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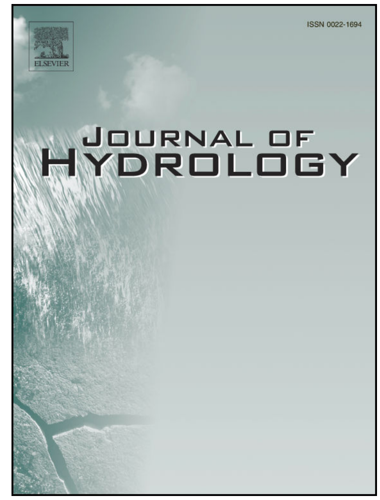

Research papers

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Effect of thermal stratified flow on algal blooms in a tributary bay of the Three Gorges Reservoir

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Abstract

After the impoundment of Three Gorges Reservoir (TGR), its tributaries have been frequented by algal blooms, especially the Xiangxi River (XXR). Stratified flow induced by temperature difference often occurs, which likely influences the water exchange and algae transport process between the tributary and TGR. To investigate the variation of flow field and algae concentration in XXR, a 2-dimensional hydrodynamic and water quality model is developed. The simulation results show good agreement with field observed data, reproducing the water exchange and algal bloom process. Notwithstanding the hydrodynamic environment of XXR is complicated, the thermal stratified flows are generalized into six typical patterns in this paper. Subsequently, algae transport processes under the influence of different thermal stratified flow patterns are examined. Thermal stratified flows from upstream and TGR intrude into the bay tributary through different layers with different combinations, resulting in water exchange of XXR is the major cause of algae transport difference. We show that when the mainstream intrusive flow and upstream inflow separately intrude into the XXR through the surface and bottom layer, hydrodynamic environments are favorable to algae transport, with the final chlorophyll-*a* (Chl-a) concentrations of entire XXR lower than algal bloom threshold value. The worst scenarios occur when the mainstream flow intrudes through middle or bottom layer while the upstream inflow enter through bottom layer, with the final algal bloom coverage rate (R_{alg}) of 82.3% and 78.1%, respectively. In terms of superimposed effect of different flow patterns, when the sequentially thermal stratified flows have different effect on algae transport direction, algae will concentrate in the reach rather than discharged which increase the risk of multiple algal blooms. These findings represent an important step towards understanding the multiple outbreaks of algal bloom in XXR during the spring and provide a new perspective for the research of algal bloom governance.

Keywords: Thermal stratified flow; Algae transport; Numerical simulation; Three Gorges Reservoir; Algal bloom

1. Introduction

Algal bloom, is of environment concern because it threatens the health of public and sustainability of ecosystems, has an increasing frequency and severity. The accumulation of water-borne microorganisms during algal bloom period can produce a number of toxicity secondary metabolites (Falconer, 1999), causing sickness in farm livestock and humans (Carmichael and Boyer, 2016; Smith and Daniels, 2018). Taking dominant cyanobacterial species as example, they could release a type of hepatotoxin named microcystin. Long-term consuming water containing microcystin higher than 0.1 μg/L (WHO, 2011) could induce a series of diseases including liver cancer (Lone et al., 2015). In a survey of China's freshwater lakes and reservoirs, 16.3% of the polluted water is attributed to eutrophication (Huang et al., 2019). And another recent nationwide assessment reveals that 28% of the total 107 surveyed reservoirs and lakes are experiencing eutrophication problems (Ministry of Ecology and Environment, P.R.C, 2020). Therefore, researches have been extensively carried out on eutrophication governance.

Algal bloom events are typically caused by the variation of a multitude of ambient conditions, such as nutrient concentration, water temperature, wind speed, illumination and water column stability (Jones et al., 1997; Paerl et al., 2016; Paerl et al., 2019; Wood et al., 2017; Wurtsbaugh et al., 2019). Among these, hydrodynamic environment is commonly considered as one of the main influencing factors (Butcher, 1932; Liu et al., 2012). Firstly, the hydrodynamic conditions are important factors for planktonic algae growth, and there is an optimal flow velocity, larger or smaller than it the growth of algae will be inhibited (Long et al., 2011; Whitford and Schumacher, 1961). Secondly, the water turbulent affects the quantity and species structure of plankton community by changing the nutrient concentration of water (Cózar and Echevarría, 2005). Furthermore, the variation of flow velocity, shear force, resistance and turbulence intensity caused by hydrodynamic environment change can also limit algae enrichment (Qi et al., 2016; Zhang et al., 2016).

As the highest profile hydraulic project, the Three Gorges Project has got a remarkable success in electricity generation, flood control and shipping capacity improvement, but it is always assailed by algal bloom problems (Yang et al., 2013). After the 175 m impoundment, 25.1% of the nutrition status of the main tributaries in the Three Gorges reservoir is in eutropher (China Three Gorges Corporation, 2019). From 2008 to 2018, according to the monitoring of main tributaries in the reservoir area, the algal bloom has an annual occurrence in XXR, and in some reaches the algal bloom events happen many times in a year. As a typical eutrophic tributary of TGR, the frequently algal bloom events in the XXR draw a great deal of attention. Previous studies have preliminarily confirmed that the changes of nutrient concentrations, illumination intensity and water temperature in the Yangtze River and its tributaries before and after the impoundment are negligible, whereas the significant variation of hydrodynamic condition is probably the main cause of algal blooms (Liu et al., 2016). Liu et al. studied the environment factors in the XXR using field data and reported that the development of thermal stratification caused by the temperature difference between the water in mainstream of the TGR and tributary is the direct and primary contributor to the onset of spring algal bloom (Liu et al., 2012). Mao et al. (Mao et al., 2015) analyzed the role of hydrodynamics in the occurrence and development of algal blooms in the XXR using the data of 2005. Some researchers also pointed out that water temperature stratification's blocking of the enriched nutrients transport of the upper reach of XXR is the primary cause of spring algal bloom (Lang et al., 2019). Xu et al. proposed that the value of Z_{mix}/Z_{eu} (mixed layer depth/euphotic layer depth) can be as the symbol of starting algal bloom control, and tried to adjust the value through the operation of TGR. Lian et al. tried to adjust the reservoir operation rules of TGR to enhance water exchange between the mainstream of TGR and the XXR tributary and change the thermal structure of XXR (Lian et al., 2014; Ma and Lian, 2011). However, most of early studies only figure out that water temperature stratification is the trigger of algal blooms in XXR, and they mainly concentrate on the decreased water velocity in the tributary after the filling of TGR and enrichment of nutrients(Ye et al., 2009; Ye et al., 2006). Even though the thermal stratification flows have been found in existing studies, before this study disturbance of these special flow patterns on tributary waterbody as well as its influence on algal concentration variation has not been fully investigated. Previous studies have shown that the nutrition concentration (primarily nitrogen and phosphorus) of XXR in the spring of 2009 is high and far beyond the thresholds for eutrophication (total phosphorus=0.02 mg/L, total nitrogen=0.2 mg/L) (Gao et al., 2018). Thus, under certain water temperature and solar radiation conditions the algal bloom of different intensity significantly depends on hydrodynamic conditions. The pattern of thermal stratified flow is a determinant of whether the hydrodynamic environment is suitable for algal dissipation or provide sufficient time for algae growth. On this basis, the study of water exchange caused by thermal stratified flow in XXR and its effect on algae transport process is of great practical significance to the aquatic environment governance of this region. Besides, there is no study concerning hydrodynamic relationship among multiple algal blooms. Additionally, operation tests and previous studies point to measures such as biochemistry method, ecological treatment and feasible reservoir operation schemes that may have positive impacts on reducing the algal bloom level in the near-dam tributaries (Sha et al., 2015). But it does not specify what governance measures should be taken under certain hydrodynamic condition.

