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Model of water regulation in the Yangtze River Basin and its effects using remote sensing techniques

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Abstract Based on remotely sensed images, about 42 000 dams, with a total storage capacity of about 270 km^3, have been constructed in the Yangtze River Basin. This large volume of water amounts to nearly one-third of the total annual discharge of the Yangtze River. Reservoir construction has dramatically changed the spatial distribution of water resources in the basin. Substantial amounts of water are now impounded in the upper reaches of the basin for energy generation and the pattern of seasonal water discharge has been altered. Future anthropogenic changes could further worsen the situation as additional large hydropower projects are completed in the upper reaches of the basin. This will cause more serious ecosystem disconnectivity through the elimination of free-flowing streams. Free-flowing streams are vanishing on the mainstem and major tributaries, such as the Jinshajiang, Wujiang, Dadu, Yuanjiang and Jialingjiang, because of reservoir construction. At present, 4688 km of streams are regulated by dams and this figure could increase to 7298 km by 2025 when all the dams currently under construction are put into operation. If all the planned dams are completed, the figure could jump to 10 675 km, or about 43% of the total length of the streams. At that time, almost all the mainstem and major tributaries will be fully regulated and this could lead to very serious negative ecosystem effects by disconnecting sediment/nutrient transport and fish migration.

Keywords water regulation; reservoirs; free flowing; the Yangtze River basin; hydropower

INTRODUCTION

Water is widely regarded as the most essential of natural resources, yet freshwater resources are directly threatened by human activities, and stand to be further affected by anthropogenically-induced climate change (Vörösmarty *et al*., 2010). At present, there are more than 45 000 large reservoirs worldwide – defined as those higher than 15 m – used for water supply, power generation, flood control, etc. (White, 2000; Lehner *et al.*, 2011). These impoundments are estimated to have a cumulative storage capacity in the range of 7000 to 8300 km^3 (Vörösmarty *et al*., 2003; Chao *et al*., 2008). Large dams are estimated to directly contribute to 12–16% of global food production. Recent projections suggest that 70% more food will be needed by 2050 (nearly 100% in developing countries (e.g. China and India) to cope with a 40% increase in world population; part of the additional food will be produced on irrigated lands that require 11% more water, much of it likely to come from reservoirs (Lehner *et al*., 2011).

The Chinese Yangtze watershed and its tributaries are being dammed at a dazzling pace. This amounts to more than 40 000 reservoirs which currently are needed to meet the large demand for water resulting from population growth and rapid economic development. The reservoirs serve more than 30% of China's population, and help to produce about 40% of the country's industrial and agricultural value (Dai *et al*., 2010). Together with planned developments in the Amazon and the Mekong, the Yangtze can be considered one of the world's hotbeds of hydropower development.

Unfortunately, reservoirs also cause a series of negative effects such as downstream riverbed scouring, sediment trapping, river fragmentation, and other environmental issues. Nilsson *et al.* (2005) show that, of some 227 worldwide rivers assessed, 37% were strongly affected by dams and altered flows, 23% were moderately affected, and 40% were unaffected. For example, the impacts of the Three Gorges Dam have been widely discussed (Park *et al*., 2003; Xie, 2003). To better manage water resources, as well as minimize the negative effects caused by dams, an understanding of current water regulation in the Yangtze River Basin is crucial; that information also can serve as a baseline against which future changes may be assessed.

The objectives of this study are: (a) to quantify the storage capacity of reservoirs by establishing empirical formulas; (b) to assess the significance of anthropogenic alterations on water regulation in the Yangtze River Basin; and (c) to analyse the effects of water regulation on the Yangtze River Basin's free-flowing stream segments.

THE YANGTZE RIVER DRAINAGE

The Yangtze (Changjiang) River Basin in southern China lies between 91°E and 122°E, and 25°N and 35°N, covers a total area of 1.8×10^6 km^2 , and is the third largest river in the world (Fig. 1). The river is generally divided into three parts: the upper, middle and lower reaches. The upper reach extends >4300 km from its Himalayan Mountain source to Yichang, a drainage area of about 1.0 million km^2. At Yichang, the middle Yangtze River (0.68×10^6 km^2) exits the Three-Gorges to enter the 950 km middle reach. The 930 km lower reach extends from Hukou to the seacoast, about 20 km north of Shanghai, and has a drainage area of 0.12×10^6 km^2. The long-term mean annual precipitation in the Yangtze Basin is about 1070 mm, but spatial and temporal distributions are highly uneven (Xu & Milliman, 2009). Annual precipitation ranges from 500 mm in the west to 2500 mm in the east. Most of the basin is affected by the southeast monsoon in summer; thus, precipitation occurs mostly from May to October.

