Impact of the Three Gorges reservoir operation on downstream ecological water requirements

Qiongfang Li, Meixiu Yu, Jianhua Zhao, Tao Cai, Guobin Lu, Wei Xie and Xue Bai

ABSTRACT

With population increase and economic growth, the flow regime of the Yangtze River has been altered to some extent by human activities, particularly dam construction. Dam-induced alterations in the flow regime of the Yangtze River will unavoidably influence water allocation among different water users and instream ecological water requirements may not be guaranteed during some months, particularly during phases of reservoir storing water. To assess the impacts of the Three Gorges reservoir operation on the downstream minimum instream ecological water requirements, this paper selected the Three Gorges reservoir and Yichang hydrological station below the reservoir as case study sites. On the basis of long-term time series of daily discharge data, the reservoir outflow was simulated under two water storing schemes and the degree to which the downstream minimum ecological flow was satisfied was computed. The results of this paper could provide references for the integrated management of the Yangtze River water resources and the assessment of dam-induced impacts on the Yangtze River ecosystem health.

Key words | minimum instream ecological flow, Three Gorges reservoir, Yangtze River, Yichang hydrological station

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INTRODUCTION

There is growing concern internationally over the increase in dam building. With the increasing demand on water and hydropower due to a rapid world population increase, industrialization and urbanization, more and more dams have been built. According to WCD (2000), two large dams were built each day during the latter half of the 20th century. By 2000, the number of large dams had risen to more than 47,000, and an additional 800,000 smaller dams now control the flow of the world's rivers (McCully 1996; Rosenberg *et al.* 2000; WCD 2000). Nilsson *et al.* (2005) state that over half of the 292 large river systems in the world have been influenced by dams.

Most of these dams provide considerable benefits to human societies and their economies by increasing water supply for municipal, industrial and agricultural uses, controlling floods and generating hydropower. However, damming of the world's rivers has come at great cost to their ecological health and ecosystem services by fragmenting and transforming the rivers (WCD 2000; Postel & Richter 2003). Dams impose significant influence on downstream river ecosystem, in many cases extending for hundreds of kilometres below a dam (McCully 1996; Willis & Griggs 2003) including alteration in water flow regimes (Li *et al.* 2007), stream temperature regimes (Liu *et al.* 2005) and sediment regimes (Vörösmarty *et al.* 2003). Of all the environmental changes induced by dam building and operation, the alteration of natural water flow regimes has had the most persistent and damaging effects on river ecosystems and species (Poff *et al.* 1997).

Dam-induced impacts on river flow regime vary with dam operation patterns (Li *et al.* 2007). Recently, the study of dam-induced impacts on downstream ecological water

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use and associated river ecosystem health and stability has attracted worldwide attention. This situation is particularly the case for large river basins and where dam-induced alterations in river flow regime are increasingly significant due to the intensive and extensive development of their water and hydropower resources. The investigation and assessment of dam-induced impacts on downstream ecological water use could provide a vital basis for river restoration and water resources management, which is the aim of the present study with the Yangtze River in China as a case study.

On the basis of the past several decades of daily flow discharge data collected from the Changjiang River Water Resources Commission, an attempt was made to quantitatively evaluate impacts of the Three Gorges reservoir operation on the downstream ecological water flow by focusing on the main stem of the Yangtze River.

CASE STUDY SITE

The Yangtze River (Changjiang) is one of the most important rivers in the world, being the third largest in annual runoff (Xia *et al.* 2007) and the fourth largest in sediment load (Eisma 1998; see Figure 1). The Yangtze plays a critical role in the global water cycle, sediment cycle, energy balance, climate change and ecological development (Xia *et al.* 2007). The alterations in its hydrological regime therefore have global-scale impacts. However, with population increase and economic growth, the flow regime of the Yangtze River has been altered by human activities, particularly dam construction. By the end of 2000, 134 large/medium-scale reservoirs had been built with a total storage capacity of 1.064×10^{11} m^3 (Zhang 2003). Dam-induced alterations in the flow regime of the Yangtze River will unavoidably influence water allocation among different water uses, such that the instream ecological water requirements cannot be guaranteed in some months (particularly during phases of reservoir storing water).

