In recent years, the water resource has an annual average diversion water of 0.56 billion m³ during the period 2006–2010. The wind changes direction with the seasons. The main wind directions are NE (northeast) and SW (southwest) in the study area. The wind speed is higher in the spring and summer.

Modeling tools

The EFDC model (Hamrick 1992; Cerco & Cole 1994; Park et al. 1995) was used to simulate hydrodynamic and water quality in the Yuqiao reservoir during this study. The model is a 3D model that is capable of simulating hydrodynamic, salinity, temperature, sediment and water quality component transport, and so on. The model uses a stretched or sigma vertical coordinate and Cartesian or curvilinear, orthogonal horizontal coordinates. Finite difference numerical schemes are available for the solution of hydrodynamic equations and transport equations in vertical and horizontal direction. For the details of model capabilities, the reader is referred to the user's manual (Hamrick 1996). The YRWQM was developed under the framework of the EFDC model.

Conservation of mass equation

For simplicity, the hydrodynamics equations and numerical schemes of the EFDC model are not presented in this paper but are detailed in the EFDC documents (Hamrick 1992).

The governing mass-balance equation for each of the water quality state variables may be expressed as (Tetra Tech 2006):

$$\begin{aligned} & \frac{\partial(m_x m_y H C)}{\partial t} + \frac{\partial(m_y H u C)}{\partial x} + \frac{\partial(m_x H v C)}{\partial y} + \frac{\partial(m_x m_y w C)}{\partial z} \\ &= \frac{\partial}{\partial x} \left(\frac{m_y H A_x}{m_x} \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{m_x H A_y}{m_y} \frac{\partial C}{\partial y} \right) \\ &+ \frac{\partial}{\partial z} \left(m_x m_y \frac{A_z}{H} \frac{\partial C}{\partial z} \right) + m_x m_y H S_C \end{aligned} \quad (1)$$

where C is the concentration of a water quality state variable; u , v and w are velocity components in the curvilinear, sigma, x -, y -, and z -directions, respectively; A_x , A_y and A_z are turbulent diffusivities in the x -, y -, and z -directions, respectively; S_C is the internal and external sources and sinks per unit volume; H is water column depth; m_x and m_y are horizontal curvilinear coordinate scale factors.

The last three terms on the left-hand side of (1) account for the advective transport, and the first three terms on the right-hand side account for the diffusive transport. The advection and diffusion for physical transport are the same as the numerical method of solution in the mass-balance equation for temperature in the hydrodynamic model (Hamrick 1992). The last term in (1) represents the kinetic processes and external loads for each of the state variables. The model solves Equation (1) using a fractional step procedure which decouples the kinetic terms from the physical transport terms:

$$\begin{aligned} & \frac{\partial(m_x m_y H C)}{\partial t_P} + \frac{\partial(m_y H u C)}{\partial x} + \frac{\partial(m_x H v C)}{\partial y} + \frac{\partial(m_x m_y w C)}{\partial z} \\ &= \frac{\partial}{\partial x} \left(\frac{m_y H A_x}{m_x} \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{m_x H A_y}{m_y} \frac{\partial C}{\partial y} \right) \\ &+ \frac{\partial}{\partial z} \left(m_x m_y \frac{A_z}{H} \frac{\partial C}{\partial z} \right) + m_x m_y H S_{CP} \end{aligned} \quad (2a)$$

$$\frac{\partial C}{\partial t_K} = S_{CK} \quad (2b)$$

with

$$\frac{\partial(m_x m_y H C)}{\partial t} = \frac{\partial(m_x m_y H C)}{\partial t_P} + m_x m_y H \frac{\partial C}{\partial t_K} \quad (3)$$

In Equation (2a), (2b) the source sink term has been split into physical sources and sinks (S_{CP}) which are associated in volumetric inflows and outflows, and kinetic sources and sinks (S_{CK}). The kinetic step is made at a constant water column depth corresponding to the depth field at the end for the physical transport step, which can be split into reactive and internal sources and sinks:

$$S_{CK} = \frac{\partial C}{\partial t_K} = K \cdot C + R \quad (4)$$

where K is kinetic rate and R represents internal source/sink term. Equation (4) is obtained by linearizing some terms in the kinetic equations. The kinetic equations for state variables are considered: algae, organic carbon, phosphorus, nitrogen, silica, chemical oxygen demand (COD) and dissolved oxygen (DO), which are detailed in EFDC Water Quality Model Theory and Computation (Tetra Tech 2006).

MODEL APPLICATION

Bathymetric data were used to generate an orthogonal horizontal mesh with 2,329 elements (200 m by 200 m, Figure 2). Due to the sensitivity of the layers, simulated constituents mean concentrations increased about 34% in the four horizontal layers than in two horizontal layers. Four horizontal layers were considered in the simulation. The model time step was 10 s which was in compliance with the Courant-Friedrich-Levy (CFL) criterion during the whole simulation period.

Stations S1, S2 and S3 (Figure 1) were used to collect water quality parameters since 1989, which typified the water in the uppermost part of the reservoir (near the contributing rivers), inside of the reservoir and the water output from the reservoir, respectively. Because the reservoir is so broad, Stations S4, S5 and S6 were additionally investigated after 1999.

