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Discussions

Development of a zoning-based environmental-ecological-coupled model for lakes: a case study of Baiyangdian Lake in North China

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Abstract

Environmental/ecological models are widely used for lake management as they provide a means to understand physical, chemical and biological processes in highly complex ecosystems. Most research focused on the development of environmental (water quality) and ecological models, separately. Limited studies were developed to couple the two models, and in these limited coupled models a lake was regarded as a whole for analysis (i.e., considering the lake to be one well-mixed box), which was appropriate for small-scale lakes and was not sufficient to capture spatial variations within middle-scale or large-scale lakes. In response to this problem, this paper seeks to establish a zoning-based environmental-ecological-coupled model for a lake. The hierarchical cluster analysis (HCA) was adopted to determine the number of zones for a lake based on the analysis of hydrological, water quality and ecological data. MIKE21 model was used to construct two-dimensional hydrodynamics and water quality simulations. STELLA software was used to create a lake ecological model which can simulate the spatial variations of ecological condition based on flow field distribution results generated by MIKE21. The Baiyangdian Lake, the largest freshwater lake in Northern China, was adopted as the study case. The results showed that the new model was promising to predict the spatial variation trends of ecological condition in response to the changes of water quantity and water quality for lakes, and could provide a great convenience for lake management.

1 Introduction

Lakes are important freshwater ecosystems in the world. They offer many irreplaceable ecological and social services, such as supporting biodiversity, regulating water cycle, supplying water resources, and maintaining regional ecological balance (Rubec and Hanson, 2009). However in recent years, complex external disturbances have caused severe water quantity and quality problems in lakes (Kingsford, 2011). For example, flow regulation by upstream dams or reservoirs have resulted in decreasing water level and shrinking water area of lakes. The increasing pollution loads derived from agriculture and industry has aggravated eutrophication status of lake. To alleviate the degradation and protect the basic functions of lake ecosystems, scientific management practices are emergently required.

Determining the relationship among water quality, aquatic ecology and management tool in a lake should be a central task for establishing scientific lake management practices (Gal et al., 2009). In general, there are two approaches to establish the relationships: statistical analysis of existing long-term databases, or modeling the interactions. In reality, only a limited number of sufficiently long-term and detailed databases exist. In contrast to this, models allow simulation of an unlimited range of variables. Nowadays, water environmental models are widely applied to the management of lakes as they provide a means to study and understand physical, biological and chemical processes in highly complex ecosystems. The use of models in planning, designing and testing management strategies has become increasingly common since the 1980s. The use of models allows us to explain water environmental problems and enhance the ecological understanding of a lake (Martins et al., 2008; Missaghi and Hondzo, 2010; He et al., 2011; Ciric et al., 2012).

Through the reviews of lake models we can find that most lake models focused on single water quality or aquatic ecological process (Jørgensen, 2010; Miller et al., 2013). In fact, water quality and aquatic ecology each other, and it is essential to take these two factors into consideration when constructing water environmental models. Recently, some scholars have attempted to construct integrated models: Muhammetoğlu and Soyupak (2000) proposed a dynamic three-dimensional water quality model for macrophyte-dominated shallow lakes, and the model is capable of simulating macrophytes and its interactions with water quality constituents such as dissolved oxygen (DO), organic nitrogen, ammonia, nitrate, organic phosphorus, orthophosphate, BOD, phytoplankton and the sediment layer; Martins et al. (2008) developed a horizontal average model to make prospective scenarios to reduce the risk of environmental degradation of Lake Sete Cidades, and the model was able to describe thermal stratification, nutrient cycling, DO and phytoplankton in the water column and adjacent sediment layer; Gal et al. (2009) applied the lake ecosystem model DYRESM–CAEDYM to estimate the impact of potential changes in nutrient loading on the Lake Kinneret ecosystem, and the hydrodynamics model DYRESM is a one-dimensional model which could be able to simulate vertical stratification dynamics.

Most ecological models in existing integrating models regard the lake as a whole for analysis, i.e., considering the lake to be one well-mixed box, such delineation is appropriate for small-scale shallow lakes, while it is not sufficient to capture large spatial variations in hydrodynamics and constituent transport among different areas where the characteristics of soil, topography, water temperature, available nutrients and vegetation show spatial heterogeneity within middle-scale or large-scale lakes, this might exist a large margin of error (Wang et al., 2012). It is essential to construct a lake ecological model which can simulate ecological change considering spatial variations.

Aiming at this situation, this paper created an integrated model system which can simulate and predict changes of hydrodynamics, water quality and aquatic ecology, and a typical middle-scale lake in China, Baiyangdian Lake, was taken as a case study. The aquatic ecological model was conceived to provide a compartmental model, which combines accuracy and computational efficiency, similar to other box ecological models, but with improved spatial resolution. Firstly a two-dimensional model MIKE21 was used to simulate hydrodynamics and water quality of Baiyangdian Lake; secondly a aquatic ecological model was constructed on the basis of aquatic ecological system characteristics in different water areas and flow field distribution generated by MIKE21 hydrodynamics model; thirdly compartmental ecological model of four water area zones was constructed as an example using STELLA software and coupled to an integrated model by means of hydrodynamic field modeled by MIKE21, which can reflect the actual ecological conditions of Baiyangdian Lake in more detail. This integrated model system can provide a reference for water management and eutrophication prevention of Baiyangdian Lake.

2 Methods

2.1 Study area and data sources

Baiyangdian Lake (115.75°–116.12° E, 38.73°–38.98° N) is located in the central North China Plain with an area of about 366 km^2 when water level is 10 m. It is a typical northern plant-dominated shallow wetland of about 143 lake parks and 67 km^2 of reed marshes. The terrain of Baiyangdian Lake is intricate, with characteristic of circumferential high, low in the east and high in the west, northwest and south.

In recent years, due to constant increasing of industrial, agricultural and domestic water use and impoundment of upstream water reservoirs, average annual volume of water flowed into Baiyangdian decreased. And coupled with the impact of continuous dry years, Baiyangdian wetland has suffered multiple times from severe drought up since 1980s, which has imposed a severe impact on aquatic ecosystem. Meanwhile, due to population growth and economic development in the basin, Baiyangdian Lake also suffers from high intensive human disturbances, with Fu River as the only inflow river carrying a large quantity of pollutants, which results in serious eutrophication, biodiversity decrease and macrophytes hypermorphosis. Its unique environment and human landscape has been gradually disappeared with severe negative effects on the lake ecosystem health and sustainable development.

Daily hydrological data for calibration and validation of hydrodynamics model were obtained from Municipal Water Conservancy Bureau. Daily meteorological data including wind velocity and precipitation taken as driving force factor were from China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn). Water quality data for calibration and validation of water quality model from February 2008 to November 2008 of 14 water quality monitoring sites (Fig. 1 and Table 1) in Baiyangdian Lake were obtained from Municipal Environmental Protection Bureau. Ecological data including phytoplankton biomass, zooplankton biomass, detritus concentration and macroohytes biomass were from bimonthly field sampling carried out from August 2009 to August 2010 which can reflect seasonally change in Baiyangdian Lake.

The Digital Orthophoto Map – Quickbird image with an area of 366 km^2 was interpreted by the software ENVI4.4 and eCognition Developer 8.0 to identify water and land boundaries. Water depths of Baiyangdian Lake were obtained through high density artificial field measurement. The spacing between measuring points differs from 50 to 300 m, and the number of measuring points was 3973 in total. Lake bed elevations were the difference between water elevation and water depths of each measuring point. Land surface elevations around Baiyangdian Lake were extracted from Google Earth. Lakebed elevation data, land surface elevation data, water boundaries and land boundaries were integrated by the geographic information system programs ArcGIS (Fig. 2a). Finally, topographic map of Baiyangdian Lake was generated by terrain interpolation (Fig. 2b).

Water area division of Baiyangdian Lake was made before the construction of water ecological model. The hierarchical cluster analysis (HCA) was adopted to objectively determine the number of zones in the Baiyangdian Lake. The HCA was based on the analysis of hydrological, water quality and ecological data of Baiyangdian Lake measured during field sampling at 14 sampling sites. Flow field distribution map was used to test the rationality of water areas zoning results. In view of complexity and feasibility of coupled ecological models, we considered four or five zones would be suitable.

2.2 Hydrodynamics and water quality model

Baiyangdian Lake is a shallow lake with an average depth of around 3 m and with no obvious stratified phenomenon, thus a two-dimensional numerical model is suitable for simulating hydrodynamics and water quality. This research used two-dimensional numerical model – MIKE21 model, which has been widely used in domestic and overseas research (Cox, 2003), to simulate hydrodynamic indices including water level, water depth, flow velocity and water quality indices including BOD, DO, phosphate, ammonia, nitrite, nitrate.

Two model boundaries (Fu River and Dashuliuzhuang) were set according to the peripheral condition of Baiyangdian Lake. Fu River was a perennial inflow transferring water upstream into Baiyangdian Lake. Dashuliuzhuang was the water inlet for Yellow River-to-Baiyangdian Lake water diversion project, and the project carried out water diversion annually recent years. Measured flow and water quality data of these two inlets were used as the boundary input condition. There is an outflow of Baiyangdian Lake – Zaolinzhuang freeing port, however according to actual situation, Zaolinzhuang freeing port is closed unless water level is above 8.5 m, so in simulation outflow volume of Baiyangdian Lake was set to zero.

