Front. Environ. Sci. Eng. 2012, 6(5): 658–671
DOI 10.1007/s11783-012-0446-3

RESEARCH ARTICLE

An approach to calculating allowable watershed pollutant loads

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Abstract To improve the management of discharge pollutants loads in the reservoirs' watershed, an approach of the allowable pollutants loads calculation and its allocation, based on the water environment model, was proposed. Establishment of the approach framework was described at first. Under the guidance of this framework, two major steps were as follows: modeling and scenario analysis were involved and should be applied to support the decision of discharge loads management; Environmental Fluid Dynamic Code (EFDC) model was selected as the kernel model in this framework. In modeling step, spatial discretization for establishing cell map in model, data preprocessing, parameter calibration and uncertainty analysis (which is considered as the significantly relevant factor of the margin of safety (MOS)), were conducted. As a result of the research, the model-based approach presented as a combination of estimation and precise calculation, which contributed to scenario analysis step. Some integrated modules, such as scenario simulation, result analysis and plan optimization were implemented as cycles in the scenario analysis. Finally, allowable pollutant loads under various conditions were calculated. The Chaihe Reservoir in Liaoning Province, China was used as a case study for an application of the approach described above. Results of the Chaihe reservoir water quality simulation, show good agreement with field data and demonstrated that the approach used in the present study provide an efficient and appropriate methodology for pollutant load allocation.

Keywords Source water protection, watershed management, pollutants load allocation, Environmental Fluid Dynamic Code (EFDC) modeling, margin of safety, statistical analysis

Received November 28, 2011; accepted July 26, 2012

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1 Introduction

At present in China, the governmental managers of reservoir watershed need to face the challenge of maintaining a balance between water environmental protection and increasing pollution load emissions due to economic development, so as to meet their functional standard at the same time [1,2]. 3-dimensional models to calculate water capacity with static input data. These approaches are usually insufficient to meet the requirement of detailed watershed management. Consequently, series of complex water environment models, which can simulate the detail processes occurred in water bodies, are studied to calculate the allowable loads more precisely. Also, in order to find an optimized scheme.

2 Methodology

2.1 Model selection

Compared to the water capacity estimation methods which were widely applied in China, some complex process simulation models, such as EFDC, WASP (Water Quality Analysis Simulation Program), and QUAL2K were studied to calculate the allowable loads of reservoir and to support the reservoir water environment management. These models had some advantages like supporting three dimensional simulating, considering more water quality variables and their biochemical interactions, and improving the mathematical kernel of the model for reducing the errors. However, requirements of input data and parameters of the process simulation models' were more rigorous. Considering the advantages and disadvantages of different kinds of models, it is important to choose a proper model which can meet both requirement of accuracy and input data.

In this paper, the EFDC (Environmental Fluid Dynamic Code) water dynamic and ecological model [3], which is recommended by USEPA (U.S. Environmental Production Agency) and has been widely and successfully applied in many reservoir water environment analysis [4,5], was selected as the basic model of the framework of allowable loads calculation. In model selection step, EFDC was advanced in its capability of establishing a 3-D water environment model, its integrated water dynamic and water quality simulation and its function of simulating the ecological factor — algae.

The EFDC model is a process simulation model with coupled modules of hydrodynamic simulation and water quality simulation, having been used successfully in many cases of lakes' or reservoirs' watershed management [6]. The data requirement of EFDC model includes initial condition of whole simulation area, the time series of boundary condition, the time series of pollutants loads and the hydrographic information. It can be used to establish the cause-and-effect relationship between the discharge pollutants loads and the water quality indices. However, as the discharge pollutants loads is required as input data in this process simulation model, researchers cannot calculate the allowable pollutants loads directly according to the designated water quality standard. Things to be done in these researches are to run the model several times, adjusting the input data of model, especially the loads, to find the proper input which can meet the designated water quality standard.

Comparing with the process simulation models, in the aspect of estimation water capacity, some zero-dimensional or one-dimensional models applied in China in past years can calculate the allowable loads in given steady hydrologic condition, according to the designated water quality standards of specific indices and the physical characteristics of water body. Fewer data requirements of these water capacity models made their widespread applications in the past. However, these models usually calculate each index independently while ignoring the internal interaction among the indices, thus the outputs, the entire water capacity of water bodies in the certain hydrologic condition and the assured location of waste loads, are imprecise to support establishing the regulation of each pollutant source. Although these models or functions are limited in reservoir allowable loads calculation, they can estimate total water capacity of the reservoir roughly, which may be benefit for initial scenario configuration in the framework. The two simple estimation models for allowable ammonia loads and phosphorous loads will be introduced in Sect. 3.3.

2.2 The modeling framework

The model-based approach, based on the EFDC water environment model which couples the simulation of hydrodynamic and water quality, includes two fundamental processes in allowable pollutant loads calculation.

The primary process is the model development of the reservoirs. In this process, the following steps are conducted: selecting concerned indices which contribute mainly to the impaired water quality or threaten water environment potentially; identifying the interested region of water for simulation, and dividing the simulation region to several discrete cells; setting time range of simulation and setting time steps; inputting the data of initial conditions, boundaries and loads by preprocessing the monitoring data; calibrating the parameters of the EFDC model; analyzing the uncertainty of simulation result and evaluate the accuracy of the model.

The second process which may be more important and more difficult is to calculate allowable loads with scenario analysis. In this process, the simple water capacity models are used to estimate the total capacity of discharge pollutants loads, which drafts the initial scenario of loads emission. Then the EFDC model should be run to simulate scenarios and the simulation results will be outputted. In scenario analysis, it is attempted to construct the cause-and-effect relationship between discharge pollutants loads and water quality indices of concerned sections. Based on the relationship, the amount of discharge pollutants loads is adjusted and the plan of loads allocation is readjusted finally. The foregoing steps are cycled until reaching the satisfied plan.

Roadmap of the approach is illustrated in Fig. 1.

2.3 The modeling process

2.3.1 Spatial discretization and data preprocessing

The first step of modeling with EFDC is spatial discretization — the process of dividing the simulation area into a number of small cells along the selected dimension or dimensions. The cell is the basic unit of simulation, in which water quality constituents are assumed to be homogenous. The constituents' transport mechanism between adjoining cells includes advection, turbulent diffusion and settling, which are based on the hydrodynamic simulation and controlled by relevant parameters. The spatial discretization is one of the most significant processes of modeling for determining the numerical accuracy of the simulation results, the stability of calculations and the time of simulation [7]. The scale of spatial discretization is also determined by data availability. The appropriate scale of spatial discretization can balance the requirement of accuracy and the time consumption, which significantly impact the efficiency in multiple simulations of scenario analysis. Similarly, the time step of simulation needs to be set at a proper scale, which is related to the requirement of model stability especially for the hydrodynamic module.