To assess the impacts of Three Gorges reservoir operation on the downstream instream ecological water use quantitatively, the Three Gorges reservoir and Yichang hydrological station below the reservoir were used as case study sites (see Figure 1). Yichang station is the control point of the upper Yangtze River Basin and is located at the starting point of the middle reach of the Yangtze River, 44 km below the Three Gorges Dam and 6 km below the Gezhouba Dam.

With a capacity of 3.93×10^{10} m^3, the Three Gorges reservoir spans the Yangtze River and is the largest hydroelectric power station in the world. Except for the ship lift, the original project plan was completed on 30 October 2008 when the 26th generator was brought into commercial operation. The Gezhouba reservoir, with a capacity of 1.58×10^9 m^3, is a run-of-river reservoir and located on the main stem of the Yangtze, 38 km below the Three Gorges reservoir. Li *et al.* (2007) revealed that the Gezouba reservoir

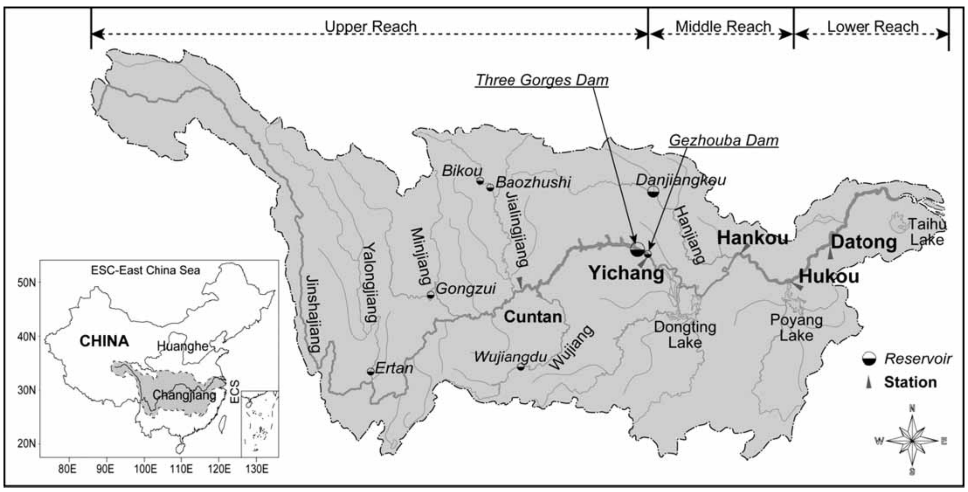

Figure 1 | Sketch map of the Yangtze River.

(a run-of-river reservoir located between the Three Gorges reservoir and Yichang hydrological station; see Figure 1) has limited impact on the downstream flow regime, and therefore the degree to which ecological flows are met at Yichang station is mainly affected by the Three Gorges reservoir operation.

METHODS AND DATA

Given that different reservoir operation modes (particularly the reservoir water storing schemes) may result in different degrees of impacts to which the ecological instream flow is satisfied downstream, two reservoir storing water schemes were adopted in this paper. The satisfying degree of the ecological instream flow is defined as the ratio of river flow to instream ecological flow (Xia *et al.* 2007). If the ratio is equal to or larger than 1, the ecological water requirements (Xia *et al.* 2007) can be satisfied; otherwise, the ecological water requirements cannot be met. The two reservoir storing water schemes are described in the following paragraphs.

Scheme I

The water storing period is initially set from 21 September to 20 October, and the reservoir water level rises linearly to its normal pool level under the condition that the guaranteed output of power generation can be ensured. If the water level cannot reach its normal pool level by 20 October, the water storing period can be extended until that level is reached.

