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DESCRIBING THE DAILY VERTICAL MIGRATION OF A BLOOMING FRESHWATER DINOFLAGELLATE AND SIMULATING THE BLOOM BY COUPLING MIGRATION EQUATION INTO ECOLOGICAL MODEL

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ABSTRACT

Freshwater dinoflagellate *Peridiniopsis penardii* has been reported blooming in a reservoir in western China annually. Being able to migrate autonomously is one of its major characteristic and is believed to have impact on its blooming development. A 24-hour field observation was conducted during the bloom in 2015 to quantitative analysis this feature, and the collected vertical profile of chlorophyll showed an evident migration rhythm. The blooming algae preferred to gather close to water surface during daytime and then dispersed through water column as night came. An empirical equation was then proposed to describe the daily migration rhythm by fitting the field data to sinusoidal function, and the maximum migration speed of this algae was determined to be 0.35m/h based on derivation of this equation. Finally, the proposed migration equation was coupled into the ecological model in CE-QUAL-W2 to simulate dinoflagellate blooming. Field data collected during a whole blooming process was used to validate the modified model, and a maximum 9.4 % decreasing of modeling error was noticed by comparing the results of modified model to original one. This improvement also suggested that the consideration of algal migration feature in model could be helpful in algal bloom simulation if dominant species have migration ability. The presented migration equation and modified model in this research could be used as a reference to simulate similar algal bloom and offer scenario information for reservoir/lake management. Further research should focus on improving the migration equation by reveal physiological mechanism underlying the phenomenon.

Keywords: freshwater dinoflagellate; algal bloom; vertical migration; ecological model

1 INTRODUCTION

Dinoflagellate is among the most common blooming algae in freshwater system, and they were often reported as the dominate species in stratified water body, since the flagella structure enable them to migrate vertically to the most suitable position for photosynthesis process or nutrient uptake (Regel et al., 2004). A diurnal migration rhythm of this algae was usually described as swimming upwards to the surface area where light is sufficient during day time and sinking to deeper layer during night where nutrients concentrated. Such an adaptive growth strategy could be beneficial for community expansion in nutrient limited systems, dinoflagellate bloom thus was more likely to be found in deep mesotrophic lakes or reservoirs (McCarthy et al., 2011).

Numerical simulation was widely used for algal blooming inversion and prediction in lakes and reservoirs for the purpose of water quality management. There were numerous ecological models have been developed targeting cyanobacteria, green algae and diatoms due to their harmful effects on freshwater system which have drawn lots of public attention (Booty and Lam, 2018). These models are capable of describing the circulation and transformation of nutrients and other materials in water body, and algae growth kinetics are usually taken into account by considering the limitation on algae growth from nutrients, light and temperature (Ji, 2017). However, there were barely no models specifically developed for freshwater dinoflagellate since it is not always related to eutrophic water body or water quality problem. Besides, the description of algae vertical migration was lacked in most of current models where only algae settling was considered to influence mass balance in water column. Consequently, most of current ecological models lack the description about the migration characteristic of dinoflagellate which could enlarge simulation error.

This study aimed to propose an equational description of dinoflagellate vertical migration which could be coupled to algae kinetic equation in ecological model. Field observation at a reservoir was conducted to provide vertical profiles during dinoflagellate blooming, and filed data was also used to test the behavior of modified model. We hope to offer an alternative option of ecological model which are more suitable for dinoflagellate simulation.

2 FIELD WORK

2.1 Study site

Zipingpu reservoir is on Min River in southwestern China, and it was constructed for multiple purposes, including water supply, power generation and flood control. As shown in Fig. 1, it is a typical canyon type reservoir with length being approximately 24 km while the widest transection is no more than 2 km. Since 2013, dinoflagellate (*Peridiniopsis penardii*) bloom has been observed in this reservoir during every early summer with different scale.

