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Numerical simulation for impacts of hydrodynamic conditions on algae growth in Chongqing Section of Jialing River, China

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ABSTRACT

Hydrodynamic conditions are important factors for planktonic algae growth, through introducing two parameters which express the optimal velocity and the velocity range for planktonic algae growth, a new velocity factor was put forward for the formula of growth rate. Therefore, the two-dimensional unsteady ecological dynamic model for algae growth was established to analyze the effects of hydrodynamic conditions on algae growth in Chongqing Reach of Jialing River in China. The temporal and spatial distribution of Chlorophyll-a (Chl-a) concentration was simulated numerically for various water levels, under climate conditions in period of high frequency for algae blooms of Three Gorges Reservoir and nutrition status at present in the research reach. The corresponding locations and areas of likely algae blooms were analyzed and forecasted. The results showed that about 0.04 m s^{-1} was the optimal velocity for algae growth, and the occurrence of algae blooms in large scale is almost impossible because of relatively high water flow velocity for Jialing River.

1. Introduction

One of the most common ecological and environmental problems of inland water bodies is eutrophication, which diminishing water quality by spurring the excessive growth of algae and increasing suspended organic material, (Chun et al., 2007; Simon et al., 2010; David et al., 2010). After impoundment of Three Gorges Reservoir, the hydrodynamic situation of the related rivers in the reservoir area had undergone fundamental changes (Deng, 2007). Because of the increasing water level in the main stream, the flow velocity of backwater section in tributaries slows down, the self-purification capacity of water body decreases, that provides favorable conditions for the occurrence of algae growth, abnormal proliferation phenomenon of algae bloom of tributaries continuously breaks out, and this phenomenon shows increasing trend recently (Shen and Qun, 2009). Jialing River is the largest tributary in Three Gorges Reservoir and Chongqing Reach of Jialing River is the entrance of the Yangtze River, the eutrophication status of Jialing River is directly related to water environmental safety of Chongqing City as well as the Three Gorges Reservoir Area, so research on algae growth conditions and the problem of water environment in Chongqing Section of the Jialing River is of great important theoretic and practical significance.

The present research results show that algal growth depends mainly on climatic conditions, nutrient concentrations in waters, hydrodynamic conditions (Milan, 2007). Because of the nutrient concentrations in Chongqing City Zone of the Jialing River are basically at a high level over recent years, hydrodynamic conditions play the most important part in the algae growth under appropriate climate conditions.

Currently, researches for the effects of hydrodynamic conditions of lake and river-type reservoir on algal growth are becoming more than researches before. Most of the researches before are mainly concentrated on the field tests and model tests in the local section (Yan et al., 2008a,b; Liu and Zhang, 2008; Cao et al., 2008; Richard et al., 2008; Sophia, 2007; Pannard et al., 2007; Zhang et al., 2007b; Gao et al., 2007; Liao and Hu, 2005; Zhong, 2004; Yamamto et al., 2002; Arfi, 2005). As for the whole region, especially for special hydrological situation of tributaries in Three Gorges Reservoir, numerical simulations of temporal and spatial distribution for algae growth are still rare (Wang and Pang, 2008; Wang et al., 2009; Li et al., 2004; Richard et al., 2006). In order to analyze the effects of hydrodynamics on algae growth in Chongqing reach of Jialing River, the two-dimensional unsteady ecological dynamic model for algae growth was developed in this paper, in this model, the formula of algal growth rate was improved, and the new velocity factor was proposed. The new velocity factor contains two parameters which have clear physical significance, they are respectively expressed the

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optimal velocity of algae growth and flow range which is in favor of algae growth. Using the measured water quality data and existing experimental results, the model parameters were optimized and calibrated, and the model was also validated. The spatial and temporal distribution of chlorophyll-a (Chl-a) concentration under different upstream and downstream water levels in the reach was numerically simulated under conditions of the present concentration of total phosphorus (TN) and total nitrogen (TP) and in the period of the high frequency of algal bloom in spring for Three Gorges Reservoir. In this paper, TN and TP represent the experimental dissolved nitrogen and phosphorus. The main purpose of this paper was to develop mathematical model to study impacts of hydrodynamic conditions on algae growth in Chongqing Reach of Jialing River by numerical simulation so that provides scientific basis and references for water environmental protection and research on algae bloom problem in Three Gorges Reservoir.

2. Materials and methods

2.1. Governing equations

Two-dimensional vertically averaged shallow water flow form was applied for the simulation. A set of partial differential equations that describe water flow motion, and matter convection, diffusion and translation (Shahram and Miki, 2010; Hongyan et al., 2008) respectively are:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial (h u_j)}{\partial x_j} = 0 \tag{1}$$

$$\frac{\partial (h u_i)}{\partial t} + \frac{\partial (h u_i u_j)}{\partial x_j} - \frac{\partial}{\partial x_j}\left(\nu_t \frac{\partial u_i}{\partial x_j}\right) = -gh\frac{\partial \zeta}{\partial x_i} - \rho C_f u_i \sqrt{u_j \cdot u_j} + \rho_a C_D \omega_{ai}\sqrt{\omega_{ai}\cdot\omega_{ai}} + F_{Ci} \tag{2}$$

$$\frac{\partial (h C_\varphi)}{\partial t} + \frac{\partial (h C_\varphi u_j)}{\partial x_j} - \frac{\partial}{\partial x}\left(h D_t \frac{\partial C_\varphi}{\partial x_j}\right) = Q_\varphi \tag{3}$$

where, subscript i = 1, 2; subscript j is summation index which expresses sum from 1 to 2.

