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Simulation of hydrodynamics and water quality in Xi'an Yanming Lake China

J L Sun[1], Y Wang[1], J Chen[1,2], Q L Zhang[1], Y Zhang[1] and Y J Guo[1]

[1]State Key Laboratory of Eco-hydraulic Engineering in Shaanxi, Xi'an University of Technology, Xi'an, Shaanxi 710048, China

E-mail: chenjunejune@163.com

Abstract. In order to facilitate works of water environment management in Yanming Lake Xi'an Shaanxi, the MIKE 21 hydrodynamic model coupled with the advection-dispersion equation was employed to develop a water quality model to investigate the characteristics of the flow field on the conditions of different wind and to simulate the variations of pollutants, which were Chemical Oxygen Demand (COD), Total Nitrogen (TN) and Total Phosphate (TP). The Back propagation Neural Net (BPPN) approach was introduced to utilize the results of simulation to evaluate water quality in Yanming Lake. Additionally, based on the distribution characteristic of pollutants, three scenarios for external pollutants' load reduction were proposed. Response Characteristics of water quality after implementation of different scenarios was conducted. The results showed that the time-average velocity value ranged from 0 to 0.01 m/s in Yanming Lake on the condition of both no wind and southwest wind. Six circulations could be induced by southwest wind in the flow field. The time-average COD concentration field could be divided into three regions, whose concentration was 12-13 mg/L, 13-14 mg/L, and 14-15 mg/L respectively. Time-average TN concentration field consisted of two regions, whose concentration was 2.85-3.00 mg/L and 3.00-3.15 mg/L separately, and TN concentration exceeded the standard of Grade V (GB3838-2002). Time-average TP concentration field had no significant zoned phenomenon and its concentration ranged from 0.040 to 0.048 mg/L. Results from evaluation of water quality indicated that water quality was in the standard of inferior Grade V. Additionally, water quality will be better improved after implementation of Scenario 2 rather than Scenario 1 and 3.

1. Introduction

As an important carrier of water resources in arid and semi-arid areas, lakes hold irreplaceable ecological structure function and sustain the balance of regional water ecosystem [1]. In recent years, complex external pollutants' load has caused severe water environment problems, which are water quality deterioration, eutrophication, etc., in lakes [2-4]. With the development of algorithms and computer technology, the water quality models were used extensively in the water environment management [5-7]. Numerous water quality models were developed by various researchers [8], and as one of the important water quality models, MIKE 21 model is widely utilized in the simulation of water quality in lakes and reservoir [8,9]. Li investigated the influence of a chemical leakage accident on the water environment based on the MIKE21 model [10]. Tang *et al* simulated the hydrodynamic characteristics of flow velocity and water level in Baiyangdian Lake with MIKE 21 model [11]. E Zavattero et al. used the MIKE 21 model to simulate the transfer of pollutants in the Var River [12]. However, the current researches in this area mainly focuse on numerical simulations but rarely involves water quality assessment. Yanming Lake, which is in Xi'an Shaanxi China, has suffered severe water environment problems that water plants overgrowth and Total Nitrogen concentration value exceeded Grade V, according to the national standard for surface water quality (GB3838-2002) of China. In order to facilitate works of water environment governance quickly and economically in Yanming Lake, the MIKE 21 hydrodynamic model coupled with advection-dispersion equation and three state variables (pollutants), which were Chemical Oxygen Demand (COD), Total Nitrogen (TN) and Total Phosphate (TP), was utilized to develop a water quality model to select the best scenario of external pollutants' load reduction for water environment management.

2. Materials and methods

2.1. Study area

Yanming Lake situates in the southern region of Chanba Ecological District and in the western region of Chanhe River (figure 1(a)). The water body in the lake is from Chanhe River, and the water flows into Chanhe River finally. Influenced by the water body in Chanhe River which suffered from serious pollutions from agricultural non-point source and rainfall runoff, the water body in Yanming Lake was threatened by many water environment problems that water quality deterioration, aquatic plants overgrowth, etc. According to the meteorological statistical data, the average wind speed is 1.7 m/s, and prevailing wind direction was southwest wind in Xi'an. The study area and the location of monitoring points S1and S2 are shown in figure 1.