Data released from the China Three Gorges Corporation show the algal bloom problem in the spring of XXR is an urgent need to resolve. To explore the relationship between thermal stratified flow variation and the three algal bloom events in the spring of 2009, this study mainly focusses on the spring season. In this study, a hydrodynamic and water quality numerical model is established using CE-QUAL-W2 and calibrated with the field observed data. Through this model, the hydrodynamic and water quality variation process of XXR in 2009 spring is reproduced and six typical thermal stratified flow patterns are generalized. Based on this, water exchange and algae transport process under these flow patterns are numerically analyzed. Further on, we also explore the sequentially superimposed effect of different thermal stratified flow patterns on algae transport and some algal bloom governance proposals are given in the end for this estuary and elsewhere. This study estimates the response of algae transport to the thermal stratified flows in XXR, and provides theoretical support for algal bloom governance.

2. Materials and Methods

2.1. Study Area

The Yangtze River is the longest in China and the third-longest in the world, with a length of

6300 km. The TGR is located at the upper reach of Yangtze and impounds a reservoir extending 667 km from Yichang to Chongqing (Fig.1a). Among the largest in the world, the normal reservoir level of TGR is 175.0 m, covering a 1084 km^2 water surface area and 39.3 billion m^3 water storage capacity. The reservoir's average annual runoff is 14,000 m^3/s, and inflow ranges from 3000 m^3/s to 30,000 m^3/s normally within a year. While the Yangtze is a subtropical river, the average annual temperature of the TGR is 17.6℃. (Gao et al., 2018)

The XXR is a tributary of the Yangtze River located 34.5 km upstream of the Three Gorges Dam. This river originates from the Shennongjia Forestry District, and flows from north to south through Xingshan and Zigui Counties. The XXR has a total distance of 94 km before flowing into the Yangtze River, and the watershed area is approximately 3099 km^2 (110°25′-111°06′E, 31°04′-31°34′N). The backwater of XXR extends up to 25~40 km from the estuary after the impoundment of TGR. Figure 1 shows the location of the Three Gorges Dam and the XXR.

In this paper, the study area includes a 598.5 km reach of TGR from the Three Gorges Dam to Chongqing (Fig.1a) and a 32 km reach of the XXR from Gaoyang Town to the estuary (Fig.1b).

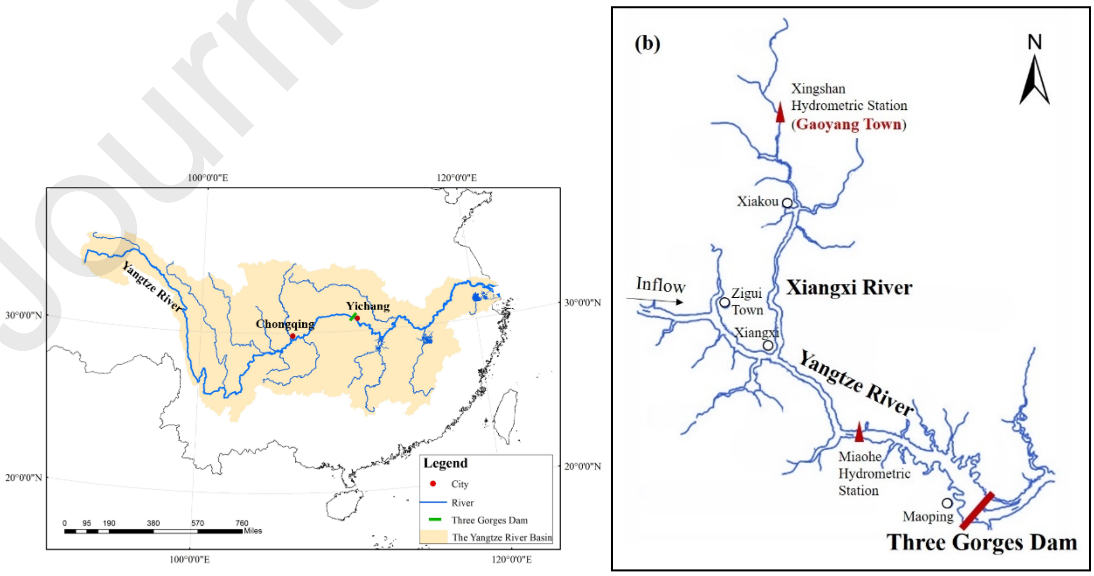


Fig.1 Study area of the TGR-XXR model. (a) The location of Three Gorges Dam in the Yangtze River Basin. (b) Sketch map of XXR.

2.2 Model development

2.2.1 Model setup

CE-QUAL-W2 is a two-dimensional (longitudinal-vertical) laterally averaged hydrodynamic and water quality model developed by the U.S. Army Corps of Engineers' Waterways Experiment Station which is suitable for numerical simulation of long and narrow rivers, estuaries, and reservoirs (Afshar et al., 2011; Norton and Bradford, 2009). This model has been successfully used in many hydrodynamic and water quality simulation covering the cases of Ameirkabir, Lake Santo Anastácio, Behesht-Abad, Sanbanxi and Zayandeh Roud Reservoir et al. (Arefinia et al., 2020; Hasanzadeh et al., 2020; He et al., 2019; Janine Brandão de Farias Mesquita, et.al, 2020; Ziaie et al., 2019)

The TGR and XXR are set as different water bodies in the model, so that each river can computes with independent conditions. The number of segments in the mainstream of the TGR is 147 with 4.5 km for each, while 130 segments in the XXR with 250 m for each (Fig.2). According to the terrain and water level, 212 vertical layers are used with 1 m interval. Each segment of the reservoir model is also characterized by its horizontal orientation and bottom friction, and the width ranges from 10 m to 1300 m.

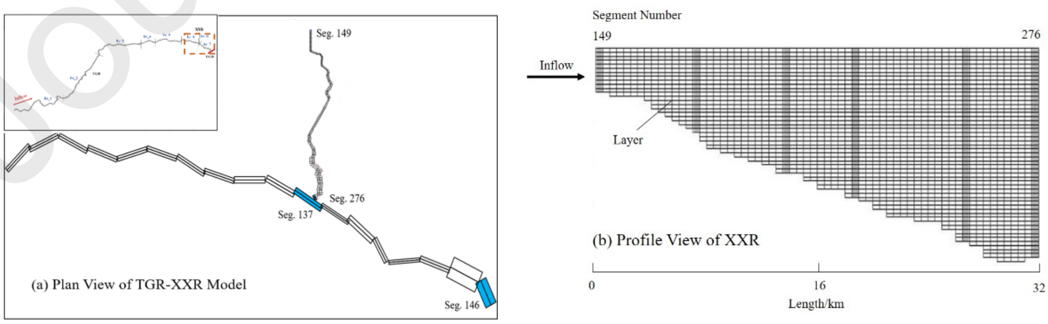


Fig. 2 Model segmentation. (a) Plan view of the TGR-XXR model. (b) Profile view of XXR.

The upstream boundary of XXR is defined by the daily average discharge and water temperature observed at the Xingshan Hydrometric Station, which is located approximately 36 km from the mainstream (Fig.1b). China Three Gorges University carries out the field observation in XXR monthly and provides the constituent concentrations over the model calibration period. Field data on the elevation of the water surface (Fig.3a) and discharge of the TGR (Fig.3b) are obtained from the China Three Gorges Corporation (http://www.ctg.com.cn/). Besides, daily meteorological data at the Zigui station are obtained from the Meteorological Administration of Hubei Province.

