Quaternary International 208 (2009) 138–144

Contents lists available at ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

Seasonal dynamics of suspended solids in a giant subtropical reservoir (China) in relation to internal processes and hydrological features

Yaoyang Xu[a,b], Qinghua Cai[a,*], Meiling Shao[a,b], Xinqin Han[a,b], Ming Cao[a,b]

[a] State Key Laboratory of Freshwater Ecology and Biotechnology, Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan 430072, P.R. China
[b] Graduate University of Chinese Academy of Sciences, Beijing 100039, P.R. China

ARTICLE INFO

Article history:
Available online 12 February 2009

ABSTRACT

To explore the factors regulating seasonal variation of total suspended solids (TSS) and its two fractions in a giant dendritic reservoir (the Three-Gorges Reservoir of China, TGR) in the subtropical monsoon region, suspended solids, chlorophyll *a* (a surrogate for lake internal processes) and water residence time (an index of hydrologic flushing) were examined monthly from August 2005 to July 2006. TSS ranged from 0.6 to 200.3 mg/L and from 0.6 to 78 mg/L respectively in the mainstream and in a typical reservoir-bay (the Xiangxi Bay) of the TGR,. TSS exhibited a typical seasonal pattern in the mainstream rather than in the Xiangxi Bay of the TGR. The fraction of non-volatile suspended solids (NVSS) was often more dominant in the mainstream than in the Xiangxi Bay, especially during the flood season. Regressions analysis showed that 87.6% and 89.8 % of seasonal variation in TSS and NVSS of the mainstream, respectively, are explained by water residence time . In contrast, suspended solids (particularly volatile suspended solids, VSS) of the Xiangxi Bay displayed significant correlation with algal biomass, and no correlation with hydrological parameters. It implies that the Xiangxi Bay was a more autochthonous system than the mainstream of the TGR where exogenous influences were the more determinant factors.

1. Introduction

Most large rivers in East Asia, North America and Europe are regulated by channelization or hydroelectric dams (Thornton et al., 1990). River regulation and damming will alter the local environment, affecting not only the hydrology but also the physical, chemical, and biological characteristics (Friedl and Wüest, 2002). The impacts of damming on aquatic ecosystem have been extensively studied (e.g., Baxter, 1977; Rosenberg et al., 1997). One of the major concerns of these studies is the disruption on the system's biogeochemical behavior (Friedl and Wüest, 2002). Total suspended solids (TSS) and its two components, volatile (VSS) and non-volatile fractions (NVSS), are generally regarded as important environmental parameters because they can reflect the biogeochemical process of aquatic ecosystems (Wehyenmeyer et al., 1997). As an important component of reservoir seston, NVSS are largely determined by exogenous influences as modified by morphology and hydrology, and can be a valid proxy of allochthonous suspended solid of fluvial origin (An and Jones, 2000). VSS as organic seston can reflect the characteristics of autochthonous production, which is regulated by nutrient input and water residence time (Jones and Knowlton, 2005). Thus, both fractions of reservoir suspended solids can be useful to judge the property (allochthonous or autochthonous dominated) of a reservoir system.

Residence time is determined by the average length of time that water remains within the boundaries of an aquatic system, and is a key parameter controlling the biogeochemical behavior of aquatic ecosystems (Rueda et al., 2006). This parameter has been proposed in the published literature to explain the extent to which these systems are self-organized or dominated by exogenous influences (Søballe and Kimmel, 1987). Generally, the increase of residence time evokes increases in autochthonous primary production and decreases in particles and turbidity when changing a stretch of a river into a reservoir (Friedl and Wüest, 2002). Thus, impoundments have the potential to induce the change of a water body from an allochthonous-dominated system to a more lacustrine system, where autochthonous production of organic matter dominates. However, it is difficult to give precise predictions of the impacts of damming on river ecosystem in subtropical regions, that have unique hydrological characteristics influenced by the summer Asian monsoon that differs from many other regions. For example, monsoons produces short hydraulic residence times and high inorganic suspended in some Korean reservoirs (An and Park, 2002). In particular, some reservoirs are characterized by the

---

[*] Corresponding author.
E-mail address: qhcai@ihb.ac.cn (Q. Cai).

1040-6182/$ – see front matter © 2009 Elsevier Ltd and INQUA. All rights reserved.
doi:10.1016/j.quaint.2008.12.019

dendritic form that usually includes many long and narrow reservoir-bays, which were the former downstream stretches of inflow tributaries prior to the impoundments of the reservoirs. In dendritic rivers, the mainstream damming impacts on both the mainstream itself and its inflow tributaries, which would make further research to estimate the impacts of this kind of large-scale dams on the biogeochemical process of aquatic ecosystems necessary.

The Three-Gorges Reservoir (TGR), located in the mainstream of the Yangtze River, is a typical representative of giant dendritic subtropical reservoirs. There were already academic concerns about the aquatic ecosystem and its biogeochemical behavior of the Yangtze River and the TGR after the damming. The impacts of the Three-Gorges Dam (TGD) on sediment transport in the Yangtze River have been widely researched (Chen et al., 2008). Studies showed that the TGD construction had remarkably reduced the sediment loads into the mid-lower Yangtze River (Dai et al., 2008). Previous studies have attributed the impoundments as the main cause for the increase of autochthonous production in the reservoir-bays of the TGR (Ye et al., 2006, 2007), but it is still difficult to accurately assess whether or not the TGR impoundment changes the water body from a river-like system to a lake-like system.