According to the records at Datong, the Yangtze River annually transports about 28 200 m^3 s^{-1} of water (1951–1990) to the estuary (Chen *et al.*, 2001). The seasonal variability of water discharge is small in comparison to that of large rivers in northern China, e.g. the Yellow River. Between 1882 and 1987, annual water discharge from the upper Yangtze River, recorded at the Yichang station, averaged 14 300 m^3 s^{-1}, or about half the total discharge to the estuary. Large yearly and seasonal fluctuations in water discharge to the sea occur. Monthly mean discharge has varied from 84 200 m^3 s^{-1} in August 1954, to 6730 m^3 s^{-1} in February 1963 (Chen *et al.*, 2001).

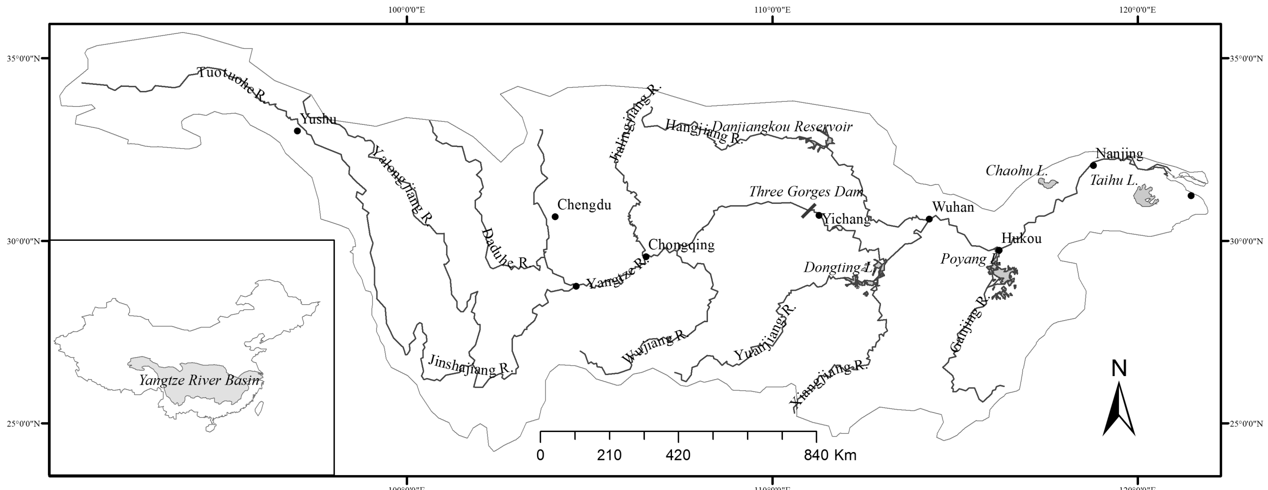

Fig. 1 Sketch map of the Yangtze River Basin.

DATA COLLECTION AND METHODS

Data collection

In this study, Landsat Thematic Mapper (TM) and ETM+ imagery, which were mainly acquired after the monsoon season (September and October) from 2005 to 2008, were used to delineate water-body boundaries. Ideally, this should be done with data collected during a single year; however, the unavailability of sufficient regional cloud-free data necessitated the use of multi-year and -seasonal data. In total, 94 cloud-free images were used, including 10 Landsat ETM+ images and 84 Landsat TM images. These were acquired from the US Geological Survey (USGS; http://glovis.usgs.gov/; last accessed in October 2011).

Additionally, very high-resolution satellite data, such as IKONOS and QuickBird from the Google Earth mapping service were also acquired for selected areas, to aid in waterbody classification and for validation purposes. DEMs (digital elevation models) with a spatial resolution of 90 m, were downloaded from the Consultative Group on International Agricultural Research (CGIAR) (http://srtm.csi.cgiar.org; last accessed in October 2011) to determine the backwater curve for each cascade reservoir.

Hydrological data used for this study, such as water discharge and annual runoff, were obtained primarily from the Changjiang Water Resources Commission (CWRC), and in part from official published materials such as the Bulletin of Changjiang Sediment (CWRC, 2001–2010).

