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Changes in water types under the regulated mode of water level in Three Gorges Reservoir, China

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ABSTRACT

The creation of a reservoir is often the most serious impact of damming on upstream river ecosystems, which may cause the dramatic change of water types. A giant subtropical reservoir (Three Gorges Reservoir, TGR) formed by the construction of Three Gorges Dam (TGD) has experienced three impoundment stages. According to the combined classification criterion of reservoir water quality management, a study of monthly change of water types was conducted in the mainstream and Xiangxi Bay of TGR from Jun. 2003 to Dec. 2009. Due to the rise of water level from the first stage to the last stage of impoundment, dramatic changes of water types were found during non-flood season for the mainstream, and during most months of the year for Xiangxi Bay. Under the planned mode of water operation, the mainstream would still be characterized by full mixing during the season of algal growth, which prevents the development of algal blooms, even though it experiences extreme drought events. However, Xiangxi Bay is characterized as a stable system similar to natural lakes (e.g., thermal stratification), which may contribute to the development of algal blooms, especially in years of extreme drought.

1. Introduction

Since the middle of the 20th century, the number of large dams (>15 m high) has increased rapidly. By the end of the 20th century, there were over 45 000 large dams in over 140 countries. China alone has built around 22 000 large dams, or close to half the world's total number (WCD, 2000; Bratrich et al., 2004). River damming shows profound societal and economic benefits including flood control, navigation, irrigation, drinking water supplies and hydropower production (Nilsson et al., 2005; Burke et al., 2009), but often create serious impacts on natural river ecosystems (Bratrich et al., 2004). The major upstream effect of the dam is the creation of a reservoir in a controlled stretch of river. Generally, river damming often has modified the characteristics of upstream water body from a natural riverine ecosystem to a man-made lacustrine ecosystem (Friedl and Wüest, 2002). These physical alterations have the potential to induce thermal stratification and cultural eutrophication, as well as dramatic changes in the hydrology and ecology (Ha et al., 2003). While the WCD (2000) report has summarized all possible ecological effects, it is difficult to give a precise and detailed prediction of the ecological impacts of a particular dam due to the complexity and individuality of aquatic ecosystems (Friedl and Wüest, 2002).

Ecological patterns and processes within a water body depend, to a large extent, on the physical processes of water transport and mixing that occur within them (Ambrosetti et al., 2003). These physical processes not only determine the spatial and temporal patterns of dissolved and suspended substances such as nutrients and solids, but they also regulate the ecological conditions for the occurrence of biogeochemical processes (Rueda et al., 2006). As a first order description of transport and mixing processes occurring in aquatic systems, residence time was often employed by limnologists to explain the variability in lake characteristics such as thermal stratification, nutrient concentration, primary production and trophic status (Monsen et al., 2002; Rueda et al., 2006; Xu et al., 2010a). Many examples published in international journals have illustrated that applications of residence time are pervasive in hydrologic, geochemical and ecological studies. For example, the experiments of Fussmann et al. (2000) suggested that the retention time is a key parameter controlling the structure of aquatic ecosystems, explaining the extent that these systems are self-organized or dominated by exogenous influences. The results of Obertegger et al. (2007) indicated that water residence time was an important factor structuring zooplankton succession. Moreover, residence time is often used as the basis for classification for water

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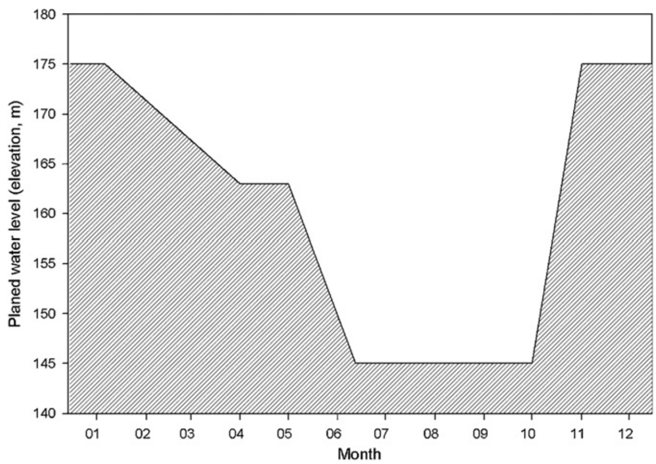

Fig. 1. Planned operational pattern of water level of Three Gorges Reservoir (from Huang et al., 2006).

types of reservoirs, because mutual relations exist among the four major criteria and the other three (mixing, trophy and water quality) were originally designed for lakes (Straškraba and Tundisi, 1999). Obviously, estimating water residence time in a reservoir is a key step in understanding the change of water types after river damming.