Wind speed and direction, solar radiation, cloud cover, air temperature, precipitation and evaporation data, inflow from tributaries and WSE observed data, water temperature and concentration of water quality constituents measured data were derived from China Meteorological Data Sharing Service System (<http://cdc.cma.gov.cn/index.jsp>) and

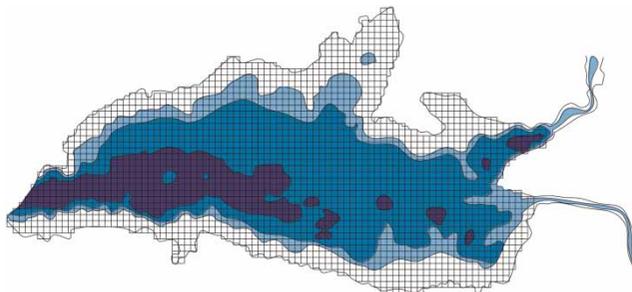


Figure 2 | The YRWQM model grid used in simulations.

Yuqiao Reservoir Administrative Bureau of Luan River-Tianjin Water Diversion Project. Water temperature was determined *in situ* using a thermometer for surface and bottom water. Measured data were taken from 1 m below the surface of the water column. We sampled, preserved and analyzed all the water quality parameters in the laboratory according to the Standard Method for Water and Wastewater of China (Standard Method for the Examination of Water and Wastewater Board 2002).

The initial and boundary conditions for the model calibration and validation were taken from measurements made at stations (Figure 1): (1) input discharge time-series and associated temperature time-series; (2) input wind time-series in the reservoir watershed; (3) input atmospheric forcing time-series; (4) inputs concentrations of water quality constituents time-series included COD, DO, ammonia nitrogen ($\text{NH}_4\text{-N}$), total nitrogen (TN), total phosphorus (TP) and Chl a ; (5) initial conditions for WSE and the concentration of water quality constituents.

The calibrated and verified YRWQM was simulated for prediction during a flood event as a case study from August 4 to 15 in 2009. The flood lasted for 12 days and the peak appears at 12 o'clock, August 9 with a flow of $951 \text{ m}^3 \text{ s}^{-1}$. The flood flowed into the reservoir along the part of north shore (length 5 km), bringing agricultural pollutants concentrations of COD 10 mg l^{-1} , and TN 10 mg l^{-1} .

RESULTS

Hydrodynamic and temperature modeling results

The YRWQM hydrodynamic model computes current discharges, velocities, the change in WSE and water temperature. The calibration methodologies for the hydrodynamic model included graphical time series comparisons and statistical calculations for continuous measurements of WSE and temperature. Hydrodynamic model calibration was done by changing the roughness (calibrated from 0.022 to 0.028 in different sediment bed conditions) and wind stress coefficient (0.001) until a reasonable agreement with reservoir measured and modeled WSE was achieved. WSE at Station S2 for year

2006 was used in the calibration (Figure 3). The root mean squared error (RMSE) for the WSE calibration was 0.18 m (Table 1).

Temperature calibration was done using data collected at the stations (S2–S6) for year 2006. Model simulation results were compared with measured temperature time series for surface and bottom water. Figure 4 displays a selection of temperature calibration results. The goodness of fit for temperature is presented in Table 1.

The reservoir is shallow so that thermal stratification is not clearly observed throughout the year. Model results showed that the maximum temperature difference between surface and the bottom layer was 3 °C at all stations. In the deeper (>7.5 m) areas of the reservoir, such as Station

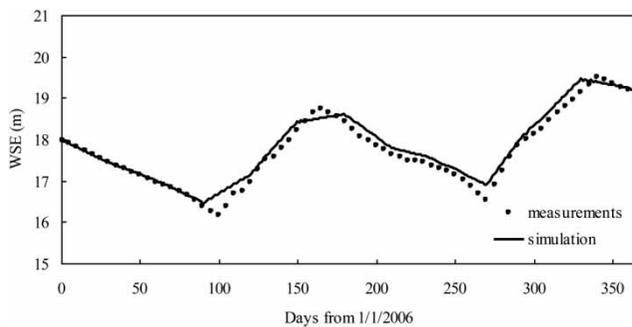


Figure 3 | Simulated and measured WSE (m) at Station S2 for year 2006.

Table 1 | Root mean square error for WSE and temperature calibration

Parameter	Location and layer	RMSE ^a
WSE (m)	Station S2	0.18
Water temperature (°C)	Station S2 surface	1.21
	Station S2 bottom	1.46
	Station S3 surface	0.98
	Station S3 bottom	1.26
	Station S4 surface	1.17
	Station S4 bottom	1.43
	Station S5 surface	1.04
	Station S5 bottom	1.38
	Station S6 surface	1.25
	Station S6 bottom	1.52

RMSE = $\sqrt{\sum_{i=1}^N (O_i - M_i)^2 / N}$ where N is the number of observations, O_i is the observed value for the i th observation and M_i is the simulated value.

^aThe root mean square error (RMSE) was used as a measure for goodness of fit.