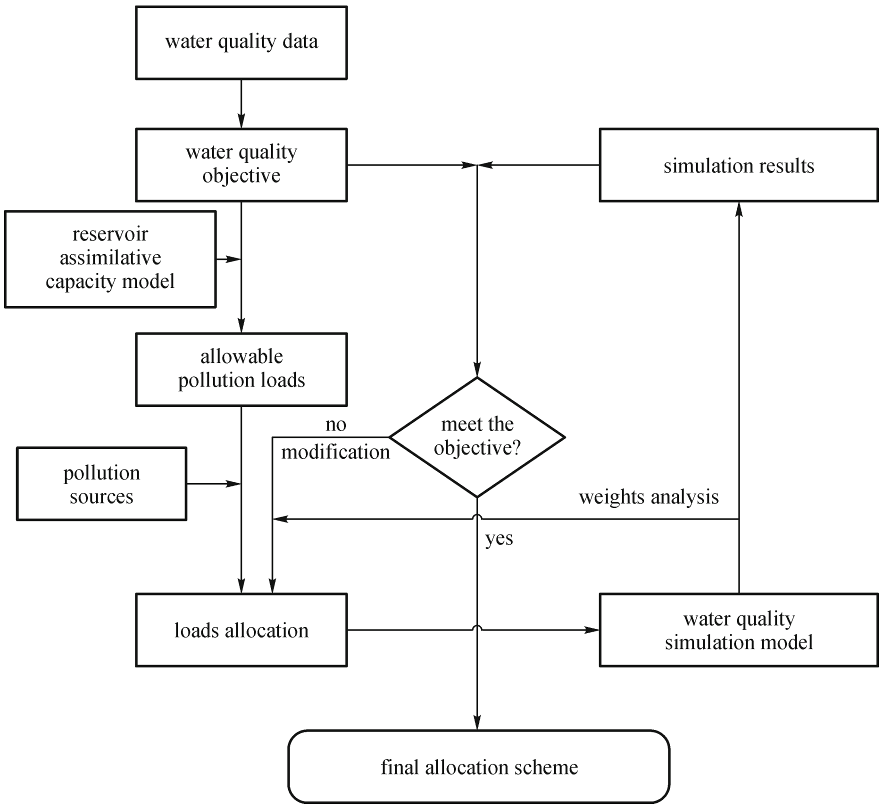

Fig. 1 Modeling process flow chart

Data preprocessing is the task that processes the raw data by interpolating spatially or temporally for augmenting necessary data, smoothing the data of irregular fluctuations and so on. The EFDC model requires spatial variations of hydrodynamic and water quality indices at the initial stage. It also needs the input data for boundary conditions, for example, inflow or outflow, pollutants loads, and meteorological data.

2.3.2 Parameters calibration

The parameters in the EFDC model affect the reaction of water constituents in cells, which include biochemical reactions such as the dynamic growth process of algae, nitrogen cycling, phosphorus cycling, the DO balance, and the physical processes such as particulate settling and releasing between water column and the sediment layer, and the balance of some water constituents in different phases through the process of adsorption and desorption. There are up to 20-two water quality constituents that can be simulated as state variables in the EFDC model, with hundreds of parameters that need to be set at appropriate values. In this study, the sensitivity of every parameter was analyzed. For low sensitivity parameters, the values were determined by using literature information [8]. High sensitivity parameters were calibrated using the field monitoring data.

2.3.3 Uncertainty and MOS

The margin of safety (MOS) term was originally proposed in the total maximum daily load (TMDL), an integrated water pollution control program administered by USEPA [9]. The rationale behind the MOS allowance is to reserve a fraction of the allowable loads in order to address the inaccuracies caused by, among other factors, model uncertainty [10]. In current practices, the MOS term is usually set as a percentage of the total allowable load [11]. In this paper, the method of First-order Error Analysis (FOEA) was selected to evaluate the uncertainty, and then to estimate the value of MOS [12]. The FOEA method is based on the assumption of a single linear system performance at the central values [13]. The basic equation of FOEA is a Taylor series expansion at the value points of parameters, and the abbreviated equation for calculating the model uncertainty is as follows:

$$[CV_Y]^2 = \sum_{i=1}^{p} [CV_x]^2 S_i^2, \tag{1}$$

where CV_Y is the overall variance of the model output in simulating single water quality variable; CV_x is the coefficient of variation of parameter i; S_i is the sensitivity of parameter i; p is the number of the related parameters.

In Eq. (1), CV_Y was considered as the total uncertainty for each water quality variable simulation in the model. It was also considered as the number of MOS in this paper.

2.4 Load allocation based on scenario analysis

For the process simulation models like EFDC, it is impossible to find the only determinate solution of allowable pollutants loads only by the designated water quality objective of special water body [14]. Scenario analysis is a flexible approach to estimate the allowable loads of discharge pollutants and search the optimized plan of loads' allocation. There are four steps from this approach. Step 1: setup the initial load allocation scheme based on the estimation of water capacity model, or by experience. Step 2: run the process simulation model and output the simulation result. Step 3: analyze the results and evaluate the scenario. Step 4: adjust and optimize the scenario. During the circulation of these four steps, multiple simulations are run for searching a satisfied plan of loads allocation.

In this four-step approach of scenario analysis, the third step is considered as the key step, which is the fundamental step of adjusting and optimizing the scenario. The efficiency of searching for the proper plan of regulating the pollutant sources, both in terms of total loads limitation and the load allocated to each source, is determined by the process of plan optimization. In this step, a cause-and-effect relationship between the load at a pollutant source and the water quality at the evaluation point is determined by linear regression analysis of the results obtained through multiple simulations. Using the statistical relationships, the impact of the pollutant load at each pollutant source on the water quality indices at the evaluation point can be estimated.

3 A case study

3.1 The study area

Chaihe Reservoir is a large man-made reservoir constructed on the Chaihe River, which is the major tributary of Liaohe River, in the south-east of Tieling City (42°13′55″N, 124°3′1″E), Liaoning Province, China. It is a river-like reservoir with a drainage area of 1355 km^2. There are kinds of land use in this area, which was identified by GIS and RS, including farm land, forest, grassland and the land for construction use (See Fig.2). Supported by DEM of Chaihe Reservoir watershed, the drainage area was divided into sub-watersheds and basin boundaries were generated automatically as shown in Fig. 3 .

Chaihe Reservoir, which is the major surface water source for Tieling City, supplies 83.7 × 10^6 m^3 drinking water per year. Therefore it is imperative to ensure that the water quality of Chaihe Reservoir can meet the source water standards. The reservoir watershed management of discharge pollutants loads is urgently desired to protect water quality from increasing pollutants emission. The total storage of Chaihe Reservoir is 636 × 10^6 m^3 and the beneficial storage is 336 × 10^6 m^3. The stage-volume relationship of Chaihe Reservoir is shown in Fig. 4. There are 34 rivers flowing into the Chaihe Reservoir with the Chaihe River as the major tributary. The average total annual inflow into the Chaihe Reservoir is 373 × 10^6 m^3.