Model calibration was configured to run from 20 February 2008 to 20 June 2008 as these months the watershed management department implement annual water transfer project in order to ensure the basic water level (6.5 m), so there were significant differences in water levels and concentrations of water pollutants. Water level and water quality data of two typical monitoring points (Site 12 and Site 11) were used. Period from 1 August 2008 to 30 November 2008 was selected as model validation period. The model was run at a daily time step.

MIKE21 model includes a large number of parameters which need to be defined by users. Parameter values were sourced from recent experimental analysis on Baiyangdian Lake as well as relevant published literature and reports. For parameter whose value was not directly available, a series of model runs were performed to test goodness-of-fit values between simulation results and observed data in order to find an optimal value, whilst maintaining parameter value within literature recommended value range.

2.3 Ecological model

The basic principle of ecological model construction is taking necessary biochemistry process into consideration according to study objective, while ensuring model structure not to be over-complicated. In view of this principle, Model hypothesis of aquatic ecological model are as follows:

1. compartment model of each water zone is a box model, thus all state variable concentrations and parameters in each compartment model are the same, i.e., there is no space heterogeneity,
2. in model simulations, input concentration of each state variable at borderline of two compartments is the same.
3. Baiyangdian Lake is a typical plant-dominant lake, it is necessary to reflect conversion process of aquatic plant in water ecological system and its influence on other ecological variables in the model.
4. Related literature (Li, 2008; Zhang et al., 2011) considered Baiyangdian Lake as a typical phosphorus limited lake. Thus in this study phosphorus was taken as the unique limiting factor among nutrients limitation factors influencing aquatic organisms in order to simplify model structure. The state variable dissolved inorganic phosphorus (DIP) of ecological model in this study refers to orthophosphate.

Ecological model of Baiyangdian Lake was constructed based on system dynamics software STELLA (isee systems, inc.) (http://www.iseesystems.com/softwares/Education/StellaSoftware.aspx). The model includes six state variables: aquatic plant biomass (AP), phytoplankton biomass (A), zooplankton biomass (Z), organic detritus (D), dissolved inorganic phosphorus in pore water (DIPP) and dissolved inorganic phosphorus (DIP). Conversion processes between state variables are shown in Fig. 3. Forcing functions included water level (WL), water temperature (*T*), solar radiation intensity (SR), river inflow and DIP concentration of river inflow. Conversion processes of each state variable and main parameter are listed in Table 2.

2.4 Models coupling and calibration

In consideration of the connection between water areas, we set three movable state variables which can transfer between compartment (zone) models – phytoplankton, organic detritus and DIP. We did not take zooplankton into consideration because of zooplankton's mobility, which generally may not move with water flow.

Boundary conditions for the three movable state variables between two compartment models were calculated as follows:

For a state variable in water area (compartment model) n, its inflow concentration C_n:

$$C_n = C_{n-1} \times F \times S_{\mathrm{cs}}/V_n \quad (1)$$

$$S_{\mathrm{cs}} = L \times D_{\mathrm{cs}} \quad (2)$$

$$V_n = A \times D \quad (3)$$

where C_{n-1} is the concentration in water area $n-1$; F is flow velocity at cross section between two compartment models; S_{cs} is cross-sectional area between two compartment models; V_n is volume of water area n; L is section length; D_{cs} is section average water depth at cross section between two water areas; A is water surface area; D is average water depth of water area n.

Water surface area of Baiyangdian Lake being constantly changing, in order to simplify the model calculation, we first used MIKE21 to simulate different water levels in each compartment model and the corresponding water surface area, and regression analysis was used for quantifying the relationship between these two variables:

$$V_n = \mathrm{d}A \times D = k \times \mathrm{WL} \times D \quad (4)$$

where k is regression coefficient; WL is water level.

F, S_{cs}, V_n, L, and D_{cs} can be obtained by MIKE21 simulation results directly.

Ecological data of six state variables from field sampling carried out from August 2009 to August 2010 were used for ecological model calibration and validation. Phytoplankton and zooplankton concentrations are negligible in the inflows and were set to zero. Calibration focus is sensitive parameters of ecological models: firstly identifying value range of each sensitive parameter according to related literature, secondly determining parameter value by the comparison between observed values and simulated values. Two coefficients (coefficient of determination and Nash–Sutcliffe efficiency coefficient) used for hydrodynamics and water quality model calibration and validation were also used for assessing ecological model performance.

3 Results and discussion

3.1 Water areas zoning

According to HCA results (Fig. 4), Baiyangdian Lake was classified into five water areas when cut-off distance was 6.0: Northwest Lake (site 6 and 7), Yuanyangdao (site 5), Zaolinzhuang (site 4), Duancun (site 12) and center water area containing other sites (Fig. 2). On the other hand, according to flow field distribution map generated by MIKE21, five water areas could reflect flow direction in Baiyangdian Lake well, which also affirmed the rationality of HCA results. On the basis of field visit, sites 5, 6 and 7 were close to Fu River. Being the only perennial inflow of Baiyangdian Lake, Fu River delivered masses of pollution loads from upstream, so these three sites were influenced by external disturbance more intensely than the other sites, and had similar aquatic ecosystem features. By combining all the analysis results above, we merged these sites into one water area. Four lake compartments – zone 1 (including water areas near site 5, 6, 7), zone 2 (in center water areas containing other sites), zone 3 (water area near site 4) and zone 4 (water area near site 12) were generated finally.

3.2 Sensitivity analysis

The results of the sensitivity analysis carried out to assess the effect of different parameters on state variables are presented in Table 3. According to sensitivity classes (Lenhart et al., 2002) set for evaluating sensitivity level of parameter *i*, the ecological model is most sensitive to five parameters: EXT, GPOVMAX, GPMAX, MAP and water ratio. Values for these five parameters have greater impact on the model performance than the others. Moreover, for different state variables, important parameters of impact could be different except these five parameters.

3.3 Calibration and validation results

3.3.1 Hydrodynamics and water quality model

Calibration results are shown in Table 4 and other parameter values are acquired by refering to model-recommended values. Judging from the comparison between observed values and simulated values (Figs. 5–11), good simulation results were achieved, indicating the model can accurately reflect the tendencies of water level and water quality in Baiyangdian Lake.

3.3.2 Ecological model

Four typical monitoring points belonging to four water areas respectively were selected for model calibration – Site 6 (Zone 1), Site 8 (Zone 2), Site 4 (Zone 3) and Site 12 (Zone 4) (Figs. 12–15). Calibration results of model parameters are shown in Table 5. Due to only one year's data available, we selected two monitoring points belonging to Zone 1 (Site 5) and Zone 2 (Site 10) for model validation, for which spatially sampled data are substituted for time series data to overcome limitations of limited time series data. Judging from the comparison results between observed values and simulated values (Figs. 16–17), good simulation results were achieved, indicating the ecological model can reasonably reflect change tendencies of ecological state variables in study area.

3.4 Model performance

For hydrodynamics and water quality model, in model calibration period, simulation effects for BOD, DO and phosphate were better than TN by comparing the values of simulations and observations. The reason might be that TN concentration from upstream inflow or non-point source discharge is stochastic with much uncertainty, and the observed values were also influenced by anthropogenic factor or extreme weather events, thus resulting in large difference between observed values and simulated values; in model validation period, simulation effects for TN showed further improvement, indicating the model has good portability and reusability. Taken together, parameter setting was appropriate and hydrodynamics and water quality model can accurately reflect the change tendencies of water level and water quality in study area.

As can be seen from Figs. 12 to 15, ecological model can accurately reflect change tendencies of ecological state variables in each water area, though there existed some discrepancy in peaks fitting during model calibration and validation period. This is not surprising given the complexity of interactions affecting species succession and bloom, and considering spatial processes taking place in each water area zone are averaged using this modeling approach. In contrast to system dynamic modeling, a weakness of the structured model is that the biological groups and characteristics are not assigned a high priority by the users (Jørgensen, 1999). The low frequency of measurements is also one possible explanation for this phenomenon. We can also see from Table 7 that sample fitting effect in Zone 1 was the worst of four water area zones during model calibration period. Main reason might be that Zone 1 was near the entrance of Fu River, which takes much wastewater inflow from upstream, and tourism is also prosperous in this water area. These two factors influence Zone 1 intensely, leading to high concentrations of nitrogen and phosphorus, showing non-responsive lake state and resulting in low simulation precision of Zone 1. Simulation results further illustrate the necessity of simulating ecological change considering spatial variations, and the compartmental ecological model we constructed can take the connection between water areas into consideration and provide a new method for simulating water ecological change accurately and comprehensively.