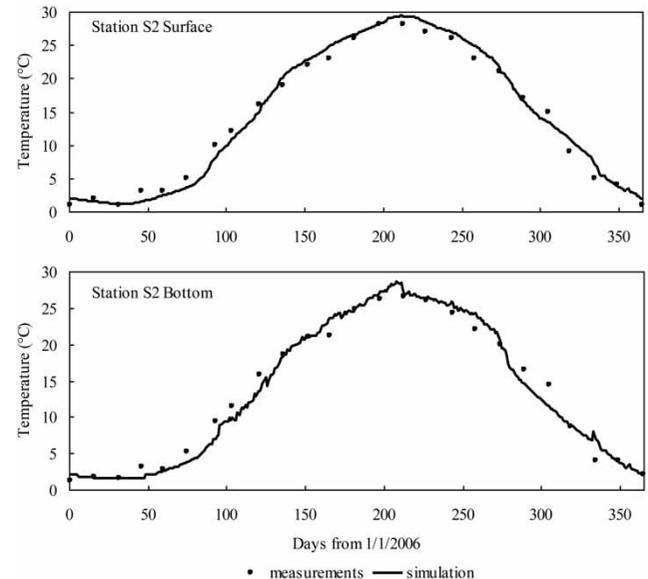


Figure 4 | Temperature time series for surface and bottom water at Station S2 for year 2006.

S2, surface temperatures ranged between 1.1 °C in winter and about 29.5 °C in summer while bottom water temperature ranged between 1.5 and 28.6 °C (Figure 4).

The calculated current velocities for surface and bottom water (Figure 5) showed two kinds of power driving the water movement in the reservoir: freshwater inflow and wind stress (Zhang & Gao 2010). The annual average wind speed for the reservoir in the studied period was 1.7 m s⁻¹ with prevailing wind direction ENE (east-northeast) (Figure 5). As a consequence hydraulically induced currents were more important than wind induced in the main body of the reservoir during the water diversion period. The velocities in the upper part of the reservoir presented higher values (surface velocity ranged from 4 to 20 cm s⁻¹ which was about four times as high as the bottom velocity) than the rest of the reservoir (surface velocity ranged from 2 to 8 cm s⁻¹ and bottom velocity from 0.6 to 2.2 cm s⁻¹) in the computed circulation for year 2006. Simulated yearly average surface velocity in the main body of the reservoir was about 8.3 cm s⁻¹. While in the large part of the surface water of the reservoir wind-induced currents were always dominant and affect mostly the surface circulation. Model results indicated that the YRWQM hydrodynamic model can be considered reasonable.

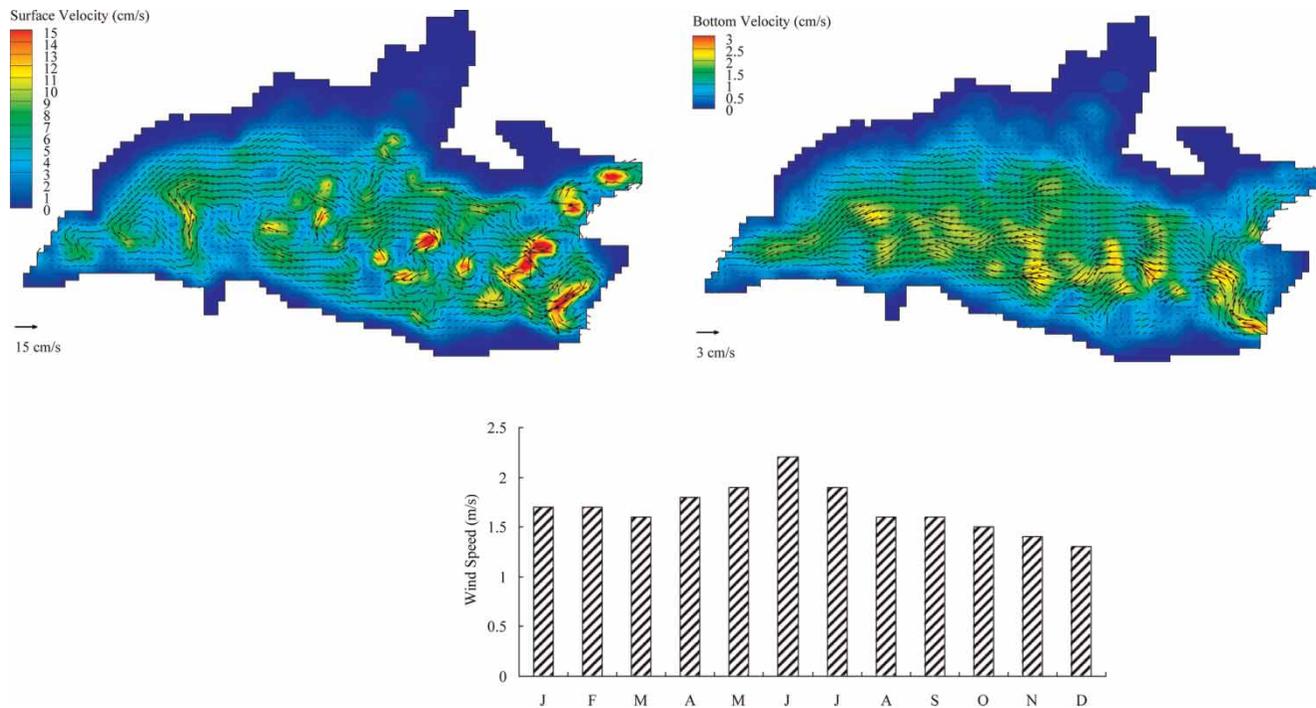


Figure 5 | (Top) Simulated surface and bottom velocity in the Yuqiao reservoir on October 15, 2006 (Day 288). (Bottom) The monthly average of measured wind speed in the reservoir. October is 1 month of water diversion period in 2006.