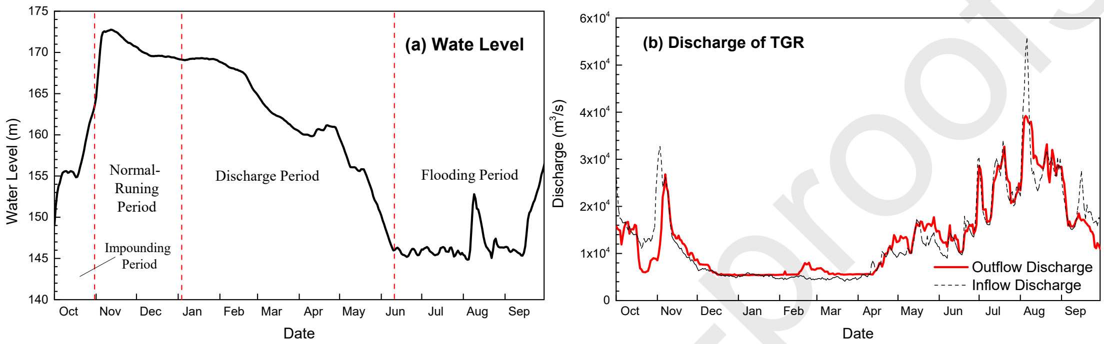


Fig. 3 Water level and discharge condition. (a) Water level of TGR during the calculation period. (b) Discharge condition of TGR during the calculation period.

2.2.2 Model calibration

The model is calibrated using the field observed temperature and water quality data from October 1st, 2008 to June 15th, 2009. Besides, the kinetic parameters in the water quality model, such as maximum growth rates for algae, respiration rates for algae, and half-saturation constants for nutrient limited growth, are initially specified from default values and literature values (Lian et al., 2014) and they are eventually identified through model calibration.

The mean absolute error (MAE) and root- root-mean-square error (RMSE) are used in this paper to examine the validity of the model (Li et al., 2020; Lian et al., 2019). The calculated water surface elevation matches the observed data well (shown in Fig.A.1). Fig.4 shows the comparisons between the model calculated and field observed temperature distributions. The vertical temperature distributions calculated by the model are generally conform with the observed at most of the conditions.

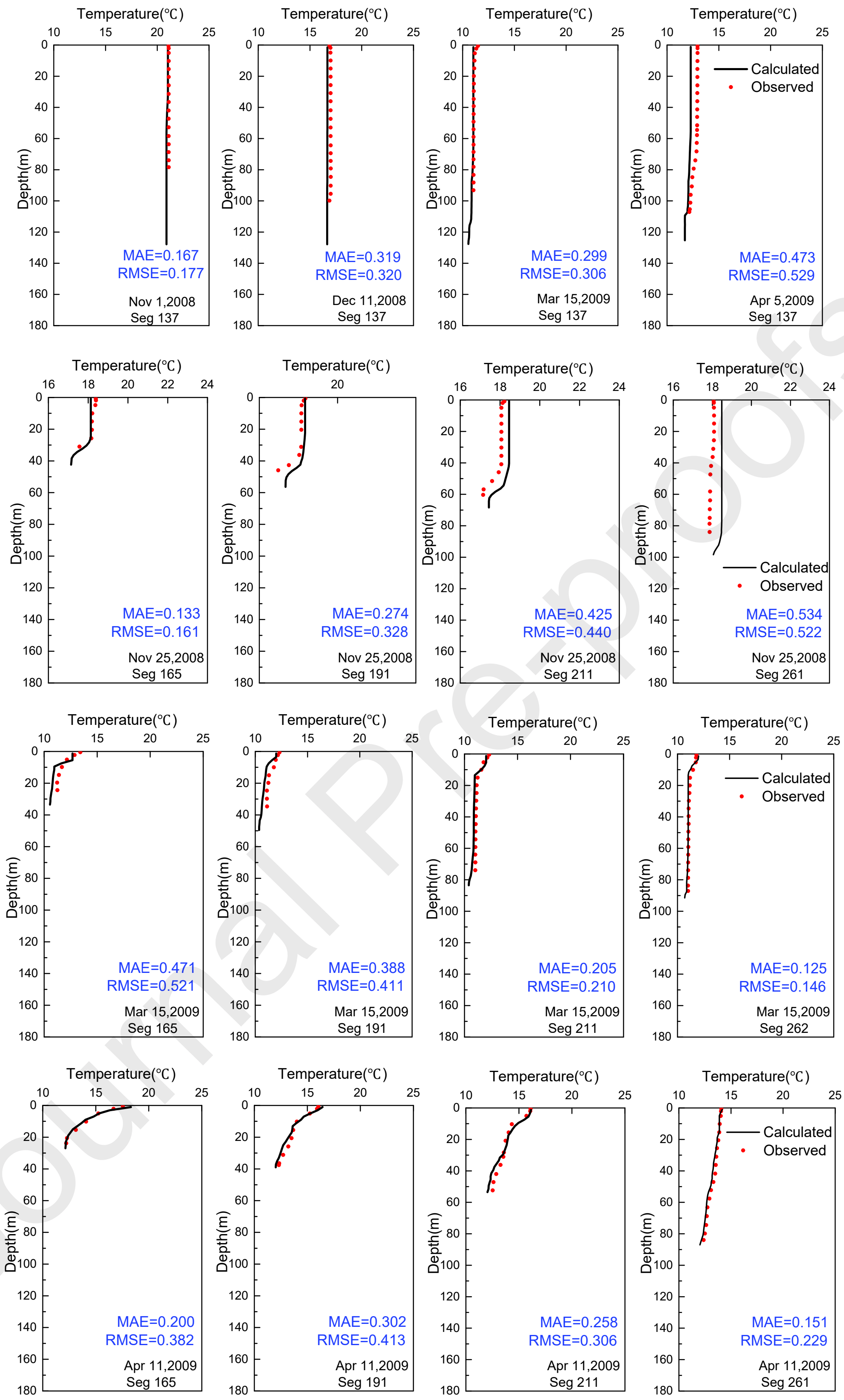


Fig. 4 Comparisons between calculated and observed water temperature distribution.

Constituents including nitrate nitrogen (NO_3-N), ammonia nitrogen (NH_3-N), phosphate (PO_4), dissolved silica (D-Si) and chlorophyll-*a* (Chl-a), playing essential roles in aquatic ecosystems, are selected for water quality calibration. Three commonly used model evaluation statistics including root-mean-square error (RMSE), Nash-Sutcliffe efficiency (NSE) and RMSE-observations standard deviation ratio (RSR) are adopted. In general, model simulation can be judged as satisfactory if NSE > 0.50 and RSR < 0.70 (Moriasi et al., 2007). Results shown in Tab.1 indicate that the model performed well in simulating the water quality of the mainstream of the TGR and XXR. In April and May, the water temperature and illumination intensity are suitable for algal growth, resulting the Chl-a concentration at a high level, which indicates a high risk of algal bloom (Fig.5).

In general, for most of the conditions, calculated results agree well with the observed, which means the model established in this study can predict the temperature stratification and algal blooms of XXR well.

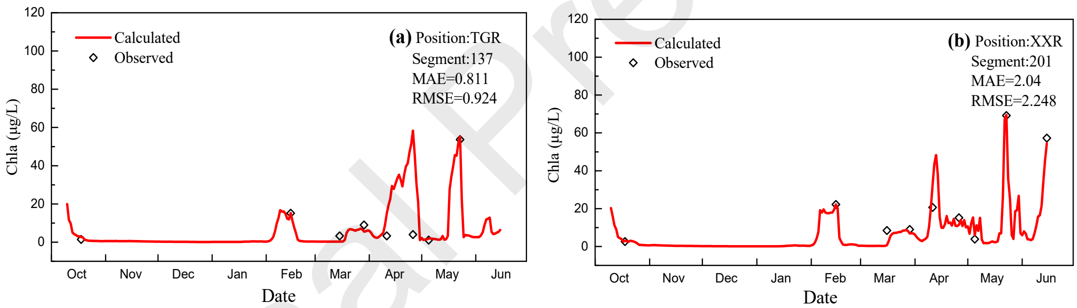


Fig. 5 Comparisons between calculated and observed Chl-a concentrations.

Table 1 Statistical summary of water quality model calibration for TGR and XXR.