In Eqs (1)–(3), ζ is water level (m); h is water depth (m); u_i is two-dimensional depth-averaged velocity in i direction (m s^{-1}); C_φ is the concentration of matter φ (mg L^{-1}); ν_t is turbulent viscosity (m s^{-1}); g is acceleration of gravity (m s^{-2}); ρ is water density (kg m^{-3}); C_f is dimensionless friction coefficient of river bed; ρ_a is air density (kg m^{-3}); C_D is dimensionless wind stress coefficient; ω_{ai} is wind speed of 10 m above water surface in i direction (m s^{-1}); F_{ci} is Coriolis force in i direction, f is Coriolis coefficient; D_t is turbulent diffusion coefficient (m^2 s^{-1}); Q_φ is source and sink items[m mg (L s)$^{-1}$] which includes biochemical reaction item and point source item imported from the shore.

Using Smagorinsky SGS formula to calculate the turbulent viscosity ν_t, that is

$$\nu_t = L^2\left[\left(\frac{\partial u_1}{\partial x_1}\right)^2 + \left(\frac{\partial u_2}{\partial x_2}\right)^2 + \frac{1}{2}\left(\frac{\partial u_1}{\partial x_1} + \frac{\partial u_2}{\partial x_2}\right)^2\right]^{1/2} \tag{4}$$

where, L is the mixing length, taking $L = c_s \Delta x$, $C_s = 0.5$ (Zhang et al., 2007a).

Friction coefficient C_f of river bed was calculated using Manning formula, which can be expressed as,

$$C_f = g n^2 h^{-1/3} \tag{5}$$

where, n is Manning coefficient, taking $n = 0.0348$ for the study reach (Zhong, 2004).

Wind stress coefficient C_D was calculated using Smith and Banke's formula, which can be expressed as,

$$C_D = \begin{cases} f_0 & \omega_a = 0 \\ f_0 + \dfrac{\omega_a}{\omega_{a1}}(f_1 - f_0) & 0 < \omega_a \le \omega_{a1} \\ f_1 & \omega_a > \omega_{a1} \end{cases} \tag{6}$$

In Eq. (6), $f_0 = 0.00063$, $f_1 = 0.002$, $\omega_{a1} = 30$ m s^{-1}.

Coriolis coefficient $f = 2\Omega \sin\varphi$, where φ is latitude, Ω is angular velocity of the Earth's rotation,$\Omega = 0.12717 \times 10^{-5}$ (°/s). The turbulent diffusion coefficient $D_t = 0.63hu_*$, where, u_* is power speed, $u_* = \sqrt{hgS}$, S is the gradient of river bed.

2.2. The source and sink items

The three kinds of matter, namely TP, TN and Chl-a, were considered in Eq. (3) for analyzing effects of hydrodynamic conditions on algae growth. In general, the growth of algae cannot be separated nutrients, especially inorganic nutrients, and nitrogen and phosphorus are the most important two elements affecting the growth of algae in nutrient. There are two forms of nitrogen and phosphorus in the presence of water, one is organic nitrogen and phosphorus, the other is inorganic nitrogen and phosphorus, they are collectively referred to as total nitrogen (TN) and total phosphorus (TP) (Simon et al., 2010). In this paper, nitrogen and phosphorus of algae absorption in the water is mainly water soluble nitrogen and phosphorus. Dissolved phosphorus mainly includes inorganic forms of phosphate ($P–PO_4$), soluble nitrogen mainly involves in nitrate ($N–NO_3$), nitrite ($N–NO_2$), ammonia nitrogen ($N–NH_4$), etc. several forms. The related studies (Shen and Qun, 2009) about the Three Gorges Reservoir show that dissolved inorganic nitrogen can be directly absorbed by algae.

For TP, subscript φ representing some matter in Eq. (3) was substituted by TP, that is, $C_\varphi = C_{TP}$ and $Q_\varphi = Q_{TP}$. Source and sink item Q_{TP} refers mainly to parts of algae growth absorption, death release and sedimentation in the reach, as well as the import from point source, and it can be expressed as,

$$Q_{TP} = -K_{TP} h C_{TP} + Q_s^{i,j} C_{TP}^{i,j} \tag{7}$$

where, K_{TP} is TP attenuation coefficient; and $Q_s^{i,j}$ and $C_{TP}^{i,j}$ is respectively the flow rate of unit area and the TP concentration of point source at (i, j).

For TN, subscript φ in Eq. (3) was substituted by TN, that is, $C_\varphi = C_{TN}$ and $Q_\varphi = Q_{TN}$. Source and sink item Q_{TN}, which includes the same parts as Q_{TP}, can be expressed as,

$$Q_{TN} = -K_{TN} h C_{TN} + Q_s^{i,j} C_{TN}^{i,j} \tag{8}$$

where, K_{TN} is TN attenuation coefficient; and $C_{TN}^{i,j}$ is the TN concentration of point source at (i, j).