Water quality model calibration and verification

Application of the proposed EFDC water quality model has been realized in three periods for YRWQM calibration, verification and prediction as follows: first period – model calibration, from January 1 to December 31, 2006; second period – model verification, from May 1 to October 31, 2007; and third period – model prediction, from August 4 to August 15, 2009. The third period, model prediction, described the case study of the model to predict the variations of water quality resulting from agricultural pollution which flowed into the reservoir with flood.

The model calibration and verification were done by comparing model simulations with measured data on different temporal and spatial scales for years 2006 and 2007, respectively. Following the calibration, statistical methods such as standard error of estimate, constrained regression analysis, RMSE and absolute error were utilized to test the goodness of fit between model simulations and measurements. The calibrated values of major model coefficients are given in Table 2. Examples of model calibration results of COD, DO, $\text{NH}_4\text{-N}$, TN, TP and Chl a at Station S2 are

Table 2 | Major model coefficients and constants of the calibrated model

Parameter	Unit	Value
Maximum nitrification rate	0.2	$\text{g N m}^{-3} \text{ day}^{-1}$
COD decay rate	0.02	1 day^{-1}
Minimum hydrolysis rate of refractory particulate organic phosphorus	0.001	1 day^{-1}
Minimum hydrolysis rate of labile particulate organic phosphorus	0.002	1 day^{-1}
Minimum hydrolysis rate of dissolved organic phosphorus	0.005	1 day^{-1}
Minimum hydrolysis rate of refractory particulate organic nitrogen	0.005	1 day^{-1}
Minimum hydrolysis rate of labile particulate organic nitrogen	0.05	1 day^{-1}
Minimum hydrolysis rate of dissolved organic nitrogen	0.05	1 day^{-1}
Setting velocity for refractory and labile particulate organic matter	0.1	m day^{-1}
Setting velocity for algae	0.1	m day^{-1}
Maximum growth rate for algae	2.0	1 day^{-1}
Basal metabolism rate for algae	0.01	1 day^{-1}
Nitrogen half-saturation for algae growth	0.01	mg N l^{-1}
Phosphorus half-saturation for algae growth	0.001	mg P l^{-1}

depicted in Figure 6. Some model verification results are presented in Figures 7 and 8. Table 3 summarizes the results of the statistical error quantification methods in calibration and verification for all water quality constituents at stations (S2–S6) except Chla (no observation at Station S3). For the perfect match between model simulations and measurements, standard error of estimate, RMSE and absolute error analysis results should be 0.0 while slope should be 1.0. The model simulations of constituents were fairly good with standard error of estimate, RMSE and absolute error results of around 1.0 mg l^{-1} (COD, DO and TN), 0.1 mg l^{-1} ($\text{NH}_4\text{-N}$), 0.01 mg l^{-1} (TP) and $5.0 \mu\text{g l}^{-1}$ (Chla) and the slope values being close to 1.0 in Table 3.

Calibration and verification results showed that the model could generally simulate the patterns of water quality constituents well.

Figures 6 and 7 demonstrate that simulated temporal variations of water quality constituents were consistent with the trends of measured data at Station S2. The model results generally compared favorably to the measured data. Following the calibration, the modeled COD varied between 2.8 and 6.1 mg l^{-1} , the mean value was 3.7 mg l^{-1} at Station S2. The higher COD value ($>4 \text{ mg l}^{-1}$) was calculated from August to October, while DO value (mean = 10.1 mg l^{-1}) was lower than 10 mg l^{-1} in this period. Since the pollution loads and