Variable	TGR			XXR		
	RMSE	NSE	RSR	RMSE	NSE	RSR
NO_3-N (mg/L)	0.122	0.581	0.647	0.142	0.751	0.499
NH_3-N (mg/L)	0.103	0.662	0.581	0.089	0.874	0.355
PO_4 (mg/L)	0.009	0.648	0.593	0.016	0.716	0.533
D-Si (mg/L)	0.439	0.542	0.677	0.673	0.983	0.131
Chl-a (μg/L)	4.701	0.928	0.269	5.374	0.939	0.247

2.3 Phenomena analysis

The XXR is disturbed by upstream inflow and mainstream intrusive flow caused by water temperature difference. The temporal variation of velocity distribution at estuary of XXR is shown in Fig.6a, where the negative value means the flow direction is from the downstream to upstream.

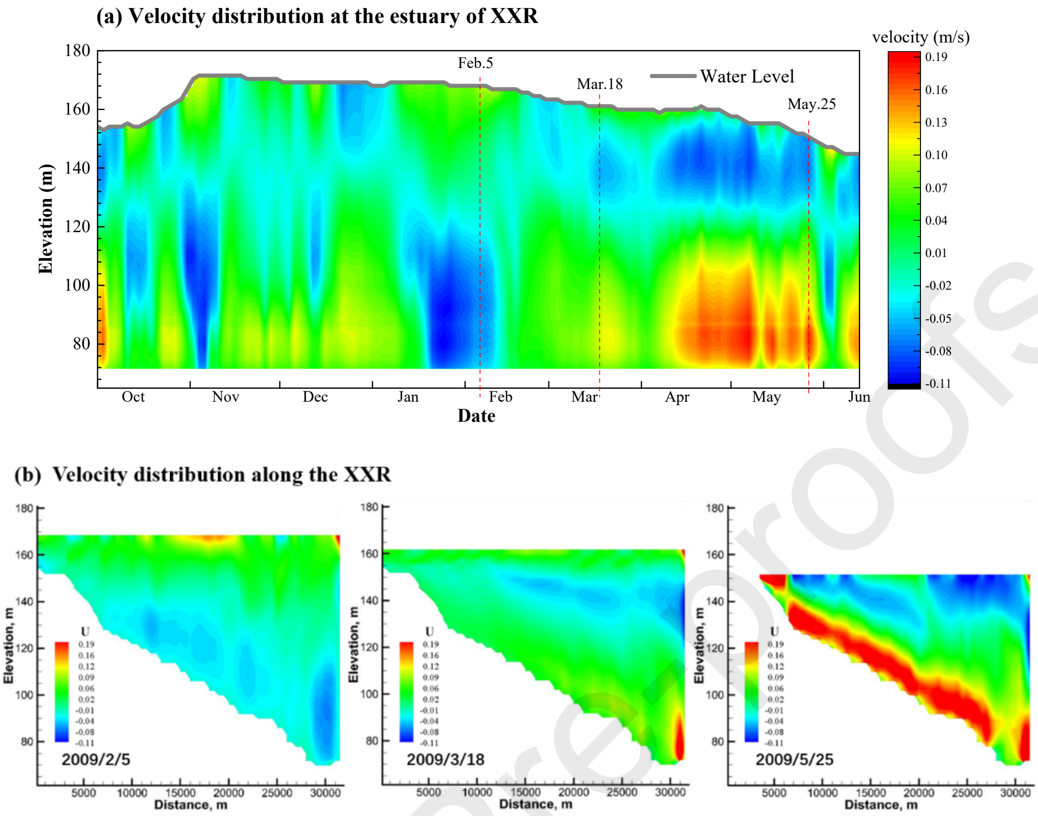


Fig. 6 Velocity distribution of XXR. (a) Temporal variation of velocity distribution at the estuary of XXR. (b) Velocity distribution along the longitudinal of XXR at three typical moments. (The mainstream intrusive flow and upstream inflow are marked by blue and red color, respectively.)

During the simulation, the flow pattern of XXR varies frequently, and the whole process can be summarized as follows.

October 1st, 2008 – December 31th, 2008: During this period, weather change is evident, and the surface temperature of XXR changes dramatically with its influence. The position of mainstream intrusive flow switches among surface, middle and bottom layers frequently.

January 1th, 2009 – January 20th, 2009: The water temperature of both the XXR and TGR decrease. In the lower reach of XXR, water temperature at the bottom of river is slightly higher than TGR, and the mainstream intrusive position gradually descends from surface to bottom layer.

January 21th, 2009 – February 5th, 2009: The mainstream intrudes through bottom layer (Fig.6a).

February 6th, 2009 – February 22th, 2009: As the air temperature rises in spring, the position of mainstream intrusive flow rises gradually and finally reaches the surface layer.

February 23th, 2009 – February 28th, 2009: The mainstream intrudes through surface layer.

March 1th, 2009 – April 15th, 2009: With the temperature of XXR rising, mainstream intrusive position changes to middle layer (Fig.6b). In addition, with the increase of discharge rate, water exchange is strengthened and the flow velocity is increased.

April 16th, 2009 –June 15th, 2009: This process is accompanied by the decrease of water level, thus the position of mainstream intrusive flow switches constantly between middle and surface layer (Fig.6c).

The flow distribution and velocity value are constantly changing, and each flow pattern lasts no more than 15 days, which confirms the complexity of thermal stratified flows. On the one hand, temperature difference between the TGR and XXR cause water from the mainstream intrudes into the tributary through the bottom, middle or surface layers. On the other hand, the upstream inflow enters into the XXR through either bottom or surface layers because the upstream river is shallow. In summary, thermal stratified flows caused by temperature difference have many variations in the XXR, which make the hydrodynamic environment of this region special.

2.4 Identification and classification of typical thermal stratified flow patterns

The XXR is disturbed by the upstream inflow (UF) and the mainstream intrusive flow (MF). As previously mentioned (Section 2.3.1), there are two intrusive positions for upstream inflow (S, B) and three for mainstream intrusive flow (S, M and B) in XXR. Therefore, six typical thermal stratified flow patterns are generalized on the basis of combinations, as shown in Fig.7.

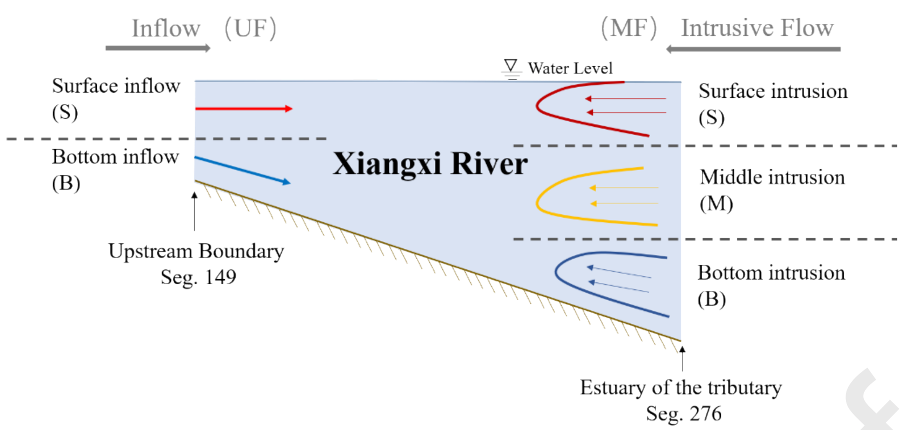


Fig. 7 Typical thermal stratified flow patterns.

Type S-B: The temperature of TGR is higher than XXR, so the mainstream water intrudes into XXR through the surface layer. Instead, the upstream inflow is cold, and enters the XXR through bottom layer.

Type S-S: The temperature of XXR is lower than TGR and upstream inflow. The mainstream and upstream flow intrude into the XXR both through the surface layer.

Type M-B: Water temperature of TGR is between the surface and bottom temperature of XXR, the mainstream water intrudes into the XXR through the middle layer. Meanwhile, the upstream inflow enters through bottom layer.