Methods to identify reservoirs

First, a density slicing and multi-threshold approach was used to classify the satellite images into two categories: water and non-water. The results were then converted to polygons of contiguous pixels and stored in a shapefile using ArcGIS 9.3. Since few reservoirs are less than four pixels, and very small water bodies have little effect on water regulation, all polygons consisting of less than four pixels were removed from the dataset. Second, with the assistance of secondary data, and high-resolution satellite imagery from the Google Earth Image Service, visual interpretation was used to classify water bodies into three main classes: lakes (lakes and ponds), reservoirs, and rivers. A major impediment to this approach occurred in the lower reach of the Yangtze River, because there are numerous paddy fields and aquaculture farms that have spectral characteristics similar to natural lakes. Hence, differentiation between fields and water bodies necessitated the use of visual interpretation. An empirical relationship (Lehner & Doll, 2004; Liebe *et al.*, 2005; Sawunyama *et al.*, 2006; Lehner *et al.*, 2011) between the surface area and the storage capacity of reservoirs was used as the basis for estimating reservoir storage capacities.

Based on the dam locations in the high-resolution images provided by the Google Earth mapping service, cascade hydropower reservoirs were identified on different tributaries. The shape of cascade hydropower reservoirs was determined based on the assumption that the water surface within a reservoir is flat. The Three Gorges Reservoir (TGR) can serve as an example (Fig. 2). First, the Yangtze River polygon was divided into two parts at the Three Gorges Dam (TGD). The part behind the TGD was then overlapped with DEMs. If a pixel near the dam intersects or partially intersects with the boundary of the polygon, the pixel would be marked to calculate the water surface level. The average elevation of all the marked pixels is the final water surface level in the TGR. Second, for each cell within or partially within the Yangtze River polygon, a height difference between the DEM value and the water level was calculated. Based on the height differences, the backwater curve could be defined and the real boundary of the TGR could be identified. In Fig. 2, the water level is 160 m; the defined backwater curve is near Chongqing; hence, the inundated area of the TGR is from the backwater curve near Chongqing to the TGD near Yichang. During waterbody identification, various attributes, such as surface area, names (if any), administrative divisions, etc. were also added to the database.

Channel fragmentation is the degree to which the river is spatially fragmented by dams. This is defined as the ratio of the river length that remains free flowing to the total length of the river (Ward & Stanford, 1995; Nilsson *et al.*, 2005):

$$D_{cf} = \sum_{i=1}^{n} L_{ff\,i} \Big/ \sum_{i=1}^{n} L_{s\,i} \tag{1}$$

where L_{ff} is the length of the river that remains free flowing (in km) in each segment fragmented by dams; L_s is the total length of a segment (in km); subscript i denotes different dams. A simple geometric argument to estimate L_{ff}:

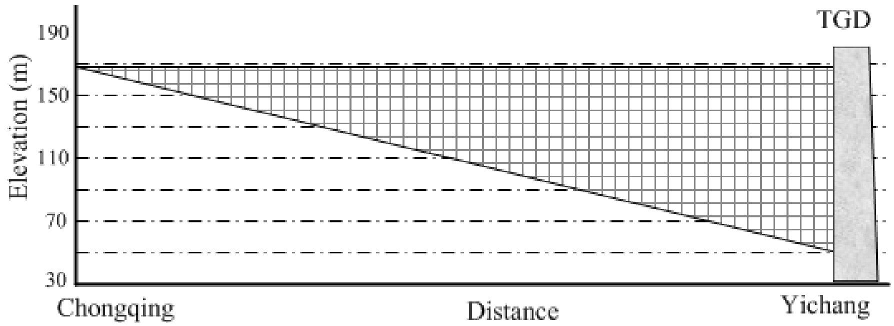

Fig. 2 Method to identify cascade reservoirs using the Three Gorges Reservoir as an example.