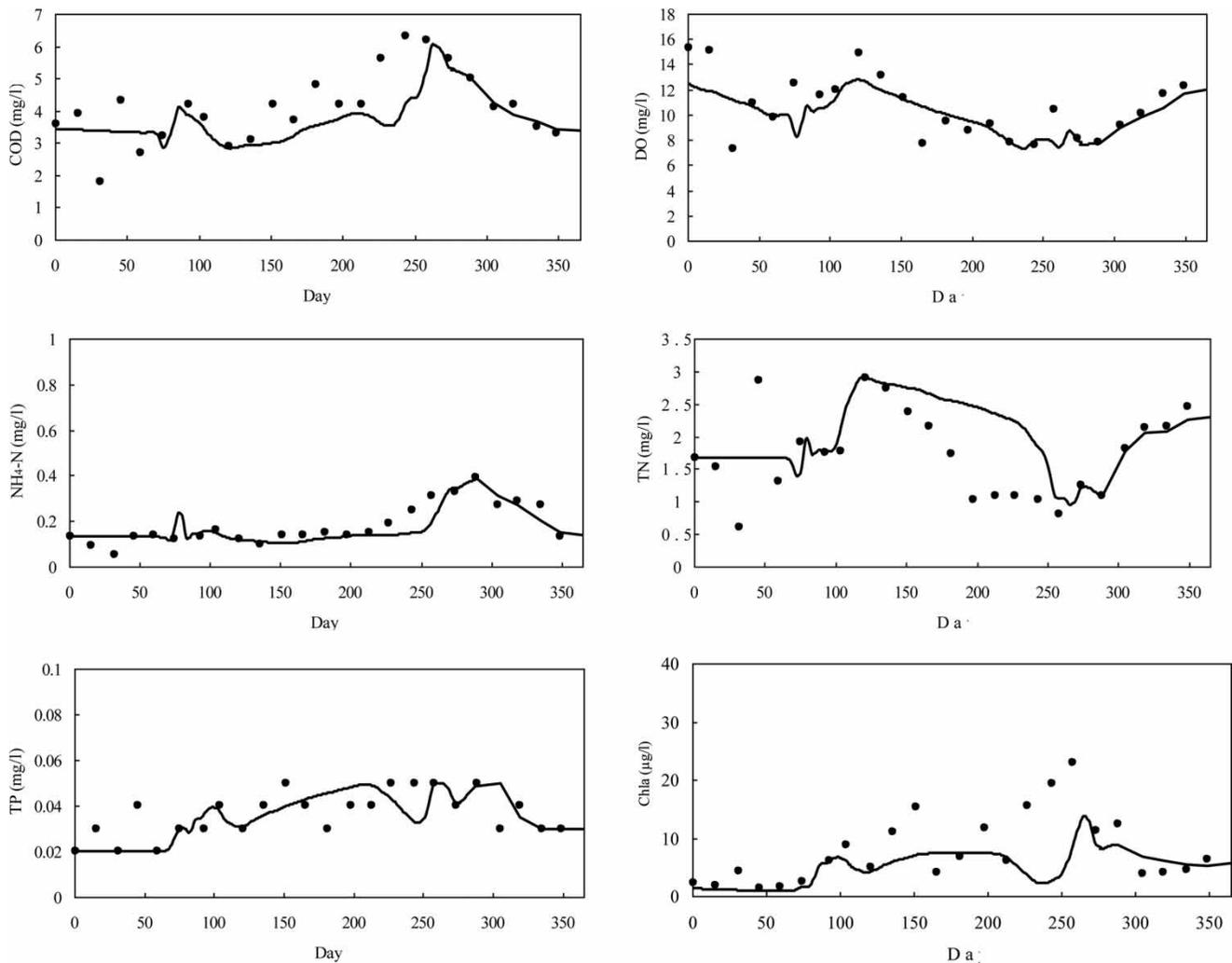


Figure 6 | Measured and calibrated water quality constituent concentrations at Station S2 for calibration period of January 1–December 31, 2006. Black points represent monitoring data. Black lines represent model results.

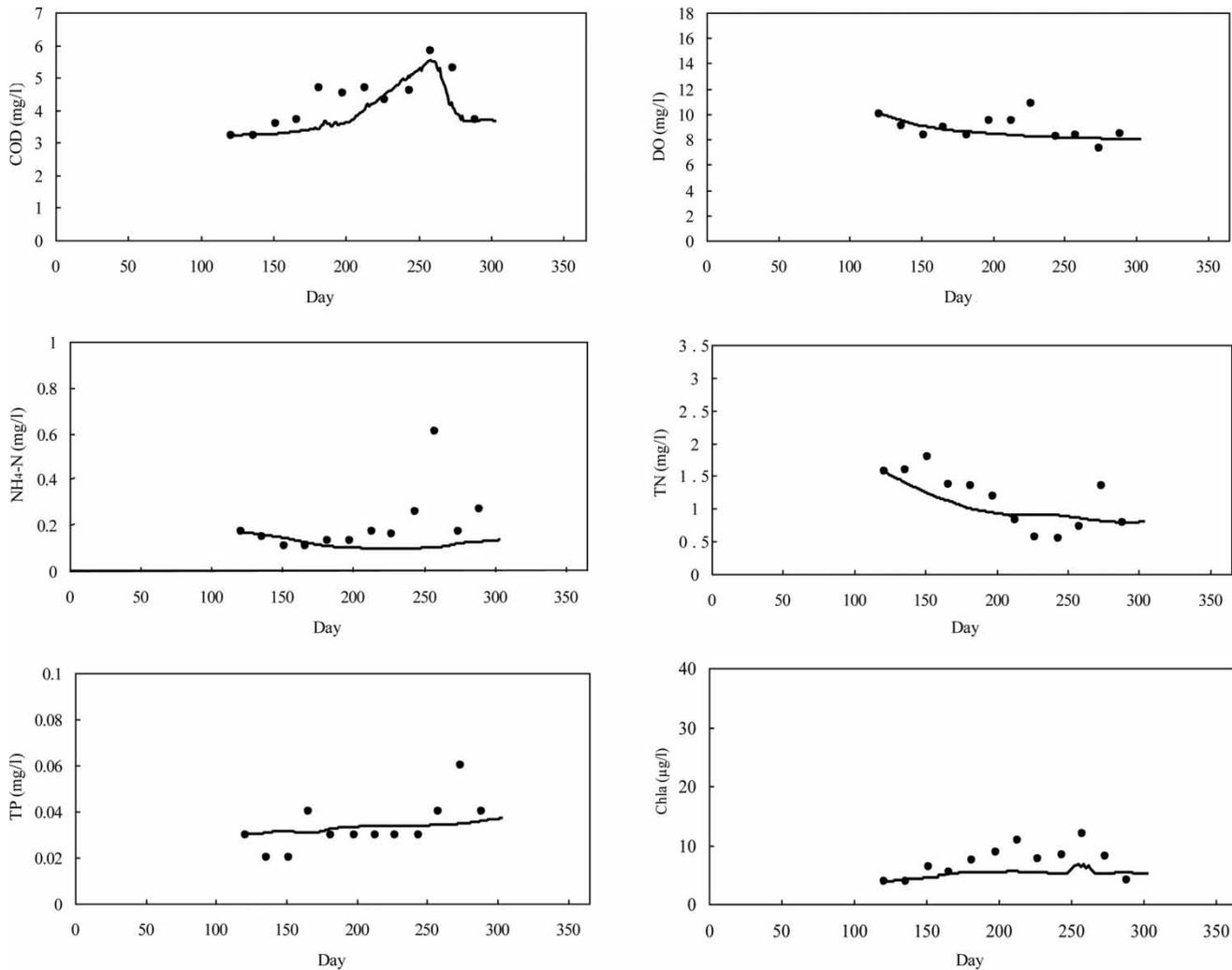


Figure 7 | Measured and verified water quality constituent concentrations at Station S2 for verification period of May 1–October 31, 2007. Black points represent monitoring data. Black lines represent model results.