For Chl-a, subscript φ in Eq. (3) was substituted by Chl-a, that is, $C_\varphi = C_{\text{Chl-a}}$ and $Q_\varphi = Q_{\text{Chl-a}}$. Source and sink item $Q_{\text{Chl-a}}$ can be expressed as

$$Q_{\text{Chl-a}} = h F_{\text{Chl-a}} + S_{\text{Chl-a}} \tag{9}$$

where $F_{\text{Chl-a}}$ is the quantity of Chl-a from biochemical reaction, which mainly include that of algae growth, decay and sedimentation, and $S_{\text{Chl-a}}$ is the quantity into the reach from bank during rainfall. The item $F_{\text{Chl-a}}$ can be expressed as

$$F_{\text{Chl-a}} = (\mu - R - K_d) C_{\text{Chl-a}} \tag{10}$$

where, μ is growth rate of algae; R is death rate of algae; K_d is sedimentation rate of algae.

The growth of algae depends mostly on the concentration of nitrogen and phosphorus nutrient, light intensity, water temperature and water flow velocity. Given their composite effects of each factor influencing algal growth rate can be expressed as the product of independent effect of each factor, the growth rate μ can be expressed as

$$\mu = F_1(T) \cdot \min\{F_2(C_{\mathrm{TN}}),\ F_3(C_{\mathrm{TP}})\} \cdot F_4(L) \cdot F_5(u) \quad (11)$$

where F_1, F_2, F_3, F_4 and F_5 mean the influence factors ,which reflect respectively the effect of water temperature, TN concentration, TP concentration, light intensity and flow velocity on algal growth rate. In Eq. (11), T, u, and L express respectively water temperature, flow velocity, and light radiation intensity in water surface. Reference to existing research results (Stefano and Elisabetta, 2008), the factors F_1, F_2, F_3 and F_4 can be written as,

$$F_1(T) = \mu_{\max} \cdot \exp\left(-\frac{2.3}{15} \times \left|T - T_{\mathrm{opt}}\right|\right) \quad (12)$$

$$F_2(C_{\mathrm{TN}}) = \frac{C_{\mathrm{TN}}}{C_{\mathrm{TN}} + K_{\mathrm{N}}},\ F_3(C_{\mathrm{TP}}) = \frac{C_{\mathrm{TP}}}{C_{\mathrm{TP}} + K_{\mathrm{P}}} \quad (13)$$

$$F_4(L) = \begin{cases} L/\mathrm{LK} & L \le \mathrm{LK} \\ 1 & L > \mathrm{LK} \end{cases} \quad (14)$$

$$\mathrm{LK} = \alpha\theta^{(T-20)} \quad (15)$$

where, $\mu_{\max}$ is the maximum growth rate of algae; K_{N} is half-saturation constant of nitrogen; K_{P} is half-saturation constant of phosphorus; LK is the half-saturation degree of light radiation intensity at water temperature T °C, α is the half-saturation degree of light radiation intensity at water temperature 20 °C, θ is the temperature parameter of half-saturation degree, and T_{opt} is the optimal growth temperature of algae.

The calculation formula (Liu and Chen, 2000) of the death rate of algae in Eq. (10) is

$$R = \begin{cases} R_{\max} \cdot \exp\left\{\dfrac{-2.3(T_{\mathrm{opt}} - T)}{15}\right\} \cdot \dfrac{C_{\mathrm{Chl-a}}}{C_{\mathrm{Chl-a}} + K_{\mathrm{m}}} \cdot \dfrac{K_{\mathrm{P}}}{C_{\mathrm{TP}} + K_{\mathrm{P}}} & T \le T_{\mathrm{opt}} \\ R_{\max} \cdot \dfrac{C_{\mathrm{Chl-a}}}{C_{\mathrm{Chl-a}} + K_{\mathrm{m}}} \cdot \dfrac{K_{\mathrm{P}}}{C_{\mathrm{TP}} + K_{\mathrm{P}}} & T > T_{\mathrm{opt}} \end{cases} \quad (16)$$

where $R_{\max}$ is the maximum death rate of algae, and K_{m} is the half-saturation constant of death rate of algae.

2.3. The velocity factor

The research results about impacts of water flow velocity on the growth of algae in lake or river-type reservoir under conditions of adequate nutrition and suitable climate have confirmed two viewpoints (Yan et al., 2008a,b; Liu and Zhang, 2008; Zhang et al., 2007b; Gao et al., 2007; Zhong, 2004; Mitrovic et al., 2003; Huang et al., 2006; Li et al., 2004; Wang and Pang, 2008). In the first place, there is appropriate velocity range of algal growth. Algae growth will accelerate when velocity is in the appropriate range, but it will be inhibited obviously or even impossible when velocity is not in the appropriate range. In the next place, there is the optimal velocity for algae growth within the appropriate range. The optimal velocity is close to zero but not equal to zero. When water flow velocity is lower than the optimal velocity, as it increases, the algae growth rate increases and vice versa. It has been approved that the optimal velocity and the appropriate range changes with local geographical and hydrological environment of water body, as well as different kinds of advantage algae, but their interrelationship are still under study because of its complicacy.