During a one-year period after the first impoundment, suspended solids and algal biomass (expressed as chlorophyll *a*) were investigated in the mainstream of the TGR and the Xiangxi Bay (located approximately 32 km upstream from the TGD), which is one of the largest reservoir-bays of the TGR (Cai and Hu, 2006; Huang et al., 2006). The main objectives of this study are: (i) to determine the key factor regulating the seasonal dynamics of TSS and its compositions; (ii) to estimate the relative importance of allochthonous vs. autochthonous sources after the impoundment; (iii) to develop empirical models for predicting the seasonal dynamics of suspended solids after the last impoundment.

2. Investigation area, data and methods

With a length of over 6300 km, the Yangtze River is one of the largest rivers in the world (Chen et al., 2008), where a subtropical monsoon climate prevails (Jiang et al., 2006). The summer monsoon starts to influence the TGR in May and generally retreats in October (Jiang et al., 2006). Consequently, the inflow discharges of the TGR is mostly concentrated from June to September (the flood season), accounting for 61% of the annual total (Huang et al., 2006). Upon its planned completion in 2009, the TGR will be one of the largest man-made lakes in the world, with a capacity of 3.93×10^{10} m^3, a water level of 175 m and a surface area of 1080 km^2 (Wang et al., 1997; Huang et al., 2006). In addition, forty reservoir-bays (watershed area of individual bay >100 km^2) will eventually be formed by the flooding of the reservoir, and water area of these bays will account for 1/3 of the total water area of the TGR (Cai and Hu, 2006; Huang et al., 2006). After the first impoundment of the TGR in June 2003, the reservoir capacity and the water level had reached ca. 1.42×10^{10} m^3 and 139 m a.s.l., respectively (Huang et al., 2006), and the lower stretches of many inflow tributaries were inundated by the reservoir and formed reservoir-bays (Cai and Hu, 2006; Huang et al., 2006). Among them, the Xiangxi River is one of the largest tributaries of the TGR. After impoundment, the lower 25-km stretch of this river became the Xiangxi Bay, with a watershed area of 3095 km^2. Seasonal changes in suspended particles and its seasonal flooding account for the operational pattern of the TGR, i.e., storing clear water after the flood season and releasing muddy water by lowering the water level of the reservoir during the flood season (Shao et al., 2008). For example, after the first impoundment, the water level fluctuated between 135 m a.s.l. (flood season) and 139 m a.s.l. (the rest of a year); after the planned last impoundment in 2009, the water level will fluctuate between 145 m a.s.l (flood season) and 175 m a.s.l. (the remaining months of a year).

Five transverse transects (CJ01–CJ05) were set up along the mainstream of the TGR, over a distance of approximately 40 km (Fig. 1). CJ01 was just upstream from the dam, and CJ05 was upstream from the mouth of the Xiangxi Bay. Three sites (left, middle and right) were set up in each transect, except for the CJ03 site due to the narrow channel. Simultaneously, eight sampling sites (XX01–XX08) were surveyed along a lengthways direction of the Xiangxi Bay in the opposite direction of inflow, over a distance of approximately 25 km. XX01 was located close to the mouth of the bay, and XX08 was located near the end of the Bay. We were unable to sample the site XX08 during the flood season, because low water levels in the mainstream prevented our sampling boat from reaching the site. The site XX08 was excluded from our analysis, because no integrated annual samples were collected. Among the eight sampling sites, XX01 and XX05 were also sampled along their transverse transects, including the left, middle and right sites (Fig. 1). During each survey, the sampling sites were relocated using a geographical positioning system (GPS).

Twelve surveys were performed monthly from August 2005 to July 2006. Suspended solids were concentrated by filtering a known volume of water through a weighed pre-ignited glass fiber filter (Whatman type GF/F). An additional known volume of water was filtered through a microfilter (0.8 μm) for chlorophyll *a* (chl. *a*) determination. All the filters were immediately placed in a dark cooler and packed in ice until the laboratory analysis. TSS and its two fractions were measured according to a Standard Operating Procedure for Total Suspended Solids Analysis (U.S. EPA, 1997). The chl. *a* concentrations were determined on a spectrophotometer (Shimadzu UV-1601, Japan) following the procedure of lake observation (Huang et al., 2000).