nutrients of upper basin were brought into the reservoir with water diversion inflow (August to October), the trends of nutrients were consistent with COD except TN. The modeled $\text{NH}_4\text{-N}$ concentration varied from 0.10 to 0.38 mg l^{-1} with an average of 0.15 mg l^{-1} . TP concentration varied from 0.02 to 0.05 mg l^{-1} with an average of 0.035 mg l^{-1} . The modeled Chla clearly presented two peak values which were $7.5 \mu\text{g l}^{-1}$ in June and $12.7 \mu\text{g l}^{-1}$ in September because of the increased biomass of aquatic vegetation and floating macrophytes in those periods, respectively. The modeled TN varied between 0.95 and 2.90 mg l^{-1} with a mean value of

2.02 mg l^{-1} . Conversely, the higher value was calculated in May and June and the lower value from August to October. The reason probably was that more dissolved inorganic nitrogen (mainly nitrate nitrogen) and organic nitrogen were absorbed by abundant aquatic macrophytes thus TN concentration decreased from August to October. The verified results in Figure 7 indicate similar temporal trends with the calibration.

Model verification results in Figure 8 show the horizontal spatial water quality constituent gradients in the reservoir. Since the upstream portion of the reservoir received high nutrient input while the downstream of the

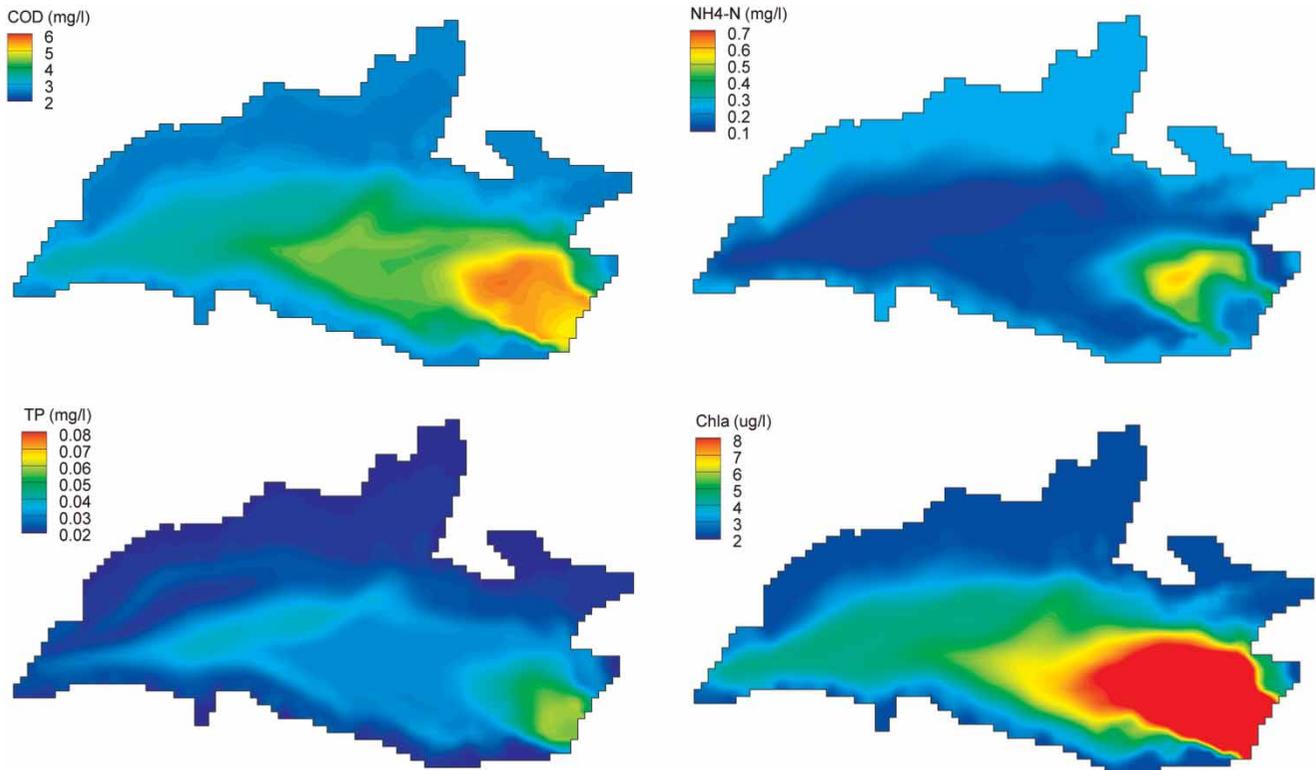


Figure 8 | Simulated spatial variations of water quality constituents for the reservoir on October 15, 2007 (Day 288).