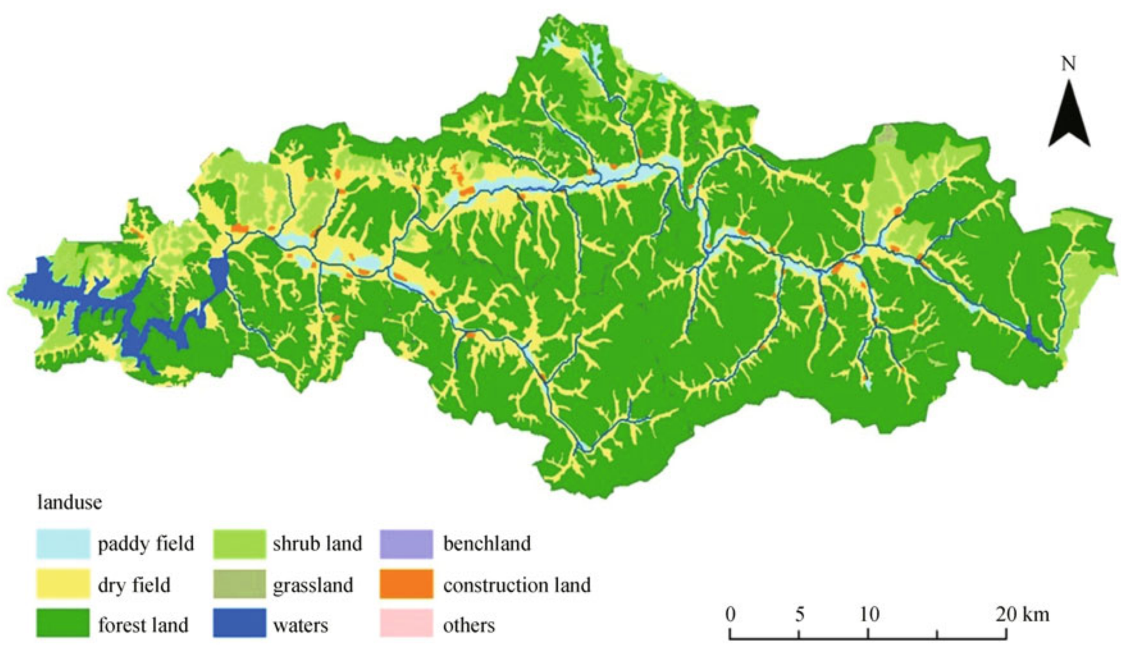

Fig. 2 Land uses in the Chaihe Reservoir watershed

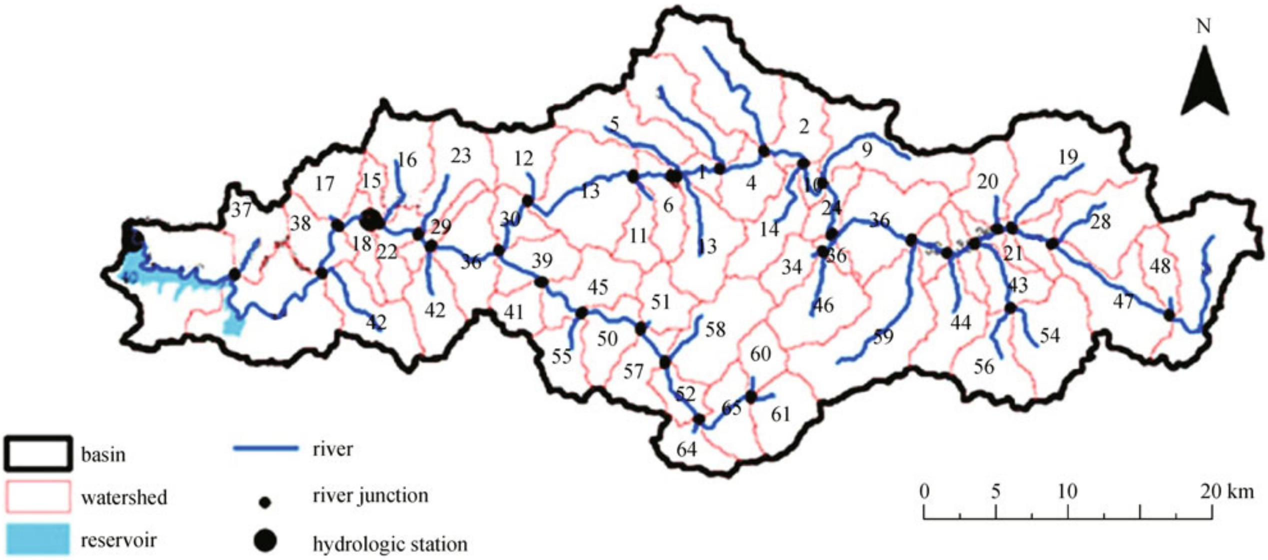

Fig. 3 The Chaihe Reservoir watershed

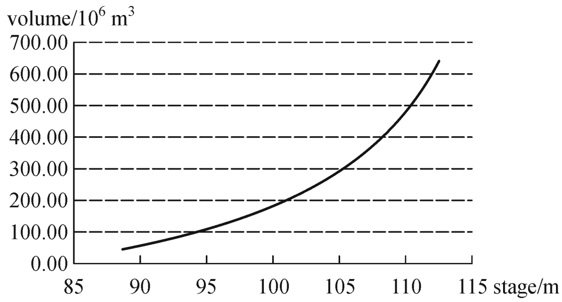

Fig. 4 The stage-volume relationship of Chaihe Reservoir

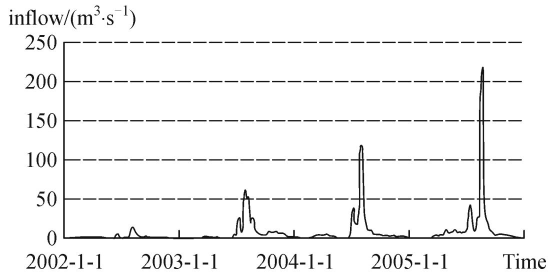

Fig. 5 The inflow rate of reservoir from Chaihe River

The records of environmental monitoring reveal that the water quality indices that occasionally surpass the water quality standard in Chaihe Reservoir in recent years are ammonia and total phosphorus (Chaihe Reservoir needs to attain Grade II of surface water standard of China, the concentration limitation of the indices are as follows: ammonia, below $0.5\,mg \cdot L^{-1}$; TP, below $0.025\,mg \cdot L^{-1}$). These pollutants are the nutriments to phytoplankton and have potentiality to lead to algae blooms in the proper condition of solar radiation and temperature [14]. The pollutants discharged into Chaihe Reservoir by inflow tributaries, mainly from then on-point source loads produced by runoff. Thus, the pollutants are more likely to surpass the water quality objective in the wet season (the months from May to September — the months which concentrate more than 80 percent of annual precipitation.) As shown in Fig. 5, the annual precipitation is variable in different years. 2005 was a typical wet year of this watershed which had the representative inflows of the years with more than 90% hydrology frequency. Therefore it can be selected as the representative year with disadvantageous condition for achieving the management goal.

Considering the hydraulic residence time (0.9 year on average), the time range for modeling is set to one year. And according to the hydrological characteristic and the water environment problem, the aims of reservoir's watershed management are settled in two points. First, the water quality indices of ammonia and total phosphorus are limited to below $0.5\,mg \cdot L^{-1}$ and $0.025\,mg \cdot L^{-1}$, respectively in the region near the intake of drinking water source. Secondly, the concentration of Chl-a is required to keep below $30\,\mu g \cdot L^{-1}$ as assurance of preventing algae bloom [15].

