

# Thermal stratification and its relationship with water quality in the typical tributary bay of the Three Gorges Reservoir

Juxiang Jin, Scott A. Wells, Defu Liu and Guolu Yang

## ABSTRACT

The effect of thermal stratification and its relationship with water quality was researched by field observation in this study. Through assessing the degree of thermal stratification by calculating the dimensionless parameter of thermal resistance to mixing (RTRM) indices from 2008 to 2010, it indicated that the water body of Xiangxi River was stratified strongly in the summer months. The analysis of the degree of thermal stratification with both the meteorological and hydrodynamic factors showed thermal stratification intensity was more sensitive to meteorological factors in Xiangxi River. Through the analysis of the relationship between thermal stratification and water quality, the results indicated that the concentration of Chlorophyll a was higher in the epilimnion affected by the thermal stratification, which could cause algal bloom. The results may further help to evaluate the thermal stratification role in eutrophication process and algal bloom formation in Xiangxi River.

**Key words** | Chlorophyll a, dissolved oxygen, thermal stratification, water quality, Xiangxi River

**Juxiang Jin** (corresponding author)

**Guolu Yang**

College of Water Conservancy and Hydropower Engineering,  
Wuhan University,  
Wuhan 430072, China  
E-mail: [xiang371@126.com](mailto:xiang371@126.com)

**Scott A. Wells**

Department of Civil and Environmental Engineering,  
Portland State University,  
Portland, OR 97207-0751, USA

**Defu Liu**

College of Resources and Environmental Engineering,  
Hubei University of Technology,  
Wuhan 430068, China

## INTRODUCTION

Thermal stratification and mixing could affect the vertical gradients of physical and chemical processes in the water body (Chimney *et al.* 2006; Elçi 2008). When the strong thermal stratification is formed in the summer months, it could prevent or slow the exchange of water in the epilimnion and hypolimnion, which could induce water quality deterioration in the bottom because of anoxia in the hypolimnion. When the thermal stratification disappears, the nutrients at the bottom would reach the upper water body with the vertical mixing, which would induce algal growth, which would cause eutrophication of the water body and endanger water safety. Understanding of thermal stratification is the basis for studying the ecosystem of lakes and reservoirs.

A lot of work has been done on thermal stratification of lakes and reservoirs in previous studies. Some research has been done on meteorological factors which could affect the formation of thermal stratification, including wind, air temperature and so on. (Hocking & Straskraba 1999; Elçi 2008;

Wang *et al.* 2012). Some research has focused on the hydrodynamics, which could affect the thermal stratification structure (Bonnet *et al.* 2000; Han *et al.* 2000; Ma *et al.* 2008a; Liu *et al.* 2011; Huang *et al.* 2014). Some work has also been done to analyze the vertical distribution of nutrients with thermal stratification patterns (Kumagai *et al.* 2000; Becker *et al.* 2008; Rangel-Peraza *et al.* 2012; Zhang *et al.* 2015). These research results showed that both the meteorology and hydrodynamics could affect the thermal stratification and that water quality could be affected by thermal stratification. After the impoundment of Three Gorges Reservoir, algal blooms have broken out in spring and fall months in some tributaries since then, and some research has been done on thermal stratification and algae bloom in Xiangxi River (Yu & Wang 2011; Dai *et al.* 2012; Liu *et al.* 2012). However, most of the previous studies just identified the patterns of thermal stratification and algal blooms, and the influence of the meteorology and hydrodynamics on thermal stratification in Xiangxi River was not indicated.

In this study, we researched the factors impacting on the thermal stratification and the relationship with the water quality variations through long-term monitoring in Xiangxi River. The degree of stratification was analyzed by calculating the dimensionless parameter of the relative thermal resistance to mixing (RTRM) from 2008 to 2010. Then we analyzed the correlation between the degree of stratification and various factors. Further, the relationship of thermal stratification with water quality had been assessed with the measured vertical profile data in 2010.