Through model calibration and validation, our hydrodynamics and water quality model and compartmental ecological model prove to be conceptually straightforward and computationally efficient tools for lake prediction and management. It is important to note that no single model for water quality or aquatic ecology is suitable for all applications, the two models we established are part of a larger of models designed to help guide the management decision making processes. We suggest that compartmental ecological model could be of value for other similar middle-scale or large-scale lake ecosystems in understanding and testing alternative scenarios for management. For a damaged system such as the Baiyangdian Lake, in which a series of ecosystem restoration measures including watershed pollution load control and ecological water transfer were carried out, modeling efforts that link hydrodynamics, water quality and aquatic ecology provide needed management decision support.

3.5 Application of coupled lake models for ecological condition prediction

The coupled lake models have been applied to simulate the spatial variation trends of ecological condition under ecological water supplement in order to reflect the application effect in lake restoration and management. The scenario has been set as follows:

- In normal year (runoff of Fu River and Xiaoyi River is equal to mean annual river runoff) two water diversion projects including Yellow River-to-Baiyangdian Lake water diversion and water diversion from the upstream reservoirs are implemented. Water volume of the former project is 100 million m^3, and water quality is equal to China Environmental Quality Standards for Surface Water (GB3838-2002) of Class III; Water volume of the latter project is 60 million m^3, and the water quality as Class IV.

- Inputting initial conditions and boundary conditions set for the scenario to MIKE21 model to perform hydrodynamic and water quality simulation. Simulation results of the scenario were shown in Tables 6 and 7.

- The changes of concentrations of TN and TP at Site 8 are shown in Fig. 18. The spatial variations of concentrations of TN and TP in Baiyangdian Lake are shown in Fig. 19. The simulation results (Fig. 18) showed that the concentrations of TP and TN presented apparent decrease after ecological water supplement. The final values of the concentrations of TP and TN were 0.13 and 1.25 $\mathrm{mg\,L^{-1}}$, which decreased by 68.1 and 82.4 %, respectively and meet the standards of Class III.

- Inputting hydrodynamic simulation results to ecological model as hydrodynamic boundary conditions between two compartmental ecological models for aquatic ecological simulation. Simulation results were shown in Table 8. Simulation results of the key aquatic ecological indexes for the four water area zones were shown in Figs. 20–23.

4 Conclusions

In view of the interplay between water quality and aquatic ecology, the coupled lake models including a hydrodynamics and water quality model established by MIKE21 and a compartmental ecological model used STELLA software have been established for middle-sized Baiyangdian Lake to realize the simulation of spatial variations of ecological conditions. On the basis of the flow field distribution results generated by MIKE21 hydrodynamics model, four water area zones were used as an example for compartmental ecological model calibration and validation. The results revealed that the developed coupled lake models can reasonably reflected the changes of the key state variables although there remain some state variables that are not well represented by the model due to the low quality of field monitoring data. Monitoring sites in a compartment may not be representative of the water quality and ecological conditions in the entire compartment even though that is the intention of compartment-based model design. There was only one ecological observation from a single monitoring site for some periods. This single-measurement issue may cause large discrepancies particularly when sampled site is not representative of the whole compartment. Therefore, increased sampling sites and sampling frequency might improve model's statistical performance.

The coupled models have been applied to simulate the spatial variation trends of ecological condition under ecological water supplement as an example to reflect the application effect in lake restoration and management. The simulation results indicate that the models can provide a useful tool for lake restoration and management. The simulated spatial variation trends can provide a foundation for establishing permissible ranges for a selected set of water quality indices for a series of management measures such as watershed pollution load control and ecological water transfer. Meanwhile, the coupled models can help us to understand processes taking place and the relations of interaction between components in the lake ecosystem and external conditions.

Taken together, the proposed models we established show some promising applications as middle-scale or large-scale lake management tools for pollution load control and ecological water transfer. These tools quantify the implications of proposed future water management decisions. Future research should focus on scenarios setting, simulation and evaluation of different management measures.

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Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

References

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Table 1. Conditions of sampling sites.

No.	Sampling sites	Coordinate	Description
1	Shaochedian	38.940° N, 115.999° E	A little aquaculture and large amount of submerged plants
2	Wangjiazhai	38.917° N, 116.011° E	Aquaculture and dense distribution of villages
3	Yangzhuangzi	38.908° N, 116.047° E	
4	Zaolinzhuang	38.902° N, 116.080° E	A little human disturbances, more species and quantity of macrophytes in clear water
5	Yuanyangdao	38.911° N, 115.955° E	Influenced a lot by tourism and Fu River
6	Nanliuzhuang	38.904° N, 115.934° E	Influenced a lot by wastewater inflow from
7	Entrance of Fu river	38.904° N, 115.923° E	Fu River and a little aquaculture
8	Zhainan	38.903° N, 115.988° E	Aquaculture
9	Guangdianzhangzhuang	38.894° N, 116.029° E	Near to village
10	Laowangdian	38.875° N, 115.996° E	Aquaculture
11	Quantou	38.860° N, 116.028° E	Near to village and a lot of aquaculture
12	Duancun	38.846° N, 115.950° E	
13	Dongtianzhuang	38.834° N, 115.991° E	Near to village and a little aquaculture
14	Caiputai	38.824° N, 116.010° E	A little aquaculture

Table 2. Conversion process of each state variable.

Symbol	Description	Unit
Uptake DIP	Uptaking phosphorus rate by phytoplankton	mg L^{-1} per day
Grazing	Grazing phytoplankton by zooplankton	mg L^{-1} per day
Mor1	Mortality of phytoplankton	mg L^{-1} per day
Sett1	Settling phytoplankton to the sediment	mg L^{-1} per day
Inflow A	Inflow rate of phytoplankton	mg L^{-1} per day
Outflow A	Outflow rate of phytoplankton	mg L^{-1} per day
Mor2	Mortality of zooplankton	mg L^{-1} per day
up P	Uptaking phosphorus rate from lake water phase by aquatic plants	mg L^{-1} per day
up PP	Uptaking phosphorus rate from pure water phase by aquatic plants	mg L^{-1} per day
Mor 3	Mortality of aquatic plant	g m^{-2} per day
Harvest	Reaping of aquatic plant	g m^{-2} per day
Sett 2	Settling detritus to the sediment	mg L^{-1} per day
Min 1	Mineralizing to DIP	mg L^{-1} per day
Min 2	Mineralizing to other materials	mg L^{-1} per day
Inflow D	Inflow rate of detritus	mg L^{-1} per day
Outflow D	Outflow rate of detritus	mg L^{-1} per day
Inflow DIP	Inflow DIP rate	mg L^{-1} per day
Dif P	Diffusion phosphorus to water phase from pore water	mg L^{-1} per day
Outflow DIP	Outflow rate of DIP	mg L^{-1} per day
Min 3	Mineralised phosphorus rate from exchangeable P in sediment	mg L^{-1} per day

Table 3. Sensitivity index (I) of parameters in ecological model.

Parameter (Initial value)	Definition	S-DIP	S-D	S-DIPP	S-A	S-Z	S-AP	All variables
CC(20)	Carrying capacity for zooplankton in a lake	0.364	−0.234	0.122	−0.324	0.175	0.018	0.206
DIFFC(0.1)	Diffusion rate	0.051	0.094	−0.213	0.107	0.072	−0.005	0.090
EXT(0.2)	Extinction coefficient	4.617	−3.170	3.836	−8.583	−1.979	−0.531	3.786
GAMAX(5)	Maximum growth rate for phytoplankton	0.057	0.790	0.030	1.475	0.412	0.884	0.608
GPMAX(0.2)	Maximum growth rate for aquatic plant (Involving water body)	−1.215	−2.280	−0.584	−3.125	−2.086	0.280	1.595
GPOVMAX (0.05)	Maximum growth rate for aquatic plant (Involving pore water)	−1.019	−2.227	−2.243	−2.615	−1.760	0.126	1.665
GZMAX(0.1)	Maximum growth rate for zooplankton	0.003	0.234	0.000	0.452	0.085	0.484	0.210
KA(0.5)	Michaelis constant for zooplankton from phytoplankton	−0.601	0.406	−0.191	0.579	−0.082	−0.025	0.314
KI1(300)	Michaelis constant for phytoplankton from sunlight	0.300	−0.231	0.102	−0.339	−0.160	0.014	0.191
KI2(400)	Michaelis constant for aquatic plant from sunlight	−0.052	0.274	0.123	0.345	0.186	−0.033	0.169
KP(0.03)	Michaelis constant for phytoplankton from DIP	0.928	−0.785	0.266	−0.948	−0.644	0.073	0.607
KPP(0.02)	Michaelis constant for aquatic plant from DIP	−0.613	0.473	−0.104	0.571	0.272	−0.108	0.357
Kpp1(0.02)	Michaelis constant for aquatic plant from DIPP	0.000	0.115	0.137	0.137	0.087	−0.006	0.080
MA(0.1)	Maximum mortality for phytoplankton	0.027	0.401	0.015	1.214	0.169	0.199	0.338
MAP(0.01)	Maximum mortality for aquatic plant	−1.845	1.354	−0.535	1.861	0.857	−0.015	1.078
MZ(0.05)	Maximum mortality for zooplankton	0.005	0.534	0.005	0.725	0.135	0.367	0.295
NDC(0.3)	Mineralization rate of organic detritus	−0.398	0.043	−0.066	0.886	0.481	−0.017	0.315
SDR(0.1)	Settling rate of organic detritus	−0.069	−0.378	−0.032	−0.294	−0.137	0.000	0.152
SDRA(0.1)	Settling rate of phytoplankton	0.006	0.114	0.006	0.285	0.017	0.142	0.095
thresh(0.3)	Threshold for zooplankton grazing phytoplankton	−0.309	0.199	−0.111	0.269	−0.120	−0.014	0.170
water ratio(0.5)	Water ratio in sediment	3.766	−1.247	1.480	−1.614	−0.624	−0.052	1.464

The results in the table are based on STELLA 9.0 program by using parameters with ±10 % changes $I = [(y_2 - y_1)/y_0]/[2\Delta x/x_0]$.