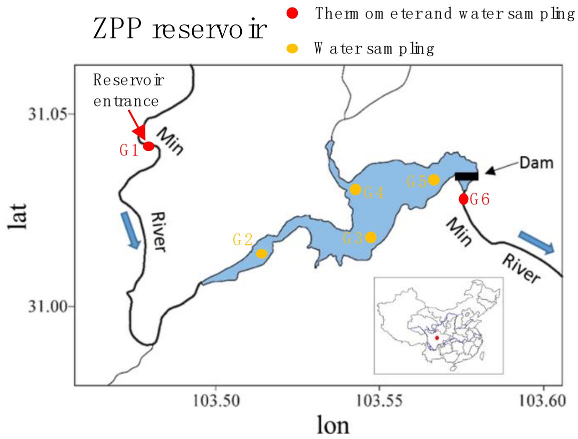

Figure 1. Map of Zipingpu reservoir and observation sites of this research

2.2 Field observation and data collection

A 24-hour observation on dinoflagellate vertical migration was conducted at G4 during the bloom in 2016. Vertical profiles of water temperature and chlorophyll were collected every hour to respectively track the mixing process and dinoflagellate's vertical distribution through water column in a day.

Meanwhile, a continuous field observation and data collection was conducted during April, 2015 to September, 2016. Hourly water temperature data was recorded at reservoir entrance and downstream of the dam using thermometer with data logger, and monthly vertical profile of both water temperature and chlorophyll were collected using a multiparameter water quality sonde (EXO2, YSI Inc.) at sampling sites, where water samples were collected as well for water quality analysis, including dissolved oxygen, total nitrogen, ammonia, total phosphorus and BOD_5 etc.

2.3 Dinoflagellate vertical distribution calculation

In order to quantitatively analysis its diurnal migration features, average chlorophyll depth were used to indicate variation of the position where dinoflagellate community gathered (Yang, 2010).

$$\bar{D} = \sum_{i=1}^{n}(C_i \times d_i) \Big/ \sum_{i=1}^{n} C_i \qquad [1]$$

Where: N is the number of layers in water column, and in this study, 0.5 m vertical resolution was adopted to divide the water column into 30 layers (only the top 15 m of water column was considered in this study since data measured in deeper place showed that there was barely no chlorophyll). Ci is the concentration of chlorophyll in layer i [mg/m^3]; di is the water depth of layer i [m], and the water depth at the center of each layer was used here.

3 NUMERICAL MODEL

3.1 Hydrodynamic model

A lateral averaged two dimensional hydrodynamic model CE-QUAL-W2 (Cole and Wells, 2015) was used in this model to simulate the hydrodynamic process in reservoir. The model solve two dimensional navier-stoke equations by using incompressible assumption and boussinesq approximation, and k-ε model was used for model closure.

3.2 Ecological model

The ecological model coupled in CE-QUAL-W2 could simulate the kinetic process in aquatic system by calculating matter circulation among different variables, including inorganic nutrients (N, P), organic matters, oxygen and algae, etc (Cole and Wells, 2015). The algal kinetic equation in this model is given below:

$$S_a = k_{ag}\Phi_a - k_{ar}\Phi_a - k_{ae}\Phi_a - k_{am}\Phi_a - \omega_a \frac{\partial \Phi_a}{\partial z} - G_a \quad [2]$$

Where s_a is the change rate of algae biomass, corresponding to the source term in the transport equation; k_{ag} is the growth rate of algae, [s^{-1}]; Φ_a is simulated by the algae biomass, g/m3; k_{ar} is the respiration rate of algae, [s^{-1}]; K_{ae} is the excretion rate of algae, [s^{-1}]; k_{am} is the mortality rate of algae, [s^{-1}]; ω_a is the settling rate of algae, [m/s]; G_a is the rate at which algae lost biomass due to predation, [g/s].

In most cases, the settling rate would be set to a fixed value to consider algae settling due to gravity. While in this research, the proposed migration velocity equation would replace the fixed value, thus vertical biomass budget would be affected by dinoflagellate's diurnal migration.