## STUDY AREA AND METHODS

### Study area

Xiangxi River, located in the western Hubei province, China, was selected for this study (see Figure 1). The length of Xiangxi River is 94 km, with a catchment area of approximately 3,095 km<sup>2</sup> that originates from the Shennongjia Forest Region, and the downstream connects with the Yangtze River. Because it is the nearest tributary to the Three Gorges Reservoir, the operation of the reservoir significantly affects the hydrodynamics and the nutrient distribution in Xiangxi River. On the impoundment of the Three Gorges Reservoir, the backwater would extend to almost 40 km when the water level of Three Gorges Reservoir reaches 175 m, then the area of the backwater forms the Xiangxi Bay (XXB). The maximum water depth is at the estuary, where it can reach almost 100 m in winter, while the upstream is just several meters. Because of the operation of the Three Gorges Reservoir, the flow velocity is very slow in Xiangxi Bay, which provides favorable conditions for algal growth, and algal blooms have been observed in spring and fall months since the impoundment of Three Gorges Reservoir.

Xiangxi River has a subtropical continental monsoon climate. The average annual air temperature is 17.1 °C, the highest air temperature usually occurs in August and the lowest air temperature usually occurs in February. The average annual wind speed is 0.73 m/s and it is usually stronger in spring and summer than in fall and winter. The average annual rainfall is almost 956 mm, with a range of between 900 mm and 1,200 mm, with most of the rainfall occurring during the summer months.

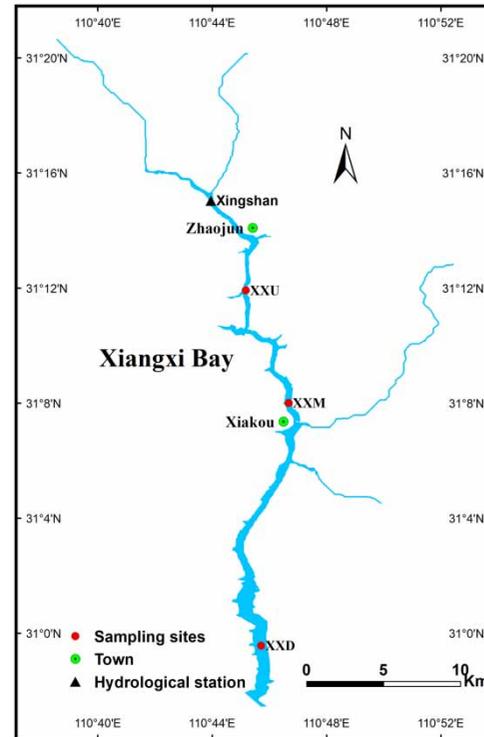


Figure 1 | Location of Xiangxi River.

### Field observations

Meteorological data were collected daily from the Xingshan Hydrological Station, with parameters including air temperature, wind speed, rainfall, and solar radiation. Daily downstream water elevations were obtained from the China Three Gorges Corporation. The water sample vertical profiles were measured by a Hydrolab DS5X multi-probe sonde (Hach, USA) with a vertical resolution of 1 m, with parameters including water temperature, dissolved oxygen (DO), Chlorophyll a, pH, conductivity, turbidity and the corresponding water depth. Water samples were measured weekly at sites XXU and XXD, and were measured daily at site XXM in 2010.

### Data analysis

The RTRM (Wetzel 2001) was used to assess the strength of thermal stratification, which can indicate the degree of stability and mixing in a reservoir.

$$\Psi = \frac{\rho_{z2} - \rho_{z1}}{\rho_4 - \rho_5} \quad (1)$$

where  $\psi$  is the RTRM (non-dimensional),  $\rho_{z1}$  and  $\rho_{z2}$  are water densities at a depth of  $z_1$  and  $z_2$ , respectively ( $\text{kg/m}^3$ ),  $\rho_4$  and  $\rho_5$  are water densities at 4 and 5 °C, respectively ( $\text{kg/m}^3$ ). Water density was calculated following Cole & Wells (2017):

$$\rho_T = 999.85 + 6.79 \times 10^{-2} * T - 9.10 \times 10^{-3} * T^2 + 1.00 \times 10^{-4} * T^3 - 1.12 \times 10^{-6} * T^4 + 6.54 \times 10^{-9} * T^5 \quad (2)$$

where  $\rho_T$  is water density ( $\text{kg/m}^3$ ) at temperature  $T$  (°C). The magnitude of RTRM is proportional to the strength of thermal stratification, a greater value means stronger thermal stratification, and the critical value is 50 for stratification according to the literature (Chimney et al. 2006).