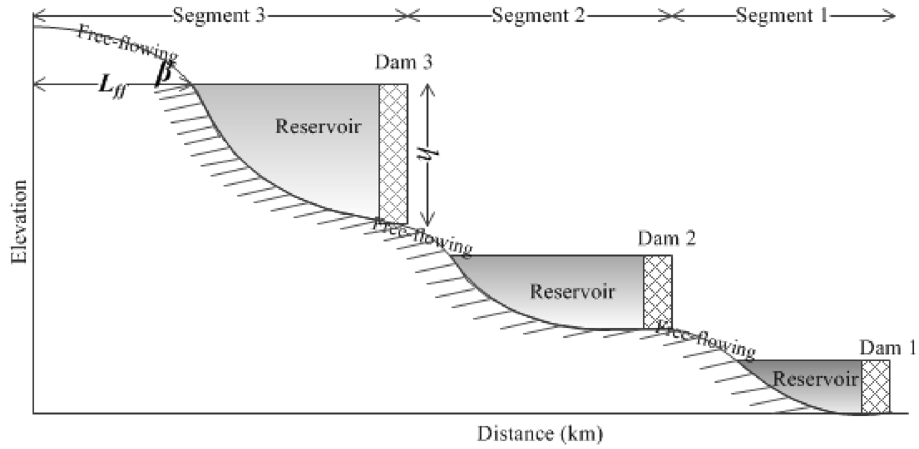

Fig. 3 A typical river fragmented by three dams. The length of the river that remains free-flowing (L_{ff}) is estimated from the total segment (L_s) length, dam height (h), and river slope (β).

$$L_{ff} = L_s - \frac{h}{\beta}\sqrt{1-\beta^2} \tag{2}$$

where h is dam height, converted to km, and β is river slope in km per km (see Fig. 3).

RESULTS

Distribution of reservoirs

This study identified a total of 41 802 reservoirs with a total surface area of about 8306 km^2. The statistical distribution of specific properties, such as reservoir size, is shown in Fig. 4, which displays a Pareto distribution (Pareto, 1897). The smallest reservoirs occur at the highest frequency, and frequency declines dramatically with increasing surface area. The results are roughly consistent with some general laws in stream morphometry, such as Horton’s Law of Stream Numbers (Horton, 1945).

It can be seen from Figs 1 and 5 that the reservoirs in the Yangtze River Basin are mainly distributed in the middle and lower reaches and that the highest concentration of reservoirs is in flat agricultural regions. This is especially true in the Sichuan Basin near Chengdu, such as in sub-basins in the Hanjiang River from Danjiangkou Reservoir to Wuhan, in the Yuanjiang River Basin, the Xiangjiang River Basin, and on the Poyang Lake Plain around the Poyang Lake. Also, there are few reservoirs in the north Jianghan Plain from Dongting Lake to Wuhan, along the Yangtze River. This is because the northern Jianghan Plain is alluvial, and the HanJiang River and thousands of lakes and marshes, are distributed along the Yangtze River in this area. These lakes

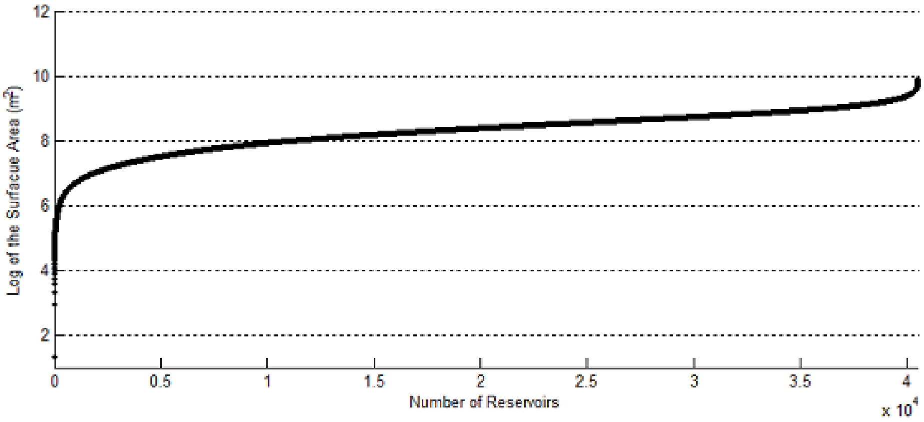

Fig. 4 Reservoir size–frequency distribution.