At present, the only expression of the velocity factor, that is, $F_5(u)$ in Eq. (11) is

$$F_5(u) = \beta^{\gamma u} \quad (17)$$

where β and γ are undetermined parameters. Eq. (17) was proposed for studying algal growth in Daning River, the secondary river of Three Gorges Reservoir.

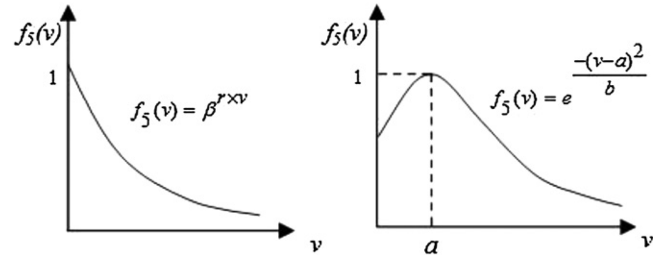

Fig. 1. Comparison of the two different velocity factors.

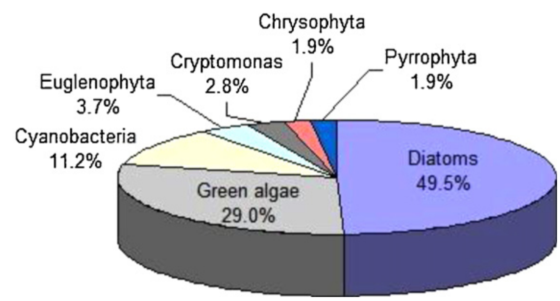

Fig. 2. Average phytoplankton composition in Chongqing of Jialing River.

According to the above analysis on the optimal velocity and the velocity range, the velocity factor was improved as follows

$$F_5(u) = e^{-\frac{(u-a)^2}{b}} \quad (18)$$

where a and b are undetermined parameters. Fig. 1 indicates the graph comparison of the two different velocity factors.

The two main improvements were found by comparing Eq. (18) with Eq. (17). The first, the optimal velocity (corresponding to the maximum value of the velocity factor $F_5(u)$) was corrected from $u = 0$ in Eq. (17) to $u = a$ in Eq. (18) because the former is not in accordance with the result of existing research. The second, the two parameters in Eq. (18) are of clear physical meaning, representing respectively the optimal velocity and the velocity range for alga growth. It is obvious that the larger the parameter b is, the more slowly the change rate of the curve describing the velocity factor is, and the wider the region of the velocity factor close to the optimal velocity is, that is to say, the flow velocity range appropriate to algae growth is greater and vice versa. The value of parameter in Eq. (18) can be calibrated and optimized by the measured data.

2.4. Phytoplankton composition

Diatoms, green algae and *cyanobacteria* constitute the major groups of planktonic algae in Chongqing city Section of the Jialing River each time. Dominant algae group is defined as the dominating algae species of number within the specific time and the river basin (Deng et al., 2010). Phytoplankton populations in exit section water of Jialing River are rich, diatoms from species and density are predominant all the time, from about 85% in winter to 65% in summer, then the type of green algae from about 20%t in summer to 5% in winter and the type of *cyanobacteria* from about 10% in summer to 5% in winter; Fig. 2 reflects average phytoplankton composition in the backwater region of Jialing River.

SJC_206

Table 1
Average monitoring results of indexes in the backwater region of Jialing River in Ci Qi-kou.

Date	t (d)	V (m s^{-1})	T (°C)	D_{TP} (mg L^{-1})	D_{TN} (mg L^{-1})	Total phytoplankton average density (μg L^{-1})
01/26/2007	1	0.1077	10.1667	0.2120	1.0874	1.024
02/06/2007	12	0.0910	10.8667	0.2673	3.1376	1.173
02/28/2007	34	0.0648	14.0333	0.2741	4.1926	0.228
03/14/2007	48	0.0787	13.1333	0.2023	2.4923	0.353
03/31/2007	65	0.0655	17.7000	0.2146	2.7139	0.186
04/13/2007	78	0.0792	17.1667	0.1094	2.7367	0.219
04/28/2007	93	0.1458	19.2333	0.2495	2.5820	0.097
05/15/2007	110	0.1057	22.8667	0.0947	3.5245	0.093
05/26/2007	121	0.1295	24.1500	0.1344	3.5473	0.117
06/15/2007	141	0.1667	25.7833	0.1010	2.5996	0.086
06/30/2007	156	0.2298	25.5667	0.2723	3.1957	0.136
07/13/2007	169	0.1952	24.7833	0.7117	2.5328	0.120
07/29/2007	185	0.1258	26.3833	0.2386	2.3851	0.044
08/15/2007	202	0.1596	27.8500	0.1882	1.7609	0.076
08/29/2007	216	0.0632	31.1167	0.0503	2.7016	0.140
09/15/2007	233	0.1134	23.5333	0.1692	2.3833	0.028
09/30/2007	248	0.2350	25.1667	0.2649	1.5885	0.162
10/15/2007	263	0.2312	19.5333	0.6733	4.8502	0.120
10/30/2007	278	0.2003	17.9667	0.0799	2.2673	0.165
11/15/2007	294	0.1167	18.4500	0.0952	2.3481	0.198
11/30/2007	309	0.0782	16.2333	0.0688	2.2286	0.243
12/15/2007	324	0.1027	14.8667	0.0808	1.3318	0.156
12/30/2007	339	0.1228	11.6333	0.0693	2.1354	0.087
01/11/2008	351	0.0908	9.5333	0.0578	3.4981	0.054
01/21/2008	361	0.1440	9.2167	0.0665	1.8470	0.049