Type M-S: The mainstream water intrudes into the XXR through middle layer, and the upstream inflow enters through the surface layer.

Type B-B: The temperature of XXR is high, mainstream intrusive flow and upstream inflow intrude into the tributary both through the bottom layer.

Type B-S: The temperature of TGR is lower than XXR, and mainstream water intrudes through the bottom layer. On the contrary, the upstream inflow enters the tributary through surface layer because of its high temperature.

Numerical simulation scenarios are set on the basis of above six thermal stratified flows. In the simulation, inflow rate is set as 47.3 m^3/s which is the annual average discharge of XXR (Li et al., 2020). Meanwhile the outflow rate is 9031.43 m^3/s, the annual average discharge of TGR in discharged period (Huang et al., 2020). Likewise, the water level of XXR is set as 160m which is the annual average value in the spring. According to previous studies, the critical value of Chl-a concentration for algal bloom in XXR is 32.59~62.81 μg/L ((Zheng et al., 2006). In this paper, the mean value 47.7 μg/L is selected as the threshold. Furthermore, the most adverse scenario where algal bloom covers the entire XXR reach is set as initial condition. According to the field measured data, algae exist within 10m beneath the water surface of XXR. Thus, in this simulation in order to highlight the impact of thermal stratified flows on algae transport, the Chl-a concentration within 10m beneath the water surface is set as threshold value.

2.5 Sequential superposition of stratified flow patterns

In practice, as the water temperature of TGR and XXR constantly changing, thermal stratified flows switching among the aforementioned six patterns. And influence of latter pattern on algae transport is possibly restricted or promoted by the former one. The sequentially superimposed effect of two flow patterns on flow field and algae transport are discussed in a premise that the algal bloom area did not completely disappear under the action of the first thermal stratified flow. Two indicators, algae transport direction and algae transport speed, are used to evaluate the sequentially superimposed effect and the score criterion are shown in Table 2.

Table 2 Score criterion of evaluation indicators for algae transport.

Indicator	Criterion	Score
Algae transport direction	Same	+1
	Opposite	-1
Algae transport speed	Faster	+1
	Constant	0
	Slower	-1

The significance of the evaluation results can be interpreted as following.

-2: The effect of two thermal stratified flows on the algae bloom area transport is reversed, and algae transport speed slows down. In this condition, the hydrodynamic environment is the worst-case for algae transport.

-1: The effect of two thermal stratified flows on the algae transport is reversed, but has little effect on algae transport speed. Hydrodynamic environment in this condition is better than "-2".

0: There are two scenarios. One is the effect of two thermal stratified flows on the algae transport is reversed, but the later flow pattern is more conducive to algae transport than the former one. And the other is the effect of two thermal stratified flows on the algae transport is consistent, but the algae transport speed slows down.

+1: The second thermal stratified flow does not have much effect on the former one, and the algae transport speed is constant.

+2: On this occasion, the effect of algae transport by former flow is enhanced and the hydrodynamic environment is the most favorable for algae transport.

The continuous encounter of three or more stratified flow patterns can be regarded as the continuous superposition of two stratified flow. The development trend of hydrodynamic conditions can be analyzed according to the evaluation results. The analysis of sequentially superimposed effect has profound meaning of predicting the trend of algal bloom and providing a guidance for algal bloom governance on the basis of water quality and temperature monitoring.

3. Results

3.1 Algae transport process in the 2009 spring

According to continuously monitored data there are three successive algal bloom events in the spring of 2009 and the numerical simulation reproduces this process (Fig.8). The first one occurs in February, with a cover area of 4~8km from the upstream. This algal bloom event is minor and lasts

15 days (Fig.8a).

The second one starts from April 1st and ends at April 11th. The algal bloom cover area moves from the upper reach to the lower reach with the surface flow (Fig.8b).

The third algal bloom is the worst one and lasts more than 20 days. Its outbreak is induced by residual algae from the second algal bloom. The residual algae at lower reach of XXR return to the upper reach with the push of upstreamward flow. During this process, the favorable external condition leads an explosion of algae growth. And algal bloom covers the entire reach in a short time. In this process the maximum Chl-a concentration is 147 μg/L, with an average of 80 μg/L. Whereafter, with the surface anticlockwise flow the algae are mixed into deep water. Ultimately, some algae die from the lack of illumination in deep water and others are discharged into TGR with bottom flow (Fig.8c).

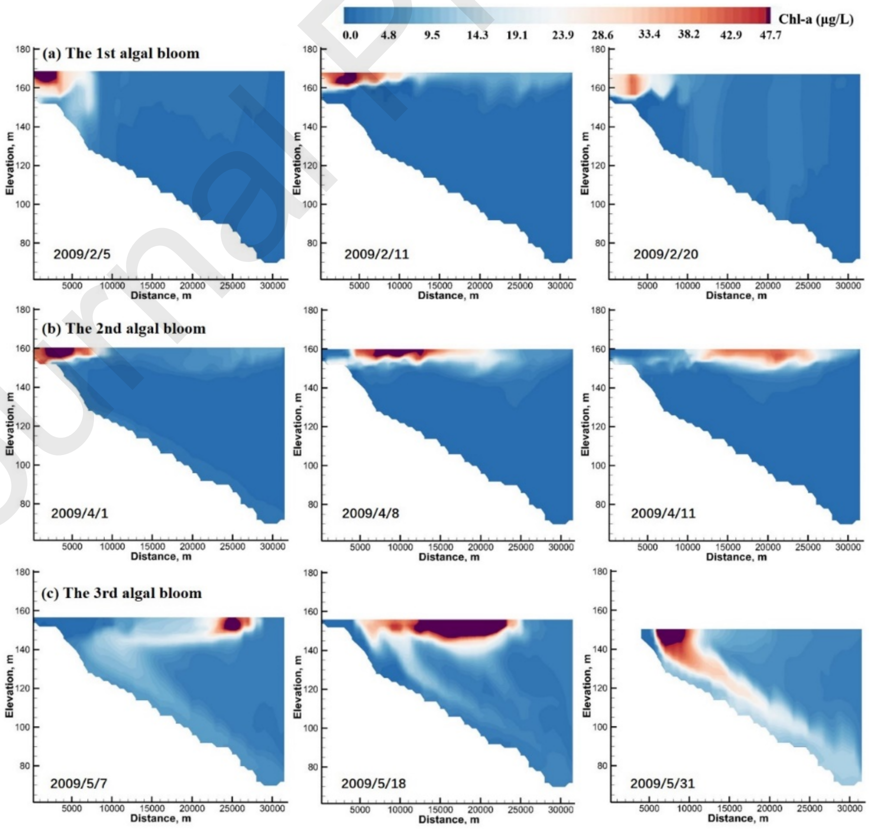


Fig. 8 Chl-a concentration distribution of three algal blooms in spring of 2009. (Purple color represents the Chl-a concentration exceed the threshold value.)