Table 4. Calibrated parameter values.

Parameters	Variation range[a]	Calibration results
Eddy viscosity	0.1–0.5 ($m^2\,s^{-1}$)	0.30
Manning number	22–32 ($m^{1/3}\,s^{-1}$)	25.00
Wind friction	0.0010–0.0015	0.0013
BOD Processes: 1st order decay rate at 20°	0–1 (per day)	0.25
Maximum oxygen production at noon, m^2	0–10 (per day)	4.00
Respiration rate of plants, m^2	0–10 (per day)	2.00
Sediment Oxygen Demand per m^2	0–10 (per day)	2.50
Nitrification: 1st order decay rate at 20°	0–1 (per day)	0.03
Nitrification: 2st order decay rate at 20°	0–2 (per day)	0.70
Ratio of ammonium released by BOD decay	0–2 (g NH_4-N g^{-1} BOD)	0.20
Amount of PO_4-P taken up by plants	0–0.1 (g P g^{-1} DO)	0.01
Death rate of chlorophyll *a*	0–0.1 (per day)	0.01
Settling rate of chlorophyll *a*	0–2 (m day^{-1})	0.18

[a] Source: DHI's Software Support Center (2007a, b).

Table 5. Calibrated parameter values.

Parameter	Variation range[a]	Value (Zone 1)	Value (Zone 2)	Value (Zone 3)	Value (Zone 4)
water ratio	0–1	0.45	0.45	0.45	0.45
CC	5–100	30	28	30	28
DIFFC	0.01–0.50	0.12	0.08	0.10	0.12
EXT	0.12–0.20	0.18	0.18	0.18	0.18
GAMAX	1–6	4.30	5.20	5.70	4.30
GPMAX	0.02–0.50	0.15	0.35	0.90	0.20
GPOVMAX	0.01–0.50	0.07	0.16	0.41	0.09
GZMAX	0.30–0.80	0.30	0.80	0.60	0.80
thresh	0.10–0.30	0.20	0.20	0.20	0.20
KA	0.50–2.00	1.00	0.80	0.60	1.20
KP	0.10–0.50	0.30	0.36	0.40	0.30
KPP	0.02–0.20	0.01	0.03	0.06	0.02
Kpp1	0.01–0.20	0.01	0.03	0.05	0.02
KI1	100–500	200	200	200	200
KI2	100–500	300	300	300	300
MA	0.05–0.40	0.05	0.09	0.08	0.05
MZ	0.01–0.25	0.04	0.05	0.05	0.06
MAP	0.005–0.10	0.10	0.13	0.02	0.10
NDC	0.20–0.80	0.20	0.40	0.40	0.60
SDR	0.10–2.00	0.16	0.40	0.40	0.80
SDRA	0.10–0.60	0.14	0.18	0.54	0.55

[a] Source: Jørgensen and Bendoricchio (2001), Tsuno et al. (2001), and Jørgensen and Brian (2011).

Table 6. Average water depth and water quality of Baiyangdain Lake.

Water depth (m)	BOD (mg L^{-1})	Chla (mg L^{-1})	TN (mg L^{-1})	TP (mg L^{-1})	DO (mg L^{-1})	Water level (m)
2.599	2.65	0.015	1.23	0.14	5.99	8.190

Table 7. Average water depth and water quality of different water area zones.

Zone	Water depth (m)	DO (mg L^{-1})	Chla (mg L^{-1})	BOD (mg L^{-1})	TN (mg L^{-1})	TP (mg L^{-1})
I	1.97	6.00	0.122	2.33	3.30	0.18
II	2.71	6.02	0.019	3.09	0.93	0.14
III	3.39	5.21	0.018	4.29	1.68	0.18
IV	2.64	6.12	0.017	3.39	0.69	0.11

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◄ | ►
◄ | ►
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 8. Water ecological indexes of different water area zones.

Zone	Z ($mg\,L^{-1}$)	A ($mg\,L^{-1}$)	D ($mg\,L^{-1}$)	AP ($g\,m^{-2}$)
I	4.29	66.95	11.29	214.58
II	4.34	37.57	10.94	742.37
III	4.75	36.33	7.34	1903.18
IV	2.81	50.78	8.41	345.21

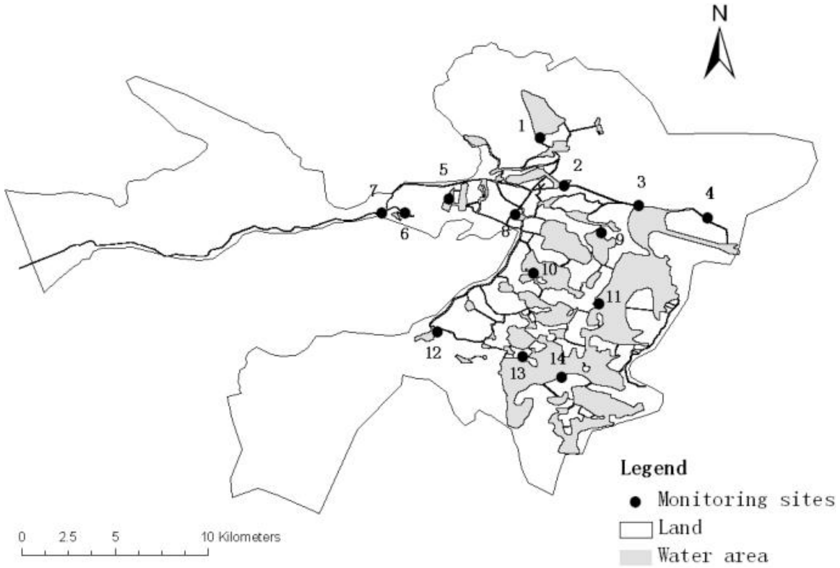

Fig. 1. The distribution of the monitoring sites in Baiyangdian Lake.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀◀ ▶▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

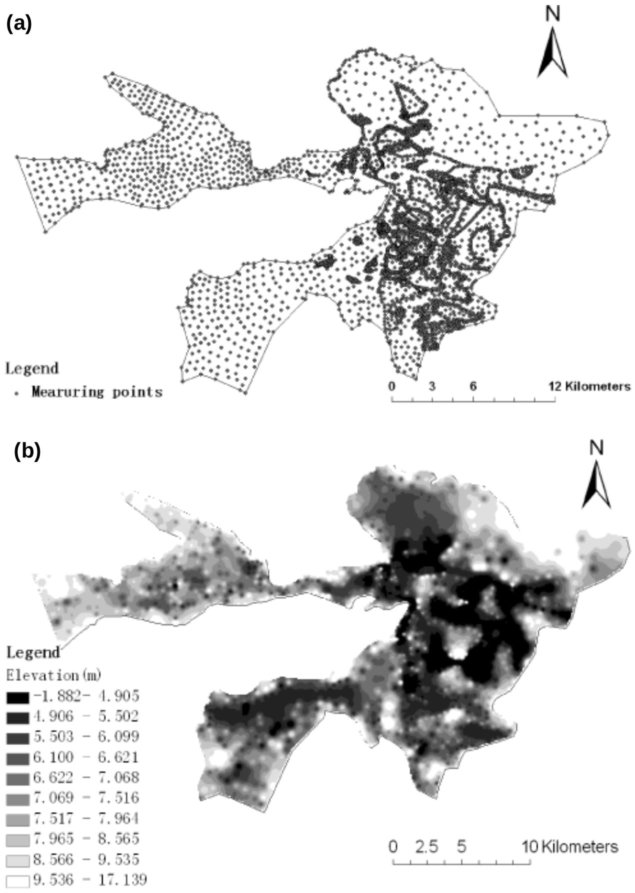

Fig. 2. (a) Measuring points distribution; **(b)** Terrain map of Baiyangdian Lake.