Three Gorges Dam (TGD), located in the mainstream of the Yangtze River (China), is one of the biggest hydroelectric dams in the world, measuring 2309 m long and 181 m high (China Three Gorges Project Corporation, CTGPC, http://www.ctgpc.com.cn). Construction of TGD has formed a giant subtropical reservoir (Three Gorges Reservoir, TGR), providing a golden opportunity for exploring the change of water types induced by the damming of a large river. Firstly, water types of the TGR can exhibit dramatic changes among three different impoundment stages (Jun. 2003, Oct. 2006 and Nov. 2008 for water level of 135 m, 156 m and 175 m, respectively) due to the raised water level. Secondly, water types of TGR can belong to different classes during different time periods, depending on seasonal pattern of water level operation (Storing clear and releasing muddy, Fig. 1, Huang et al., 2006) in relation to water inflow discharges regulated by the subtropical monsoon (Jiang et al., 2006). Thirdly, water types of the TGR can be

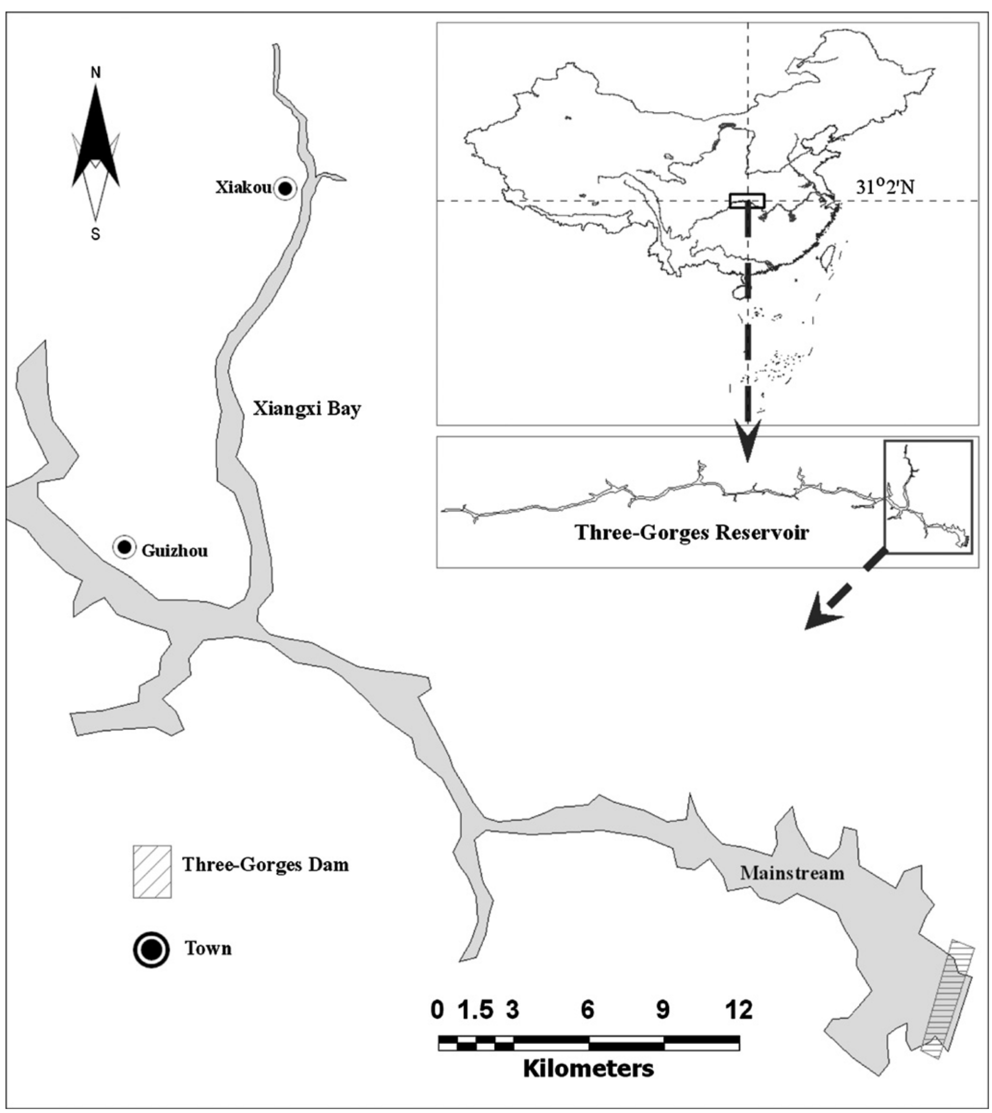

Fig. 2. The mainstream and Xiangxi Bay of TGR for long term ecological observation and research carried out by the Xiangxi Ecosystem Station.

Table 1
Interrelations between basic reservoir types as characterized by throughflow mixing and trophy.[a]

	Throughflowing	Intermediate	Long retention
Retention time	$R \leq 20$	$20 < R \leq 300$	$R > 300$
Mixing class	Fully mixed	Intermediate stratification	Well-developed stratification
Trophic class	Flow prevents full plankton development	Additional effects of flow and stratification	Classical trophic classes

[a] From Straškraba and Tundisi (1999).