Scheme II

The water storing period is initially set from 16 September to 15 October, and the reservoir water level rises linearly to its normal pool level under the condition that the guaranteed output of power generation can be ensured. If the water level cannot reach its normal pool level by 15 October, the water storing period can be extended until the level reaches normal pool level.

To obtain the reservoir outflow time series, the same reservoir inflow data time series was used to simulate reservoir outflow under the two different schemes. Because the daily inflow is unknown, the daily discharge data at Yichang before the Three Gorges reservoir came into operation in 2003 was assumed to equal the total reservoir daily inflow. On the basis of the 1950–2002 time series of daily discharge data from Yichang station, the reservoir outflow processes were simulated for the two schemes. As Chinese sturgeon spawning takes place in October and November each year, and is quite sensitive to flow magnitude, the study period is September, October and November of each year. Minimum instream ecological flow process is the lower envelope of flow processes below which the stability and health of river ecosystem cannot be maintained and aquatic creatures cannot survive. The amount of water corresponding to minimum instream ecological flow process is minimum instream ecological water requirement.

According to the simulation results and the computed minimum instream ecological flow (Zou 2008), the monthly satisfying degree of the minimum instream ecological flow at Yichang for September, October and November was computed. The mean daily satisfying degree of the minimum instream ecological flow at Yichang was calculated for five types of year, i.e. extremely wet year of 1964 with frequency of 5%, wet year of 1993 with frequency of 24%, average year of 1975 with frequency of 50%, dry year of 1976 with frequency of 76% and extremely dry year of 1972 with frequency of 95% (Zou 2008). The frequency of river flow less than the minimum instream ecological flow in September, October and November was computed for each of the five types of year. The computation results for the two schemes were compared.

RESULTS

Table 1 lists the frequencies of river flow less than the minimum instream ecological flow in September, October and November for the five different types of year under the two different water storing schemes. Figure 2 shows the monthly satisfying degree of the minimum instream ecological flow in September, October and November of each year for both water storing schemes. Figures 3 and 4 demonstrate the mean daily satisfying degree of the minimum instream ecological flow in September and October, respectively, for the five types of year for both water storing schemes.

Table 1 | Frequency of river flow less than the minimum instream ecological flow (%) (EWY: extremely wet years; WY: wet years; AY: average years; DY: drier years; EDY: extremely dry years)

Scheme	Month	EWY	WY	AY	DY	EDY
I	September	4.8	5.4	16.7	25.5	42.2
	October	23.5	24.8	26.6	50.0	64.0
	November	2.9	2.6	1.8	10.7	7.2
II	September	6.7	7.9	20.8	33.1	48.9
	October	16.1	15.4	16.9	36.6	52.2
	November	2.9	2.6	1.8	10.7	7.2

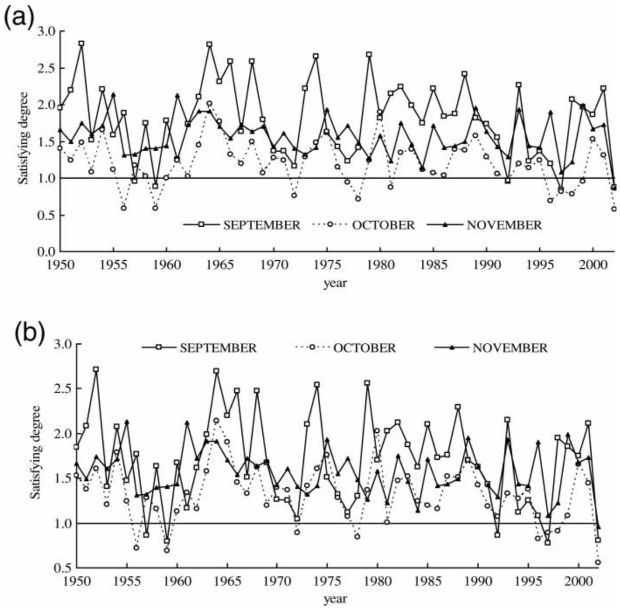

Figure 2 | Monthly satisfying degree of the minimum ecological flow for different years: (a) Scheme I and (b) Scheme II.