Figure 1. Location and geometry of Yanming Lake.

2.2. Model set up

In this thesis, the Yanming Lake was generalized as a shallow lake with 1300 meters in length from south to north, 300 meters in width, and 1.5 meters in average depth. The method of unstructured triangular grid was utilized to generate the calculation mesh, and the grid independent analysis showed that 12,916 grid cells were good for simulation. The two-dimensional hydrodynamic model coupled with the advection-dispersion equation and three state variables, which were Chemical Oxygen Demand (COD), Total Nitrogen (TN) and Total Phosphate (TP), was employed to develop the water quality model. The simulation period is from January 1, 2008 to December 31, 2008, and the time step for the model is 10 seconds. This time step could ensure the accuracy of results. When the southwest wind was embedded into the model, the wind friction was 0.0026 [13], and the wind speed and direction were 1.7 m/s and 225° separately.

The volume flow of both inlet and outlet was given by two-dimensional data (dfs1), and the state variables' concentration of inlet and outlet was given by one-dimensional data (dfs0). Additionally, eddy viscosity and dispersion coefficient, which had been calibrated by the tool named Auto Calibration in MIKE Zero, was set as 0.005 m^2/s and 0.6 respectively. Decay coefficients of COD, TN, and TP were 1.1e-7 s^{-1}, 9.7e-8 s^{-1}, and 6.1e-9 s^{-1} respectively [13]. The bed resistance, which was Manning coefficient in this paper, was calculated by the method supplied by Xia F [14]. The initial concentrations of COD, TN, and TP were 15, 5.3, and 0.02 mg/L respectively [13]. Finally, other parameters, which were not mentioned in this research, would be set as the default value in the water quality model.

3. Results and discussion

3.1. Model verification and assessment

There are several measures of goodness of fit being utilized to evaluate the model performance. The measures contain the absolute mean error (AME), the coefficient of determination (R^2), and the root mean square error (RMSE) [9]. Moreover, the higher value of R^2 is, the better the model performs, whereas the lower values of AME and RMSE are, the better the model performs. AME, R^2, and RMSE are calculated as follows:

The absolute mean error (AME)

$$AME = \frac{\sum_{i=1}^{n} |p_{mi} - p_{si}|}{n} \quad (1)$$

The coefficient of determination (R^2)

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (p_{mi} - p_{si})^2}{\sum_{i=1}^{n} (p_{mi})^2} \quad (2)$$

The root mean square error (RMSE)

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (p_{mi} - p_{si})^2}{n}} \quad (3)$$

Where p_m and p_s are measured data and simulated data of investigated parameters respectively.

The three state variables, which were Chemical Oxygen Demand (COD), Total Nitrogen (TN), and Total Phosphorus (TP) respectively, were selected to assess the model performance and to verify the model at S2 point. The simulated values showed good agreement with measured values (figures 2-4), and the parameters for assessing model performance guaranteed the accurate prediction (table 1). It was clear that the model could simulate the variations of COD, TN, and TP accurately.

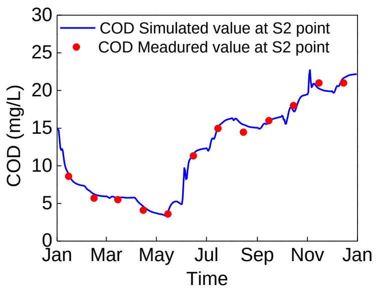

Figure 2. The comparison between simulated and measured values of COD at S2 point.

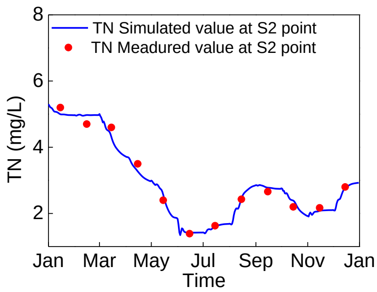

Figure 3. The comparison between simulated and measured values of TN at S2 point.