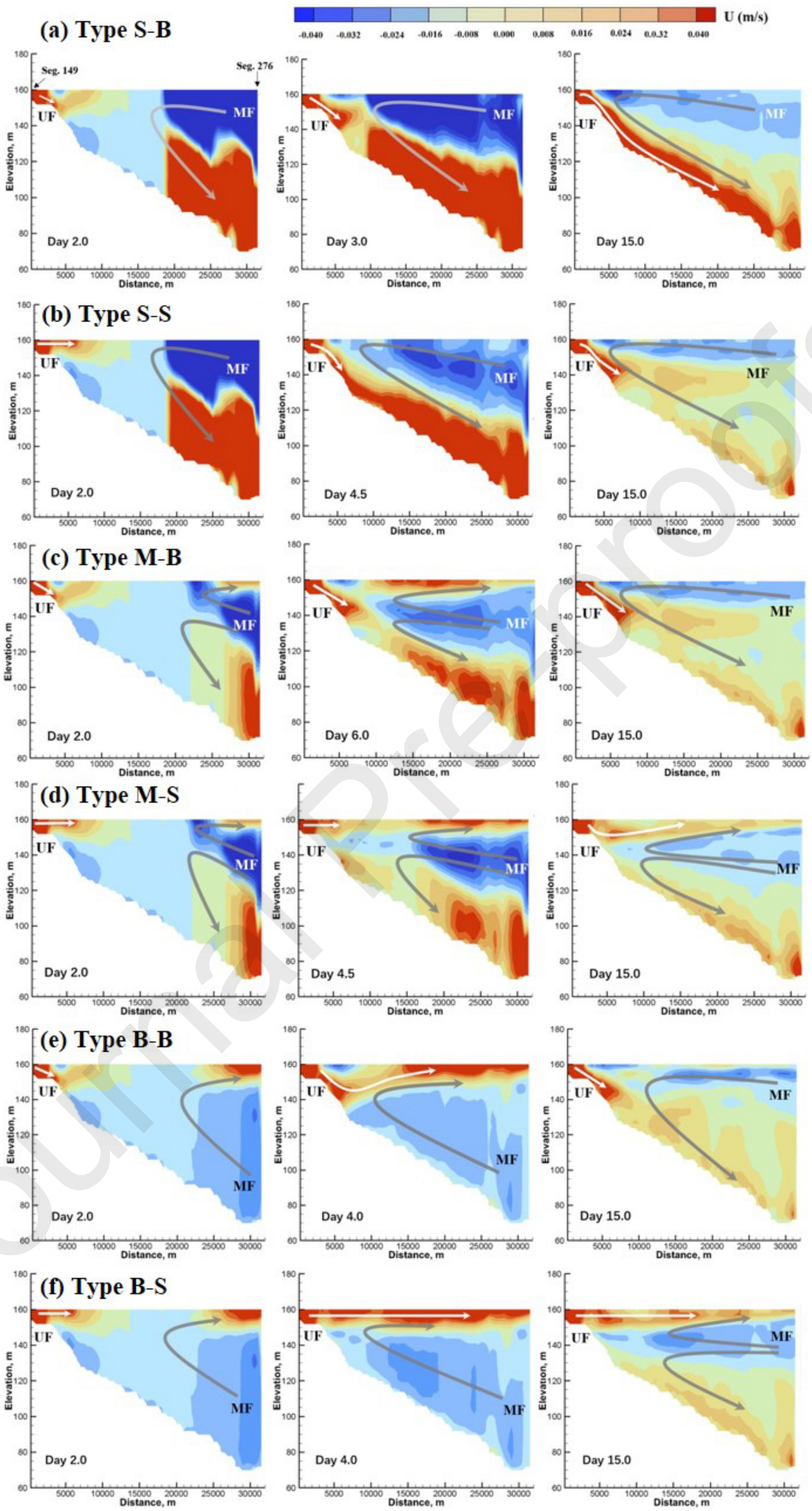
3.2 Simulation results under typical thermal stratified flow patterns

3.2.1 Water exchange

The longitudinal velocity distribution in XXR at the moment of earlier, medium and later stage of simulation under six typical thermal stratified flows are shown in Fig.9. The mainstream intrusive flow (upstreamward) and upstream inflow (downstreamward) are marked with MF and UF on the graph, respectively.

- Type S-B: An anticlockwise circulation forms at the estuary of tributary and orients towards the upper reach. Instead, the upstream inflow enters the tributary from bottom layer (Fig.9a). The inflow and reverse compensation flow converge on the 3rd day, 9 km away from the upstream boundary. Thus, a stable stratified flow with anticlockwise circulation is formed. However, with the inflow of high-temperature mainstream water the temperature of XXR increases gradually, resulting the weakness of mainstream intrusive intensity.
- Type S-S: The mainstream intrusive flow and upstream inflow with opposite directions meet on the 2.5th Day, 13 km away from the upstream boundary of XXR (Fig.9b). The upstream inflow flows to the bottom layer under the pressure of mainstream intrusive flow. Ultimately, the flow pattern is the same as Type S-B.
- Type M-B: At first, the mainstream intrusive flow intrudes into the XXR from the middle layer, 13~49 m below the water surface, causing an anticlockwise compensation flow at bottom layer and a clockwise one at the surface (Fig.9c). The clockwise-bottom-circulation and downstreamward bottom-layer inflow meet on the 5th day, and then the bottom flow is enhanced. With the discharge of surface high-temperature water, temperature difference between XXR and TGR is decreasing, and the position of intrusive flow gradually rises. From the 10th Day, the flow pattern is the same as Type S-B.

- Type M-S: The two surface downstreamward flow join on the 4th day (Fig.9d). But due to the inflow of upstream high temperature water, the surface temperature of XXR is still higher than TGR. Although the position of mainstream intrusive flow unchanged, its intensity decreases.
- Type B-B: While the mainstream water intrudes into the XXR from bottom layer, a clockwise circulation is formed at the estuary of tributary and expands to upper reach (Fig.9e). The bottom layer upstream inflow (UF) is blocked and then flows along the upper edge of intrusive flow. With the influx of cold mainstream water, the temperature of XXR gradually decreases, and the intrusion position rises.
- Type B-S: The upstream inflow enters XXR through the surface layer and join with the compensation flow of mainstream intrusive flow on the 3rd day, 14km from the upstream boundary (Fig.9f). Due to the inflow of upstream high temperature water, temperature change of XXR more slowly than Type B-B. Therefore, at the end of simulation mainstream water intrudes through the middle layer.



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342 Fig.9 Longitudinal velocity distribution in the XXR of six typical thermal stratified flows. (The
343 mainstream intrusive flow and upstream inflow are marked with MF and UF, respectively.)

3.2.2 Algal bloom coverage rate

The ratio of the reach where Chl-a concentration exceeds the threshold of algal bloom to the whole river is defined as the algal bloom coverage rate (R_{alg}). Fig.10 shows the temporal variation of R_{alg} under six typical thermal stratified flows. Besides, the final Chl-a concentration distribution of XXR is shown in Fig.11. From the eutrophication governance point of view, Type S-B has the optimal hydrodynamic environment for algae transport, on the 6th day the algal bloom entirely disappears. In Type B-S, the R_{alg} decreases slowly but eventually reaches 0. On the 15th day, algae density of upper and middle reach is low, while most of algae aggregate at the estuary. The worst cases occur in Type M-B and B-B, with the final R_{alg} of 82.3% and 78.1% respectively, and the final algal bloom cover the reach 5~28km away from the upstream boundary of XXR.

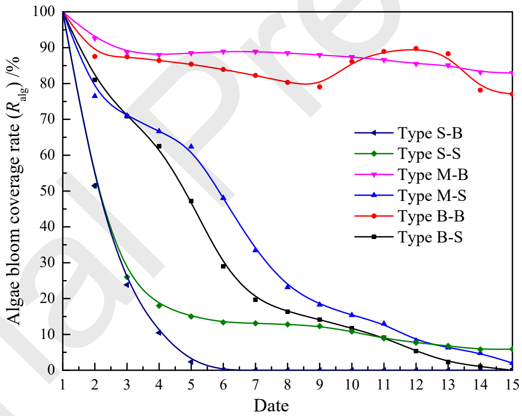

Fig.10 Temporal variation of algal bloom coverage rate (R_{alg}).

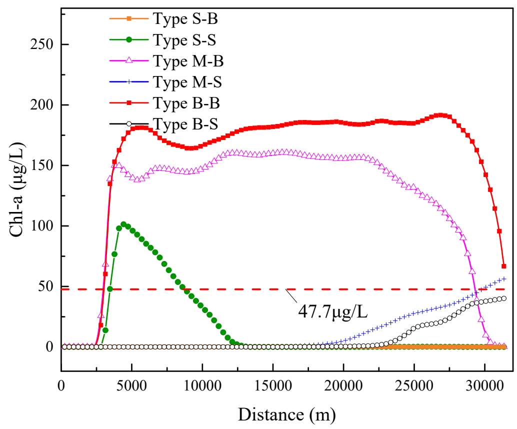

Fig.11 The final Chl-a concentration distribution in XXR. (Note the distance shown on the horizontal axis is from the upstream to downstream ends.)