Overall, Phytoplankton cell density in export section of Jialing River is still at low level. The variational trends of each point are basic consistent, algae cell density in Jialing River Section is highest in summer and lowest in winter (Guo et al., 2009). From the annually overall statistical outcome, phytoplankton population structure in export section of Jialing River water has obvious seasonal variation. Seasonal succession model of Jialing River water body is diatom – *cyanobacteria* – green algae – *cryptophyta* (fall) → diatom – green algae – *cyanobacteria* – *cryptophyta* (winter) → diatom – green algae – *cyanobacteria* (spring) → diatom – *cyanobacteria* – green algae (summer).

2.5. Spot location and sampling method

Selected principles of samples: fully take into account before and after export section of Jialing River (the confluence of the Yangtze River and Jialing River) the hydrodynamic conditions, channel shape, water fetching and field testing factors to facilitate spot location; Specific layout of samples: set 5 points in the Jialing River Section, the left and right bank of Ci Qi-kou, the right bank of Hua Long-qiao, the left and right bank of Chao Tian-men (Fig. 3). Sampling methods: water sampling was located at 30 cm below the surface water with the sample collecting bottle, each sampling three bottles of each point, collection of each point was 2 L water. After water samples back to the lab, three bottles of water samples in each point would be mixed evenly, and water samples were treated and tested by conventional methods.

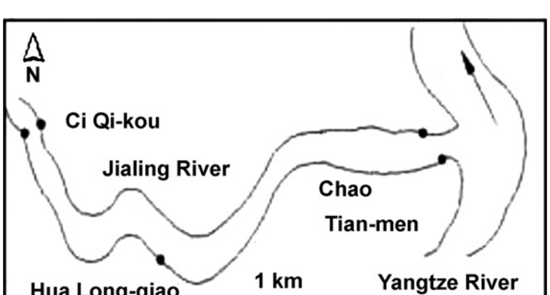

Fig. 3. General sketch map of research area.

2.6. Simulation domain

Simulation domain is Chongqing Reach of the Jialing River form Ci Qi-kou of Shapingba District to Chao Tian-men of Yuzhong District, which flows about 14 km from northwest to southeast, and then eastward to Yangtze River in the Chao Tian-men (Fig. 3). The data of river bed topography and 50 m × 50 m computing grid was used for numerical simulation.

2.7. Initial and boundary conditions

Initial conditions are to set the initial time value (initial value) of the state variable (water level, chlorophyll-a, total phosphorus, total nitrogen). And generally taking the boundary average value of the initial moment, or the average value for many years as the initial conditions. In this study, the initial values of chlorophyll-a, total phosphorus and total nitrogen in the simulating process were determined by the average import and export boundary value.

The initial conditions of hydrodynamic Eqs. (1) and (2) are that velocities equal to zero and water level is given a constant in whole domain. Boundary conditions in Eqs. (1) and (2) are the given discharges at upstream inlet and the given water level at downstream outlet. The initial conditions of Eq. (3) are the given concentrations in whole domain, and boundary conditions are the given concentrations separately at the inlet and the outlet. The discharges, water level or concentrations, at any moment of simulation in the boundary are obtained by interpolation using the daily measured values from hydrological services and our study group. Fig. 4 and Table 1 are respectively expressed as observed value of DTP, DTN and Chl-a in Hua Long-qiao and monitoring results of indexes in the backwater region of Jialing River in Ci Qi-kou.

The discharges of industrial wastewater and domestic sewage from the shore are considered as point source. The location of the point source, point source runoff, TP and TN concentrations were obtained from the data of local environmental protection depart-

Table 2
Model parameter values.

Item	K_N (mg L^{-1})	K_P (mg L^{-1})	α (kJ (m^2 d)$^{-1}$)	θ	T_{opt} (°C)	a (m s^{-1})	b (m s^{-1})	μ_{max} (d^{-1})	R_{max} (d^{-1})	K_m (μg L^{-1})	K_d (d^{-1})	K_{TP} (d^{-1})	K_{TN} (d^{-1})
Value	0.22	0.0205	12318.57	1.05	25	0.04	0.15	1.27	0.185	18	0.05	0.01	0.015
Δ	0.024	0.013	0.037	–	0.077	0.063	0.146	0.09	0.001	–	0.134	0.026	0.028
Range	0.14–4.0	0.015–0.35	1000–12500	–	20–30	0.01–0.1	0.10–0.3	0.8–3.0	0.05–0.5	–	0.05–0.2	0.01–0.04	0.012–0.05

Note: Δ is the impact level for parameter change on the net growth rate of algae, it is obtained from sensitivity analysis of parameters in the model.