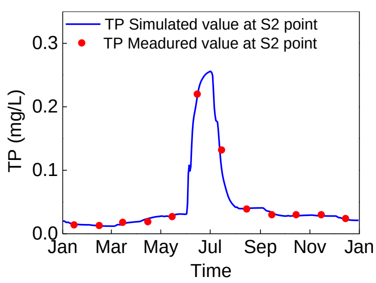

Figure 4. The comparison between simulated and measured values of TP at S2 point.

Table 1. Performance measures for comparison of observed and simulated parameters.

	AME	R^2	RMSE
COD at S2 point	0.1192	0.9998	0.1500
TN at S2 point	0.1378	0.9972	0.1683
TP at S2 point	0.0045	0.9870	0.0086

3.2. The analysis of the flow field

The figure of time-average flow field showed that the flow direction of the water body was mainly from south to north (figure 5(a)). The velocity value in the region of inflow and outflow was more than it in other regions, and the velocity value around the island was also more than it in the Main Lake. Additionally, two anti-clockwise circulations appeared in the region of west coast of the lake. The time-average velocity value mainly ranged from 0 to 0.01 m/s (figure 5(a)).

Disturbed by the southwest wind, the distribution of time-average flow field was apparently distinguished from it on the condition of no wind. Six circulations, which indicated three circulations were clockwise and another three were anti-clockwise, occurred in the region of 'Main Lake' (figure 5(b)). The distribution pattern of circulations induced by southwest wind was apparently distinguished from it generated by function of inlet and outlet flow. Although the time-average velocity value mainly varied from 0 to 0.01 m/s on the conditions of no wind or southwest wind, velocity value in some regions of 'Main Lake' ranged from 0.02 to 0.03 m/s on the condition of the southwest wind.

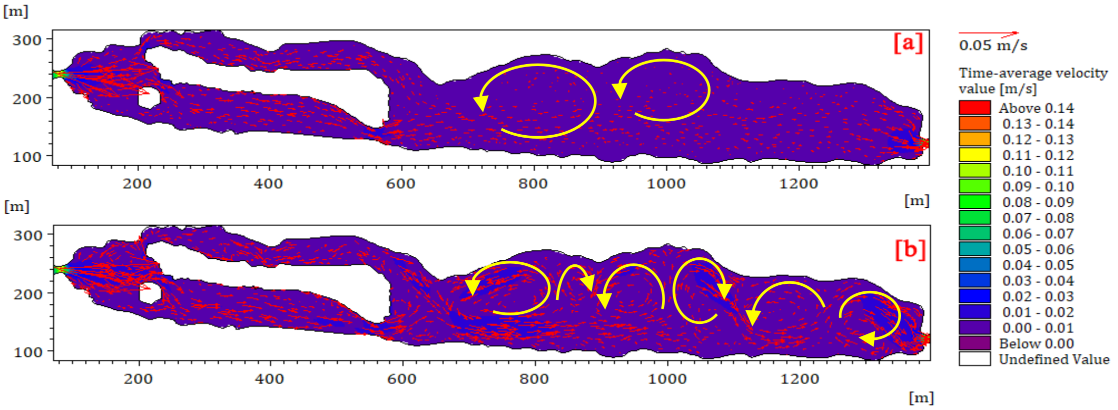

Figure 5. Time-average velocity vector field and velocity value on the conditions of no wind (a) and southwest wind (b).

3.3. The analysis of concentration field

The limited field data could hardly represent the whole state of the water body, so it was necessary to utilize the pollutants' concentration field to analyze the characteristics of the water body. The distribution patterns of of different pollutants' concentration fields were analyzed.

The COD concentration decreased along with water flow direction for the reasons of diffusion by the water current and the degradation (figure 6(a)). Moreover, based on the concentration gradient of COD, the COD concentration field could be divided into three regions, whose concentration values were 12-13 mg/L, 13-14 mg/L, and 14-15 mg/L respectively.

The TN concentration value also decreased along with the flow direction, and it mainly ranged from 2.85 to 3.15 mg/L. The TN concentration field could be divided into two regions, whose values were 2.85-3.00 mg/L and 3.00-3.15 mg/L (figure 7(a)) separately.

