Spatial and seasonal distribution of phosphorus in the mainstem within the Three Gorges Reservoir before and after impoundment

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ABSTRACT

The Three Gorges Reservoir (TGR) began to store water in 2003. The water level reached 135 m in 2003, 156 m in 2006, 172 m in 2008 and 175 m (target level) in every year from 2010 through 2013. Impacts of dams on the environment are a concern all over the world. A major concern for reservoirs is phosphorus and possible eutrophication. Therefore, total phosphorus (TP) in the TGR mainstem was determined at five stations (S1–S5) from 1998 through 2013 to investigate variations of phosphorus with water level elevations. Results revealed that a new spatial and seasonal TP distribution has occurred after the impoundment. TP levels in the reach between S3 (nearly 300 km from the dam) and S5 (near the dam) have decreased sharply compared with those before the impoundment. The reduction degree of TP in wet season was greater than in dry season. Additionally, TP spatially decreased from upstream to the dam after the impoundment. The reduction of TP levels was mainly attributed to the settling of suspended solids and adsorbed phosphorus. These findings will inform research about transport and fate of phosphorus in TGR and Yangtze River. The challenge remains to implement measures to limit the release of phosphorus from sediments.

Key words | eutrophication, impacts, impoundment, phosphorus, suspended solids, Three Gorges Reservoir

ABBREVIATIONS

TGD  Three Gorges Dam
TGP  Three Gorges Project
TGR  Three Gorges Reservoir
TP  total phosphorus
DRP  dissolved reactive phosphorus
SS  suspended solids

INTRODUCTION

The Yangtze River is the third largest river in the world and the largest one in China in terms of length and water flow. The river, which is 6,300 km long and drains 1.8 million square kilometers, rises from the Qinghai-Tibet plateau and flows to the East China Sea (Zhao et al. 2000). It represents 36% of China’s total water resources at 9.619 × 10¹¹ m³, of which 99% is surface water. The Three Gorges Reservoir (TGR), with a huge storage capacity of 3.95 × 10¹⁰ m³, is located at the downstream end of the upper reach of the Yangtze River. The Three Gorges Dam (TGD) is the largest dam in the world, with a height of 185 m and a length of 2,335 m. Its installed capacity and annual electricity generation are 18,200 MW and 8.47 × 10¹⁰ kWh, respectively (Huang et al. 2006).

The Three Gorges Project (TGP) is a huge multi-purpose project for the development and utilization of the Yangtze water resources, and is greatly beneficial in flood control, power generation and navigation improvement, etc. However, its potential impacts on environment and ecology have also attracted wide and great concern both in China and abroad. The Chinese Government and its relevant authorities have paid great attention to these issues.

Beneficial aspects and adverse aspects coexist with TGP (YWRPB (Yangtze Valley Water Resources Protection Bureau), MWR & NEPA 1999; Chen 2004; Huang 2004).
For instance, changes of transport, fate of pollutants and deterioration of water quality characterized by abnormal growth of algae are two of the water quality problems (Codd 2000; Šimek et al. 2011; Zhao et al. 2011). In fact, since the impoundment of TGR in 2003, algal blooms have been found in some tributaries, such as the Xiangxi River and the Daning River (Wang et al. 2013), and algae bloom mainly appears in back water reaches in some tributary rivers (Cai & Hu 2006; Zhang et al. 2007; Liu & Wu 2013). Harmful algae blooms in eutrophic reservoirs have been also reported elsewhere in the world (Flores 2011; Paerl et al. 2011; O’Neil et al. 2012).

Phosphorus is an important plant nutrient, and often acts as the limiting nutrient for plant growth in streams, lakes or reservoirs (Holas et al. 1999; USEPA 2000). Too much available phosphorus can result in algal blooms, which can damage the ecology/aesthetics of waters, as well as the well-being of the community which relies on the waters to support agriculture, industry and drinking water sources.

Above studies and others (YWRPB 1999; Tullos 2009; Subkiew et al. 2010) have involved phosphorus in reservoirs or have mentioned impacts of TGP on phosphorus concentrations, but few of these are concrete and detailed in prediction or description about impacts of a big dam on phosphorus distribution. This is the reason why the study was conducted and is reported in this paper.

The objectives of this paper were to:

(i) evaluate the impacts of the TGP on total phosphorus (TP) concentrations in the Yangtze River within the reservoir area; and

(ii) identify spatio-temporal distributions of TP in the Yangtze River within the reservoir area, to inform research about the transport and fate of phosphorus in TGR, and decision-making of measures to control eutrophication in the reservoir and its tributaries.

MATERIALS AND METHODS

Study area

The study area in this paper is the region of TGR, which is located in the upstream reach of the Yangtze River. It crosses the boundary of Chongqing municipality and Hubei province with an area of 59,900 km² and with the population of 16 million. The mountainous areas represent 74% of the region, with only 4.3% plain area in the river valley and 21.7% hilly area. The dam is located in the Xilingxia gorge, one of the known ‘Three Gorges’ of the river, and controls a drainage area of 1 million km², with an average annual runoff of 451 billion m³/yr.