As reservoir water storing did not take place in November, the variation patterns of the mean daily satisfying degree in November for all types of years are the same under both water storing schemes; see Figure 3(c).

DISCUSSION

Different water storing schemes adopted by the Three Gorges reservoir impose different impacts on the downstream ecological water use; it is therefore necessary to analyze the impacts under different water storing schemes and compare them.

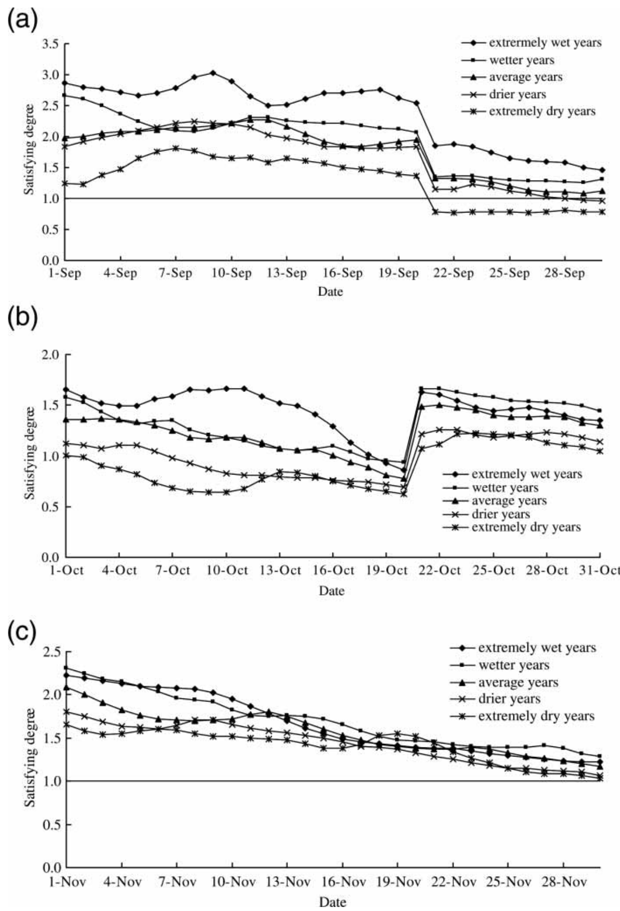

Figure 3 | Mean daily satisfying degree of the minimum ecological flow in five types of years (Scheme I): (a) September; (b) October and (c) November.

Scheme I

From Table 1 it can be seen that the frequency of river flow less than the minimum instream ecological flow in September in drier years was higher than those in wetter years. The same situation occurs in October and November, revealing that the impacts induced by reservoir operation on the downstream ecological water use vary with reservoir inflow conditions. If more water flows into the reservoir from upstream, the downstream ecological water use can be better guaranteed. Table 1 also shows that, for the same type of year, the frequency of river flow less than the minimum instream ecological flow in October was generally significantly higher than that in September, and that the value in September is obviously higher than that in November (because more days for reservoir storing water fell in October than in September). No water storing took place in November; thus,