There was no obvious concentration gradient in the TP concentration field, and its concentration value mainly ranged from 0.040 to 0.048 mg/L (figure 8(a)).

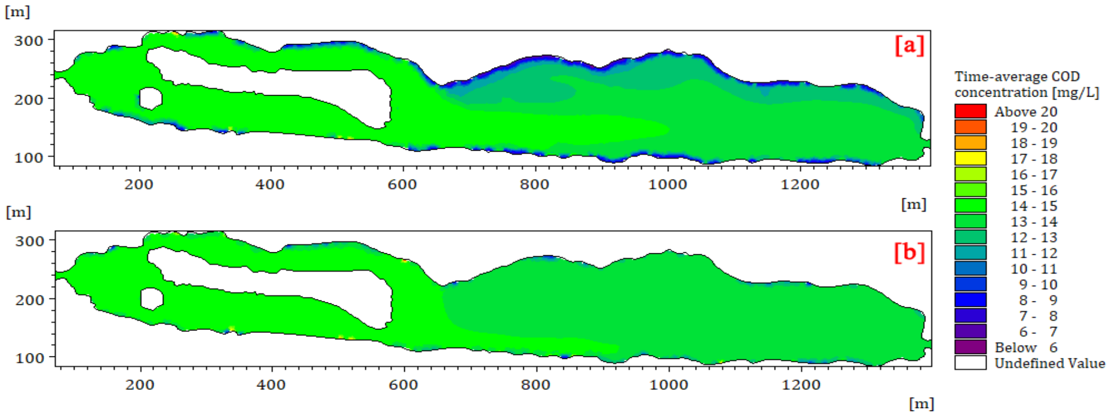

Figure 6. Time-average COD concentration field on the conditions of no wind (a) and southwest wind (b).

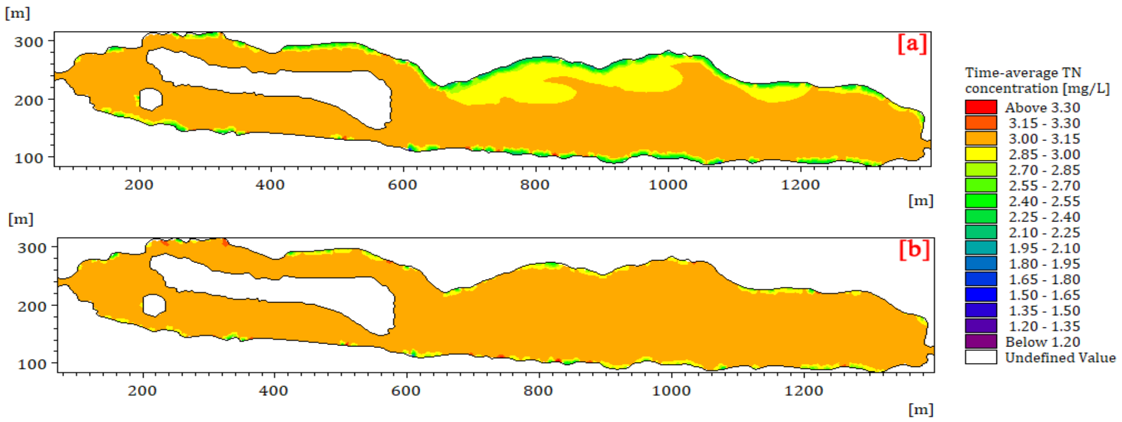

Figure 7. Time-average TN concentration field on the condition of no wind (a) and southwest wind (b).