3.2 Modeling of the Chaihe Reservoir system

3.2.1 Preprocessing

Modeling with EFDC, a finite-difference model, of the Chaihe Reservoir, began with the spatial discretization of the reservoir system. The simulation area of reservoir for modeling includes the area submerged in mean annual water level. Based on the analysis of the shape, depth and other spatial data of Chaihe Reservoir, a three-dimensional hydrodynamic and water quality model was established with EFDC. In the vertical direction, it was divided into two layers, the upper and the lower; each of them is 50 % of the total depth, respectively. The division in vertical is for simulating the water indices difference caused by the vertical differences in solar radiation, temperature, reaeration rate, flow and other conditions. Each layer was discretized to 480 cells which are arranged in Cartesian coordination. And the size of each cell is 200 m×200 m. Figure 6 shows the cells map as the result of spatial discretization. The different colors displayed in the figure represent the difference of bottom elevation of each cell in the reservoir.

3.2.2 Parameter calibration

The hydrodynamic module and the water quality module are coupled in the EFDC model. And the hydrodynamic module is run previously and then output the velocities and the directions of flows of all cells in each time step. The outputs will be utilized by the followed water quality module as the basis of simulating the exchanges of water constituents.

In hydrodynamic module, the important parameters in experiential include roughness coefficient and couples of turbulence diffusion parameters, which reference the previous research [15]. The hydrological and meteorological records of the year of 2005 are used to calibrate the hydrodynamic parameters. For the reason that 2005 is a typical wet year of Chaihe Reservoir Watershed, the calibrated parameters can be used properly in the scenario simulation of wet year. And then the records of the year of 2009 are served as the data for modeling validation. Figure 7 shows the comparison between monitoring data and simulation result of hydrodynamic module in calibration and validation, representing high coherence and verifying that the series of hydrodynamic parameters are reliable in this modeling process.

The water quality module of EFDC is built with a complex system including a series of biochemical reactions. In modeling the Chaihe Reservoir, the water quality indices of concern are phytoplankton (cyanobacteria); ammonia and total phosphorus, which consists of RPOP (refractory particulate organic phosphorus); LPOP (labile particulate organic phosphorus); DOP (dissolved organic phosphorus) and PO4(phosphate). Additionally, other relevant water quality indices such as DO, DOC, nitrate, TON, which influence the concentration of concerned indices, are also simulated. There are a total of 34 relevant model parameters that need to be calibrated. Prior to parameter calibration, a sensitivity analysis was made in order to identify the most significant parameters the values of which should be calibrated closely. The most significant parameters, together with their calibrated values and standard deviations *Si*, are listed in Table 1.

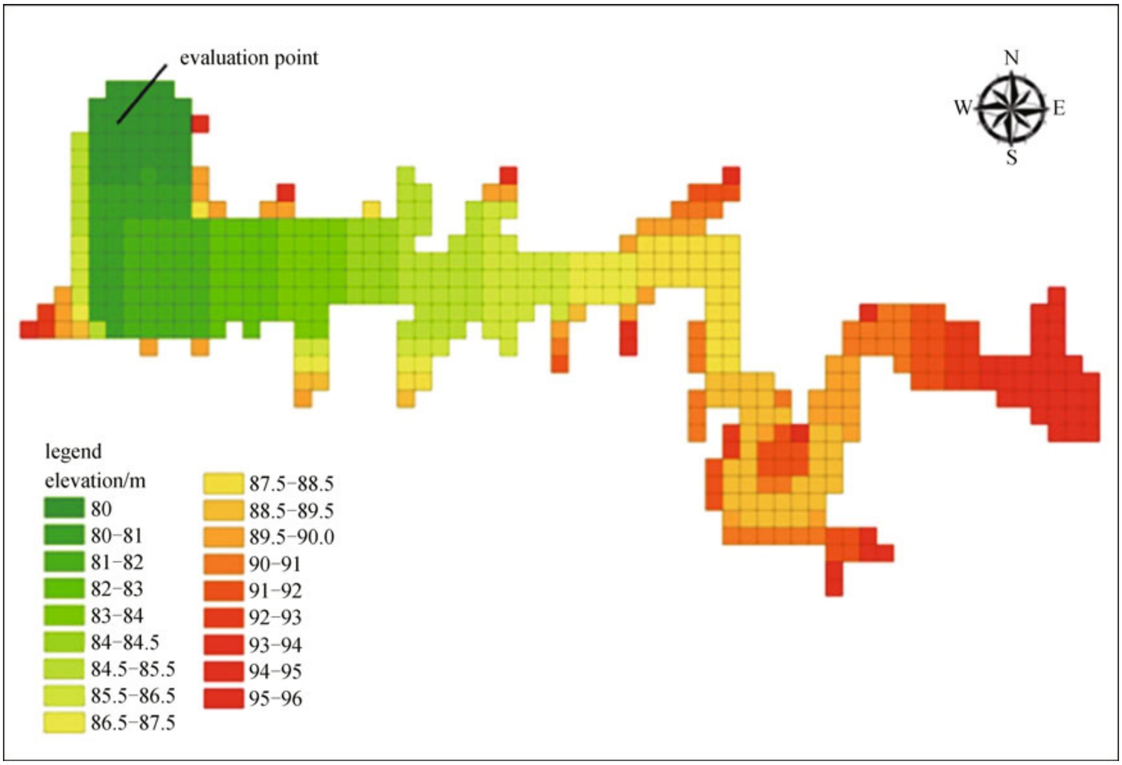

Fig. 6 Discretization of Chaihe reservoir system for the EFDC model

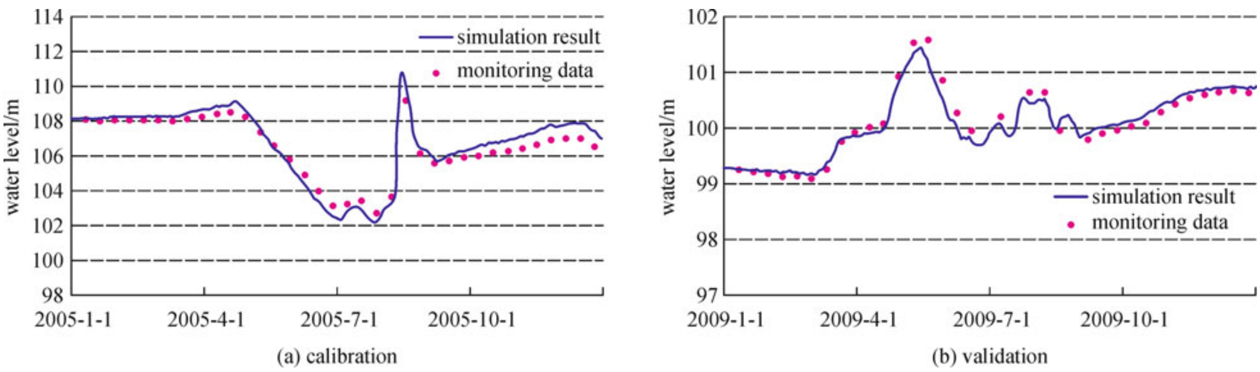

Fig. 7 Simulation results of hydrodynamic parameter calibration

Table 1 Sensitivity analysis of significant parameters

parameter	description	value	*Si*
rNitM	maximum nitrification rate/($gN\cdot m^{-3}\cdot d^{-1}$)	0.8	6.76%
KNit1	suboptimal temperature effect constant for nitrification	0.059	15.64%
KNit2	superoptimal temperature effect constant for nitrification	0.003	0.114%
KDN	minimum hydrolysis rate (1/day) of DON	0.04	16.83%
KHNitDO	nitrification half-sat. constant for DO	1	0.582%
KDRN	DON Percentage of TON	0.58	34.50%

The model runs after the configuration of calibrated parameters. And simulation results of calibration and validation is shown in Fig. 8, taking ammonia, TN, TP for instance.