3.3 Modeling assessment

Mean absolute error (MAE) and root mean square error (RMSE) were used to assess model performance. The two indexes could be calculated as follow:.

$$MAE = \frac{\sum_{i=1}^{n} \left| X_{obs,i} - X_{model,i} \right|}{n} \quad [3]$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(X_{obs,i} - X_{model,i} \right)^2}{n}} \quad [4]$$

Where: n is the number of measured values; $X_{obs,i}$ is the i-th measured value of variable X; $X_{model,i}$ is the simulated value of variable X corresponding to the measured value $X_{obs,i}$.

4 RESULTS AND DISCUSSION

4.1 Dinoflagellate diurnal migration

Fig. 2 shows the results of vertical chlorophyll variation observed for 24 hours from 13:00 on June 28, 2016 during the bloom period. Sunset was at 20:13 on June 28, and sunrise was at 6:05 on June 29. As can be seen from the figure, before sunset, the algae were obviously distributed within about 5 meters below the water surface, behaving an obvious stratification feature. .The maximum value at water surface was 16.57 mg/m^3 which appeared at 17:00. From around 19:00 when it was before sunset, the bottom boundary of chlorophyll distribution began to extend downward, and the stratification phenomenon within the surface layer also began to weaken simultaneously. At midnight, chlorophyll on the water surface decreased to 6.76 mg/m^3, and chlorophyll concentration was still greater than 1 mg/m^3 at the depth of nearly 15m. At 5:00 of the next day, chlorophyll in the water surface dropped to 6.1 mg/m3, and the contour line of 1 mg/m^3 went down to about 18 m depth. After that, it can be observed that the chlorophyll distribution gradually concentrated upwards, and the chlorophyll concentration reformed a stratification structure within the top layer, as well as chlorophyll concentration on the surface increased. At 11:00, the surface chlorophyll concentration reached 19.04 mg/m^3, while the contour line of 1 mg/m^3 rose back to the depth of about 10m.

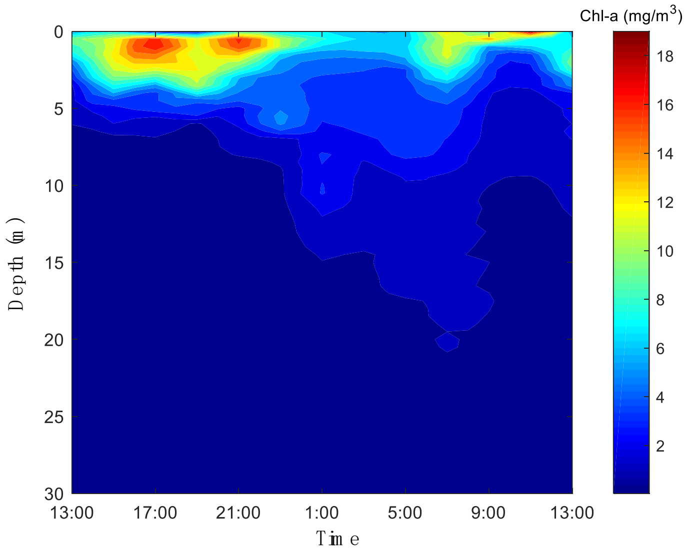

Figure 2. Vertical profiles of chlorophyll for 24 hours collected during dinoflagellate bloom

Figure 3 shows how the calculated average depth varied during the 24-hour observation. The chlorophyll average depth was 3.28 m at the beginning, and there was still a slow trend of upward migration. Average depth rose to 2.34 m at 17:00, after when it started to move down, lowering to the depth of 2.66m around sunset. Average depth dived sharply to 5.51 m by 1:00 and stayed below 5m before 5:00 in the morning. After sunrise, then it moved upwards gradually.