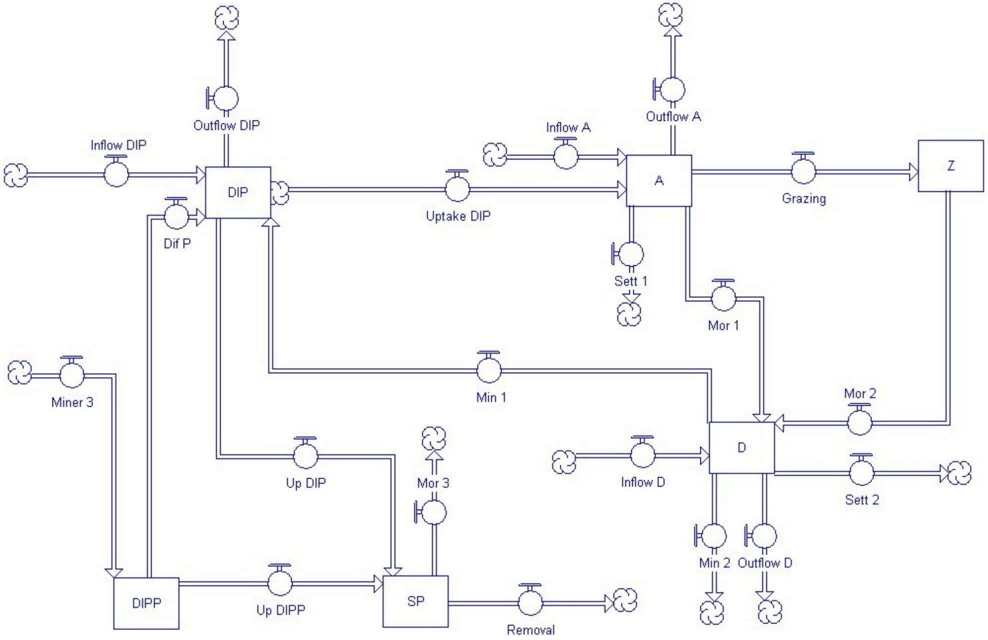

Fig. 3. Conceptual diagram of each compartment model.

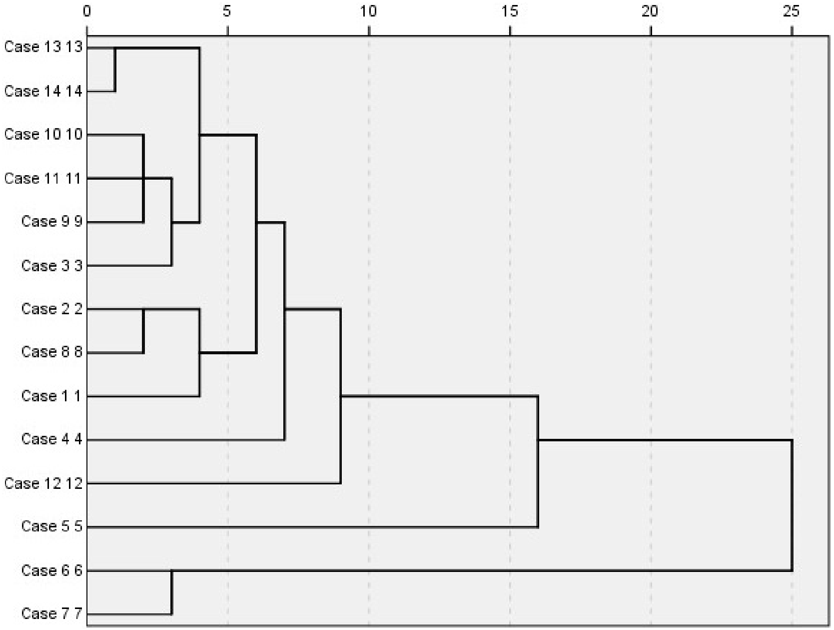

Fig. 4. HCA results of 14 sampling sites.

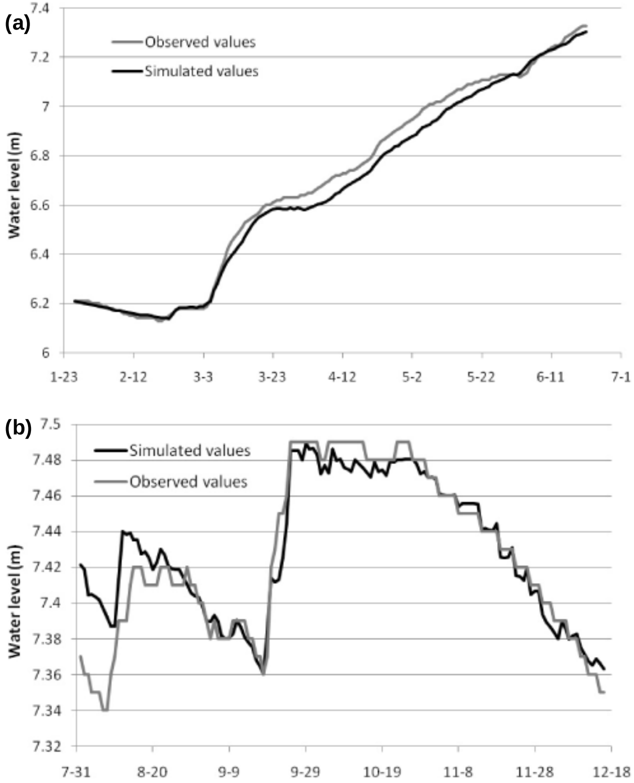

Fig. 5. Calibration **(a)** and validation **(b)** results for the water level.

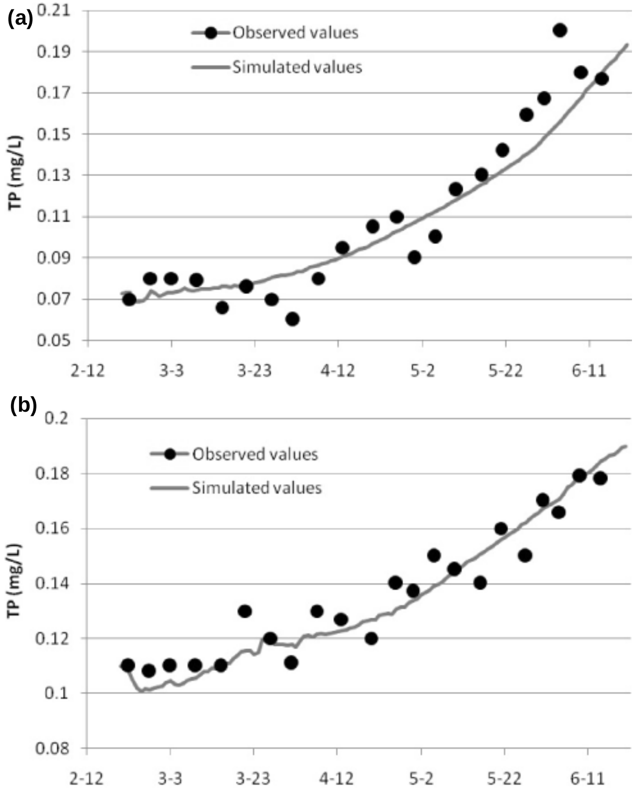

Fig. 6. Calibration results for phosphate at Sites 12 **(a)** and 11 **(b)**.

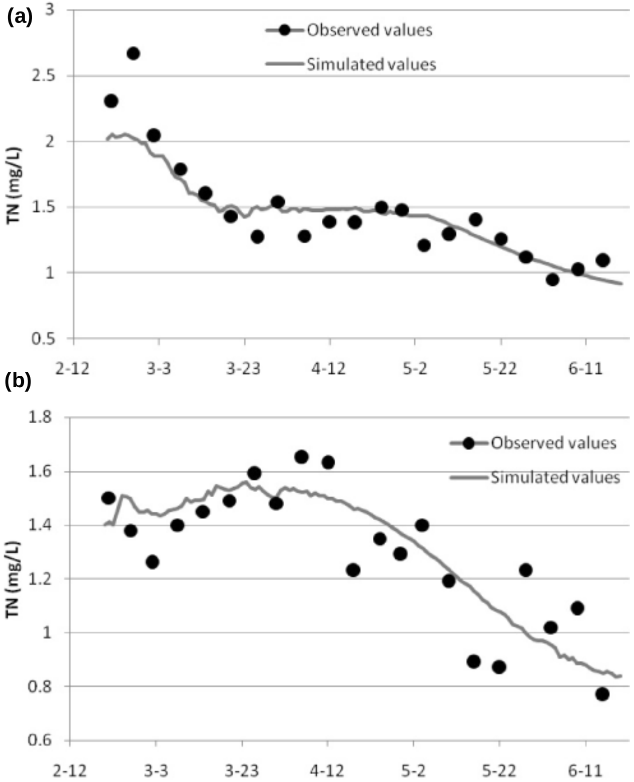

Fig. 7. Calibration results for TN at Sites 12 **(a)** and 11 **(b)**.