To evaluate the precision of simulation in certain parameters, the median error was used as recommended in the literature [16]. The formula of median error is as follows:

$$E = 0.6745\sqrt{\frac{\sum\left(\frac{x_o - x_p}{x_o}\right)}{n-1}}, \quad (2)$$

where x_0 is water quality variable observed in monitoring, x_p is simulation result, n is the number of observed values.

The error analysis, shown in Table 2, suggests that the calibrated parameters facilitate the model to generate acceptable simulation results.

3.3 Scenario simulation and allowable loads calculation

3.3.1 Configuration of initial scenario

In the framework of this research, it is recommended that using a simple model to estimate the total allowable loads is beneficial for setting a more reasonable initial scenario of EFDC model. The zero-dimensioned model with the consideration of nutriments degradation or settling in reservoir is chosen and shown as followed expressions are used to estimate total capacity of ammonia and TP in the Chaihe Reservoir.

Ammonia estimation model:

$$r(c) = -KC, \quad (3)$$

$$W = 30 \times (QC_s + KC_sV) \times 10^{-6}, \quad (4)$$

where W is allowable loads of nitrogen; V is the volume of reservoir; C_s is the water quality standard of nitrogen; Q is the steady flow rate; K is the first order decay rate.

TP estimation model:

$$W = P(\sigma Z + 31.536Q_{out}), \quad (5)$$

$$\sigma = K_1 + K_2H\varepsilon, \quad (6)$$

$$\varepsilon = 3153.6\frac{Q_{out}}{V}, \quad (7)$$

where W is allowable loads of phosphorus; P is the concentration which meet the standard; σ is the average settling velocity of particulates; Z is the area of reservoir; H is the average depth of reservoir; ε is the coefficient of scouring, representing the ratio of quantity of outflow and volume of reservoir.

The basic assumption of the estimation model is that the hydrodynamics and the degradations of pollutants are steady-state processes, reflected in the constant quantity of inflow and outflow of each month and in the constant degradation or settling rate of pollutants. Basing on this

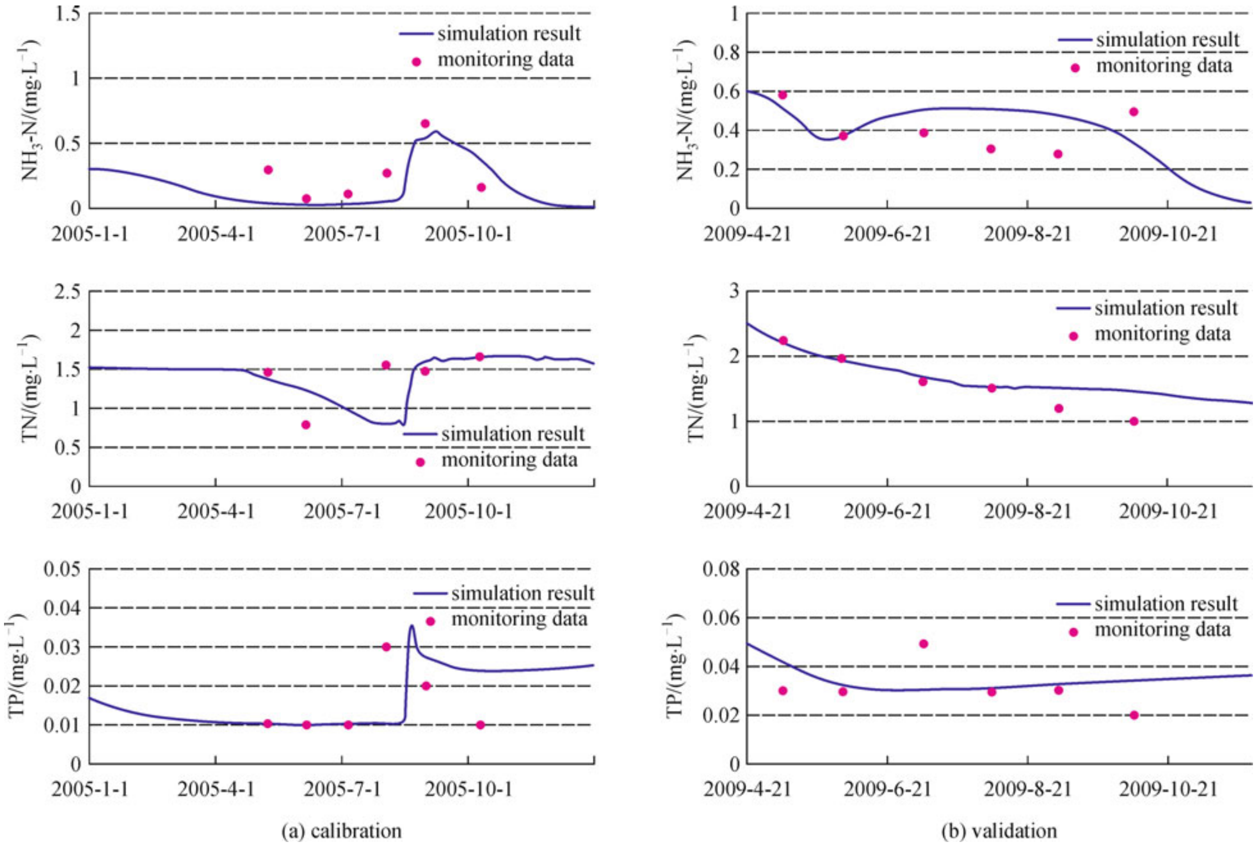

Fig. 8 Results of water quality parameter calibration and validation

Table 2 Error analysis of calibration and validation

areas	indices	calibration	validation
upstream of reservoir	NH_3-N	7.3%	15.1%
	TN	6.8%	7.8%
	TP	30.1%	25.2%
middle of reservoir	NH_3-N	43.4%	27.5%
	TN	15.6%	11.6%
	TP	34.0%	37.8%
before dam	NH_3-N	50.2%	21.0%
	TN	35.4%	21.1%
	TP	27.8%	19.7%

assumption, the result of water capacity calculation is invariable in each month, which facilitates the initial scenario with constant loads emission. Regardless of the variation of reservoir's volume, the capacity of receiving reservoir in each month is related to the quantity of inflow. The result of the estimation model: allowable ammonia concentration is $0.88\ mg\cdot L^{-1}$ and allowable TP concentration is $0.044\ mg\cdot L^{-1}$.