Table 3 | Statistical error quantification analysis results of calibration and verification for water quality constituents at five stations (S2–S6)^a

Parameter	COD	DO	NH ₄ -N	TN	TP	Chla
<i>i. Calibration period</i>						
Number of measurements	71	71	71	71	71	60
Standard error of estimate	0.68	1.18	0.08	0.63	0.01	4.46
Slope	0.88	0.70	0.76	1.31	0.60	0.76
RMSE	0.87	0.96	0.10	1.10	0.01	5.56
Absolute error	0.69	0.98	0.07	0.88	0.01	4.12
<i>ii. Verification period</i>						
Number of measurements	60	60	60	60	60	48
Standard error of estimate	0.56	0.94	0.09	0.50	0.01	2.16
Slope	0.82	0.73	0.65	1.26	0.69	0.70
RMSE	0.64	0.97	0.11	0.86	0.01	4.40
Absolute error	0.48	0.70	0.08	0.74	0.01	3.90

^aStandard error of estimate, RMSE and absolute error analysis results are in $\mu\text{g l}^{-1}$ for Chla and mg l^{-1} for other constituents. Slope is unitless.

reservoir was deeper, the concentration of nutrients in the upper part was higher than in the middle and lower parts. The spatial pattern of COD was consistent with nutrients.

DO constituent had an unapparent gradient in the reservoir while the concentration difference of large parts was in the range $1\text{--}2 \text{ mg l}^{-1}$. The Chla concentration was

higher in shallower portions (water depth from 2.5 to 6.0 m) of the reservoir because these portions were probably more favorable for floating macrophytes and aquatic plants growth. The highest deviations between model results and measurements were found at Station S4 located in the east of center part of the reservoir. Most measurements in this area presented high variability.

Case study

The YRWQM predicted the variations of water quality resulting from agricultural pollution which flowed into the reservoir with a flood lasting for 12 days in 2009. The model results of the patterns of COD and TN at the peak and end of the flood are depicted in Figure 9, respectively. Model prediction results indicated that the pollution and nutrient were convectively transported to the dam direction after entering the reservoir. The high concentration (10 mg l^{-1}) was diffusing in the large northeast parts of the reservoir while the rainfall increased. Moreover, high concentration diffused from the northeast to the center of reservoir (S2

and S4) after the peak moment. Finally, the concentrations of COD and TN were 7.8 and 8.9 mg l^{-1} , respectively, increased compared with initial concentration (no agricultural pollution) by 225 and 314% at Station S4, respectively. The YRWQM is capable of simulating the variations of water quality resulting from agricultural pollution. The result suggests that agricultural pollution by flood flow would be a threat to water quality of the Yuqiao reservoir.

DISCUSSION

Effects of water transfer and wind on the advection-dispersion process

To assess the effect of water transfer from Li River to the reservoir, model simulations were conducted with different flow discharges during the period of the water diversion. The daily average of flow discharge was $20.6 \text{ m}^3 \text{ s}^{-1}$ from April to June and from October to December in 2006 and was $2.7 \text{ m}^3 \text{ s}^{-1}$ in the other months. There were significant