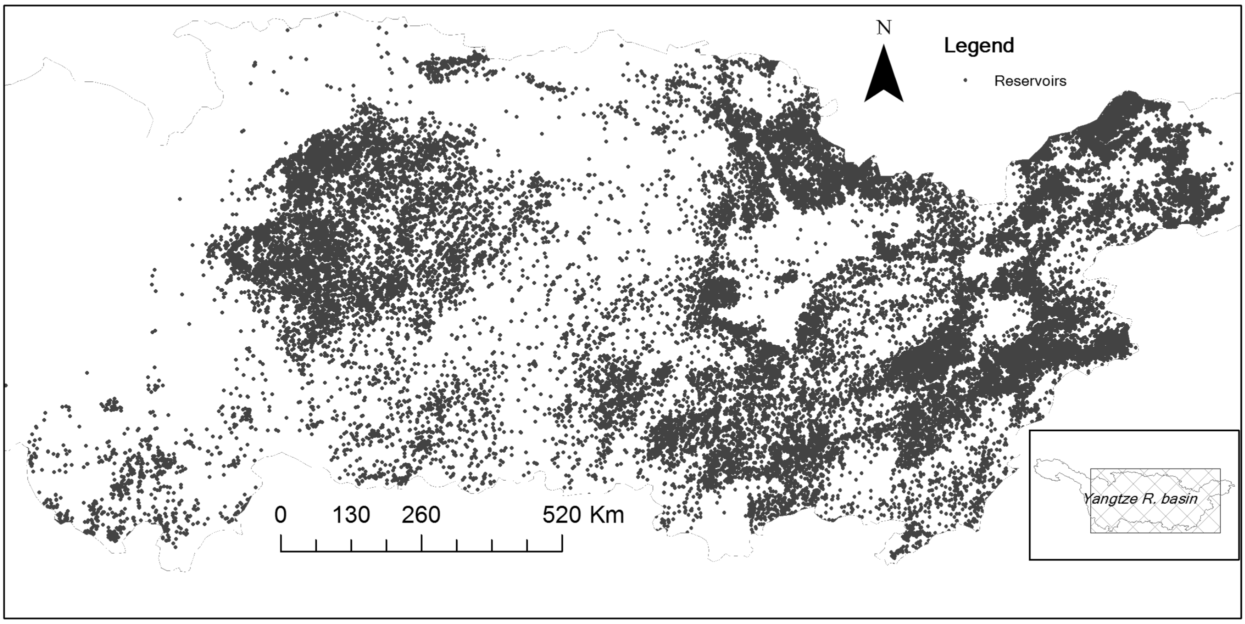

Fig. 5 Reservoir spatial distribution in the Yangtze watershed.

and marshes both supply water to regional agriculture, as well as acting as "efficient reservoirs" which control flooding. Similar conditions apply in the Poyang Lake Plain around Poyang Lake.

Estimating reservoir storage capacity

Many studies have demonstrated the existence of a robust relationship between the surface area and the storage capacity of reservoirs at both regional and global scales (Lehner & Doll, 2004; Liebe *et al.*, 2005; Sawunyama *et al.*, 2006; Lehner *et al.*, 2011). That relationship provides the means for estimating reservoir storage capacities. The equations established for large (storage capacity ≥ 1 km^3) and small reservoirs (storage capacity < 1 km^3) in the Yangtze River Basin are as follows:

Large reservoirs: $C = 28.386 \times A^{1.0516}$ $(R^2 = 0.8438)$ (3)

Small reservoirs: $C = 30.382 \times A^{0.9859}$ $(R^2 = 0.8801)$ (4)

where C is storage capacity in 106 m^3 and A is reservoir area in km^2.

Table 1 The number of reservoirs extracted from remote sensing data and their volumes derived from equations (3) and (4).

Surface area (km^2)	Num. of reservoirs	Total area (km^2)	Volume (km^3)
<0.1	36 515	892	29
0.1–1	4 476	1 252	39
1–10	707	1 838	56
10–100	98	2 509	85
100–1000	6	1 815	70
Total	41 802	8 306	279

The total estimated capacity of all the reservoirs in the Yangtze River Basin is about 279 km^3, or 29% of the average annual runoff (Table 1). This study identified 192 large reservoirs (≥0.1 km^3 storage capacity), 1136 medium reservoirs (0.01 km^3 ≥ storage capacity < 0.1 km^3), and 40 474 small reservoirs (storage capacity < 0.01 km^3). Although the number of large reservoirs amounts to <1% of the total, their capacity accounts for about 65% of the total storage capacity. This proportion is similar to the percentage (60%) for 633 large reservoirs (storage capacity > 0.5 km^3) in the world proposed by Vorosmarty *et al*. (2003). In contrast, small reservoirs constitute more than 96% of the total number of reservoirs; however, their total storage capacity accounts for only about 18% of the total (Table 1). Thus, large and medium reservoirs control most of the water (more than 82%) in the Yangtze River Basin; hence, they play a key role in water regulation.