3.2.3 Algae transport

Algae transport simulation results under six typical thermal stratified flows are shown in Fig.12, and these processes can be summarized as follows.

- Type S-B: Pushed by strong surface anticlockwise intrusive flow, some algae in lower reach plunge into deep water directly (Fig.12a). Others move towards upper reach and then are mixed into deep water at 5km from the upstream. Algae in deep water form a belt that is parallel with the bottom slope, die from the lack of illumination or discharge with flow into the TGR. The whole process, from the beginning to the entirely disappearance of algal bloom, last 6 days.
- Type S-S: Algae transport process in this scenario is the same as Type S-B. But the surface upstream inflow and intrusive flow from both sides push the algae gather at the upper reach, 5km downstream further than Type S-B, resulting in the Chl-a concentration of this area exceeding the threshold and final R_{alg} is 8.3% (Fig.12b).
- Type M-B: Algae on the surface of water are discharged into TGR with the flow of upstream inflow in earlier stage. But with the variation of intrusive position, the surface discharge channel is blocked (Fig.12c). And from the third day to the 15th day, the value of R_{alg} is barely changed with a final value of 82.3%.
- Type M-S: Algae are pushed to lower reach under the effect of surface upstream inflow and compensation flow of middle layer intrusive flow (Fig.12d). With the decrease of inflow, the algae transport process is slowed. Eventually, residual algae gather at the estuary of tributary before being discharged, with the final R_{alg} of 2.1%. The maximum of final Chl-a concentration in the whole reach is 52.2μg/L, a little higher than the threshold.
- Type B-B: The earlier stage condition of this scenario is similar to Type M-B, under the action of the surface downstreamward flow, a small group of algae are discharged (Fig.12e). But

different from others, the variation of R_{alg} is fluctuating in this scenario. On the 9th day, the mainstream intrusive position rises to surface. Meanwhile, algal bloom area is pushed to upper reach and the value of R_{alg} has a slightly increase. But with the weakness of intrusive flow, algal bloom area moves towards downstream again. The maximum of final Chl-a concentration is up to 190μg/L and final the final R_{alg} is 78.1%.

- Type B-S: The upstream inflow pushes the surface algae transfer towards lower reach. But the algae located at the bottom of cover area move towards upper reach under the influence of mainstream intrusive flow. These two flows create a clockwise movement of the algae cover area throughout the XXR (Fig.12f). The bottom algae are continuously mixed to the surface layer and then discharged into TGR with surface downstreamward flow. On the 7th day, R_{alg} reduce to 16.3% and the algal bloom decay process slows down after that. At end of this process, most algae discharge into TGR through the surface layer with the final R_{alg} is 0.

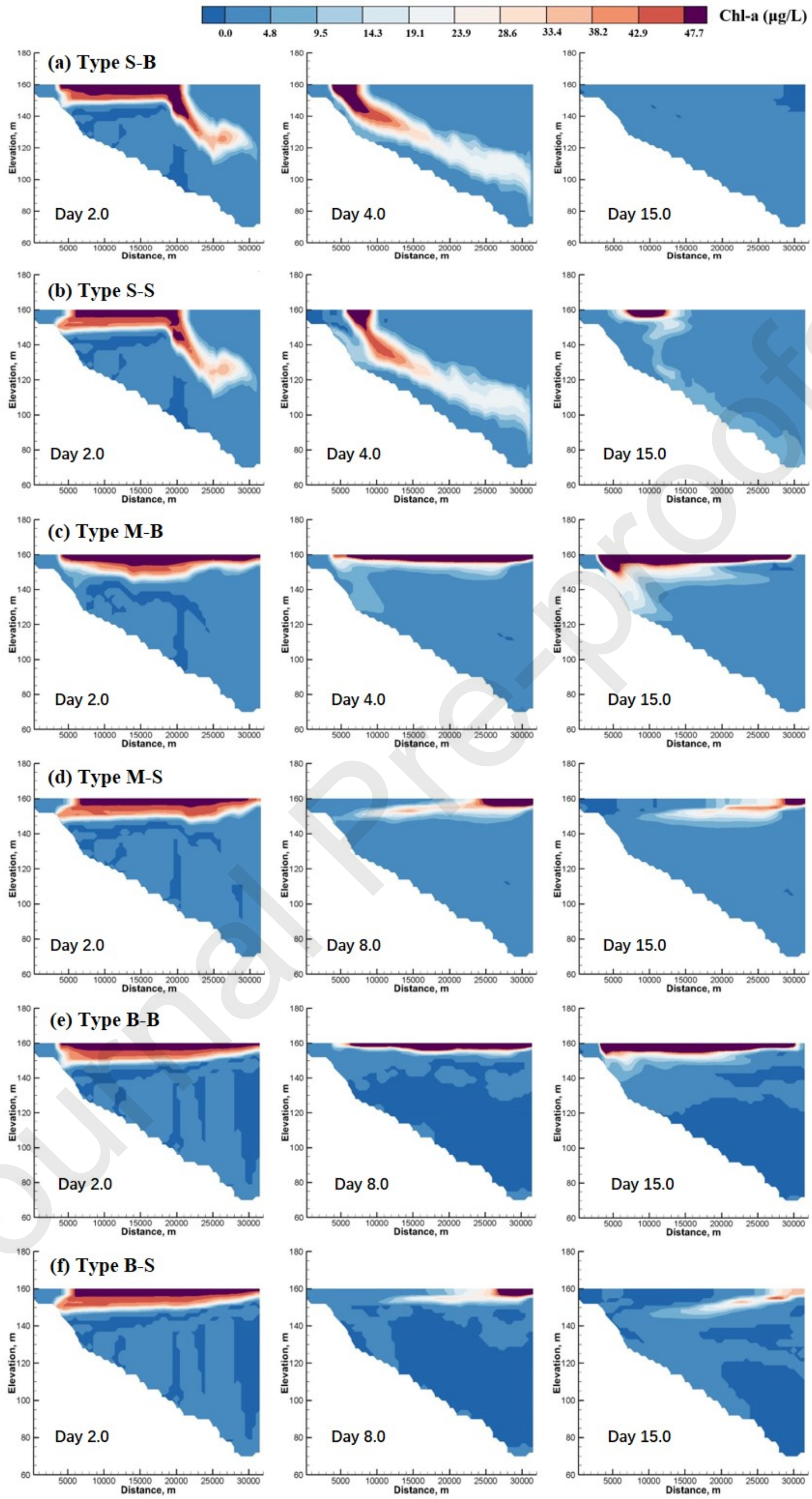

Fig. 12 Algal concentration distribution in the XXR of six typical thermal stratified flows. (Purple indicates algae concentrations exceed the threshold of algal bloom.)

Through the above algae transport process analysis, algae transport characteristics under the action of six typical thermal stratified flows are summarized as shown in Table 3.

Table 3 Characteristics of algae transport processes for different stratified flow patterns.

	Type S-B	Type S-S	Type M-B	Type M-S	Type B-B	Type B-S
Algae transport Intensity	High	Medium	Low	Medium	Low	High
Mainstream Intrusive Position	Surface	Surface	Middle	Middle	Bottom	Bottom
Tributary Inflow Position	Surface	Bottom	Surface	Bottom	Surface	Bottom
Algae Discharge Position	Bottom	Surface	Surface	Bottom	Surface	Surface
Algae Transport Direction	*←	*←	**→	**→	**→	**→
Algae Transport Speed	Fast	Medium	Low	Medium	Low	Fast
Final R_{alg}	0	8.3%	82.3%	2.1%	78.1%	0

Notes: * indicates the algae in lower reach is pushed from the downstream to upstream and then mixed into deep water. ** indicates the algae transport direction is from upstream to downstream. R_{alg} indicates the algal bloom coverage rate.