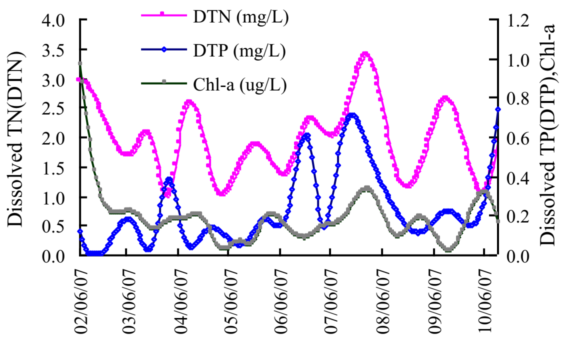

Fig. 4. Observed value of DTP, DTN and Chl-a in Hua Long-qiao.

ment (Huang et al., 2006). The TP, TN and Chl-a concentrations flowing into from the shore during raining is negligible. Besides, in numerical simulation, the domain is divided into many small units by 50 m × 50 m. Because water level changes as time, the domain, or the quantity of units will change. The wet water depth and dry water depth is set so as to distinguish automatically the quantity of units need to calculation by computer (Verteeg et al., 1995). This study sets 0.1 m as dry water depth, and 0.3 m as wet water depth. Because they also need to set moving boundary conditions in addition to fixed boundary conditions, that is, the change of calculation cell volume caused by the fluctuation of water level. In order to simulate unsteady rivers, lakes and oceans, it needs to set the water depth of wet and dry, so it makes the MIKE software determine whether to calculate the cell. Specifically, the water level rising makes some of the original shore become water, that is to say, the cells change from the "dry" to "wet", they are required to be included when calculation, and the number of calculation cells increases; while the water level dropping makes some local dot become dry, that is, the cells change from the "wet" to "dry", without consideration of these cells when calculation, and the number of calculation cells reduces. When the water depth of a cell is less than dry water depth (0.1 m), the cell does not participate in calculating, it is to believe that this cell is for the land; when the water depth is greater than dry water depth (0.1 m) and smaller than the wet depth (0.3 m), the cell needs to be participated in calculating, but only participate in physical conservation terms, and does not participate in the momentum calculation; when the water depth of cells is greater than wet-depth (0.3 m), the cells need to participate in substance conservation and momentum calculation.

Finite Volume Method (FVM) was selected for numerical simulation of the governing Eqs. (1)–(3). Alternating Direction Implicit (ADI) method was used to solve the dispersed equation from Eqs. (1)–(3). Water depth less than 0.1 m was set river bed in numerical calculation. Courant number is less than 20 so as to divergence.

2.8. Model parameters calibration and model validation

Based on existing research results of rivers and lakes eutrophication (Zhong, 2004; Wang et al., 2009; Li et al., 2004; Liu and Chen, 2000), the ranges of relevant parameters in the control equation were determined. The simplex method was applied for the parameter calibration in the governing equations. The measure data from February 6, 2007 to May 26, 2007 were used in calibration. The changing ranges of parameters were determined on the basis of existing research results before calibration. The sensitive parameters determined by the perturbation method were paid particular attention in the course of calibration. Some of main parameters are given in Table 2, and the velocity factor is $f_5(u) = e^{-\frac{(u-0.04)^2}{0.15}}$. The optimal velocity is 0.04 m s^{-1}, basically consistent with the result of 0.03 m s^{-1} from laboratory experiments on water drawn from the Jialing River in the spring by Liu and Zhang (2008).

The spatio-temporal distribution of TP, TN and Chl-a concentration from June 10, 2007 to October 14, 2007 in the study river reach were simulated and compared with measured values. The compared results show that the simulated values are in good agreement with the measured values. The mean relative error of the simulated and measured TP concentration is 8%, TN concentration is 8%, and the Chl-a concentration is 10%. In addition to these validation experiments, satisfactory model performance was confirmed for 2 m away from the left bank of Hualongqiao section which is located in the middle of the reach (Fig. 5).

If the velocity factor $F_5(u)$ in Eq. (17) was replaced by the unimproved one in Eq. (18), the velocity factor $F_5(u) = 0.65^{9.4u}$ and other parameters of having nearly the same values in the model were acquired. The mean relative error of the simulated and measured Chl-a concentration is 14% for using the unimproved velocity factor (the error is 10% for using the improved velocity factor). The simulated values of TP and TN concentrations are basically the same for two kinds of different velocity factor. Fig. 6 shows the comparison of simulated and measured values of Chl-a concentration from two different influence function of velocity in 2 m away from the left bank of Hua Long-qiao section (the "simulated values 1" in Fig. 6 corresponds to the improved influence function , that is, Eq.