The data for the inflow discharge and the water level of the TGR were downloaded from the website of China Three Gorges Project

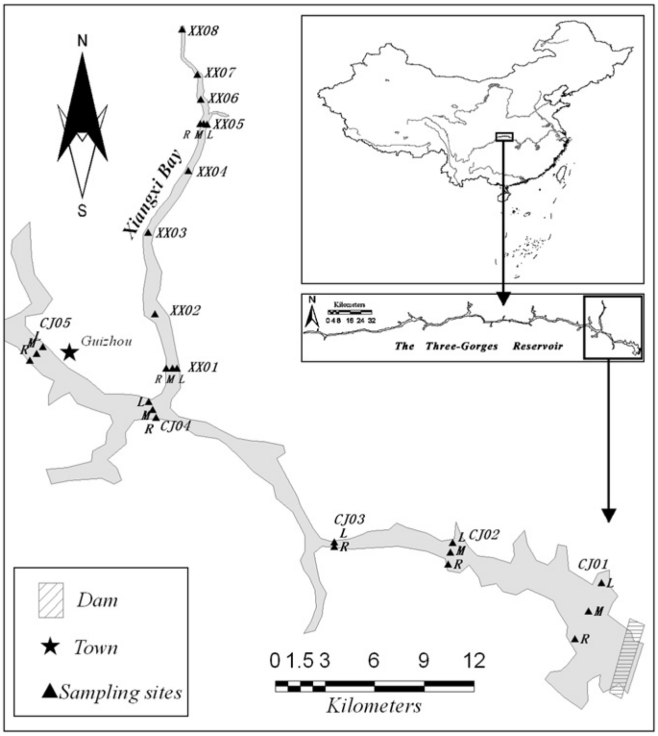

Fig. 1. Location of the sampling sites in the mainstream of the Three-Gorges Reservoir and the Xiangxi Bay.

Corporation. In addition, discharge data of the Xiangxi River after the impoundment was provided by the Xingshan Hydrological Station, which is a station upstream from XX08. The reservoir capacity of the TGR and the Xianxi Bay in the given water level were mainly obtained from Huang et al. (2006). The estimated value of water residence time is generally calculated by relating the annual amount of water passing through the reservoir with the volume of the whole reservoir. Here, the residence time for each month of a year was calculated as (modified from George and Hurley, 2003):

$$\tau = \frac{V_T}{Q_T},$$

Where τ is water residence time (days) for each month; V_T is the monthly volume (m^3) of the reservoir for $T = 1 \ldots 12$; Q_T is the monthly average inflow discharge ($m^3\,d^{-1}$).

To describe the temporal-spatial pattern of TSS and %NVSS, we drew a time-distance diagram using the Inverse Distance Weighted (IDW) in Golden Software Surfer 8.0. The differences in chlorophyll *a* and water residence time between the mainstream and the Xiangxi Bay were examined using nonparametric test and paired samples *T*-test, respectively. We explored the contribution of chl. *a* on suspended solids using an association analysis. We also performed association tests to examine the relationships between suspended solid variables and water residence time. After exploratory examination, we further modeled the relationships between residence time and suspended solid variables with power regression, linear regression and inverse regression. All of the association tests performed were 2-tailed Pearson correlation tests. Significant tests (paired samples *T*-test and nonparametric test), association analysis and regression model were all performed in the software SPSS 13.0.

3. Results and discussion

3.1. Suspended solids and algal biomass

In the mainstream of the TGR, TSS ranged from 0.6 to 200.3 mg/L, with a mean of 21.3 mg/L ($n = 153$). Mean monthly concentrations of TSS and NVSS ranged from 1.5 to 71.8 mg/L and 0.7 to 66.5 mg/L, respectively, and both displayed a clear seasonal trend, with a peak during the flood season. From November to April, the concentrations of TSS were < 4 mg/L, whereas the concentrations were > 25 mg/L from July to October (Fig. 2). NVSS was a dominant fraction of TSS from May to September ($>$80%), while VSS appreciably dominated from January to March ($\approx$60%) (Fig. 2). As mentioned above, the seasonal pattern of flooding in the Yangtze River was derived from monsoon precipitation. Therefore, large amounts of silt-laden water were brought by floods. In the Xiangxi Bay, there were no seasonal patterns of suspended solids (Fig. 3). The mean concentrations of TSS were 8.0 mg/L ($n = 118$), ranging from 0.6 to 78 mg/L. In winter, TSS concentrations were also < 4 mg/L. The concentrations ranged from 13 to 25 mg/L in March, July and September, and ranged between 4 and 9 mg/L in the other months. The visible difference between Figs. 2 and 3 clearly showed that the fraction of NVSS in TSS was always larger in the mainstream than in the Xiangxi Bay.

Algal biomass significantly differed between the mainstream and the Xiangxi Bay (nonparametric test, $p < 0.001$). The average chl. *a* concentrations of the mainstream and the Xiangxi Bay were 2.54 μg/L ($n = 153$, ranging from 0.03 to 116.67 μg/L) and 15.70 μg/L ($n = 118$, ranging from 0.38 to 120.46 μg/L), respectively (Fig. 4). In the mainstream, there was no significant correlation between algal biomass and suspended solid variables, whereas the chl. *a* concentrations of the Xianxi Bay did correlate to TSS, VSS and %VSS, as shown by Pearson's correlation test (Table 1). VSS was usually positively correlated with chl. *a* in natural lakes or lake-like systems, i.e., autochthonous systems (Wehyenmeyer et al., 1997). Jones and Hoyer (1982) point out that the correlation between VSS and chl. *a* ($r = 0.97$) indicated that they are fundamentally interchangeable as indices of algal biomass in autochthonous systems. In Missouri reservoirs, the strongest influence of watershed features on TSS was also mediated through the control of algal growth (Jones and Knowlton, 2005). The present study showed that, compared with the mainstream, the Xiangxi Bay was a more lacustrine system due to the significant relationships between chl. *a* and VSS.