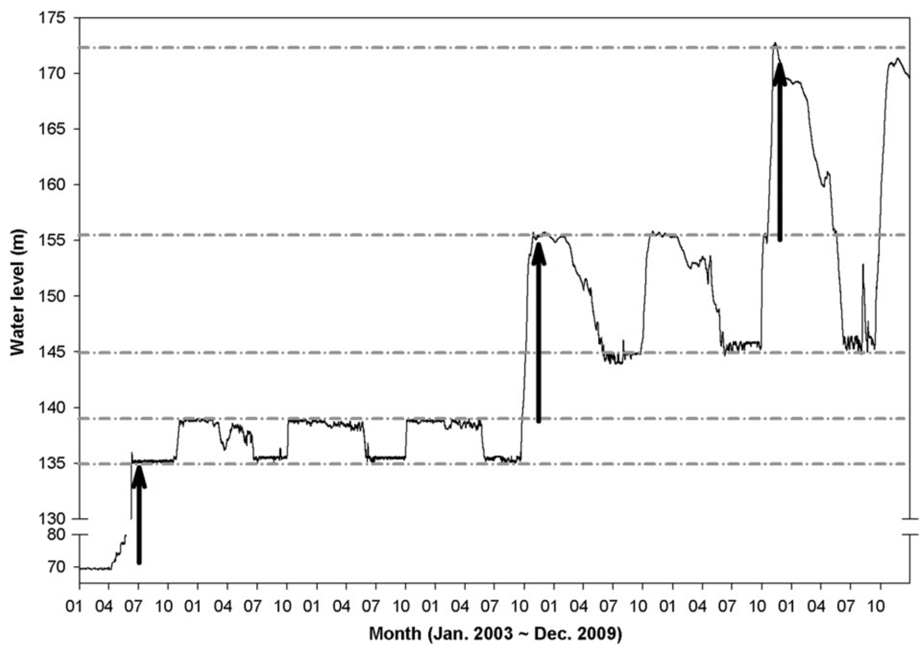

Fig. 3. Fluctuation characteristics of water level in Three Gorges Reservoir (three arrow indicate three stages of reservoir impoundment, respectively).

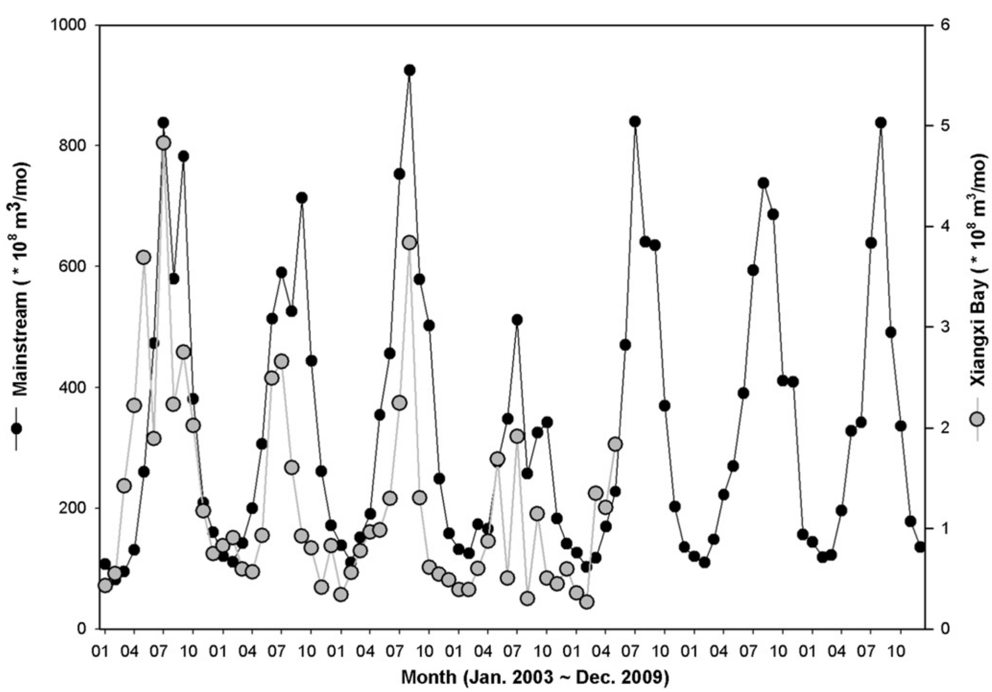

Fig. 4. Temporal changes of inflow discharge in the mainstream and Xiangxi Bay of the TGR.

characterized by high spatial heterogeneity, because the large reservoir includes 40 large bays with full supply volumes, watershed areas and mean yearly inflow discharges ranging from 0.02×10^8 to 17.11×10^8 m^3, 113–157990 km^2 and 0.6×10^8 to 34.24×10^8 m^3, respectively (CRAES, 2004).