Based on the estimation, the initial scenario is configured with the monitoring data in 2005, are representative wet year. The boundary condition is set by variable flow and invariable pollutants' concentrations. The EFDC model is run after the configuration and the simulation result is shown in Fig. 9.

As shown in Fig. 10, the allowable loads of ammonia is overestimated in the initial and draft scenario, while the allowable loads of total phosphorus is underestimated. It is possible that the differences in simulation results of ammonia between the estimation model and the EFDC model are caused by the different consideration of ammonia related reactions. In the estimation model some reactions that increase the concentration of ammonia such

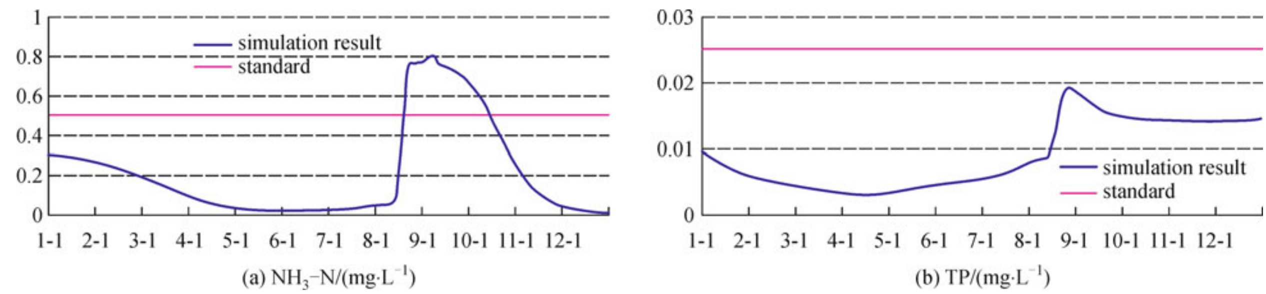

Fig. 9 Concentration of NH_3–N (a) and TP (b) at the evaluation point in the initial scenario simulated by EFDC model

as the release from sediment and the transformation from other forms of nitrogen are ignored, only considering the first order decay process. And in estimation model of phosphorus, the sedimentation rate of total phosphorus may be underestimated in the former model. The adjustments of scenario are required, basing on, if possible, the analysis of cause-and-effect relationship between the discharge pollutants loads and the pollutants concentration at the end point.

3.3.2 Cause-and-effect relationship

After running the hydrodynamic and water quality model by inputting the data of the representative wet year, the transportation and transformation of pollutants are clearly simulated. Fig. 10 illustrates the spatial distribution of ammonia in different time simulated by the EFDC model. It is shown that these two major processes contribute to the variation of distribution and concentration. There are two months with intense precipitation in this typical wet year. The wet months begins in the later July which is reflected in the figure of 210th day shown the increase of ammonia concentration in upstream of the reservoir. And more intense precipitations occurred during the August, taking mass pollutants loads to the reservoir. It caused the ammonia concentration surpass the standard of water quality almost all the reservoir including the endpoint — the point of drinking water source. The simulation results show that process of pollutants' transportation is the dominant process from 230th day to 255th day, when the ammonia concentration at the end point is over standard. The degradation of ammonia is occurred in the reservoir chronically and the concentration at the end point decrease gradually after the floods. The variation of total phosphorus in the wet months is similar with the trend of ammonia.

The cause-and-effect relationship between the pollutants loads from inflow of Chaihe River and the pollutants concentration at the endpoint, which is caused by both transportation and degradation, was established by simulating a series of different scenarios configured invariance inflow concentrations. The simulation results are shown in Table 3.

The cause-and-effect relationship can be expressed in regression functions. Based on this relationship, the allowable loads of Chaihe Reservoir in typical wet month was calculated. As a simulation result, in the typical wet months when the pollutants concentrations are more likely to surpass the water quality standard, the allowable load of ammonia is constrained to be less than 128.25 t/month, and the limitation of TP load is 17.53 t/month.

3.3.3 Uncertainty and MOS

In the process of allowable pollutant load calculation of Chaihe Reservoir, the MOS of the pollutants loads is needed to be estimated, in order to reserve a margin capacity to guarantee that the water quality standard of Chaihe Reservoir should be reached even with the simulation error from the model uncertainty. An estimation method based on the uncertainty analysis of model's key parameters rather than the widely applied method which determine MOS through experience, was selected to calculate the MOS of ammonia. The method FOEA referred before, which presented a lot of advantages in analyzing complex model, is used to estimate the simulation results' uncertainty caused by the variation of key parameters. Meanwhile, the MOS of total phosphorus was estimated by reserving a portion of total pollutant capacity. The portion was 5 percent of total pollutant of TP.

The sensitive analysis of parameters is accomplished in the step of calibration of parameters. The coefficient of variation of each parameter is selected reference to previous research [17] [18]. Then, the overall variance (CVY) that means the uncertainty of model output caused by parameters was calculated as showed in Table 4.

3.4 Allowable loads calculation and management aim verification

According to the estimation results of MOS, the limitations of pollutants are formulated. See Fig. 11, which take ammonia for instance. The final allowable pollutants loads, shown in Table 5,which are directly related to determine the plan of loads allocation in the regulation of Chaihe