Saturation DO concentration (mg/L) was calculated following Elçi (2008):

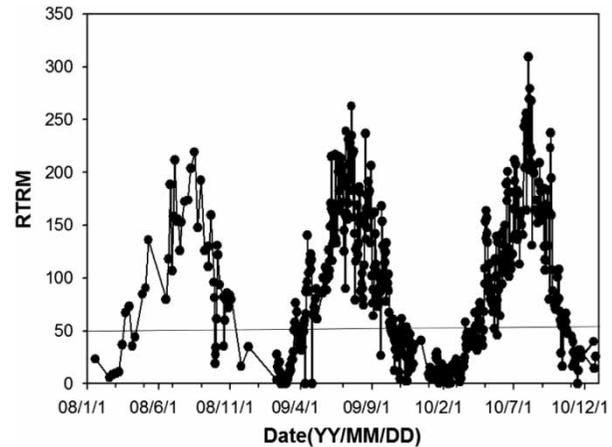
$$DO_{sat} = 0.0043T^2 - 0.36T + 14.48 \quad (3)$$

where  $DO_{sat}$  is the saturation DO concentration (mg/L), and  $T$  is water temperature (°C).

## RESULTS AND DISCUSSION

### Seasonal variation of the thermal stratification

Analysis of the intensity of thermal stratification was undertaken by calculating the dimensionless parameter of the RTRM between 2008 and 2010. The higher RTRM values almost always occurred in summer months, which indicated that the water body stratified strongly during this period. As shown in Figure 2, the average RTRM was 85 with a range from 0 to 309. The results showed that the strong stratification lasted from April to August, and decreased from September to the following February, which indicated that thermal stratification varied seasonally. The maximum value of RTRM was 221 in 2008, and the maximum value of RTRM was 309 in 2010, which all occurred in August. As for the duration of thermal stratification, it was almost the same from 2008 to 2010. Thermal stratification was formed in April, the strongest thermal stratification occurred in August, and the weakest thermal stratification occurred in February. The value of RTRM 0 usually occurred in February, which indicated the water body was well mixed during this period in Xiangxi River.



**Figure 2** | Seasonal variation of thermal stratification index (the RTRM) at site XXM of Xiangxi River during 2008–2010.

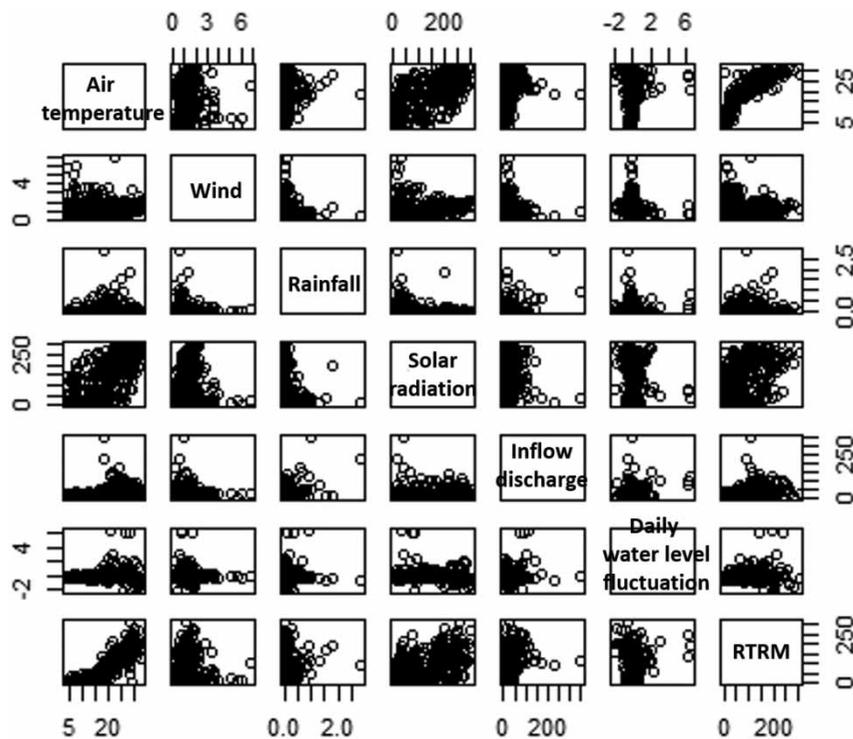
Thermal stratification was determined both by meteorological variables (such as air temperature, wind speed, solar radiation and so on) and hydrodynamics, and the seasonal variation of meteorological and hydrological factors was obvious in Xiangxi River (see Table 1). Through analysis of the relationship of the different factors, including air temperature, wind, rainfall, inflow discharge and daily water level fluctuations, with the thermal stratification, the results showed that the RTRM had a strong positive relationship with the air temperature ( $r = 0.86$ ,  $p < 0.05$ ); the relationship of RTRM with other meteorological variables such as wind ( $r = -0.09$ ,  $p < 0.05$ ), rainfall ( $r = 0.12$ ,  $p < 0.05$ ) and solar radiation ( $r = 0.48$ ,  $p < 0.05$ ) was not significant. This indicated that the thermal stratification was more closely related to air temperature, then to solar radiation. The relationship of RTRM with inflow discharge ( $r = 0.37$ ,  $p < 0.05$ ) and daily water level fluctuation ( $r = 0.10$ ,  $p < 0.05$ ) was not obvious either (see Figure 3). The results indicated that the meteorology was a more important factor affecting thermal stratification than the hydrodynamics in Xiangxi River.