The impacts of TGD on ecological processes of water body have caused concern to aquatic ecologists worldwide (Cai and Hu, 2006). Many ecological studies of TGR after the first impoundment have been published in Chinese and international journals, including suspended solids (Xu et al., 2009a), water eutrophication (Cai and Hu, 2006; Xu et al., 2010a), algal blooms (Ye et al., 2006, 2007; Xu et al., 2009b,c), phytoplankton (Zeng et al. 2006), zooplankton (Xue et al., 2006), and macroinvertebrates (Shao et al., 2008). For example, it was found that water residence time is an important regulatory factor for seasonal dynamics of suspended solids (Xu et al., 2009a), trophic status (Xu et al., 2010a) and water clarity (Xu et al., 2010b) after the first impoundment. These studies provide some critical baseline information on the ecological conditions of TGR after the dam was constructed, but more thorough assessments of reservoir ecosystems are still required because the last two impoundments were completed. Based on multi-year data of water level and water discharges, the residence time for the mainstream and Xiangxi Bay of TGR were estimated to explore the temporal variations of water types among three impoundment stages, predict seasonal pattern of water types under the planned mode of water level, and discuss the related phenomenon occurring in the aquatic ecosystem of TGR.

2. Study area, data and methods

Three Gorges Reservoir (TGR) created by TGD, is one of the largest artificial lakes in the world, with capacity of 3.93×10^{10} m^3, water level of 175 m asl, surface area of 1080 km^2 and watershed area of over 1.00×10^6 km^2 (Huang et al., 2006). As one of the largest bays of the reservoir, Xiangxi Bay can be considered as representative of most eutrophic bays of TGR (Cai and Hu, 2006). The mainstream and Xiangxi Bay of the reservoir both are main

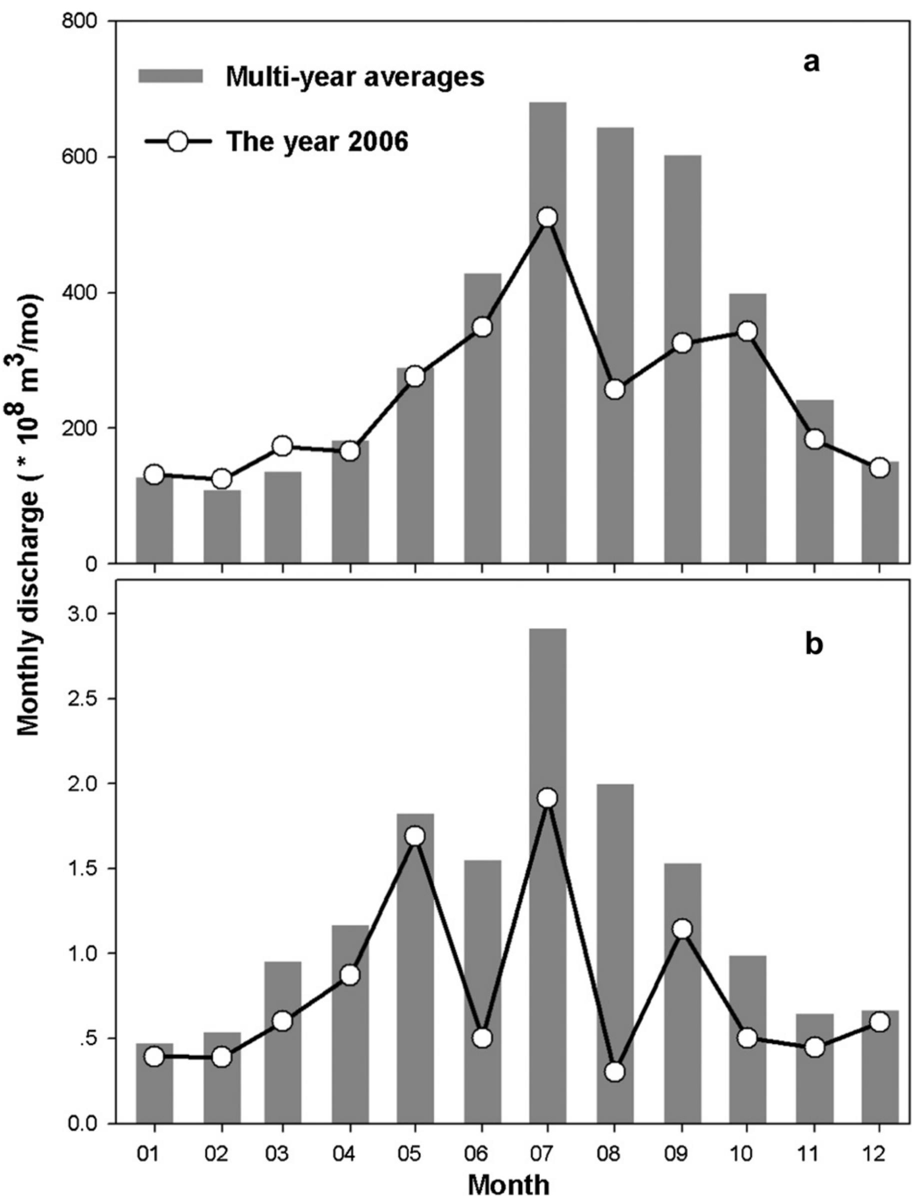

Fig. 5. Monthly comparison of inflow discharge between multi-year averages and the year 2006 for the mainstream (a) and Xiangxi Bay (b).

areas (Fig. 2) of long term ecological observation and research carried out by the Xiangxi Ecosystem Station, Chinese Academy of Sciences and China Three Gorges Project Corporation, and more detailed descriptions of the study areas can be found in the published literature (e.g., Shao et al., 2008; Xu et al., 2009a,c; Zhang et al., 2010).