3.2. Residence time and reservoir classification

Residence time was significantly shorter in the mainstream of the TGR (5–35 days) than in the Xiangxi Bay (22–219 days; Fig. 5;

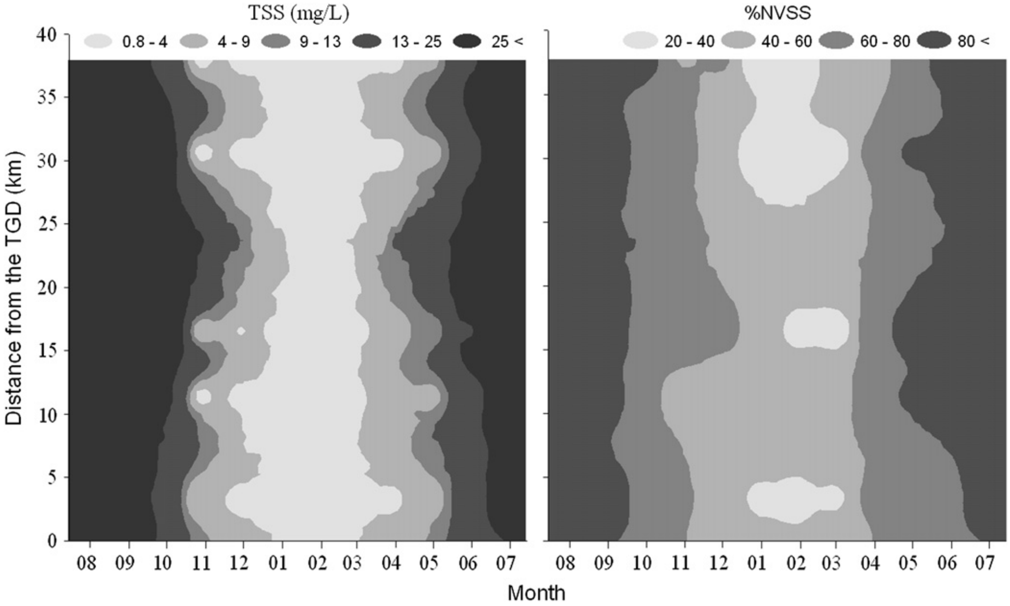

Fig. 2. Temporal–spatial distributions of TSS and %NVSS in the mainstream of the TGR.

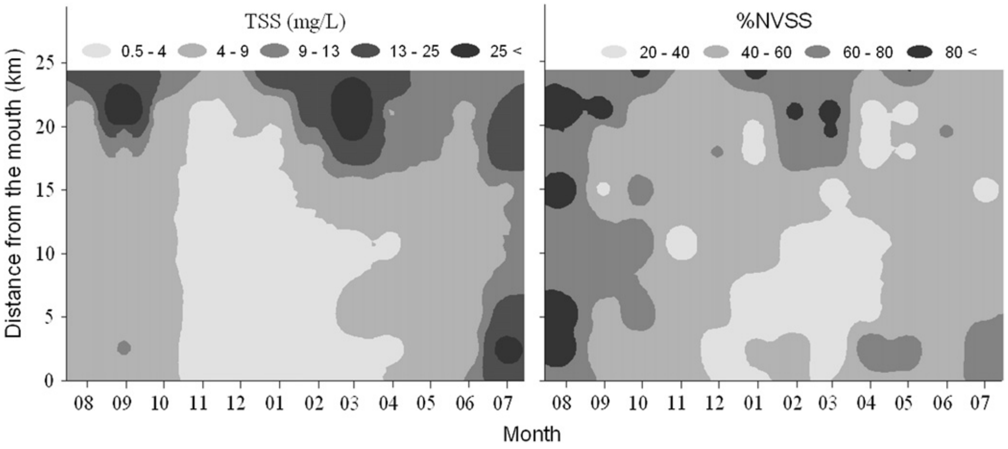

Fig. 3. Temporal–spatial distributions of TSS and %NVSS in the Xiangxi Bay.

paired samples *T*-test, $p < 0.001$). Following the classification of Straškraba and Tundisi (1999), a reservoir with a residence time less than 20 days can be grouped into Class A, i.e., a fully mixed system with river characteristics, and a reservoir with a residence time ranging between 20 and 300 days should be grouped into Class B, i.e., an intermediate system between rivers and natural lakes has both river-like and lake-like characteristics. If the residence time is longer than 300 days, the reservoir should be identified as Class C, i.e., a steady system with natural lake characteristics that may be characterized by well developed stratification. According to this criterion, the mainstream of the TGR belonged to Class A during summer and autumn (May–November) and belonged to Class B during the other months. The Xiangxi Bay belonged to Class B throughout the year (Fig. 5), which suggests that the Xiangxi Bay was similar to natural lake more than the mainstream, where the riverine dominance still existed.