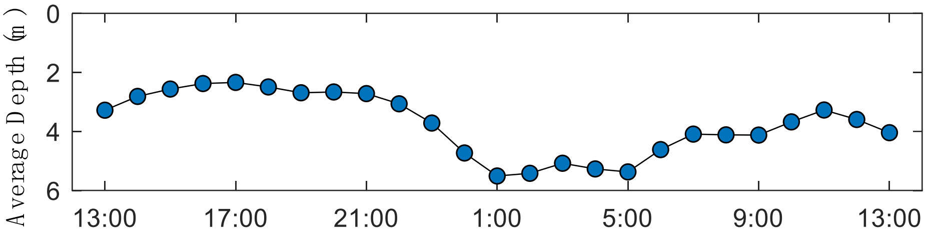

Figure 3. Calculated averaged chlorophyll depth through water column

It could be found that the variation characteristics of the average depth during a day basically match the variation feature of sinusoidal function. Therefore, the vertical migration depth equation of dinoflagellates was constructed as shown below:

$$h(t) = a\sin(\frac{2\pi}{24}(t+b)) + c \quad [5]$$

Where, h is water depth [m]; t is the hour; a, b and c are fitting coefficients. By fitting the data shown in figure 3 to the equation, the fitting coefficients was determined as shown in Table 1, and fitting results was shown in figure 4.

Table 1. The fitting results of vertical migration depth equation

	a	b	c	R^2	RMSE
Value	1.335	1.547	3.779	0.8222	0.46

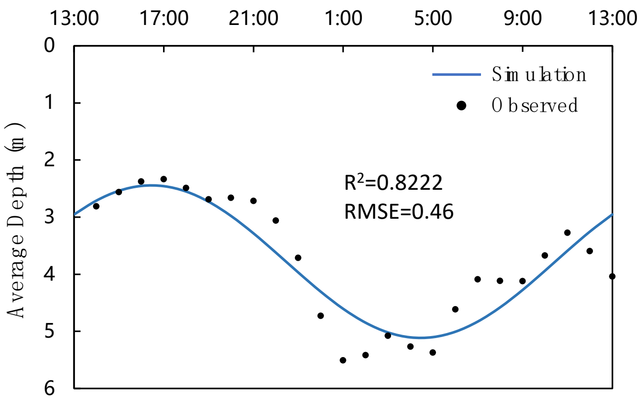

Figure 4. The fitting curve of vertical migration depth equation

The vertical migration velocity equation of dinoflagellate could thus be proposed by taking the derivative of equation (5) with respect to time, meaning the derivative of average depth with respect to time, as shown in equation (6). And from the equation, it could be easily found that the maximum migration velocity would be 0.35m/h.

$$\frac{\mathrm{d}h}{\mathrm{d}t} = v(t) = 0.35\cos(\frac{2\pi}{24}(t+1.547)) \quad [6]$$

4.2 Ecological modeling for Dinoflagellate

In algal kinetic equation, the settling term was modified to migration term by replacing fixed value of settling velocity to the proposed migration velocity equation, as shown in equation (7)

$$S_{a\_migration} = -0.35\cos(\frac{2\pi}{24}(t+1.547))\frac{\partial\Phi_a}{\partial z} \quad [7]$$

After coupling this modified migration term into algal kinetic equation in ecological model, we tested the simulation behavior of both models with/without modification. The simulation period was from May 2015 to August 2016, when our field word was being conducting. The data collected was used as input for the model, and all parameters has been calibrated before the model was modified.

As shown in Figure 5, water level and water temperature simulation results were used for validation of hydrodynamic modeling. Results showed that simulation value agreed well with observed data, confirming that the model performance is reasonable.