DISCUSSION

Change in water distribution

Before the founding of the People's Republic of China, there were few reservoirs in the country; subsequently, reservoir construction developed rapidly. By the end of the 1970s, state-organized campaigns for electricity, irrigation and flood control resulted in the construction of nearly 80 000 reservoirs, more than half of which were located in the Yangtze River Basin. After this initial rapid development, less than 4000 reservoirs were built in the basin (Xu, 2005); however, the growth rate of large reservoirs was higher than in the initial phase, indicating that the government mainly focused on large projects. By 1992, when the Three Gorges Project was approved for construction, the Yangtze River Basin already had accommodated 125 large reservoirs (Liu, 2010). By 2009, when the Three Gorges Project was completed, the number of large reservoirs in the Yangtze watershed had increased to more than 190 (MWRC, 2009).

A total of 1328 reservoirs (capacity ≥ 0.01 km^3) account for more than 90% of the total storage capacity in the Yangtze River Basin. Growth in both the number and capacity of the reservoirs in the Yangtze River Basin was discontinuous. Total reservoir capacity jumped from <1 km^3 in 1949 to more than 210 km^3 in 2007, and the number of reservoirs (capacity ≥ 0.01 km^3) increased from only 2 in 1949 to more than 1000 in 2007. By the end of the 1970s, nearly 80% of the 1328 reservoirs (capacity ≥ 0.01 km^3) investigated had been built; but their total capacity was only 89.3 km^3, and only 12 reservoirs with a capacity >1 km^3 (e.g. Danjiangkou Reservoir: 20.8 km^3, Zhelin Reservoir: 7.9 km^3) had been built. After the 1970s, growth in reservoir construction slowed; however, total capacity experienced a sharp increase, especially after the 1980s. Hence, after the 1980s, the focus was on large reservoir projects.

Because of reservoir impoundment, the spatial distribution of water resources in the Yangtze River Basin has undergone dramatic changes. Before 1949, water resources in the middle-lower reaches were sufficient to meet requirements, especially in the Jianghan Plain, which is known as the "water bag" because it abounds in lakes. These lakes impound nearly 30 km^3 of water that is used for agriculture and aquaculture. However, with the construction of numerous large reservoirs in the upper reach of the Yangtze River Basin, more and more water was impounded upstream. Based on this study, all the reservoirs with capacities >10 km^3 are located in the upper Yangtze reach except the Danjiangkou Reservoir. Total reservoir capacity in the upper reach is more than

180 km^3. The dramatic increase in the amount of water impounded in the upper Yangtze reach could cause problems, such as insufficient water in the middle and lower reaches, as well as substantial variations in annual and particularly seasonal water discharge. For example, from April to June 2011, the middle and lower reaches were plagued by a severe drought. Water was released from the Three Gorges Reservoir to ease the shortage; however, over 50 km^3 of water, larger than the maximum storage of the Three Gorges Reservoir itself, was still impounded for power generation by the many other large reservoirs in the upper reach. The cumulative effects of these reservoirs on the Yangtze's large-scale hydrological regime is obvious (Lu *et al.*, 2011).

Another result of reservoir impoundment is a sharp decline in the mass of sediment discharged to the sea. According to Yang *et al.* (2005) and Lu *et al.* (2003, 2005), in response to widespread soil erosion and increasing specific yields, sediment accumulation rates in reservoirs has increased from <1 × 10^6 t year^{-1} in the 1950s to >850 × 10^6 t year^{-1} in 2003. From the 1960s to 2003, total fluvial sediment discharge at Datong displays a strong declining trend, primarily as a result of reservoir construction and subsequent infilling.

Impact on the free-flowing environment

Using the approach introduced above, the impact of dams on the free-flowing segments in all the large tributaries (24 991 km) in the Yangtze River Basin was evaluated (Fig. 6). The length of streams which remain free-flowing is 20 303 km; hence, nearly 20% of the streams currently are regulated. Among all the rivers evaluated in this study, the Wujiang and Yuanjiang rivers (Fig. 1) are the most seriously affected, with only 35% and 42% respectively, of their free-flowing segments remaining. The free-flowing streams primarily are located in the upper reach (e.g. the Tuotuo and Yanglongjiang rivers in the upper reach), in the flat areas in the middle reach, and in the rivers flowing into Poyang Lake.