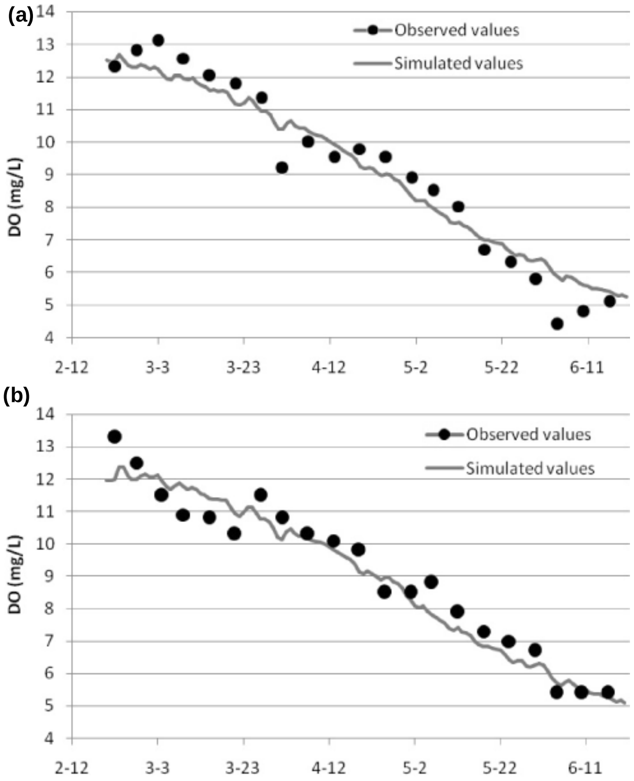

Fig. 8. Calibration results for DO at Sites 12 **(a)** and 11 **(b)**.

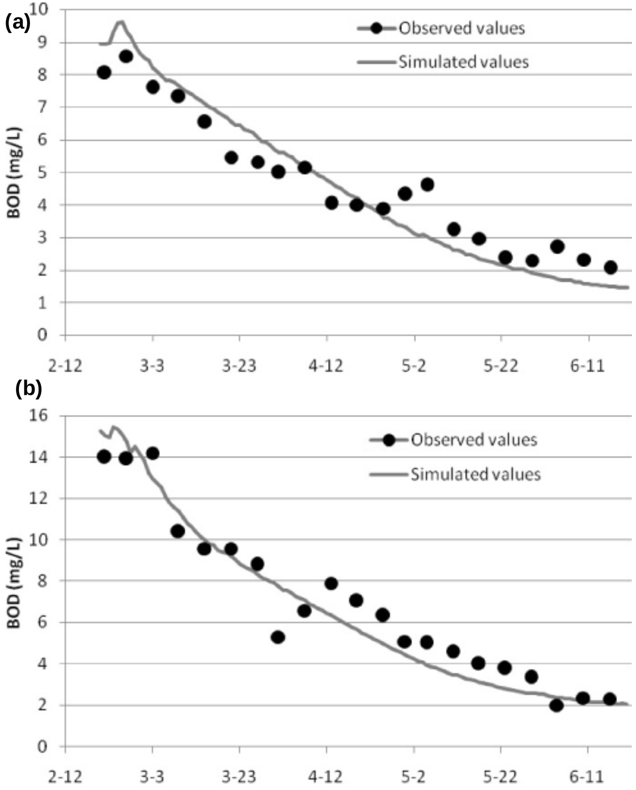

Fig. 9. Calibration results for BOD at Sites 12 **(a)** and 11 **(b)**.

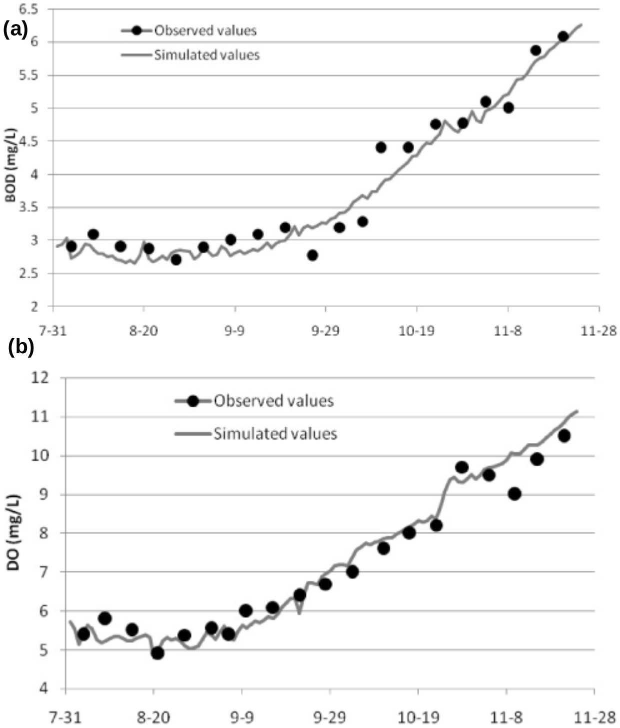

Fig. 10. Validation results for BOD **(a)** and DO **(b)** at Site 2.

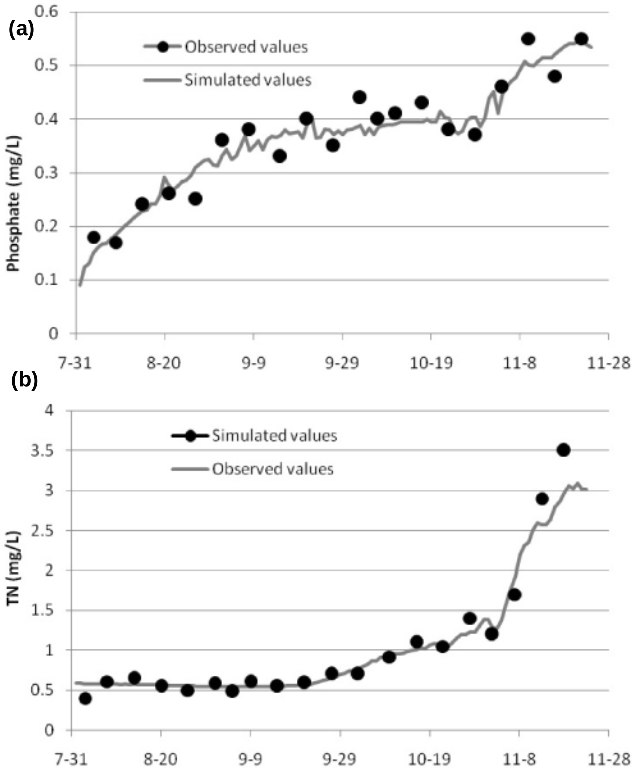

Fig. 11. Validation results for phosphate **(a)** and TN **(b)** at Site 2.

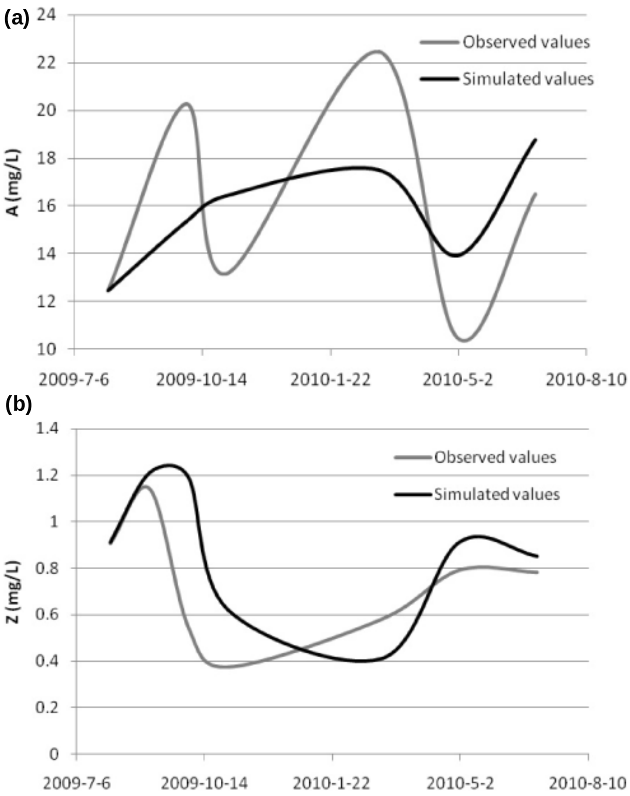

Fig. 12. Calibration results for phytoplankton biomass **(a)** and zooplankton biomass **(b)** at Site 6.

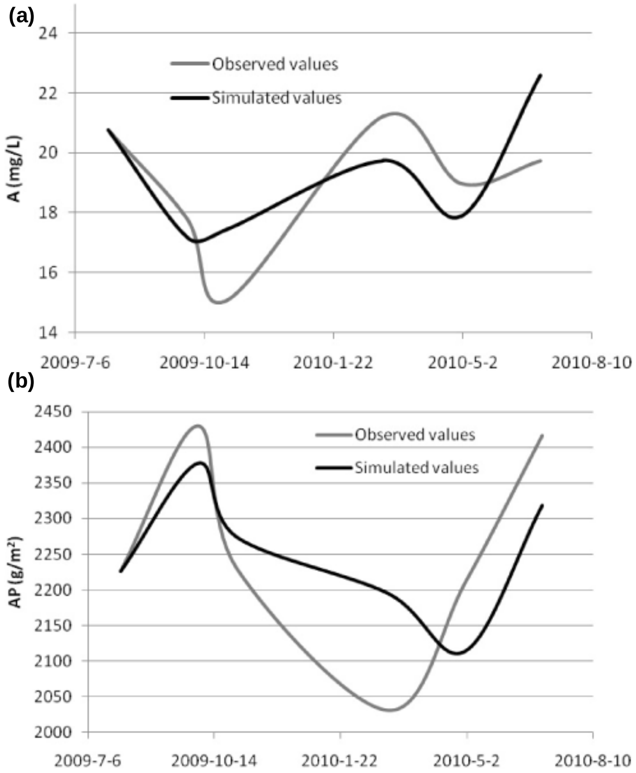

Fig. 13. Calibration results for phytoplankton biomass **(a)** and aquatic plant biomass **(b)** at Site 8.