The data used for this study includes water level of TGR and inflow discharges of the mainstream and Xiangxi Bay. The data of seven years (Jan. 2003 ~ Dec. 2009) for water level of TGR and inflow discharges of the mainstream were obtained from the CTGPC, and inflow discharge data of four and half years (Jan. 2003 ~ May 2007) for Xiangxi Bay was provided by the Hydrological Station, located upstream of the bay. The reservoir capacity of TGR and Xiangxi Bay in a given water level was obtained from CRAES (2004).

The estimated value of water residence time is calculated by relating the annual amount of water passing through a water body with the volume of the water body. 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 waters for $T = 1, \ldots, 12$; Q_T is the monthly average inflow discharge ($m^3\ d^{-1}$). The monthly values of the estimated residence time are used in the classification of water types for the mainstream and Xiangxi Bay of TGR, following the combined classification criterion (Table 1) in reservoir water quality management (Straškraba and Tundisi, 1999).

3. Results

3.1. Water level regulation

According to the schedule of Three Gorges Project (TGP) construction, the water level of TGR were raised up to 135 m, 156 m and 172 m above sea level by the first filling in Jun. 2003, the second filling in Oct. 2006, and the last filling in Nov. 2008, respectively (Fig. 3). Due to the start of the adoption of the "impounding clear water and discharging turbid water" operating mode, the water level of TGR showed a unique pattern with the highest values after flood season and lowest during flood season. After the first filling and before the second filling, the water level remained at about 135 m during flood season and 139 m during non-flood season. After the second filling and before the last filling, the water level was usually maintained at about 145 m during flood season and 156 m during non-flood season. After the last filling in Nov. 2008, the planned operational mode has thoroughly been put into practice in the TGP. The autumn water level was elevated by about 28 m from the summer water level and has thereafter been drawn down in each late spring due to the demand of summer flood control.

3.2. Temporal variation of water inflow discharge

Water inflow discharge of the TGR mainstream ranged from 81.4×10^8 to $924.5 \times 10^8\ m^3$/mo (month), with mean and median values of $332.1 \times 10^8\ m^3$/mo and $258.6 \times 10^8\ m^3$/mo, respectively, while that of Xiangxi Bay ranged between 0.3×10^8 and $4.8 \times 10^8\ m^3$/mo, with mean and median values of $1.2 \times 10^8\ m^3$/mo and $0.9 \times 10^8\ m^3$/mo, respectively (Fig. 4). Under the control of subtropical monsoons (May ~ October), water inflow discharge of the TGR mainstream and Xiangxi Bay both showed consistent seasonal patterns. During the impacts of monsoons, 69–81% and 65–74% of water inflow discharge occurred at the TGR mainstream and Xiangxi Bay, respectively. In 2006, the reservoir experienced an extreme drought event, and water inflow discharge of the mainstream and Xiangxi Bay both reached their lowest levels after the first impoundment. Annual water inflow discharge of the mainstream ($2981.1 \times 10^8\ m^3$) was 25% less than the seven year mean ($3985.5 \times 10^8\ m^3$), and that of Xiangxi Bay ($9.4 \times 10^8\ m^3$) was 38% less than the four year mean ($15.2 \times 10^8\ m^3$). An obvious decrease in water discharge occurred at the TGR mainstream between July and September, and monthly discharge decreases were drastic in Xiangxi Bay during summer periods (Fig. 5).