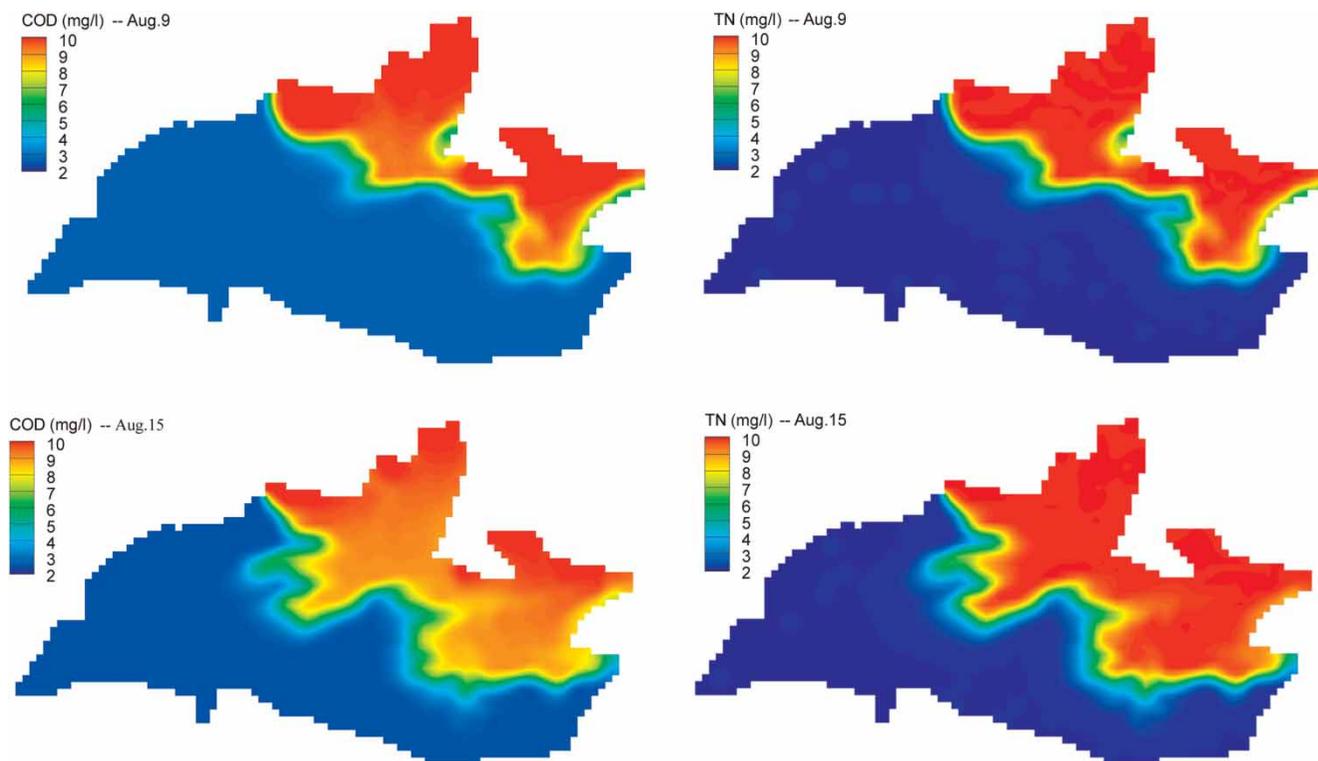


Figure 9 | Predicted spatial variations of COD and TN for the reservoir at 12 o'clock on August 9 (top) and August 15 (bottom), 2009.

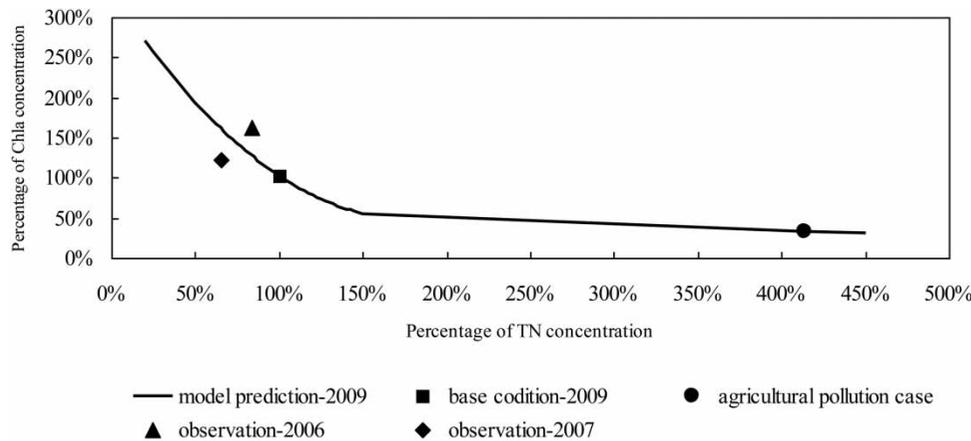


Figure 10 | Sensitivity of chlorophyll-a concentration to TN at Station S2.

differences for concentrations of most water quality constituents in the reservoir during the water diversion period (Figure 6). In Station S2, TN concentration rose to 2.90 mg l^{-1} on May 1, an increase of 44% from the average value 2.02 mg l^{-1} . Also, COD concentration rose to 5.0 mg l^{-1} on October 15, an increase of 35% from an average value 3.7 mg l^{-1} . The results demonstrated that the advection-dispersion action was enhanced by water transfer.

Four different wind directions with a constant magnitude of 2 m s^{-1} (Zhang & Gao 2010) were simulated. From the literature results, the effects of east and west wind direction were significant in the reservoir. In this study, the observed maximum wind speed and direction were 2.2 m s^{-1} and ENE in June 2006. In Station S2, TN concentration was 2.67 mg l^{-1} (increased 32%) on June 15. The results demonstrated that wind was one of the important controlling factors for the advection-dispersion process in the reservoir.

Sensitivity of chlorophyll-a concentration to nitrogen

In the case study, COD and TN concentrations significantly increased in the reservoir during a flood event. A large amount of nutrients from agricultural pollution were brought into the reservoir. Is that a benefit to the growth of phytoplankton? In our research, this is not so.

The interactions between Chla and nitrogen in the reservoir were considered in the model. The extended prediction periods (March to October 2009) were selected for the sensitivity study. To show the sensitivity of Chla concentration to TN, a series of simulated Chla and TN concentrations at

Station S2 were carried out (Figure 10). The result showed that the relation between them was inverse. In the figure, the simulated mean concentrations of Chla and TN under the base condition (square, TN = 100%, Chla = 100%) were 5.9 and 2.15 mg l^{-1} , respectively. The simulated Chla increased 94% when TN was reduced by 50%, and it reduced 50% when TN increased from 100 to 150%. And then, the simulated Chla only showed a slight reduction (18%) when TN increased from 150 to 400% in this case study. Field observations of Chla and TN in the years 2006 and 2007 were used to evaluate the model sensitivity analysis. Mean concentrations of TN were reduced to 83 and 61% of the base condition, and the Chla concentrations increased to 162 and 122%, respectively. The numerical results are reasonable with the measurements. As expected, it indicated that the nitrogen was abundant, and the reservoir was not a nitrogen-limited environment.

CONCLUSIONS

In this study, the YRWQM was developed based on the EFDC model and was calibrated and verified. The results showed that the YRWQM represented the hydrodynamic and water quality processes reasonably well. During the period of the water diversion, the advection-dispersion processes of water quality parameters in the reservoir would be enhanced by water transfer from the Li River. In particular, the enhanced processes were significant in the spring and summer due to wind-induced driving. After considering these processes, the numerical results showed better agreements with field observations.

Model prediction result showed that COD and TN concentrations significantly increased in the reservoir during a flood event. The model was successfully applied to the study of the sensitivity of Chla concentration to TN. The reservoir's primary productivity was not mainly limited by nitrogen, which was probably limited by light penetration and phosphorus. We suggest the management should focus on agricultural pollution strategies for the reservoir during the flood period.

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