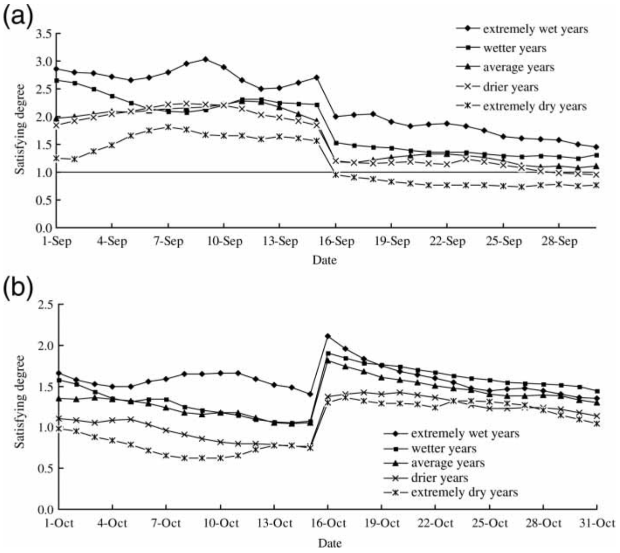

Figure 4 | Mean daily satisfying degree of the minimum ecological flow in five types of years (Scheme II): (a) September and (b) October.

compared with October and September, the frequency of river flow less than the minimum instream ecological flow in November was lowest for the same type of year.

It can be concluded that the influence of reservoir water storing on the downstream ecological water use is closely associated with reservoir inflow and water storing.

As the monthly reservoir inflow in September was apparently larger than that in October and November, the monthly satisfying degree of the minimum instream ecological flow in September was generally higher than that in October and November during 1950–2002 (Figure 2(a)). This indicates that reservoir inflow plays a more critical role in determination of the monthly satisfying degree in September than reservoir water storing, although in a number of years the value was less than 1 due to reservoir water storing. As November and October fall within the dry season and wet season, respectively, the monthly reservoir inflow in October was obviously larger in all years than that in November. The monthly satisfying degree was mostly lower than that in November due to reservoir storing water, however. In comparison with September, the influence of reservoir water storing on the monthly satisfying degree evidently increased in October.

Figure 3 shows that the mean daily satisfying degree was lower than 1 only in extremely dry years in some days of September, while the value in all other types of year was higher than 1 or slightly lower than 1. The mean daily satisfying degree in some days of October for all types of years was lower than 1, and in drier years and extremely dry years the number of days with a value less than 1 increased significantly. The mean daily satisfying degree in November for all types of years was all higher than 1. To satisfy the downstream minimum ecological water requirements, more water should be released on days when the daily satisfying degree is lower than 1.

Scheme II

Similar conclusions were obtained under Scheme II for the frequency of river flow less than the minimum instream ecological flow (see Table 1); however, the difference was that the frequencies of river flow less than the minimum instream ecological flow in September under Scheme II increased for all types of year due to the time of water storing being brought forward, while the values in October declined for all types of year because the number of reservoir storing water days decreased.

The results for monthly satisfying degree of the minimum instream ecological flow depicted in Figure 2 demonstrate a similar variation of the monthly satisfying degree in September, October and November for both schemes. The distinction was that the monthly satisfying degree in September under Scheme II decreased in all years due to earlier water storing while the value in October increased in all years because the time for reservoir storing water was shortened; as a result, the ecological water requirements could be better met. Compared with Scheme I, the number of years evidently declined with the monthly satisfying degree in September being higher than that in October or November due to water storing time having been brought forward.

The daily data, Figure 4(a), illustrate a similar variation of mean daily satisfying degree in September for all types of year as in Figure 3(a), but the number of days with a value less than 1 increased in extremely dry years because the time of water storing was brought forward. After Scheme II was adopted, the situation improved in October for all five types of years (particularly in drier and extremely dry years, as the days when downstream minimum ecological water requirements could not be met diminished; Figure 4(b)).

CONCLUSIONS

This paper evaluated the impacts of the Three Gorges reservoir operation on the downstream ecological water use. The results reveal that the impacts varied with the reservoir water storing schemes adopted and inflow conditions. Compared with Scheme I, Scheme II could obviously improve the situation that the downstream minimum ecological water requirements could not be met in October. This situation will benefit Chinese sturgeon spawning. Therefore, if flood safety can be ensured in September, advancing the reservoir water storing time from 21 September–20 October to 16 September–15 October is a better choice and could benefit the river ecosystem health and stability.

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