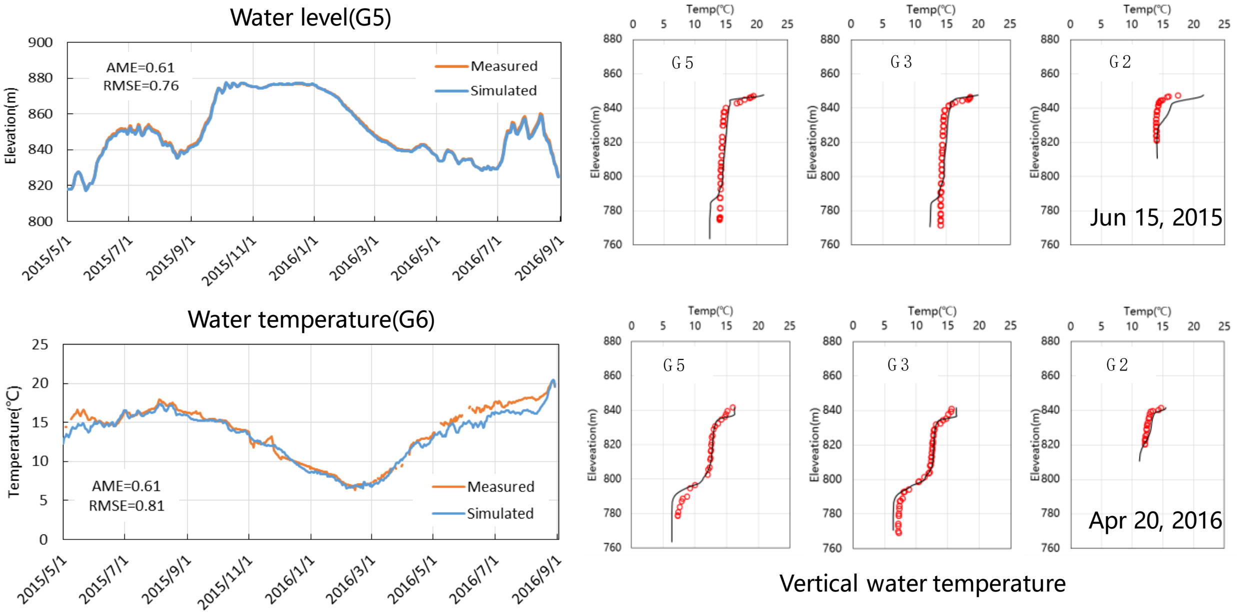

Figure 5. Validation of water level and water temperature simulation results

Figure 6 shows the comparison of chlorophyll simulation results from original model and modified model. Meanwhile, the chlorophyll data collected from two sampling sites, G4 and G5, were used to be compared to simulation results. Result from both models matched the general variation feature of observed data. While MAE and RMSE results (Table 2) showed that there was indeed an improvement in simulation accuracy after the vertical migration was considered in the model. MAE decreased more than 5% at both sites, and at G4, RMSE decreased almost 10%. It could be also noticed that the influence of considering algal migration on simulation accuracy was more significant during the time when algal bloom is disappearing. This might suggest that the effect of algae vertical migration features on the process of bloom fade is remarkable.

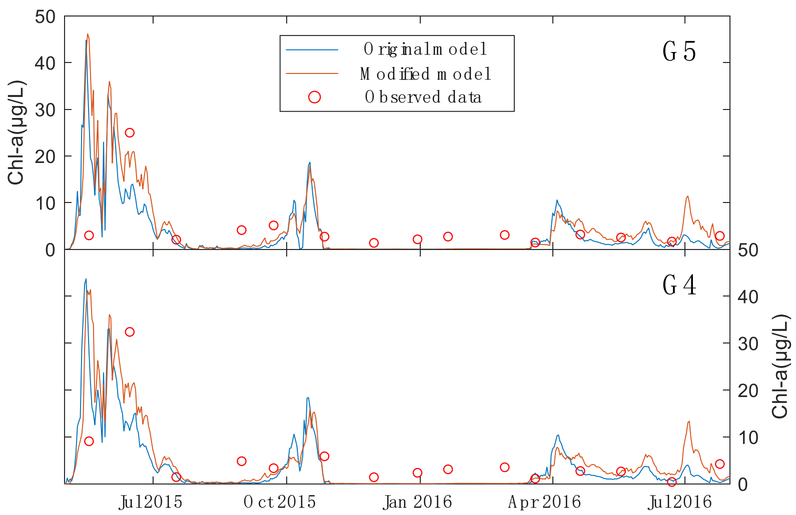

Figure 6. Comparison of chlorophyll simulation results from both original and modified model

Table 2. Simulation performance assessment

		Original model	Modified model	Improvement
G4	MAE	4.68	4.42	5.5%
	RMSE	8.06	7.30	9.4%
G5	MAE	4.31	3.95	8.2%
	RMSE	7.59	7.58	0.2%

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