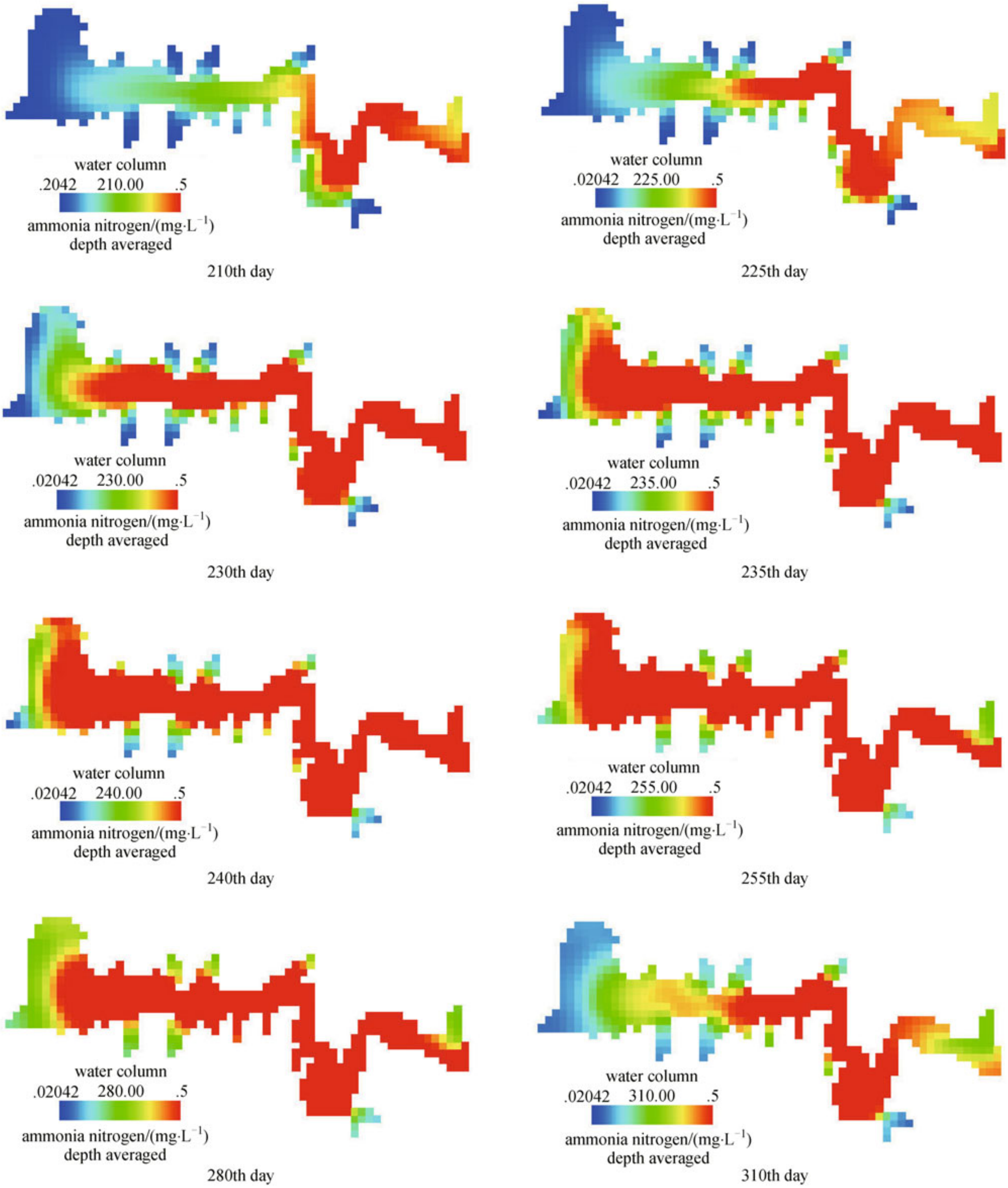

Fig. 10 The spatial distribution of ammonia in the simulation of the scenario configured by the monitoring data of 2005

Table 3 The cause-and-effect relationship

ID	NH_3-N		TP	
	concentration of inflow /$(mg \cdot L^{-1})$	concentration of end point /$(mg \cdot L^{-1})$	concentration of inflow / $(mg \cdot L^{-1})$	concentration of end point /$(mg \cdot L^{-1})$
1	0.80	0.676	0.044	0.0192
2	0.70	0.618	0.050	0.0208
3	0.65	0.588	0.060	0.0233
4	0.40	0.446	0.070	0.0288
5	0.60	0.559	0.080	0.0326
6	0.55	0.531	0.065	0.0272
7	0.50	0.501	0.055	0.0225

Table 4 Coefficient of variation

Parameter	CV	*Si*
rNitM	25%	6.76%
KNit1	5%	15.64%
KNit2	5%	0.114%
KDN	25%	16.8%
KHNitDO	25%	0.582%
KDRN	30%	34.50%
CVY	$CV_Y = \sqrt{\sum_{i=1}^{p} (CV_{x_i})^2 \cdot S_i^2}$	11.33%

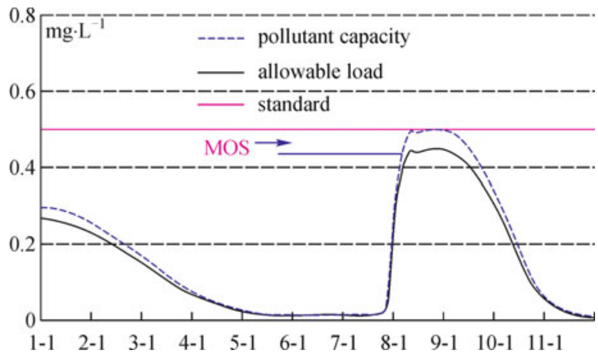

Fig. 11 Allowable allocation loads of NH_3–N

Table 5 The result of allowable loads

	water environmental carrying capacity/$(t \cdot month^{-1})$	MOS/$(t \cdot month^{-1})$	allowable loads/$(t \cdot month^{-1})$
NH_3-N	142.78	14.53	128.25
TP	17.53	0.88	16.65

Reservoir watershed, can be calculated relied on the former cause-and-effect relationship by inputting the limitations of pollutants concentrations.

To meet another aim of watershed management of Chaihe Reservoir, the concentration of Chl-a, which represents the population of algae, is simulated as a check factor. The simulation result is shown in Fig. 12. These two figures show the peak value of Chl-a concentration in 238th day and 247th day respectively, both of which below 30 $\mu g \cdot L^{-1}$, the concentration that is the limitation of avoiding algae blooming in former related study [19]. So the foregoing calculated allowable loads are verified to meet the requirement of watershed management.

3.5 Loads allocation

The goal of watershed management is to manage pollutants loads, dominated by agricultural non-point source, to meet the water quality requirement of the reservoir. The final scheme of loads allocation should give consideration to both equity and efficiency. As shown in Fig. 13, there are seven towns in the Chaihe Reservoir drainage area. Agricultural non-point source is the main pollutant source of ammonia and phosphorous. Current pollutant loads from each town in the drainage area were obtained from a parallel study on non-point source pollution simulation [20].

The allowable pollutants loads were allocated to each administrative town in Chaihe Reservoir watershed. And the amount of loads reduction of nonpoint source required for each town was calculated by considering the contributing weight of the pollutant sources. The contributing weight is a coefficient that represents the rate of pollutants flow into the reservoir to pollutants generated by precipitation. The weight values range from 0.6 to 1, related to the average distance from source to Chaihe Reservoir [21]. The equations to allocate the load primarily are as followed:

$$L_{\text{total}} = L_1 W_1 + L_2 W_2 + \cdots + L_n W_n, \qquad (8)$$

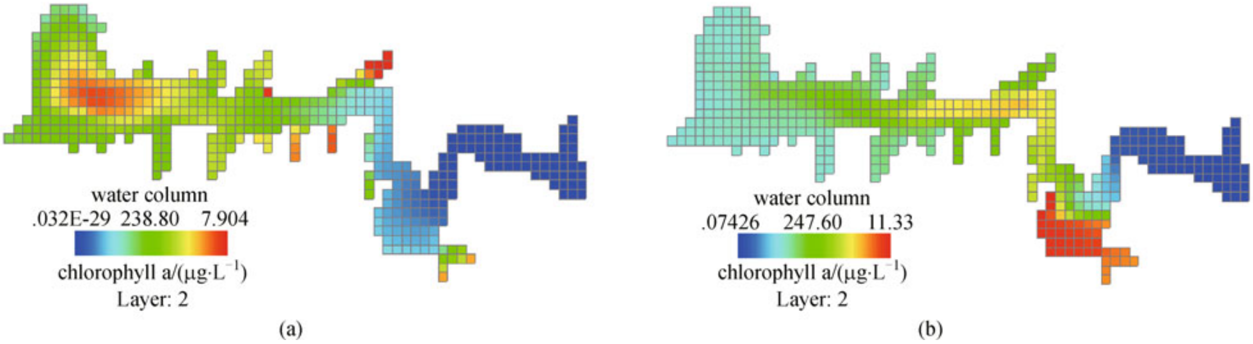

Fig. 12 The simulation result of Chl-a, (a) is for 238th day, concentration of Chl-a: 7.9 $\mu g \cdot L^{-1}$; (b) is for 247th day, concentration of Chl-a: 11.3 $\mu g \cdot L^{-1}$