Through analysis of the relationship of impact factors with thermal stratification, we found that the seasonal variation trend of the temperature difference between the surface layer and the bottom is basically consistent with the air temperature in Xiangxi River (see Figure 4). Other studies also found that air temperature was a major factor in water temperature. Arhonditsis et al. (2004) analyzed long-term records of temperature from Lake Washington and the results showed a warming trend for the overall

**Table 1** | Meteorological and hydrological data of Xiangxi River in different seasons in 2010

Months	Air temperature (°C)	Solar radiation (W/m <sup>2</sup> )	Inflow discharge (m <sup>3</sup> /s)	Water depth (m)	The temperature difference between surface and bottom (°C)
3–5	6–26 (16.9 <sup>a</sup> )	7–300 (133.5)	2–64 (14.9)	27	0–7 (3.1)
6–8	19–32 (26.9)	13–304 (192.1)	8–349 (51.0)	23	0–9 (5.6)
9–11	10–29 (19.2)	9–238 (122.0)	3–167 (22.5)	40	0–8 (2.8)
12–2	3–16 (7.4)	6–188 (64.7)	3–29 (9.9)	36	0–1.9 (0.8)

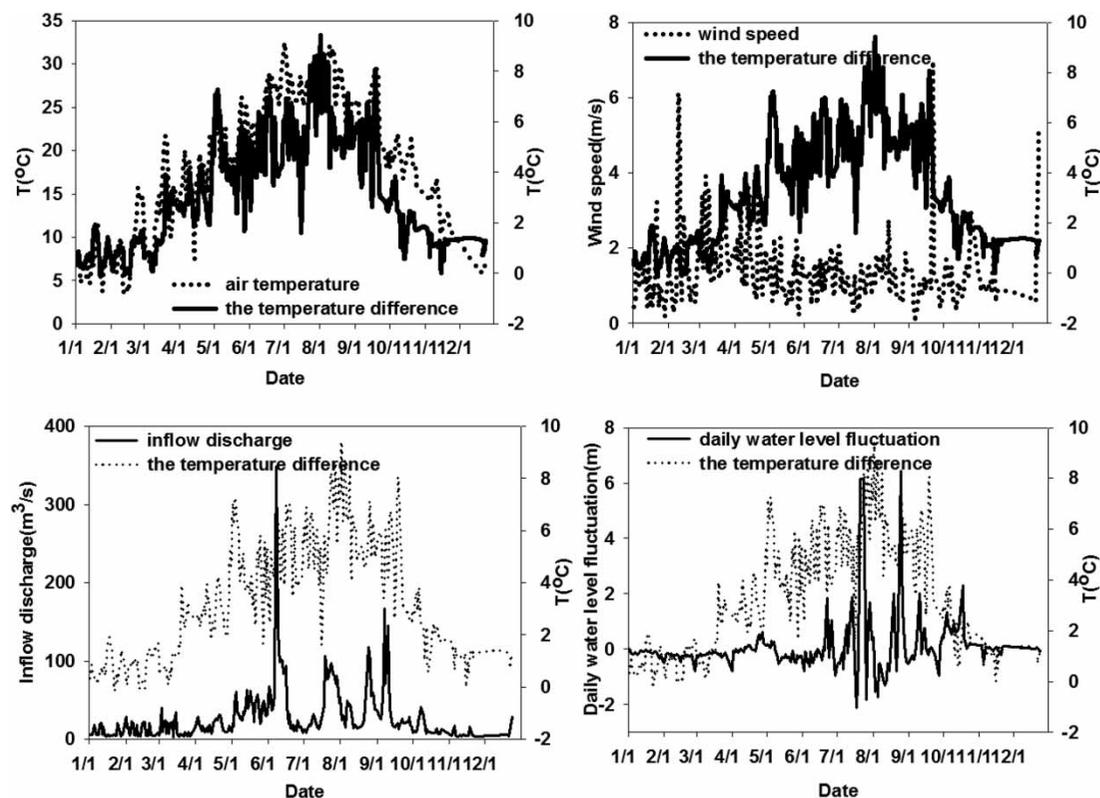
<sup>a</sup>The values in brackets are the mean value.