Further, both in the mainstream and in the Xiangxi Bay of the TGR, the concentrations of total nitrogen and total phosphorus had already exceeded the threshold values of eutrophic state (Cai and Hu, 2006). Therefore, algal blooms had the potential to occur both in the mainstream and in the Xiangxi Bay. However, no algal blooms were reported in the mainstream until now, whereas the Xiangxi Bay was one of the most representative of eutrophied reservoir-bays of the TGR, and algal blooms often occurred in the bay, as well as the other bays (Cai and Hu, 2006). It is reasonable to believe that water residence time played a key role for the difference between the mainstream and the Xiangxi Bay as noted by Søballe and Kimmel (1987), who demonstrated that water residence time was a useful system-level index, having ecological implications for rivers and natural lakes. Their study showed that algal biomass per unit of phosphorus significantly rose as water residence time increased from river to natural lakes. Thus, the mainstream of the TGR to some extent was still an allochthonous dominated system, whereas the Xianxi Bay was changing from an allochthonous dominated system to a more autochthonous system.

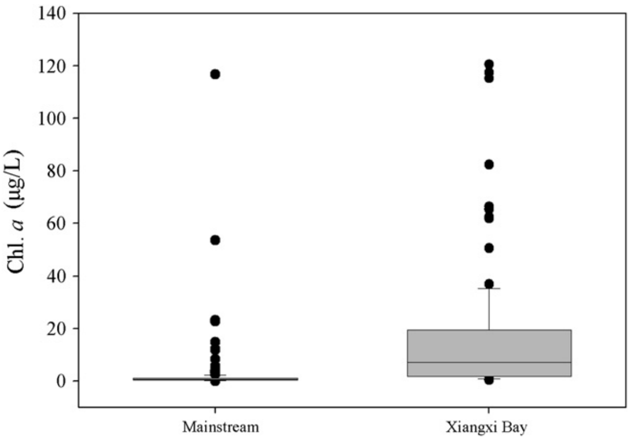

Fig. 4. Boxplot for chl. *a* concentration in the mainstream and the Xiangxi Bay of the TGR.

3.3. Relationships between residence time and suspended solids

Residence time of the mainstream was negatively correlated with the suspended solid variables, whereas there was no correlation between residence time and TSS and its two fractions in the Xiangxi Bay (Table 2), suggesting that water residence time can explain the seasonal variation in TSS, especially NVSS in the mainstream. It is well known that water residence time can be an index of hydrological flushing. In the mainstream, hydrological flushing was a main factor regulating suspended solid concentrations, suggesting that suspended solids in the mainstream were mainly from the drainage basin. It indicated that the direct influence of allochthonous input on the mainstream still dominated. However, the situation in the Xiangxi Bay was obviously different from that in the mainstream. In the Xiangxi Bay, both TSS and VSS were significantly correlated with chl. *a*, instead of water residence time. This observations suggest that the prolonged water residence time of the Xiangxi Bay evoked particle settling, turbidity decreases and an increase of light transmissivity, as well as enhancing *in-situ* primary production. Therefore, the water storage of the reservoir mediated the direct impacts of allochthonous inputs on TSS in the Xiangxi Bay.

Table 1
Pearson's correlations between algal biomass (chl. *a*) and suspended solid variables.

Variable	Correlation coefficient	
	Mainstream	Xiangxi Bay
TSS	0.054	0.333[a]
NVSS	0.043	0.152
VSS	0.024	0.662[a]
%VSS	−0.058	0.392[a]

[a] Correlation is significant at the 0.01 level (2-tailed).

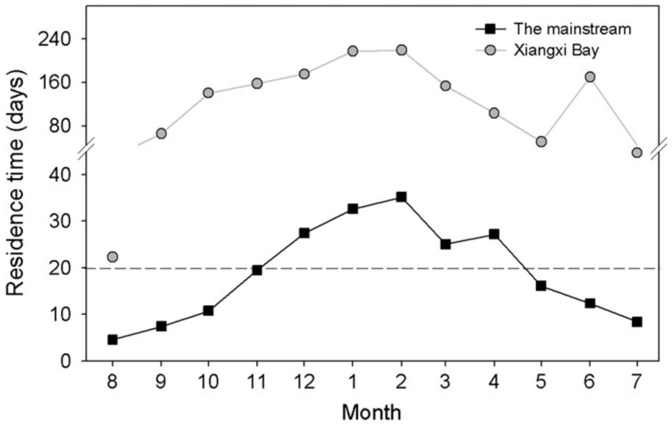

Fig. 5. Temporal changes of water residence time (τ) in the mainstream and the Xiangxi Bay of the TGR after the first impoundment of the reservoir. The dashed line indicates the threshold value ($\tau = 20$ days) for the classification of Class A and Class B.

Table 2
Pearson's correlations between residence time and suspended solid variables.