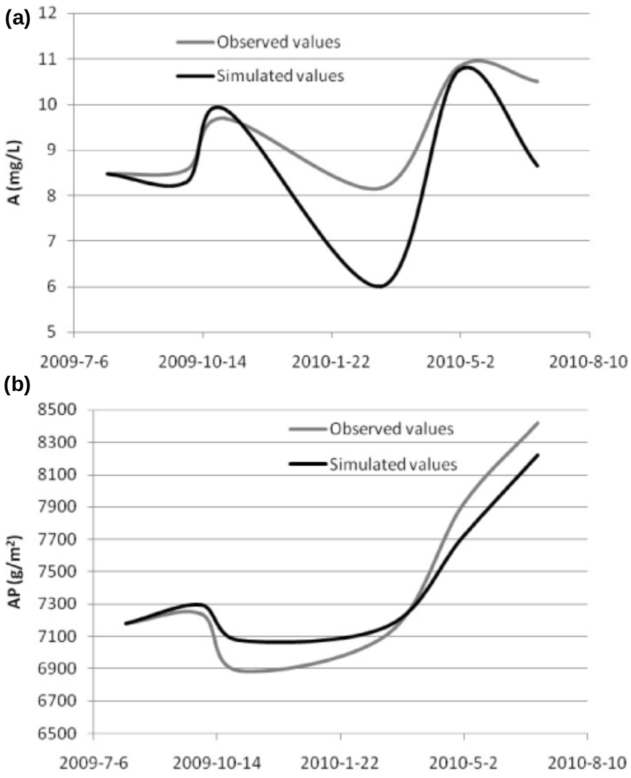

Fig. 14. Calibration results for phytoplankton biomass **(a)** and aquatic plant biomass **(b)** at Site 4.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀▮ ▶▮
◀ ▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

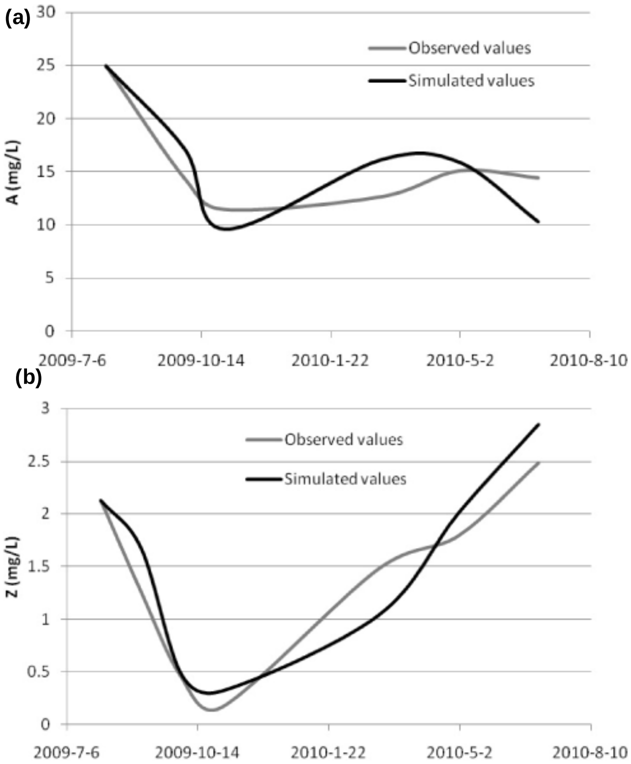

Fig. 15. Calibration results for phytoplankton biomass **(a)** and zooplankton biomass **(b)** at Site 12.

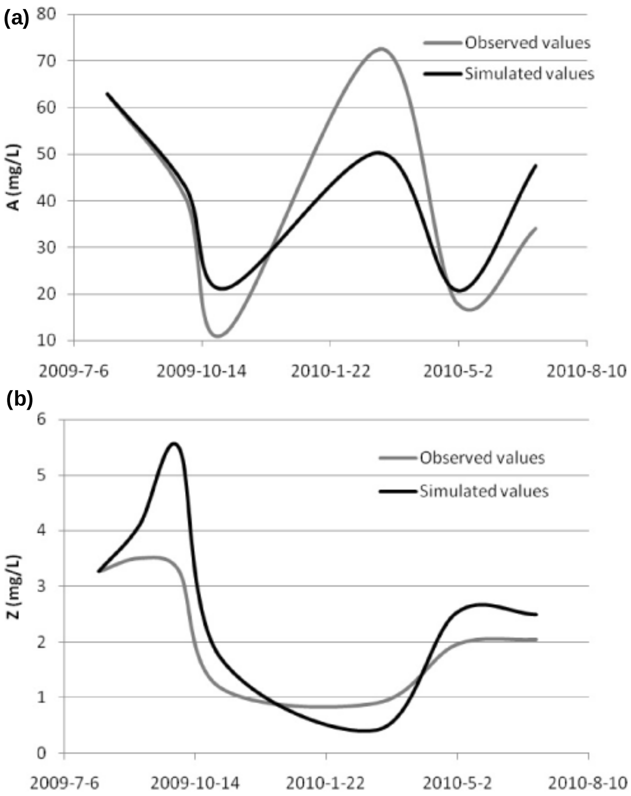

Fig. 16. Validation results for phytoplankton biomass **(a)** and zooplankton biomass **(b)** at Site 5.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀▌ ▶▌
◀ ▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

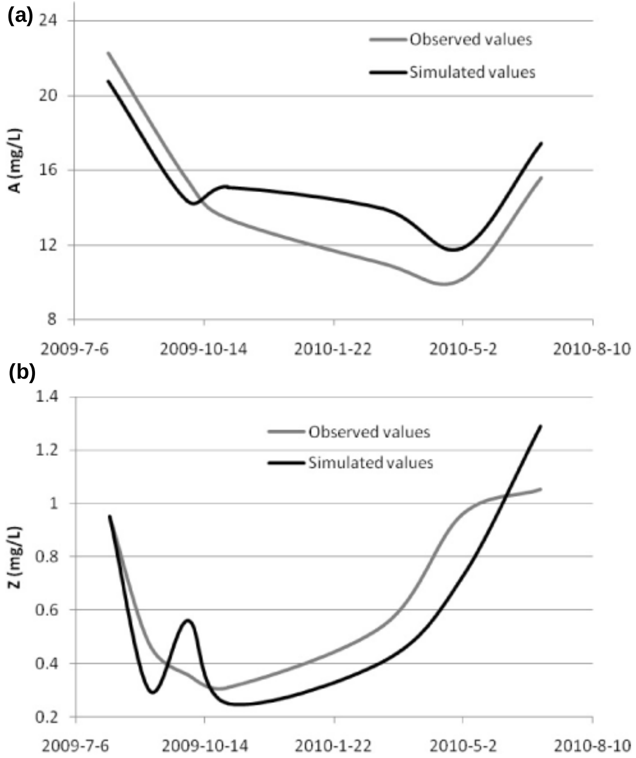

Fig. 17. Validation results for phytoplankton biomass **(a)** and zooplankton biomass **(b)** at Site 10.

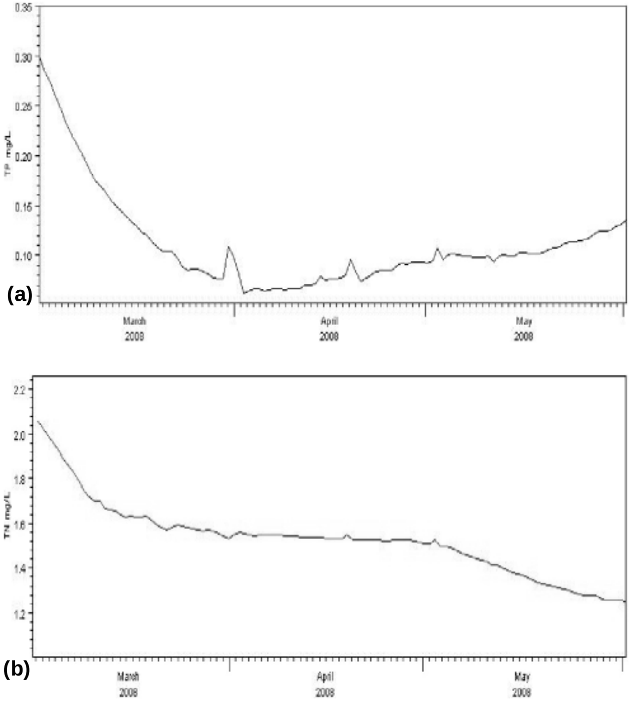

Fig. 18. The changes of concentrations of TP **(a)** and TN **(b)** at Site 8.