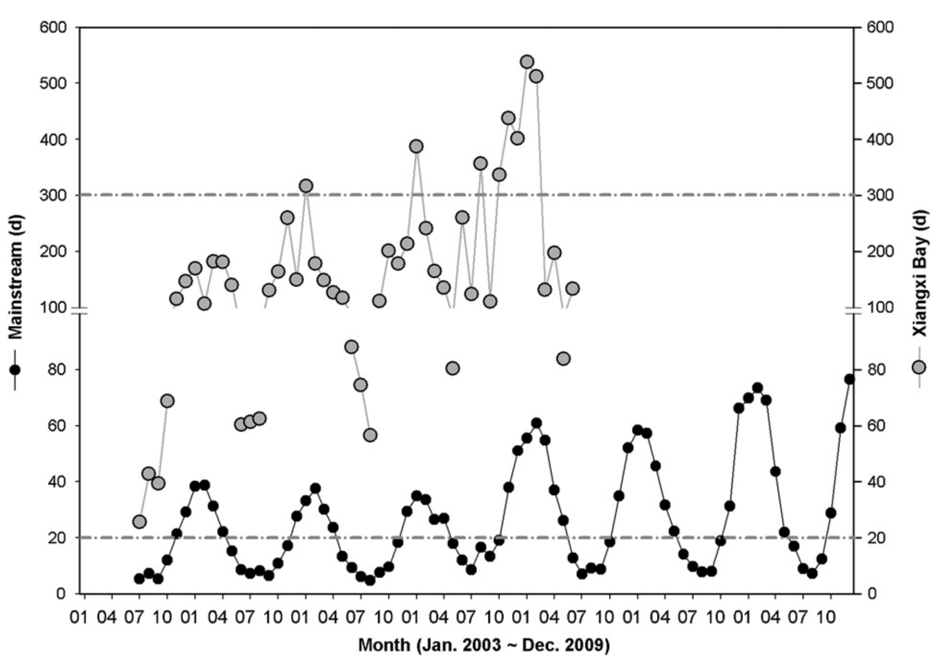

Fig. 6. Temporal changes of water residence time for the mainstream and Xiangxi Bay of TGR (Dashed line indicates the threshold value for the classification of water types).

3.3. Historical evaluation of water types

During the study period, monthly residence time for the TGR mainstream ranged from 5 to 77 d (day), with mean and median values of 27 and 22 d, respectively, while that for Xiangxi Bay varied between 26 and 538 d, with mean and median values of 179 and 146 d, respectively (Fig. 6). Monthly residence time was often shorter in the mainstream than in Xiangxi Bay, but showed consistent seasonal variation. According to the classification criterion of Straškraba and Tundisi (1999), the mainstream after the first filling was often grouped into Class A ($\tau \leq 20$ d), i.e., a fully mixed system with river characteristics during half year (May ~ October) and Class B (20 d $< \tau \leq 300$ d), i.e., an intermediate system between rivers and natural lakes during the other months, while Xiangxi Bay belonged to Class B during most months of year and Class C ($\tau > 300$ d), i.e., a steady system with lake characteristics during a few other months. After the second filling, Class A and B can still be found in the mainstream during most months of flood season and during other months, respectively, while water types of Xiangxi Bay had undergone dramatic changes and belonged to Class C from October to February. Although water residence time after the last filling was clearly prolonged in the mainstream due to the rise of water level, water types and seasonal patterns did not change dramatically.

3.4. Predictions for seasonal patterns of water types

If the estimates are based on monthly data of average discharge collected over multi-years and the planed operational pattern of water level, the predicted residence time for the TGR mainstream ranged from 8 to 88 d, with mean and median values of 40 and 32 d, respectively, and that for Xiangxi Bay varied between 36 and 489 d, with mean and median values of 195 and 154 d, respectively (Fig. 7). Water types of the mainstream still show typical seasonal patterns with river characteristics during flood periods and intermediate characteristics after flood seasons. The seasonal