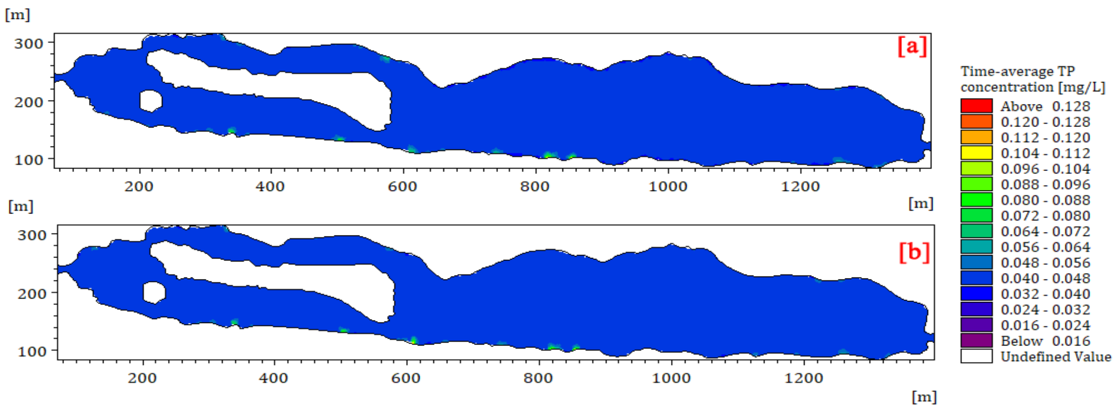

Figure 8. Time-average TP concentration field on the condition of no wind (a) and southwest wind (b).

Influenced by the southwest wind, the time-average concentration fields of COD and TN were significantly different from them without consideration of wind (figure 6(b) and 7(b)). The COD concentration field could be divided into two regions, but there was no obvious concentration zoning in TN and TP concentration fields. Additionally, the TN concentration ranged from 3.00 to 3.15 mg/L and the TP concentration mainly ranged from 0.040 to 0.048 mg/L. The conclusion was drawn that the circulation induced by southwest wind would enlarge the mixing degree of the water body for the COD, TN, and TP concentration value tended to be consistent respectively. The concentration of TN exceeded the standard of Grade V (GB3838-2002) on the condition of no wind and the southwest wind, the COD concentration was within the standard of Grade I and II, and the TP concentration was within the standard of Grade Ⅱ and Grade Ⅲ (GB3838-2002).

3.4. Spatial-temporal variations of water quality

Back Propagation Neural Net (BPNN) was selected to evaluate the water quality in Yanming Lake. Based on the Liu Y's research [15], a modified BPNN was developed.

Based on data calculated by the water-quality model and BPNN, the figure about grade of water quality was drawn (figure 9). The time-average water quality was mainly ascribed to inferior Grade V, according to the national standard for the surface water quality (GB3838-2002) of China. Moreover, we could get the information from the figure 9 that although the southwest wind enlarged the mixing degree of the water body, it could hardly affect the water quality. The water quality grade also indicated that the water had deteriorated apparently, so there should be some measures being taken to reduce the further deterioration of water quality.

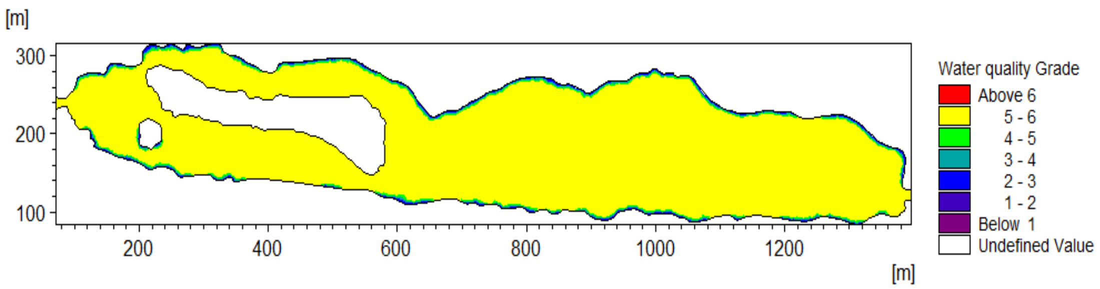

Figure 9. Time-average water quality grade on the conditions of no wind or southwest wind, and Time-average water quality state after implementation of scenario 1 or scenario 3.
notes: The characters of 'Below 1', '1-2', '2-3', '3-4', '4-5' and '5-6' in the legend represent Grade I, Grade II, Grade III, Grade IV, Grade V, inferior Grade V respectively ,according to the national standard for surface water quality (GB3838-2002) of China.