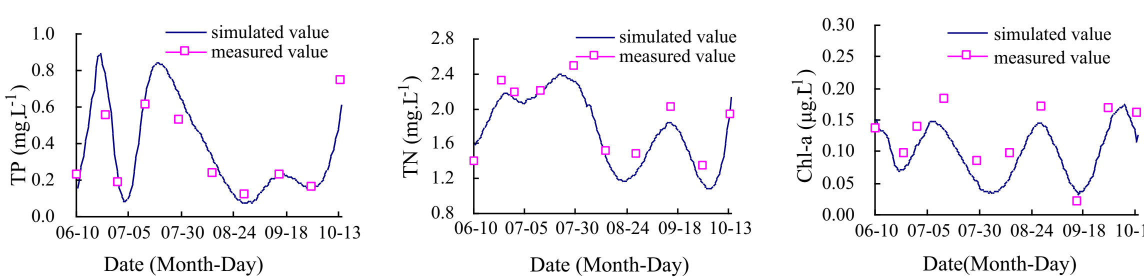

Fig. 5. Comparison between simulated and observed values.

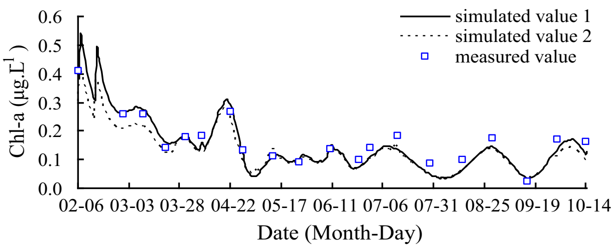

Fig. 6. Comparison of simulated results using different velocity factor function.

(18), and the "simulated values 2"to Eq. (17)). It can be seen in Fig. 6 that the simulation validity of Chl-a concentration by the improved influence function of velocity is better, especially for low flow velocity in the Three Gorges Reservoir before May. So the Gaussian form fits to the data better. In a word, it is shown that the established ecological dynamic model for algae growth in this paper is reasonable, the given velocity influence function can simulate better the flow velocity impact on the algae growth.

3. Results and discussion

Water pollution in Chongqing Reach of Jialing River in recent years is serious .The comprehensive nutritional index is at light or medium eutrophication (Bai et al., 2008). There are enough nutritious matters to meet the need of algae growth in the reach. Therefore, climatic conditions and hydrodynamic conditions become key impact factors on algae growth. According to monitoring data after impoundment of Three Gorges Reservoir, the weather and hydrodynamic conditions of March and April usually were the most appropriate for algae growth. Therefore, in order to study the impact of hydrodynamic conditions on algae, the climatic conditions from April 1, 2008 to April 15, 2008 were considered as better, and chosen for further simulation.

In order to predict the growth and occupation of algae in the research area for the three scenarios of water level variation, we conducted a numerical simulation with the estimated parameters and three scenarios of the water level variation. The reasons for selecting the three scenarios of the water level variation are as follows.

Based on the available hydrological data in 2008, taking Ci Qikou water level as selection criteria, the duration of lowest water level for 15 days was selected as a dry season, water level of dry season was taken as the base, starting from the low water level (−21.3 m), the lower boundary was gradually changed to high level. In this study, the simulation period was selected from March 31 to April 15. Variable water level simulation condition was used to study the impacts from storage stage of the Three Gorges Reservoir on the algae growth, during the storage period, sub-river was held by reservoir backwater, the water level difference between the two sections reduced and the flow rate became smaller. Three cases

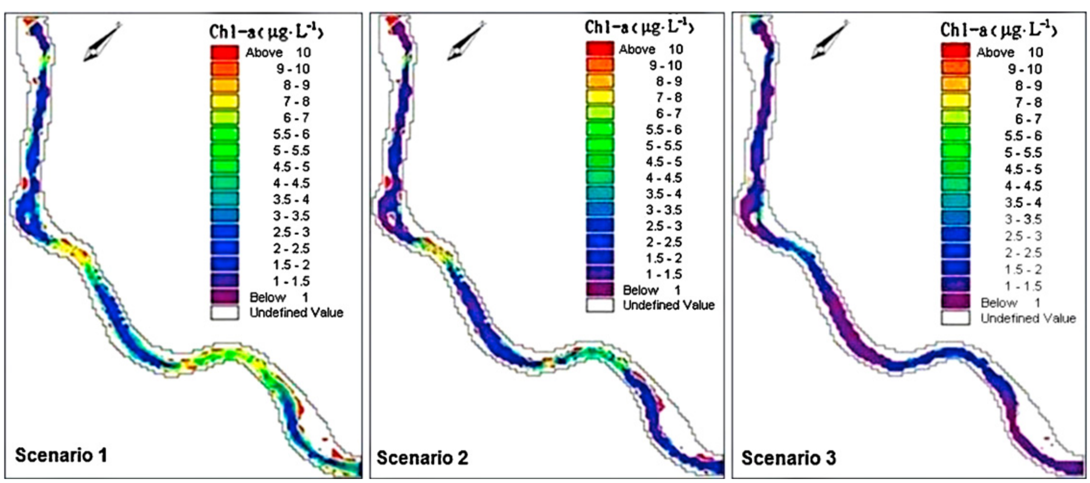

Fig. 7. Distribution of Chl-a concentration for various water levels.