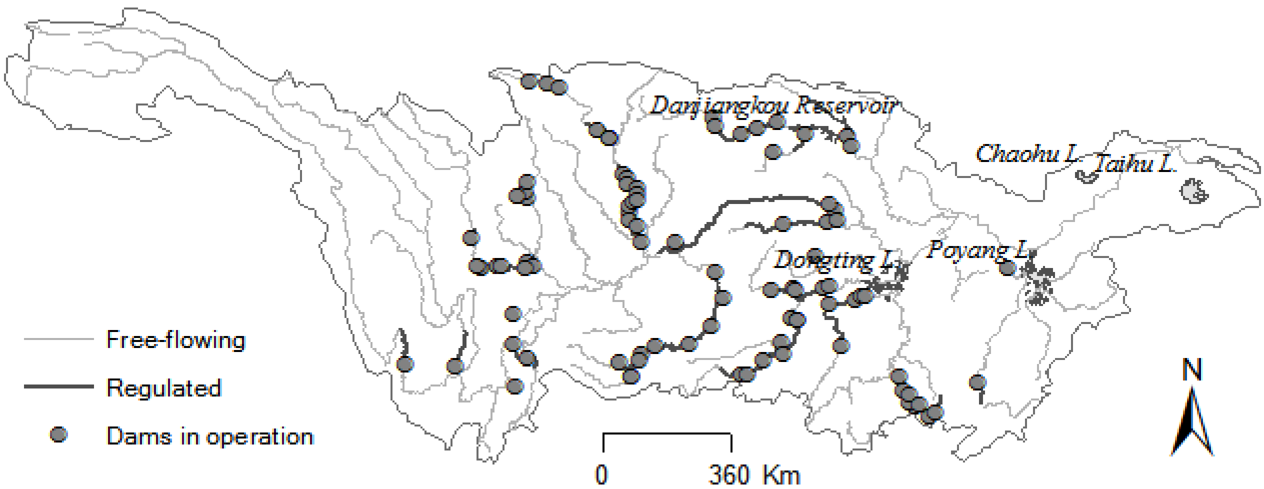

Fig. 6 The current condition of the free-flowing streams with respect to hydropower dams in operation.

China is undergoing tremendous economic growth which also is accompanied by a constant demand for more energy. The country is looking for alternative energy sources to coal, in an effort to lower greenhouse gas emissions. The construction of hydroelectric dams remains the first option to boost non-fossil fuel energy consumption and due to its vast exploitable hydroelectric resources, the upper reach of the Yangtze River Basin is an ideal location for hydropower projects. China recently unveiled its latest five-year plan covering 2011 to 2015, which sets an ambitious target for hydropower production, despite the problems caused by reservoirs. It is inevitable that more reservoirs will be built in the future, especially in the Yangtze River Basin. Under this scenario, the reduction in free-flowing stream segments also was evaluated during this study (Figs 7 and 8).

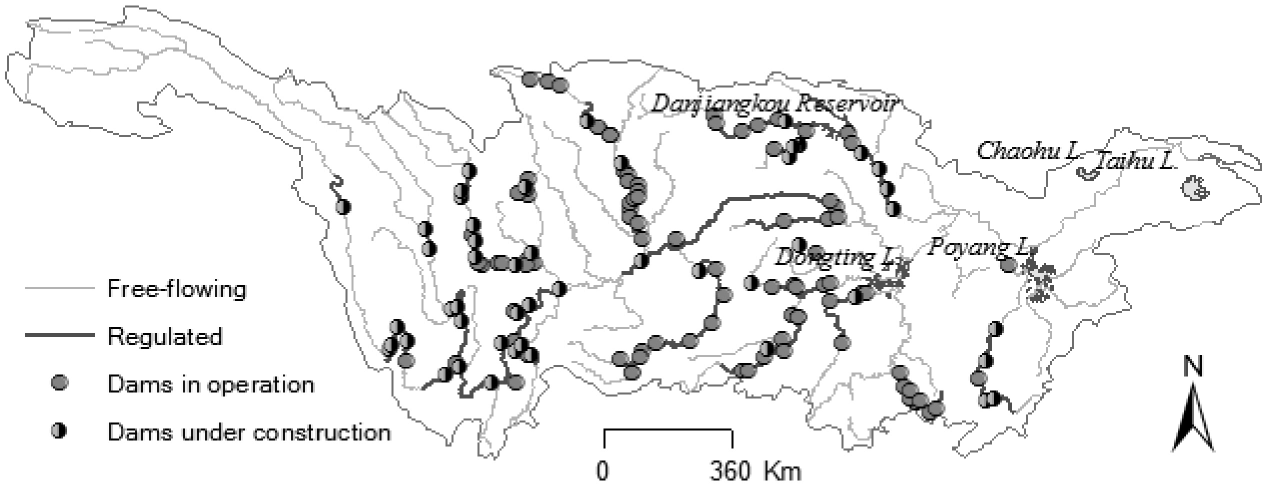

Fig. 7 The condition of the free-flowing streams in future with respect to hydropower dams in operation and under construction.