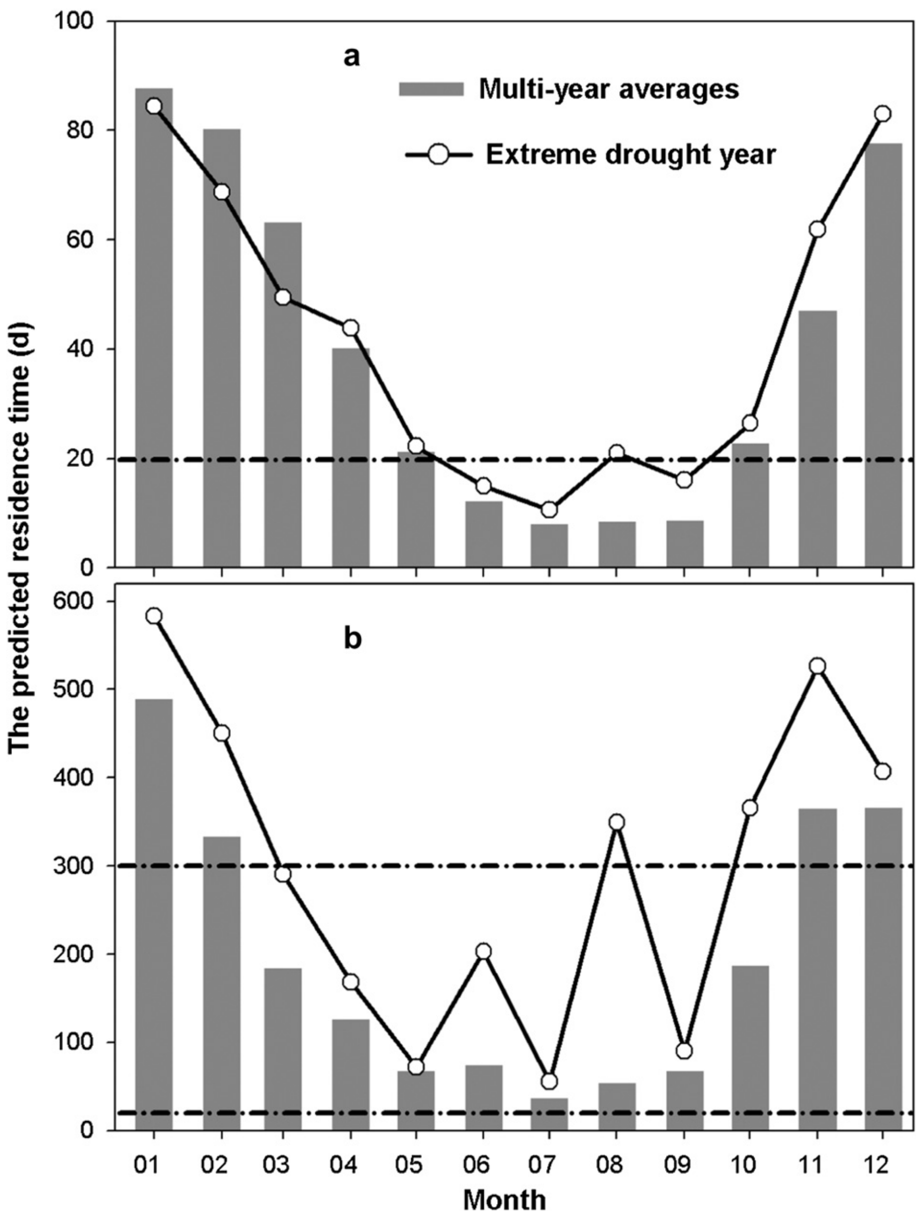

Fig. 7. The predicted value of residence time for the mainstream (a) and Xiangxi Bay (b) under the planned mode of water level (Dashed line indicates the threshold value for the classification of water types).

cycle of water types can also be observed at Xiangxi Bay, with Class C during late autumn and winter and Class B during other months. If the reservoir encounters an extreme drought event similar to that of 2006, the predicted residence time for the TGR mainstream will range from 11 to 84 d, with mean and median values of 41 and 35 d, respectively, and that for Xiangxi Bay will range between 55 and 583 d, with mean and median values of 296 and 319 d, respectively (Fig. 7). Extreme drought will have little impact on the water types and seasonal cycle of the mainstream, but will result in a change of Xiangxi Bay from Class B to C during August and October.

4. Discussion

4.1. Possibility of thermal stratification

Seasonal cycle of lake thermal stratification is a popular topic in classical physical limnology (Wetzel, 2001). A lake classification based on stratification and circulation patterns introduced by Hutchinson and Löffler (1956) was widely accepted because it possessed minimal ambiguity. Six lake types including Amictic, Cold monomictic, Dimictic, Warm monomictic, Oligomictic and Polymictic, were generalized in relation to altitudinal and latitudinal distributions (Fig. 8, Hutchinson and Löffler, 1956). Following the schematic arrangement of thermal lake types, the subtropical man-made lake (TGR) with elevation of 145–175 m (Fig. 1) and latitude of 31°2′N (Fig. 2), should be best classified as a Warm monomictic water body, as temperatures do not drop below 4 °C. These lakes circulate freely in the winter at or above 4 °C and they stratify stably in the summer (Hutchinson and Löffler, 1956). Generally, the high solar radiation input and warm air temperatures of late spring and summer contribute to a strong thermal stratification of the lake (Fischer et al., 1979). As the air temperature gets cooler and the solar radiation input decreases in the fall, the surface water and thermocline cool down to the temperature of the hypolimnion and the lake is no longer stratified (Wetzel, 2001).

However, if the flow through the lake is too fast, there is not adequate time for stratification to develop and turbulent mixing is too rigorous (Fischer et al., 1979). The limit of this case would be a river, where the residence time in a given section is short and stratification is negligible (Wetzel, 2001). In the TGR mainstream of the present study, the development of stratification can thus be limited by short residence time during the summer flood period. Since the reservoir became operational, the well-developed stratification of the mainstream has not been reported in the published literature until now, and has not also been found in the related field observations carried out by the Xiangxi Ecosystem Station, Chinese Academy of Sciences and China Three Gorges Project Corporation. The predicted seasonal patterns of water types further suggest that the mainstream will well be mixed throughout the water column for the majority of the year, even during extreme drought events. For Xiangxi Bay, the field observations of Xu et al. (2010c) showed that thermocline (Temperature gradient >1 °C m^{-1}) was present in the middle reach of the bay after the second filling of TGR. Based on the prediction of seasonal patterns, it is reasonable to believe that Xiangxi Bay may be characterized by well-developed stratification due to the prolonged residence time during the summer periods, especially for the years of extreme drought.