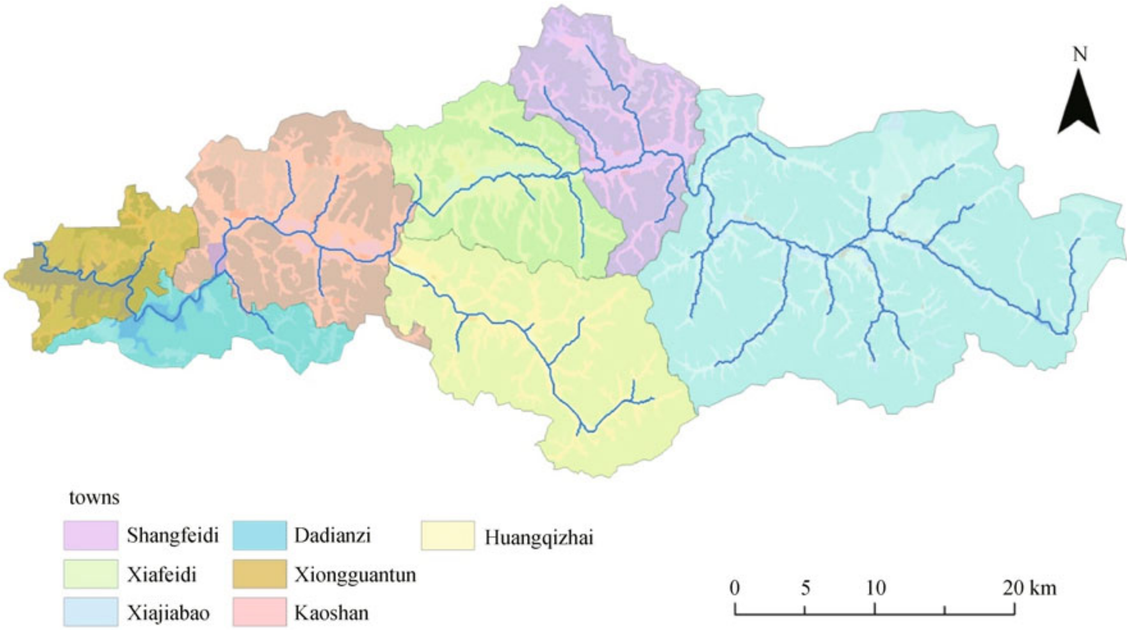

Fig. 13 The towns in the Chaihe Reservoir watershed

Table 6 The loads allocation in watershed management of Chaihe Reservoir

town	contributing weight	ammonia			TP		
		current load /($t \cdot month^{-1}$)	allowable discharge load /($t \cdot month^{-1}$)	reduction /($t \cdot month^{-1}$)	current load /($t \cdot month^{-1}$)	allowable discharge load /($t \cdot month^{-1}$)	reduction /($t \cdot month^{-1}$)
Qingyuan	0.6	105.20	74.53	30.67	19.59	7.45	12.14
Shangfeidi	0.6	27.77	19.53	8.24	5.17	4.12	1.05
Xiafeidi	0.8	30.30	23.40	6.90	5.64	3.96	1.68
Huangqizhai	0.8	47.13	37.69	9.44	8.78	3.96	4.82
Kaoshan	0.8	23.35	20.04	3.32	4.35	2.60	1.75
Chaihe	1.0	16.83	8.54	8.29	3.13	1.54	1.59
Dadianzi	1.0	26.09	5.34	20.75	4.86	0.69	4.17
total		276.68	189.07	87.60	51.52	24.33	27.19

$$\frac{L_1}{S_1} = \frac{L_2}{S_2} = \frac{L_3}{S_3} = \cdots = \frac{L_n}{S_n}, \tag{9}$$

where L_{total} is total allowable load of Chaihe Reservoir; L_n is load of one town; W_n is the contributing weight of one town; S_n is the area of the town in the drainage area.

Considering the importance of equity for all the main stakeholders (the government of each town can be considered as the representatives of all the stakeholders of the town) of the watershed, loads allocation was implemented with the equal weight approach. Based on the initial scheme of loads allocation, adjustments were made to increase the efficiency, and to design the allocation scheme with less total pollutants reduction required. The results of the adjusted load allocation are shown in Table 6.

4 Conclusions

The water environmental problems of reservoirs are serious in China. However, the water environmental management for reservoir is laggard. In this paper, the model-based approach, which is used to estimate the allowable pollutants loads of reservoirs by simulations and analysis of scenarios, is proposed to improve the water environmental management in reservoirs' basin and to provide an alternative way to supersede the conventional method of total pollutants quantity control in China. Results obtained in this study have demonstrated that the approach can provide more efficiently and accurately estimations of allowable pollutant loads.

The EFDC model is studied as an instance in the implement of the approach, presenting the advantages in the simulation of complex hydrodynamic condition and in the prediction of multi-indices with intricate correlations.

The scenario analysis method is utilized to assist the EFDC model to estimate the proper allowable loads and to find the optimized allocation scheme. To support the EFDC model's configuration of loads input, simple capacity models are used to draft the initial scenario. And the cause-and-effect relationships between the discharge pollutants loads and the water quality indices of interested sections are established to assist analyzing the contribution of each pollutants source. The scenario analysis method is studied to help the directionally adjustment of scenario to reach to the final scheme effectively.

In the case study of the Chaihe Reservoir in Tieling City, a 3-D hydrodynamic-water quality model is developed relying on the EFDC. Then, the model is calibrated and verified using monitoring data of 2005 and 2009 respectively. The sensitive analysis of model's key parameters is accomplished, which not only assist the parameters' calibration, but also bolster the model uncertainty analysis by FOEA method. The MOS is determined to be 11.33% of allowable ammonia nitrogen and 5% of allowable TP. Finally, the allowable pollutants loads were estimated considering the margins of safety: the limitation of pollutants loads taken by Chaihe River in wet months is as followed: Ammonia nitrogen is limited to 128.25 t·month^{-1}; TP is limited to 16.65 t·month^{-1}. The allowable pollutants loads allocation scheme is formulated by the method that by poising the equal contribution to end point of each source.

Acknowledgements This research was supported by the Program of Introducing Talents of Discipline to Universities (the 111 Project) (B07002); and the Mega-Projects for Science Research for Water Environment Improvement (No. 2009ZX07526-005-04).

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