Variable	Correlation coefficient	
	Mainstream	Xiangxi Bay
TSS	−0.810**	−0.397
NVSS	−0.803**	−0.347
VSS	−0.678**	−0.450

*Correlation is significant at the 0.05 level (2-tailed), ** at the 0.01 level (2-tailed).

In the mainstream, the relationships between TSS, NVSS and residence time could be modeled by power regression (Table 3). Furthermore, linear regression between %NVSS and residence time showed that an equivalent NVSS and VSS could be found at $\tau = 27$ days in the mainstream of the TGR (Table 3, Fig. 6). In the Xiangxi Bay, the equivalent NVSS and VSS could be found at $\tau = 119$ days, as shown by inverse model (Table 3, Fig. 6). Accordingly, VSS of the mainstream and the Xiangxi Bay will be dominant when $\tau > 27$ days and $\tau > 119$ days, respectively.

Table 3
Relationships between TSS, NVSS, %NVSS and residence time (τ) in the mainstream and the Xiangxi Bay.

	Models	N	r^2	p
Mainstream	$\text{TSS} = 3342.529\tau^{-2.175}$	12	0.876	<0.001
Mainstream	$\text{NCSS} = 7581.2869\tau^{-2.619}$	12	0.898	<0.001
Mainstream	$\%\text{NVSS} = 104.63 - 1.98\tau$	12	0.859	<0.001
Xiangxi Bay	$\%NVSS = 42.728 + \frac{863}{\tau}$	12	0.655	<0.001

3.4. Predictions for suspended solids

The estimated residence time of the mainstream will range from 5 to 85 days (with an annual mean of 40 days) when the maximal reservoir capacity and water level will reach 3.93×10^{10} m^3 and 175 m a.s.l., respectively after the last impoundment of the TGR in 2009, which is significantly longer than the present residence time (paired samples T-test, $p < 0.001$). A similar pattern was also found in the Xiangxi Bay and the estimated residence time ranged from 27 to 564 days, with an annual mean of 264 days (Fig. 7). According to the estimated value, the mainstream of the TGR will be a fully mixed system (Class A) from June to September. During the rest of the year, the mainstream will change to be an intermediate system (Class B). Compared with the present status, the limnological types of the mainstream will not change dramatically (Fig. 7a vs. Fig. 5). In the Xianxi Bay, however, there will be a significant shift in limnological types (Fig. 7b vs. Fig. 5). From October to March, the Xiangxi Bay will be a system like a natural lake, whereas the bay will be an intermediate system (Class B) during the other months of the year. However, thermal stratification of a natural lake always has seasonal transitions in relation to many factors, such as weather conditions. Therefore, further research will be necessary to explore the duration of stratification in the TGR, although the Xiangxi Bay may be stratified from October to March, as indicated by the reservoir classification.

We predicted the TSS and NVSS concentrations of the mainstream after the last impoundment by the empirical models in Table 3. However, the concentrations of TSS and NVSS will not significantly decrease compared with the present concentrations (paired samples T-test, $p > 0.05$ in two cases; Fig. 8). Presumably, it was strongly related to the operational pattern of the TGR. It is well known that the seasonal patterns of sediment loadings of the Yangtze River are closely related to the summer monsoon, which initiates the coming of the flood season (Jiang et al., 2007 ;Dai et al., 2008). During this period, the water level of the TGR will lower to 145 m a.s.l. as planned. Consequently, residence time in the mainstream will still be short during the flood season after the last impoundment (Fig. 7a). In addition, residence time during the flood season will be lower than the threshold value of 50% NVSS dominance ($\tau = 27$ days, Fig. 7a). It implied that allochthonous inputs may still be the main control for TSS and its composition in the mainstream.

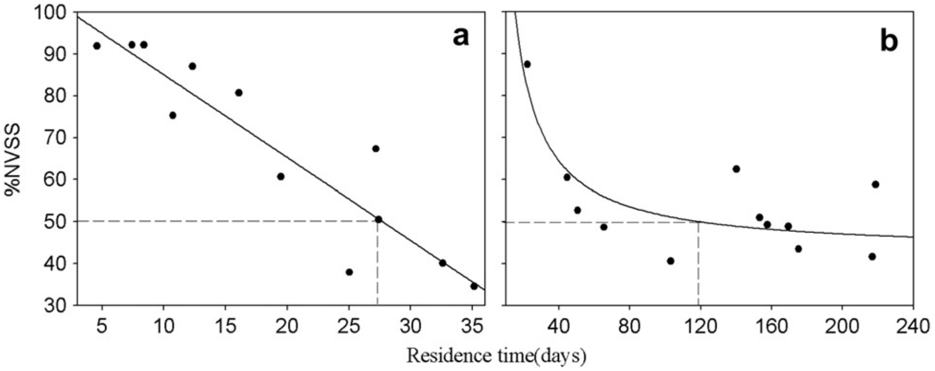

Fig. 6. Linear regression in the mainstream of the TGR (a), and inverse regression in the Xiangxi Bay (b) between residence time (τ) and %NVSS. The dashed line indicates a 50% probability of NVSS dominance.