3.2.4 Superposition effects

According to section 2.5 the sequentially superimposed effect of two different thermal stratified flows can be summarized as six grades and the evaluation results are shown in Fig.13.

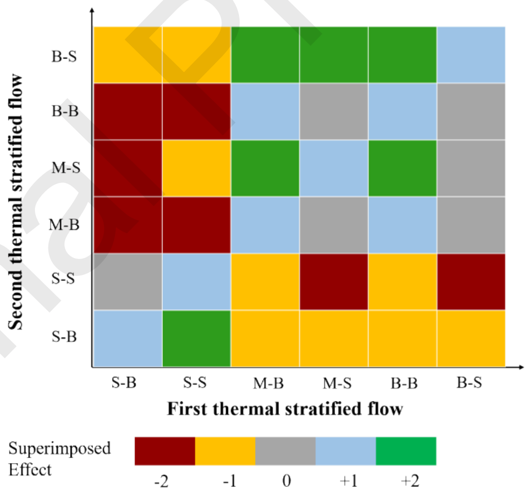

Fig. 13 The sequentially superimposed effect of two different thermal stratified flows.

For Type S-B and B-S, the hydrodynamic environment of first stratified flow is conducive to algae transport, so it won't make a positive effect no matter what pattern of flow is to follow. Conversely, the hydrodynamic environment of Type M-B and B-B is the most unfavorable for algae transport. Thus, when followed by other patterns, as long as the two thermal stratified flows have the same effect on the algae transport, the sequentially superimposed effects are all positive. Overall, the sequentially superimposed effects are not optimistic under most conditions, and algal bloom governors should pay special attention to the situation where the result is “-2”.

4. Discussion

Based on the above results, the three algal bloom events of XXR in the spring of 2009 can be reviewed. As shown in Fig.3b, water temperature of TGR is lower than XXR from January 1st to March 21th in 2009. Subsequently, the temperature of TGR gradually rises and finally higher than XXR. For upstream inflow, the XXR originates from Shennongjia Forestry District and the temperature of upstream inflow is generally cold. The thermal stratified flow pattern changes from Type B-B to M-B then to S-B. In Type B-B, a small number of algae can be discharged from the reach. When the flow pattern changes to M-B, the sequentially superimposed effect is “+1”, which means the hydrodynamic conditions have not been improved. The algae transport speed is still low, leaving a lot of time for algal growth. Soon after that, the flow pattern changes to Type S-B and the corresponding sequentially superimposed effect is “0”, indicating the hydrodynamic condition goes through the process of getting worse first and then getting better. Residual algae in the middle and lower reach of XXR are pushed towards upstream, and algal concentration of upper reach increase rapidly which eventually lead to the third algal bloom. Ultimately, under the continuous action of Type S-B thermal stratified flow, algae either discharge into the TGR with bottom flow or die from the lack of illumination.

The superimposed effect of different thermal stratified flows indicates the connection between sequentially algal blooms. The action of previous stratified flow on algae effects the aggregation location and degree of remaining algae in the reach, thus effecting the next algae transport process. When the direction of sequentially thermal stratified flows on algae transport is different, transport channel is blocked and algae concentrate in the reach which causes a hidden danger for algal blooms. This can be used to predicate algal bloom events. In general, the current algae concentration of XXR reach can be measured, and the thermal stratified flow variation trend can be calculated according to the meteorological forecast data. On this basis, we can foresee the followed stratified flow pattern as well as its sequentially superimposed effect on algae transport according to the evaluation method mentioned in section 2.5, response countermeasures and programs can be proposed according to the predicted results.

There are many other tributaries simultaneously influenced by thermal stratified flows caused by mainstream backwater and upstream inflow (Li et al., 2020; Zhang et al., 2020; Zhao et al., 2016), so the results obtained from the simulation of XXR can be used for algal bloom governance in waterbodies with the same hydrodynamic environment as the XXR.

When the waterbody is disturbed simultaneously by thermal stratified flows from upstream and downstream, a large clockwise or anticlockwise circulation is formed (Fig.9a and f). In this condition, the hydrodynamic environment is favorable for algae transport and should be maintained or promoted by reservoir operations. In this process, algae will be discharged with the surface downstreamward dominant flow (Fig.12a) or mixed into deep water and then die from the lack of illumination (Fig.12f).

If the hydrodynamic environment is adverse to algae transport, the dominant flow formed in the middle or bottom layer of water body with an extremely weak surface flow, leading to the obstruction of surface layer algae discharge channel (Fig.12c and e). Measures should be taken to minimize the algal aggregation area. For example, rising water level or increasing the discharge rate as much as possible through reservoir operations (Lian et al., 2014). Subsequently, partial algae control measures such as ecological treatments can be adopted for improving water quality.

5. Conclusion

In this study, a 2D longitudinal-vertical TGR-XXR numerical model is established to investigate the water exchange and algae transport process caused by thermal stratified flow in XXR. The model results have successfully reproduced the special hydrodynamic and water quality characteristics including thermal stratification and algal bloom events of XXR, the model results show good agreement with field observations. The main findings of this research are as follows:

(1) There are notable thermal stratified flows that occur in the XXR due to the water temperature difference between the XXR and mainstream of the TGR, and the flow patterns have a seasonal variation. In terms of the water temperature difference between upstream inflow, mainstream intrusive flow and XXR, the thermal stratified flows can be generalized into six patterns.

(2) The thermal stratified flows of Type S-B and B-S are conducive to algae transport, in these two patterns algae can be discharged into TGR entirely. The worst-case scenarios are Type M-B and B-B, they occur when the temperature getting warmer and the heating rate of XXR is faster than TGR or the discharge of TGR increased causing a large number of surface high-temperature water released. The two conditions are common in spring season, which is one of the main reasons for frequent occurrence of algal blooms, measures such as increasing the frequency of water quality and temperature monitoring and adjusting the reservoir operation should be taken in time for algal bloom governance.

(3) The sequentially superimposed effect of different thermal stratified flows on algae transport gives a good explanation of the multiple algal blooms in spring. This method can be used to predict algal blooms, which provide a theoretical foundation for ameliorating algal bloom problem through

adjusting reservoir operation.

In this study, the effects of thermal stratified flow on the hydrodynamic and algae transport process are investigated. The results are also suitable for other reservoirs and tributaries with hydrodynamic environment similar to XXR, which provide an explanation for algal blooms in spring and further studies can be taken in this basis. Focusing on algal bloom governance, the research results are of guidance significance for conducting feasible reservoir operation rules of reservoirs. Moreover, the model and the method adopted in this study could provide a new perspective on solving the algal bloom problems in similar reservoirs and tributaries.

Acknowledgments

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Appendix A Supplementary data

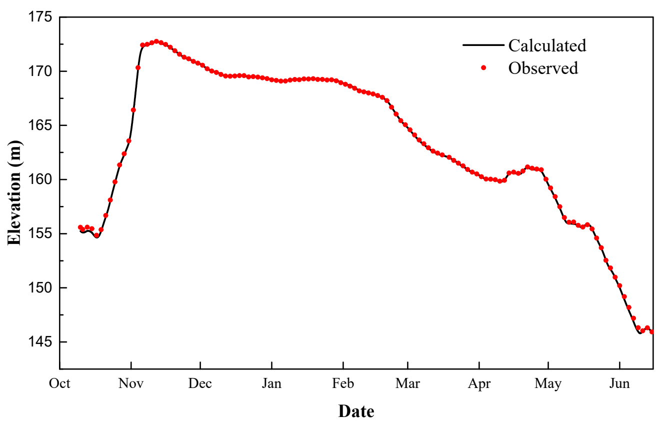

Fig.A.1 Comparison of modeled and observed water surface elevation for TGR. (location before TGD site)

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