3.5. The response of water quality to external pollutants' load reduction

In order to investigate the response of water quality to external pollutants' load reduction and to select an effective scenario for water environment management in Yanming Lake, three scenarios (table 2) were proposed in this research. Scenario 1 indicates that the COD, TN and TP loads of inflow will be reduced by 50%, 50% and 50% (table 2). The water-quality model was used to simulate the different scenario, and the evaluation of water quality was also conducted.

Table 2. The scenario of pollutants load reduction.

No.	COD	TN	TP
Scenario 1	-50%	-50%	-50%
Scenario 2	-75%	-75%	-75%
Scenario 3	50%	-75%	-50%

As the figure 9 depicts, the water quality will be still in the standard of inferior Garde V after the implementation of scenario 1, which could be ascribed to the reason that water quality grade is restricted by the comprehensive effects of COD, TN and TP, although COD and TP concentration value is in the standard of grade I, TN concentration is still in the standard of Grade Ⅳ.

Compared with the water quality after implementation of scenario 1 or 3, the water quality would change significantly and would be up to be in Grade Ⅳ and V after the implementation of scenario 2 (figure 10). Additionally, the proportion of water body, whose water quality was in the standard of Grade Ⅳ, was significantly more than it, whose water quality was in the standard of Grade V.

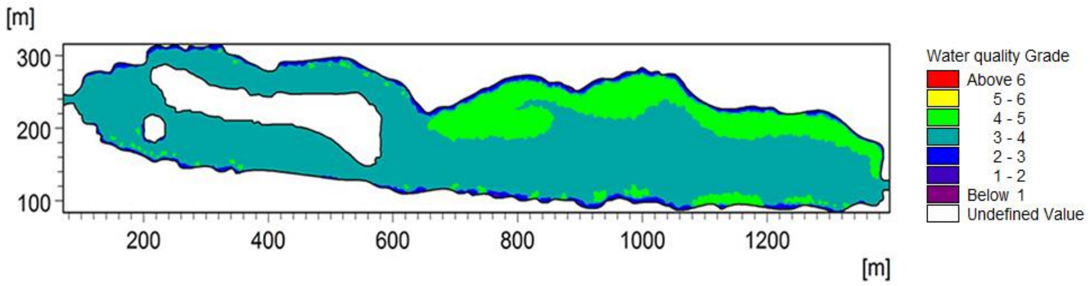

Figure 10. Time-average quality grade after implementation of scenario 2.

Compared with scenario 1, the water quality had no change after the implementation of scenario 3 (figure 9), which could indicate that the water quality grade of the water body in Yanming Lake was not mainly influenced by TN concentration. If only the TN load were reduced by a large percentage, it would hardly help improving water quality in this lake.

4. Conclusions

The water quality model induced by the MIKE 21 hydrodynamic model coupled with the advection-dispersion equation and three state variables was developed, and it was used to investigate variations of flow field and pollutants' concentration field. Additionally, results calculated by the water quality model were used to evaluate the water quality in Yanming Lake by BPNN approach. Finally, the evaluation of water quality after implementation of different scenarios was conducted. The conclusions would be drawn as follows:

- The water quality model induced by MIKE 21 hydrodynamic model coupled with the advection-dispersion equation could be used to study the variations of flow field and pollutants' concentration fields and water quality state in Yanming Lake.
- The time-average velocity mainly value varied from 0 to 0.01 m/s in the water body of Yanming Lake, and six circulations would be induced by the southwest wind.
- TN concentration exceeded the standard Grade V by 50% to 65%, and the water quality had been to be inferior Grade V in this lake.
- The southwest wind could enlarge the mixing degree of the water body in Yanming Lake, but it could hardly affect the water quality.
- According to the results of scenario 1 and scenario 3, the water quality grade of the water body in Yanming Lake was not mainly influenced by TN concentration.
- The water quality in Yanming Lake could be definitely improved to Grade IV and V after implementation of scenario 2 rather than scenario 1 and scenario 3.

Acknowledgments

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