According to the regulations of TGR, the reservoir is normally maintained at the flood control limit level of 145 m and operated to store or release flood water based on the flood control regulation options in the event of a large flood in the wet season from middle of June to late September. The reservoir level is raised from 145 to 175 m in October and/or November and maintained at 175 m during November to April of the following year. If the inflows cannot meet the needs for guaranteed output of the power station, the reservoir draws down gradually to 155 m by the end of May and to 145 m by 10 June.

In Yangtze River, June through September is regarded as the wet season; March through May and October is regarded as the even season; and January, February, November and December are regarded as the dry season.

Sampling methods

Sampling was performed once a month from 1998 through 2013. Based on the hydrological and geochemical characteristics of the reservoir, a total of five sampling stations were selected. Stations S1, S2, S3, S4 and S5 are located at the reservoir mainstem travelling from upstream down to the dam (Figure 1). Station S5 is located in the deep region, close to the dam, while station S1 is located nearly 600 km from the dam, and it is representative of water quality from upstream of the reservoir.

Three vertical lines were set at every station and three sampling sites were set at every line. Water samples were taken from every station in the reservoir mainstem and were collected at different depths in each line. The surface water samples were collected from the water column at 0.5 m depth, the bottom samples were collected at 1–15 m depth above the sediment, and the middle layer samples were collected from mid-depth positions for every vertical line. Samples were initially stored in colored glass bottles and kept cool until processing within 12 h after collection. The samples were all analyzed for TP and suspended solids (SS).

Analysis methods

TP was analyzed using ammonium molybdate spectrophotometer method (GB 11893-1989, China) while SS was measured using a gravimetric method (GB 11901-89, China). In order to probe the mechanism of TP variation
and correlation between variation of TP and reservoir sedimentation, some samples were selected to simultaneously determine TP concentrations in filtered samples (0.45 μm filtration membrane) in order to study the ratio of phosphorus in dissolved water to that in the whole sample.

Temporal breakpoint

The first impoundment of the TGP was marked by the formation of the reservoir in 2003 and reached a water level of 135 m. Subsequent impoundments raised the water level to 156 m in 2006, 172 m in 2008 and 175 m (target level) in 2010. Consequently, 1998–2002 was selected to represent the period before the impoundment, and 2009–2013 was selected to represent the period after the impoundment. The year 2003 is the temporal breakpoint for the formation of the reservoir.

RESULTS AND DISCUSSION

The mean values of SS concentrations in the mainstem of the reservoir before and after the impoundment are shown in Figure 2. After the impoundment reached a water level of 172 m in 2009, average concentrations of SS decreased sharply compared with the concentrations before the impoundment in 2003, especially in the reach from S3 to S5. The SS concentrations at stations S1, S2, S3, S4 and S5 reduced by 38.2, 33.8, 72.1, 85.8 and 92.1% in comparison with pre-impoundment concentrations, respectively. The reduction of SS concentrations in the mainstem of the reservoir indicated a high degree of deposition of SS after the impoundment due to the reduction in the velocity of flow caused by the raising of water levels after 2003.

Concentrations of SS in different seasons at stations S1–S5 are presented in Figures 3 (before the impoundment) and 4 (after the impoundment). The common characteristics of SS before and after impoundment are that concentrations of SS in the wet season are much greater than in the even season and the dry season. After the impoundment, the concentration of SS spatially decreases significantly in the downstream direction, especially in the wet season. The SS concentration reduced by nearly 87% from station S1 to S5.
Decline of concentrations of SS in TGR after the impoundment was regarded as the first order environmental impacts caused by TGD (World Commission on Dams 2000), and this reservoir sedimentation is expected to influence environment and ecology both upstream and downstream of the dam. Upstream of the dam, sedimentation can influence water quality and ecology in the mainstem and tributaries up to Chongqing; downstream of the dam, the sediment reduction is anticipated to have multiple effects, for example, channel erosion, habitat of Chinese dolphin, and water quality, etc. Variation of TP concentrations discussed below was correlated with impacts of sedimentation.

Figure 5 presents the mean value of TP concentrations on the mainstem of the reservoir before and after the impoundment. After the impoundment and with achievement of a water level of 172 m in 2009, the mean concentrations of TP at stations S4 and S5 are markedly less than those before the impoundment, with concentrations of TP at stations S4 and S5 reduced by 36.2 and 53.0%, respectively, even though the mean concentrations of TP at stations S1 and S2 are greater than those before the impoundment. The research on the impacts of Itezhi-Tezhi Reservoir on concentrations of P in the water column showed that 60% of the TP was removed (Kunz et al. 2011); Burfurd et al. (2012) studied the sources and fate of nutrients in a subtropical reservoir (Wivenhoe reservoir), and found that over a 6 year period, there was 60% of phosphorus inputs retained (net retention), which is similar to the decrease in TP concentrations in the reach between stations S4 and S3 within the TGR in the present study. On the basis of different latitude and longitude, different scale and different flow, it is an interesting issue that three reservoirs have a similar ratio of phosphorus retention, which is worthy of conducting an in-depth study.