**Figure 3** | The relationship of different impact factors with RTRM in 2010.

lake temperature that was most strongly associated with air temperature. Shimoda *et al.* (2011) summarized that climate change influenced the structural properties of aquatic ecosystems in several north temperate deep lakes, and their analysis showed that the increase in the overall lake and (especially) epilimnetic temperature was the main response to external meteorological forcing. Schmid & Köster (2016) investigated the causes of excess warming of a representative deep and stratified lake and concluded that increased air temperature was attributed to 60% of the observed warming of spring and summer lake surface temperature, and increased solar radiation for the other 40%. These results

indicated that air temperature plays an important role in water temperature, which could induce the forming of thermal stratification.

The effect of wind on the water body was also an important factor in some cases, because wind could induce the wind current to influence the thermal structure and water quality in the water body. Kimura *et al.* (2016) studied a small shallow lake in response to meteorological conditions and the simulated results showed wind sheltering altered current patterns, especially in sheltered areas. Magee *et al.* (2016) found that freeze-over water temperature, hypolimnetic heating, and fall turnover date were more closely



**Figure 4** | The relationship of different impact factors with the water temperature difference of the surface layer and the bottom in site XXM in 2010.

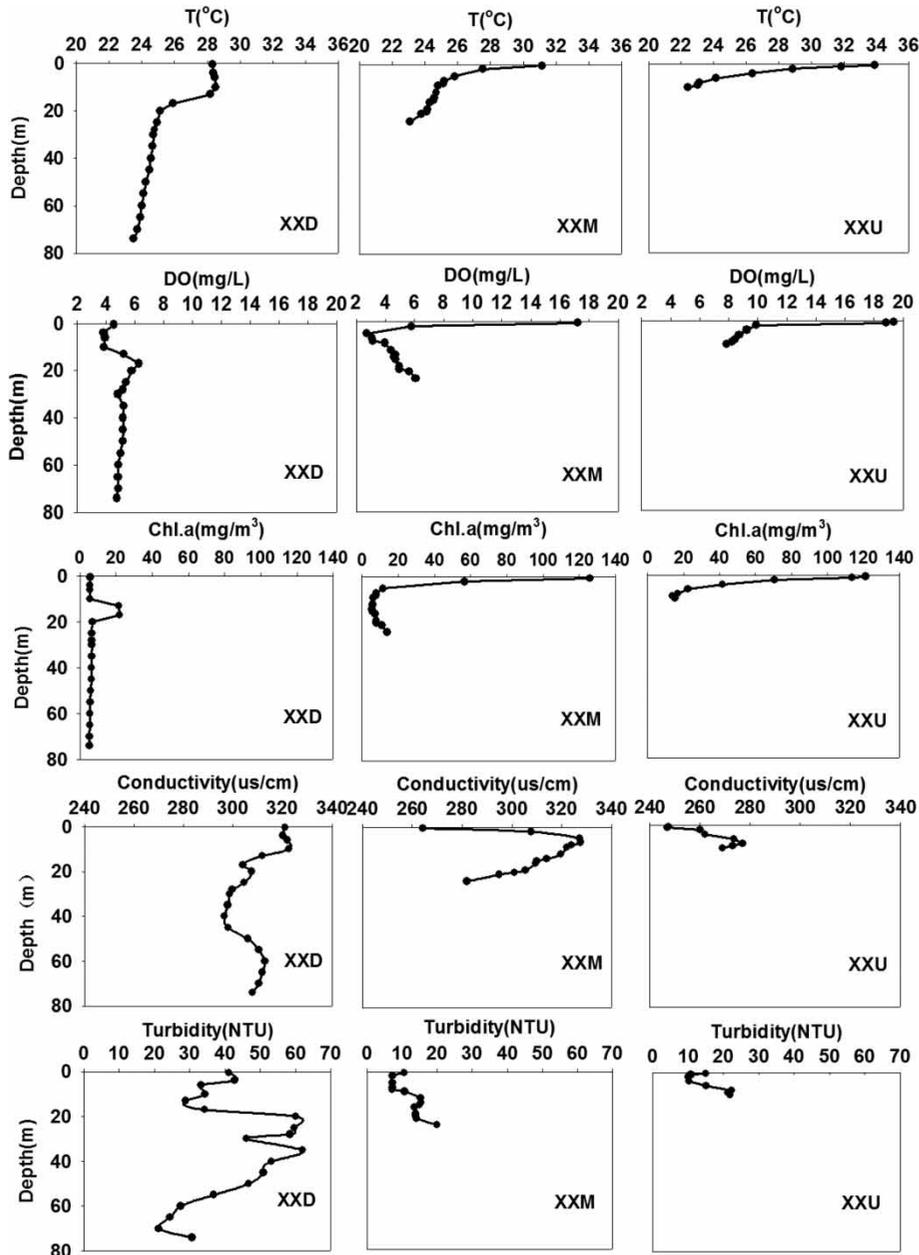
related to wind speed. Snorheim *et al.* (2017) studied three meteorological drivers (air temperature, wind speed and relative humidity) of hypolimnetic anoxia in a eutrophic, northern temperate lake and found that wind speed had a negative correlation with the anoxic factor. Through analysis of the relationship of the wind speed with the water temperature difference between the surface layer and the