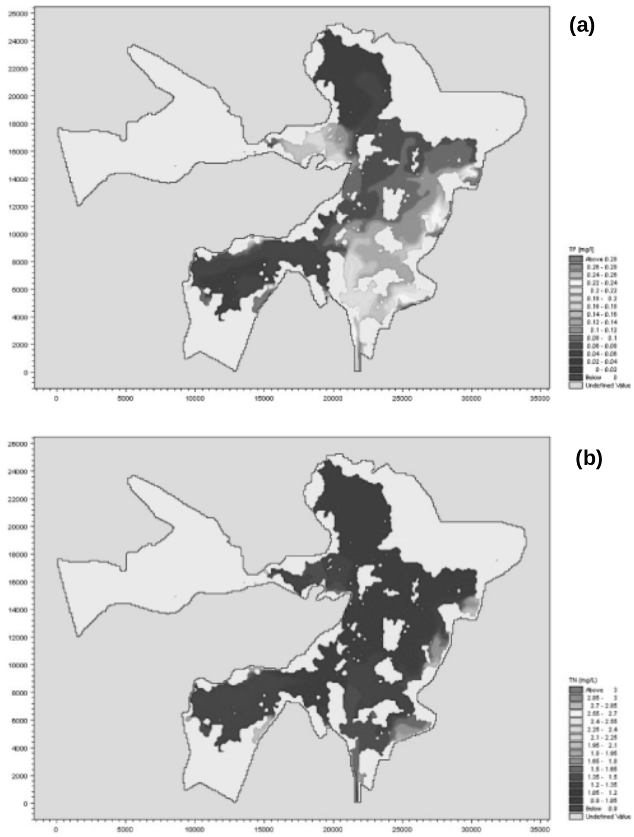

Fig. 19. The spatial variations of concentrations of TP **(a)** and TN **(b)**.

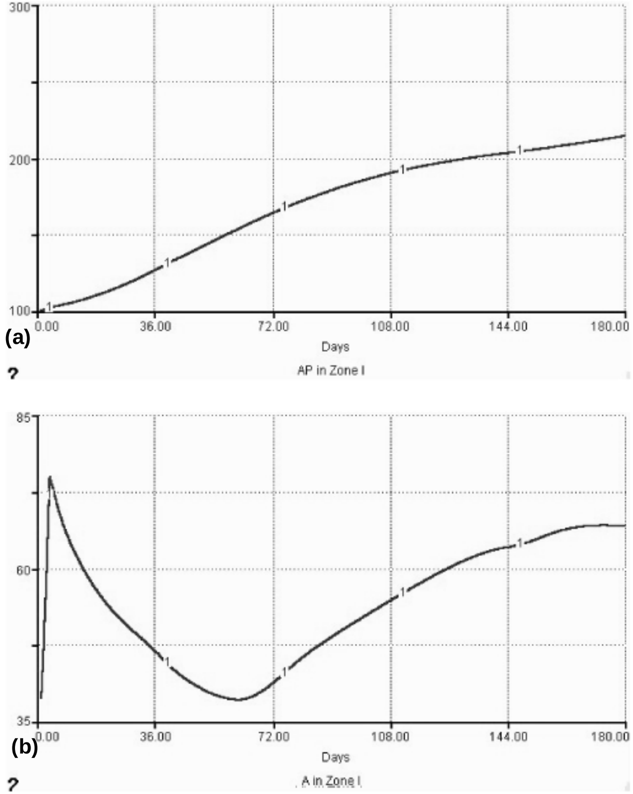

Fig. 20. Simulation results of the main ecological indexes at zone I. **(a)** aquatic plant biomass (AP); **(b)** phytoplankton biomass (A).

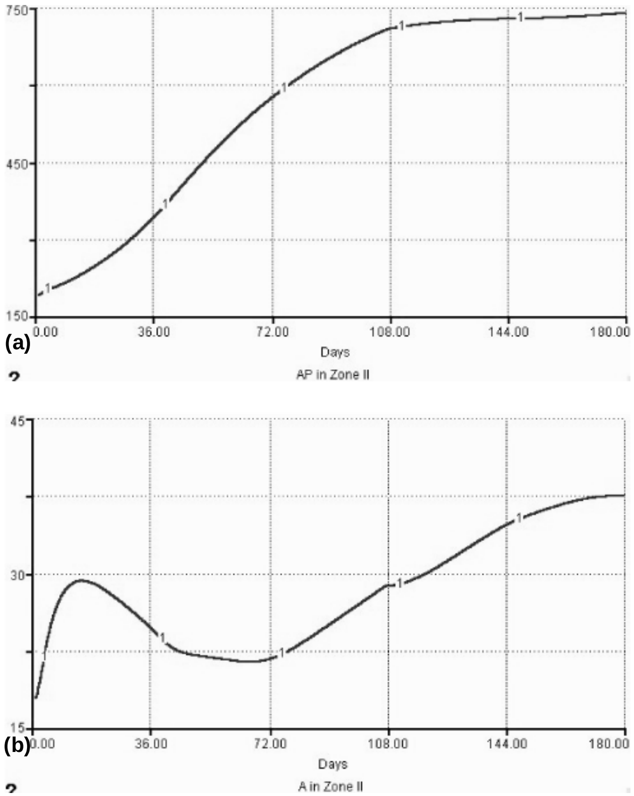

Fig. 21. Simulation results of the main ecological indexes at zone II. **(a)** aquatic plant biomass (AP); **(b)** phytoplankton biomass (A).

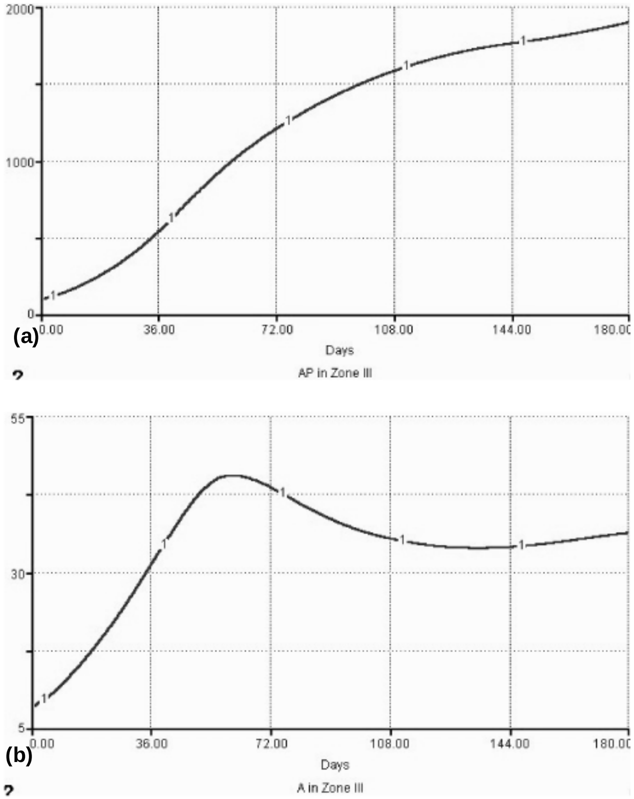

Fig. 22. Simulation results of the main ecological indexes at zone III. **(a)** aquatic plant biomass (AP); **(b)** phytoplankton biomass (A).

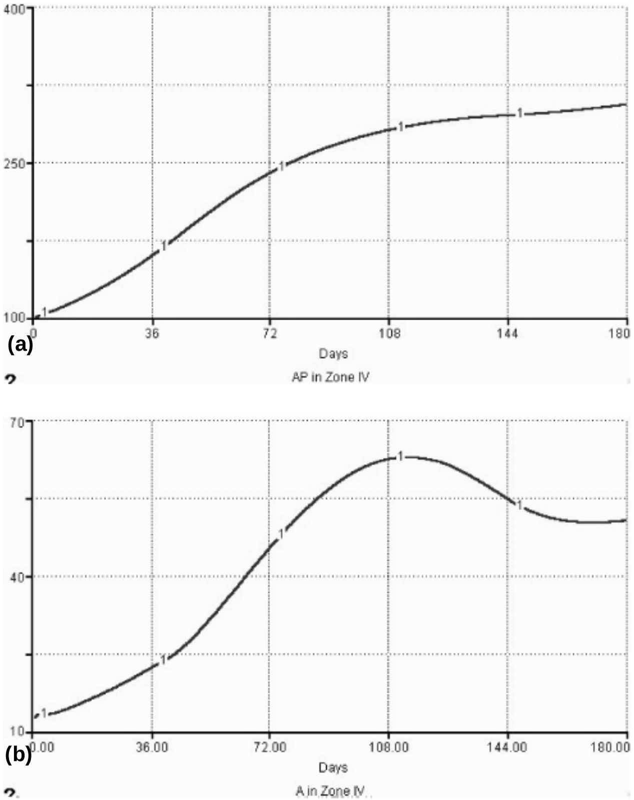

Fig. 23. Simulation results of the main ecological indexes at zone IV. **(a)** aquatic plant biomass (AP); **(b)** phytoplankton biomass (A).