Figures 6 and 7 give the TP concentrations in different seasons before and after the impoundment, respectively. The common characteristics of the distribution of TP concentrations before and after the impoundment are that concentrations of TP in the wet season are much greater than in the even season and in the dry season.

As shown in Figure 7, after the impoundment the TP concentrations have shown significant reduction in the downstream direction. Reductions of TP concentrations
were nearly 65.1% in the wet season, 39.2% in the even season and 28.9% in the dry season in the downstream direction.

There was no algae bloom in tributaries in the reservoir area before the impoundment, while algae blooms often occurred after the impoundment in backwater reaches of some tributaries (Qiu et al. 2011), which is seemingly contradictory to reduction of TP concentrations in the mainstem of TGR after the impoundment. In fact, occurrence of water bloom after the impoundment was mainly attributed to changes in hydrological regime, such as sharp decreasing of flow rate. Both before and after the impoundment, TP levels in water column in the reservoir area all exceeded the minimum level of phosphorus required for water bloom.

There is a high similarity in spatial and seasonal characteristics of TP and SS concentrations after the impoundment in 2003, which demonstrated that TP concentrations after the impoundment in 2003 are linked to the sedimentation of SS.

Phosphorus in the water column consists of both the dissolved (DRP) and the particulate (PP) form which is adsorbed on SS. It was found that the ratio of DRP/TP is linked to the concentration and composition of SS. Natural sediments consist of a number of components, including minerals, organic matter and activated metal (hydro-) oxides (Table 1), which play a major role in the adsorption of phosphorus onto SS. Specifically, oxides of the elements...
Fe and Al in chlorite and illite can significantly adsorb phosphate (Zhang & Huang 2007).

Figure 8 plots the variation of the ratio (DRP/TP) against SS concentrations (samples were collected from the mainstem of TGR; determination work was conducted simultaneously with monitoring in this paper). This figure shows that phosphorus exists mainly in the form of particulate phosphorus as long as SS concentrations are not very low. The water level rising and velocity slowing the deposition of SS in the reservoir has resulted in a great quantity of phosphorus being removed from the water column and residing in the bed sediments, which is the main reason why concentrations of TP came down sharply at S4 and S5 relative to the impoundment (shown in Figures 5 and 7). The challenge will be to implement measures and practices to limit the release of phosphorus from the bed sediments in the tributaries and mainstem as far as possible to control eutrophication and algal blooms in the reservoir.

Results above indicate that the TGP has significantly impacted TP concentrations and distributions in the mainstem of the reservoir, which could provide a considerable reference for the environmental impact assessment of hydropower projects. These results are also helpful for researching the transport and fate of phosphorus in TGR and the downstream reach of the Yangtze River.

According to the operational regulation of the TGP, the water level at the dam varies between 145 and 175 m in TGR. This in turn creates transition zones in the backwater reaches in tributaries within the reservoir area where the water level can vary with a height of 30 m, which can result in water exchange between the main stream and the tributaries. Consequently, TP concentrations in the mainstem can influence TP concentrations and trophic level in a tributary. The mean concentrations of TP, varying from 0.11 to 0.28 mg/L in the mainstem, are relatively high (the standard value for lakes and reservoirs is 0.05 mg/L in China), which means that TP concentrations in the mainstem need to be considered when formulating and implementing countermeasures to control eutrophication in the tributaries. At the same time, it is necessary to strengthen research on limiting the release of phosphorus from sediments in the tributaries and mainstem, although it is a challenge to implement measures and practices at present.

**CONCLUSIONS**

After the impoundment of TGR, concentrations of TP in the reach near the dam decreased sharply compared with the concentrations before the impoundment, with the mean value of TP concentration at station S5 reducing by 53.0%. The reductions in TP concentrations were even greater in the wet season, with lower reductions in the even and dry seasons after the impoundment. TP concentrations spatially decrease from the upstream to the dam (by 55.4% from station S1 to S5). The reduction of TP concentrations is mainly attributed to the sedimentation of SS after the impoundment due to the water level rising and the flow velocity reducing. This information will provide significant references for research into impacts of the large hydropower projects on environment and ecology.

TP concentrations in the mainstem need to be considered when formulating and implementing countermeasures to

<table>
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<th>Sampling station</th>
<th>Organic carbon (%)</th>
<th>Chlorite (%)</th>
<th>Illite (%)</th>
<th>Quartz (%)</th>
<th>Dolomite (%)</th>
<th>Feldspar (%)</th>
<th>Calcite (%)</th>
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</tr>
<tr>
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</tr>
</tbody>
</table>

Reference: Lou et al. (2006).

Figure 8 | Variation of ratio of dissolved phosphorus to total phosphorus with concentrations of SS.
control eutrophication in the tributaries. Also, it is necessary to strengthen research on limiting the release of phosphorus as far as possible from sediments in the tributaries and mainstream, although it remains a challenge at present.

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