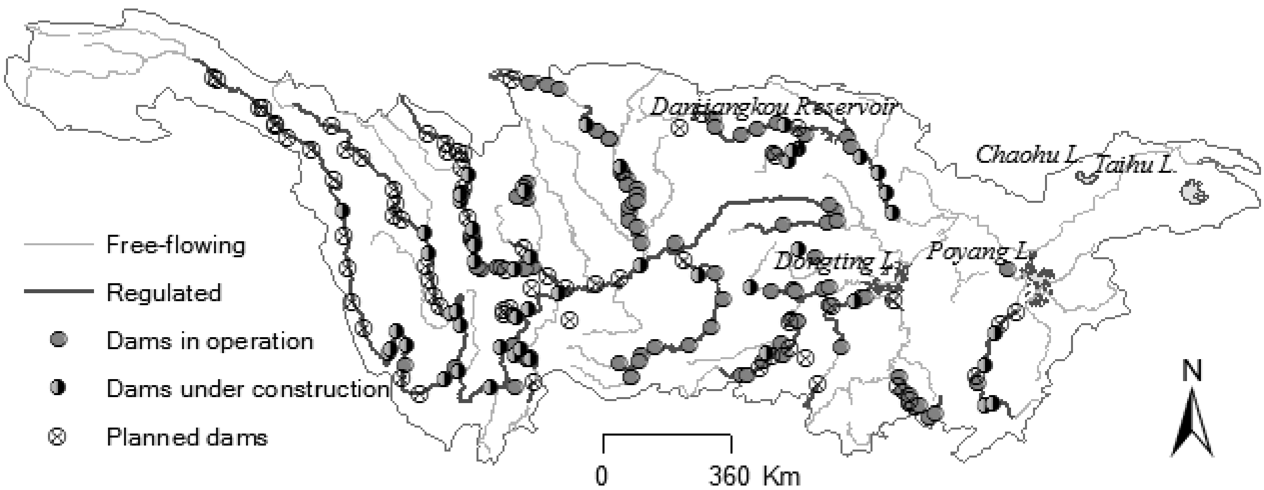

Fig. 8 The condition of the free-flowing streams in the future with respect to planned dams and hydropower dams in operation, under construction.

Figure 7 shows the future condition of free-flowing stream segments with respect to the hydropower dams expected to become operational before 2025. By that time, regulated stream length will increase to 7298 km or nearly 30% of the total. The newly regulated streams mainly are on the major tributaries, such as the Hanjiang, Jinshajiang and Jialingjiang. Further, when all the planned dams are included, the length of regulated stream segments jumps to 10 675 km, or about 43% of the total (Fig. 8). Almost all the major tributaries in the upper-middle Yangtze reaches will be fully regulated (e.g. the Dadu, Yalong, Minjiang, Jinshajiang, Wujiang, Jialing and Yuanjiang rivers); this group even will include the Tuotuo River in the source area. The percentage of regulated segments in all eight major Yangtze tributaries will exceed at least 80% (e.g. Jinshajiang (~100%), Dadu (~100%), and Yalongjiang (92%).

This study indicates that most of the dams constructed on the Yangtze mainstem, or its major tributaries, cause more serious impacts than those constructed on the minor tributaries. Further, when all the planned dams become operational, almost all the free-flowing stream segments in the mainstem and eight major tributaries in the upper-middle Yangtze reaches will vanish. Lastly, poorly evaluated and/or uncontrolled dam development could push the Yangtze River ecosystem past the point where natural processes such as sediment and nutrient transport, as well as fish migration, may become unsustainable.

CONCLUSIONS

Since the founding of the People's Republic of China, there have been dramatic changes in the hydrological regime of the Yangtze River Basin. About 42 000 reservoirs have been constructed, which caused an increase of 8306 km^2 in water surface area. Reservoir construction substantially changed the spatial distribution of water resources in the Yangtze River Basin. Much more water is now impounded in the upper-middle reach for energy generation and this, in turn, has altered both the annual and especially the seasonal water discharge patterns. These changes could cause insufficient water supply in the lower reach of the Yangtze River Basin. Further, it may cause serious aquatic ecosystem disconnectivity by eliminating free-flowing stream segments. The cumulative effects caused by these hydrologic changes need to be addressed.

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