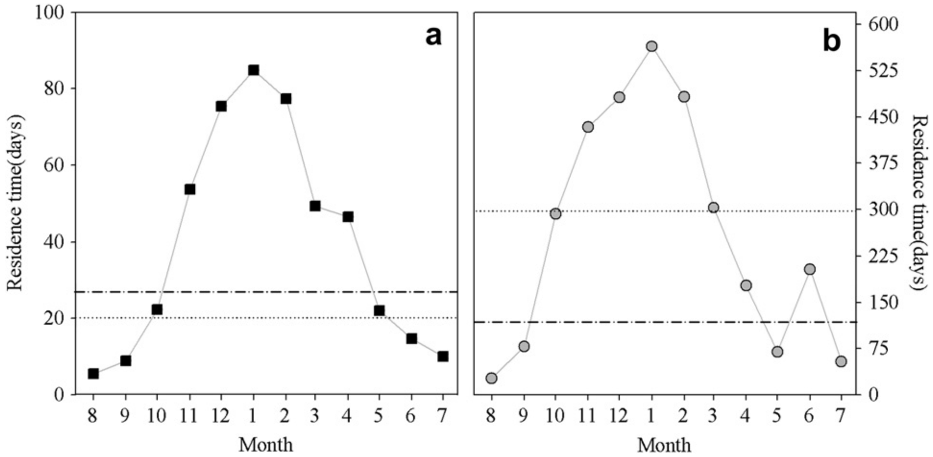

Fig. 7. The estimated value of residence time (τ) in the mainstream (a) and the Xiangxi Bay (b) of the TGR after the last impoundment of the reservoir in 2009. The dash-dot lines indicate a 50% NVSS dominance in the mainstream ($\tau = 27$ days) and the Xiangxi Bay ($\tau = 119$ days), respectively. The dotted line indicates the threshold value ($\tau = 20$ days) for the classification of Class A and Class B, or the threshold value ($\tau = 300$ days) for the classification of Class B and Class C.

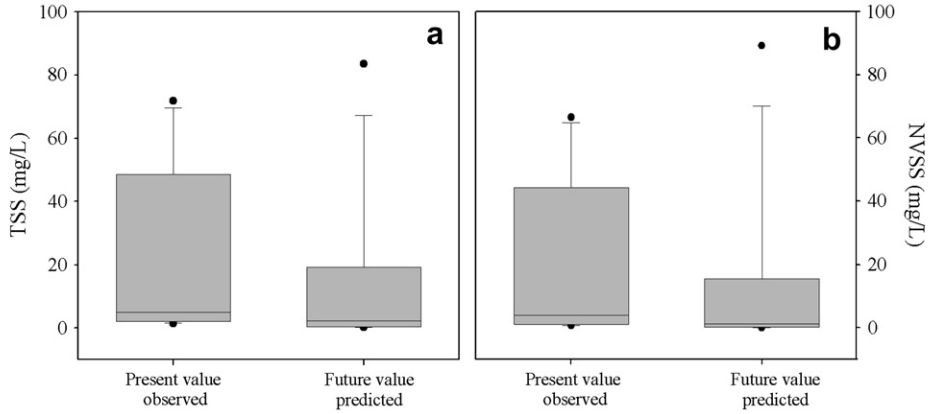

Fig. 8. Boxplot for the present observed value and the predicted future value of mean TSS (a) and NVSS (b) in the mainstream of the TGR. Dots represent extreme values, and lines represent 25%, 50% and 75%.

In most reservoir-bays, the prolonged residence time may further induce increases in algal biomass. In terms of residence time, the Xiangxi Bay will be a more lacustrine system (Class C) during the half of the year, and the residence time will be longer than the threshold value of 50% NVSS dominance ($\tau = 119$ days, Fig. 7b) during the whole spring, suggesting that reservoirs-bays of the TGR will be more autochthonous systems. The spring is often favorable for algal blooms in most reservoir-bays of the TGR after the first impoundment (Cai and Hu, 2006; Ye et al., 2007). Therefore, algal blooms may become more frequent, and phytoplankton growth may exert more important influences on VSS and TSS in reservoir-bays.

4. Conclusion

TSS in the mainstream generally includes large non-volatile fractions derived from allochthonous inputs. The seasonal patterns of suspended solids are still regulated by hydrological features in the mainstream. However, suspended solids of the Xiangxi Bay (especially VSS) are strongly correlated to a surrogate for lake internal processes, instead of hydrological features. Although the empirical models can predict concentrations of suspended solids and their composition, the predicted results will require additional monitoring.

Acknowledgements

This work was funded by National Natural Science Foundation of China (No. 30330140, 40671197), the National Basic Research Priorities Programme (973 Programme) (No. 2002CB412300) and the Key Project of Knowledge Innovation Program of CAS (No. KZCX2–YW–427). We would like to thank Dr. S. Zhou, X. Jia, F. Li, X. Fu, N. Wu, and L. Wang for their assistance in the field and in the lab. Special thanks are due to Sonja C. Jähnig, Lucie Vaucel and anonymous reviewers for their useful comments on the manuscript.