bottom in Xiangxi River, the results showed that the relationship between wind speed and the water temperature difference between the surface layer and the bottom was not obvious (see Figure 4). It may be caused by the relatively small water surface, irregular shape and the far distance of the measured site from the estuary of Xiangxi River, which could result in low wind stress at the water surface, and then weaken the effect of wind on thermal stratification in Xiangxi River.

The relationship of inflow discharge and daily water level fluctuation had a weak positive correlation with thermal stratification (see Figure 4). Some studies found that the location of the withdrawal could affect the thermal stratification structure in the reservoir (Çalışkan & Elçi 2008; Ma *et al.* 2008a, 2008b), which may be because the effect of the withdrawal

on thermal stratification in the reservoir was direct, while the influence of the water level fluctuation on thermal stratification in Xiangxi River was limited.

### Variation of water quality with thermal stratification

Analysis of the water quality and the thermal stratification showed water quality parameters accompanied the patterns of thermal stratification. The water temperature difference between the surface layer and the bottom increased from site XXD to site XXU, which indicated that thermal stratification intensity increased from downstream to upstream in Xiangxi River. The concentrations of DO and Chlorophyll *a* were both higher in the upper water body than that at the bottom in Xiangxi River. The vertical distribution of conductivity and turbidity also showed stratification in the middle part and the upstream of Xiangxi River, there was no significant characteristic in the downstream, which may be caused by the frequent exchange of water between Yangtze River and Xiangxi River.



**Figure 5** | Variation in vertical profiles of water temperature, DO, Chl.a, conductivity, turbidity from downstream (XXD) to upstream (XXU) of Xiangxi River on August 9th in 2010.