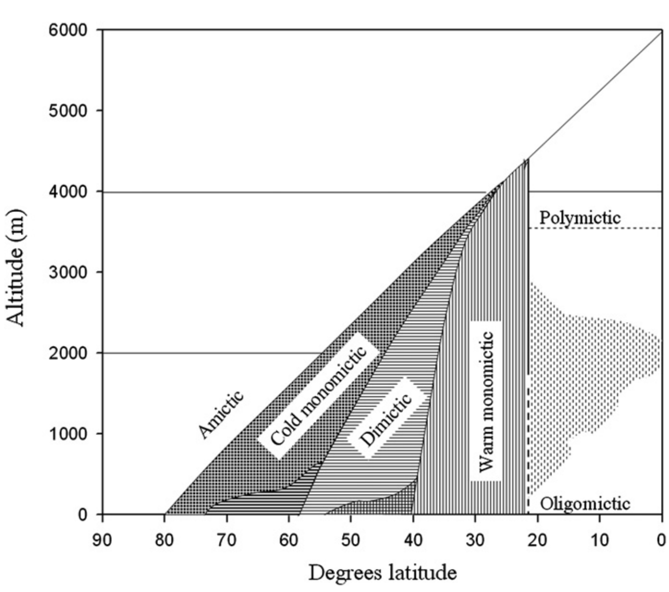

Fig. 8. The schematic arrangement of thermal lake types in relation to altitudinal and latitudinal distributions (Modified from Hutchinson and Löffler, 1956).

4.2. Algal blooms

Eutrophication and algal blooms have proven to be stubborn environmental problems all over the world for decades (Schindler, 2006; Smith et al., 2006), and also have become major problems of aquatic ecosystem degradation after many river dammings (Ha et al., 2003). Long-term studies of phytoplankton succession showed increases in algal biomass in many regulated rivers, resulting from increased nutrient inputs coupled with hydrologic changes (Górniak et al., 2003). Surprisingly, there have been no algal blooms reported until now in the mainstream of TGR. Many examples of algal blooms from Xiangxi Bay were published in Chinese and international journals (Ye et al., 2006, 2007; Wang et al., 2009; Xu et al., 2009c, 2010c; Zhang et al., 2009). For example, daily and weekly observation during spring of the year 2005 showed that algal blooms occurred in the Xiangxi Bay with maximum chlorophyll *a* of 179.39 μg/L (Ye et al., 2006, 2007). Afterward, high chlorophyll *a* concentrations were frequently detected in Xiangxi Bay during spring of each year (Xu et al., 2009c, 2010c). Moreover, the development of cyanobacterial blooms and chlorophycean blooms were first observed during summer 2008 in most areas of Xiangxi Bay by Wang et al. (2009) and Zhang et al. (2009).

Nitrogen and phosphorus are often essential elements contributing to eutrophication and algal bloom (Conley et al., 2009), but they were not the primary factors limiting the development of algal bloom in the mainstream. Firstly, the nutrient concentrations of the mainstream and Xiangxi Bay both already exceed the threshold values of the eutrophic state (Xu et al., 2009b; Xu et al., 2010a). The research results of Xu et al. (2010a) also showed that nutrients (TN and TP) were not considered as the primary factors limiting primary production in the TGR mainstream. Secondly, phytoplankton development of the mainstream has been prevented by high flow due to the short residence time during the season of algal growth such as spring and summer, following the interrelations between throughflow and trophy (Table 1). This is not surprising, as a larger watershed area is more likely to contribute throughflow of water body than a smaller watershed. For example, Burford et al. (2007) argued that watershed inputs, particularly nutrients, were not the only driver of algal growth, and hydrological factors such as residence time also affected algal growth in subtropical reservoirs. Ferris and Lehman (2007) also demonstrated that hydrologic conditions strongly controlled spring diatom dynamics in an urban impoundment. According to the predicted patterns of water types, it is reasonable to conclude that high flow of the mainstream may still be the main limitation for the development of algal blooms in the future, even in extreme drought years. For Xiangxi Bay, the prolonged residence time may further contribute to increases in algal biomass which will enhance the hazard of algal blooms, especially for extreme drought years.

5. Conclusion

In the present study, monthly residence time of the mainstream and Xiangxi Bay were estimated based on water inflow discharge and water level regulation from Jun. 2003 to Dec. 2009. When the reservoir experienced three impoundment stages, the dramatic changes of water types occurred at the mainstream during non-flood season and Xiangxi Bay during most months of the year. According to monthly average discharge over multi-years and the planned mode of water level, the predicated residence time showed that water types after the planned last filling will still display a seasonal cycle in the mainstream with river characteristics during the flood period and intermediate characteristics after the flood season. Xiangxi Bay will have Class C during late autumn and winter and Class B during other months. While extreme drought will not affect the water types and seasonal cycle in the mainstream, the event will cause the change of water types in Xiangxi Bay from Class B to C during August and October, as predicted by the estimated residence time based on the monthly average discharge from 2006 and the planned mode of water level. Full mixing during the season of algal growth will still prevent the development of algal blooms in the mainstream, even in extreme drought events, whereas the formation of thermal stratification will enhance the development of algal blooms in Xiangxi Bay, especially in extreme drought.

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