References

An, K.G., Jones, J.R., 2000. Temporal and spatial patterns in salinity and suspended solids in a reservoir influenced by the Asian monsoon. Hydorobiologia 436, 179–189.

An, K.G., Park, S.S., 2002. Indirect influence of the summer monsoon on chlorophyll-total phosphorus models in reservoirs: a case study. Ecological Modelling 152, 191–203.

Baxter, R.M., 1977. Environmental effects of dams and impoundments. Annual Review of Ecology and Systematics 8, 255–283.

Cai, Q.H., Hu, Z.Y., 2006. Studies on eutrophication problem and control strategy in the Three Gorges Reservoir. Acta Hydrobiologica Sinica 30, 7–11 (in Chinese with English abstract).

Chen, X.Q., Yan, Y.X., Fu, R.S., Dou, X.P., Zhang, E.F., 2008. Sediment transport from the Yangtze River, China, into the sea over the Post-Three Gorge Dam Period: a discussion. Quaternary International 186, 55–64.

Dai, S.B., Lu, X.X., Yang, S.L., Cai, A.M., 2008. A preliminary estimate of human and natural contributions to the decline in sediment flux from the Yangtze River to the East China Sea. Quaternary International 186, 43–54.

Friedl, G., Wüest, A., 2002. Disrupting biogeochemical cycles – consequences of damming. Aquatic Sciences 64, 55–65.

George, D.G., Hurley, M.A., 2003. Using a continuous function for residence time to quantify the impact of climate change on the dynamics of thermally stratified lakes. Journal of Limnology 62, 21–26.

Huang, X.F., Chen, W.M., Cai, Q.M., 2000. Survery, Observation and Analysis of Lake Ecology. Standards Press of China, Beijing (in Chinese).

Huang, Z.L., Li, Y.L., Chen, Y.C., Li, J.X., Xing, Z.G., Ye, M., Li, J., Lü, P.Y., Li, C.M., Zhou, X.Y., 2006. Water Quality Prediction and Water Environmental Carrying Capacity Calculation for Three Gorges Reservoir. China WaterPower Press, Beijing (in Chinese with English abstract).

Jiang, T., Zhang, Q., Zhu, D.M., Wu, Y.J., 2006. Yangtze floods and droughts (China) and teleconnections with ENSO activities (1470–2003). Quaternary International 144, 29–37.

Jiang, T., Su, B., Hartmann, H., 2007. Temporal and spatial trends of precipitation and river flow in the Yangtze River Basin, 1961–2000. Geomorphology 85, 143–154.

Jones, J.R., Hoyer, M.V., 1982. Sportfish harvest predicted by summer chlorophyll *a* concentration in midwestern lakes and reservoirs. Transactions of the American Fisheries Society 111, 176–179.

Jones, J.R., Knowlton, M.F., 2005. Suspended solids in Missouri reservoirs in relation to catchment features and internal processes. Water Research 39, 3629–3635.

Rosenberg, D.M., Berkes, F., Bodaly, R.A., Hecky, R.E., Kelly, C.A., Rudd, J.W.M., 1997. Large-scale impacts of hydroelectric development. Environmental Reviews 5, 27–54.

Rueda, F., Moreno-Ostos, E., Armengol, J., 2006. The residence time of river water in reservoirs. Ecological Modeling 191, 260–274.

Shao, M.L., Xie, Z.C., Han, X.Q., Cao, M., Cai, Q.H., 2008. Macroinvertebrate community structure in Three-Gorges Reservoir, China. International Review of Hydrobiology 93, 175–187.

Søballe, D.M., Kimmel, B.L., 1987. A large-scale comparison of factors influencing phytoplankton abundance in rivers, lakes, and impoundments. Ecology 68, 1943–1954.

Straškraba, M., Tundisi, J.G., 1999. Guidelines of Lake Management (volume 9): Reservoir Water Quality Management. International Lake Environment Committee.

Thornton, K.W., Kimmel, B.L., Payne, F.E., 1990. Reservoir Limnology: Ecological Perspectives. J.Wiley & Sons, New York.

U.S. Environmental Protection Agency (U.S. EPA), 1997. Lake Michigan mass balance, methods compendium (volume 3): LMMB 065 (ESS Method 340.2).

Wang, J., Wang, B.S., Luo, Z.Q., 1997. Dictionary of the Yangtze River. Wuhan Press, Wuhan (in Chinese).

Wehyenmeyer, G.A., Håkanson, L., Meili, M., 1997. A validated model for daily variations in the flux, origin, and distribution of settling particles within lakes. Limnology and Oceanography 42, 1517–1529.

Ye, L., Xu, Y.Y., Han, X.Q., Cai, Q.H., 2006. Daily dynamics of nutrients and chlorophyll *a* during a spring phytoplankton bloom in Xiangxi Bay of the Three Gorges Reservoir. Journal of Freshwater Ecology 21, 315–321.

Ye, L., Han, X.Q., Xu, Y.Y., Cai, Q.H., 2007. Spatial analysis for spring bloom and nutrient limitation in Xiangxi bay of Three Gorges Reservoir. Environmental Monitoring and Assessment 127, 135–147.