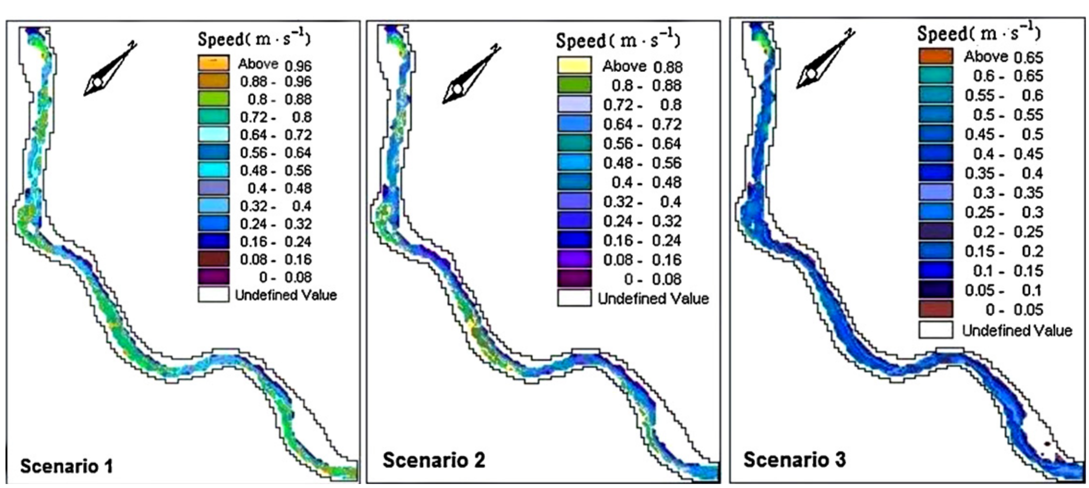

Fig. 8. Spatial distribution of velocity for various water levels.

Table 3
Chl-a statistics and area percent of algae bloom for each scenario.

Stat. index	Scenario 1	Scenario 2	Scenario 3
Chl-a ($\mu g\,L^{-1}$)	1.785	2.966	4.708
Ai (m^2)	19,200	2,75,200	5,56,800
A (m^2)	4,416,000	4,492,800	4,940,800
Area ratio (%)	0.43	6.13	11.27

Note: Chl-a is average value of chlorophyll *a*; Ai is for a possible water surface area of algae bloom; *A* is the total surface area of study region under the each scenario; area ratio is the percentage for possible water surface area of algae bloom accounted for the total area of water surface under the corresponding scenario.

was selected in this study, because after the dam sluiced to the 175 m, the water level difference between Chao Tian-men and Ci Qi-kou will reduce a great many, but what the specific degree will be reduced was not reported.

Therefore, according to the hydrodynamic conditions in March and April of 2008 and over the years, and combining with water quality in recent years in the study river section, three kinds of scenarios of water level were also identified for the simulation, that is: (1) Respectively take the average water level at the upstream inlet and downstream outlet of March and April in 2008 as the corresponding boundary value, namely $H_{up} = -21.3$ m for the inlet and $H_{down} = -24.9$ m for the outlet; (2) $H_{up} = -21.3$ m and $H_{down} = -23.9$ m; (3) $H_{up} = -21.3$ m and $H_{down} = -21.9$ m. Water level elevation takes sea level of 186 m as base level. The concentration boundary condition of upstream inlet and initial conditions for the three matters under the three kinds of water level scenarios are: $C_{TP} = 0.1\,mg\,L^{-1}$, $C_{TN} = 2\,mg\,L^{-1}$ and $C_{Chl\text{-}a} = 1\,\mu g\,L^{-1}$. The measured data by the shore from April 1, 2008 to April 15, 2008 were used for point source.

Fig. 7 shows that the Chl-a concentration in the reach for the three scenarios respectively, at the most prosperous moment of algae growth in the simulation period. Fig. 8 shows the velocity fields corresponding Fig. 7. It was obvious that, on the whole, the flow velocity in the reach is too high to be good for algae growth even under the conditions of impoundment of Three Gorges Reservoir, and the higher Chl-a concentration appears only in range of low velocity near the shore. The region suitable for algae growth increases as the raise of downstream water level. If the Chl-a concentration of $10\,\mu g\,L^{-1}$ was taken as the critical value for algae bloom, the percentages of the area of occurred algae bloom accounted for the total area are shown in Table 3 for three scenarios. We can deduce the conclusion from the simulating results that the occurrence of algae bloom in large scale is almost impossible because of relatively high flow velocity in the reach, but possible in some places near the shore with very low flow velocity.

4. Conclusions

This work has focused on the development of mathematical model to study impacts of hydrodynamic conditions on algae growth in Chongqing Reach of Jialing River. In the model, through introducing two parameters which express the optimal velocity and the velocity range for alga growth, a new velocity factor was put forward for the formula of algae growth rate. The spatial and temporal distribution of Chl-a concentration has been obtained by numerical simulation. It has been shown that the model established here can be successfully used to simulate algae growth in river.

Hydrodynamic conditions have significant impacts on the growth of algae, and the flow velocity of about $0.04\,m\,s^{-1}$ is optimal. The occurrence of algae bloom in large scale is almost impossible because of relatively high flow velocity in the reach, but possible in some places near the shore with very low flow velocity.

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