DO represents the process of oxygen consumption and reoxygenation in a water body. DO concentration profiles throughout the Xiangxi River were stratified to some degree (see Figure 5). The water body at site XXD was more poorly oxygenated than that at the site XXU. The surface DO concentration at site XXD was less than 5 mg/L and the maximum value was 6.29 mg/L at a depth of 17 m, which is also the bottom of the thermocline; the

average DO concentration was 4.95 mg/L. Since the DO saturation concentration at the surface should be 7.73 mg/L, it indicated that DO saturation concentration was almost less than 50% throughout the waterbody. As shown in Figure 5, the highest DO concentration occurred at site XXU, and the maximum value could reach 19.35 mg/L at the water surface layer, where the water surface DO concentration exceeded the concentration of the DO saturation, and the

mean DO concentration was 11.32 mg/L at site XXU. Because of the thermal stratification, some research results showed that stratification could develop anoxia in the hypolimnion (Elçi 2008; Zhang *et al.* 2015). While the case may be different in Xiangxi River, the water with high dissolved oxygen in the upstream of the river flowed down to the downstream, and could supply some DO at the bottom, which could reduce anoxia at the bottom.

The vertical profiles of Chlorophyll a were consistent with the vertical distribution of DO concentration. Mean Chlorophyll a concentration throughout the water body at site XXD was 7.7 mg/m<sup>3</sup> with a maximum value of 22.03 mg/m<sup>3</sup> at a depth of 17 m; the average Chlorophyll a concentration throughout the water body at site XXM was 20.09 mg/m<sup>3</sup> with a maximum value of 126.05 mg/m<sup>3</sup> at the water surface; and the average Chlorophyll a concentration throughout the water body at site XXU was 51.93 mg/m<sup>3</sup> with a maximum value of 121.18 mg/m<sup>3</sup> at the water surface (see Figure 5). The Chlorophyll a stratification was more obvious from the downstream to the upstream in Xiangxi River. The depth of the thermocline was from 13 m to 17 m at site XXD, 7 m at site XXM, and 7 m at site XXU. There was a tendency for Chlorophyll a to increase at the water surface layer from downstream to upstream of Xiangxi River. The low concentration of Chlorophyll a in the downstream may be caused by the frequent water exchange between Yangtze River and Xiangxi River. The concentration of Chlorophyll a was the main indicator for algal blooms; Liu *et al.* (2012) found that thermal stratification was the main reason for algal blooms in spring in Xiangxi River. So the distribution of Chlorophyll a with thermal stratification could be used as an indicator to evaluate the algal blooms.

The conductivity could represent the total dissolved solids in the water body. As shown in Figure 5, the vertical distribution of conductivity indicated that the conductivity was very low at the surface and the maximum value occurred in the depth of the thermocline. The turbidity could be affected by algae and suspended solids; the vertical distribution of the turbidity indicated that the minimum value was in the depth of the thermocline in the upstream and middle part of Xiangxi River. This showed that the vertical distribution of conductivity was opposite to that of Chlorophyll a; the low concentration of conductivity in the upper water may be due to algal consumption. The vertical

distribution of turbidity also showed stratification in the water body, and the minimum value was in the depth of the thermocline. This may be caused by the algae in the upper water body and suspended solids in the lower water body. Elçi (2008) found that turbidity was highly affected by thermal stratification and strong winds could increase the turbidity in the water body. As the effect of wind on thermal stratification was small, the turbidity profile was mainly affected by thermal stratification in Xiangxi River.

## CONCLUSIONS

In this study, results from field monitoring showed that the RTRM increased from April to August in Xiangxi River. This indicated that the water temperature difference between the water surface and the bottom increased with the surface layer water temperatures quickly warming, which could result in stronger thermal stratification and greater stability in the water body during this period.

Through the analysis of the factors that affect the thermal stratification, the results indicated that both the meteorology and hydrodynamics can affect thermal stratification in Xiangxi River, while thermal stratification was more sensitive to the meteorological factors. It showed that air temperature was more closely related to thermal stratification, the second impact factors were the solar radiation, and then the inflow discharge, and the relationship between thermal stratification and other factors was not obvious in Xiangxi River.

The strong thermal stratification could influence the vertical distribution of the water's chemical characteristics, and the results showed that water quality was highly affected by thermal stratification and the Chlorophyll a concentration had a close relationship with thermal stratification and DO concentration. These results will aid in the understanding of ecosystems and provide useful information to control the algal blooms in Xiangxi River.

## ACKNOWLEDGEMENTS

This research was supported financially by the Natural Science and Technology Major Special Program of China (Grant No. 2014ZX07104-005-02), the International Science and Technology Cooperation Program of China

(Grant No. 2014DFE70070), and the authors would like to thank all of the members of the Eco-hydrodynamics group in the Hubei University of Technology and the Three Gorges University for participating in the field monitoring.

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