Delineation of China's reservoirs and lakes using remote sensing techniques

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Abstract We used remote sensing images to provide the first complete picture of the reservoirs and lakes located within China. We extracted 89 691 reservoirs, covering about 26 755 km^2 of the land surface. By applying an empirical formula relating reservoir storage capacity and surface area, we estimated the total storage capacity to be about 770 km^3. Also, we delineated more than 180 000 lakes and ponds, with a total surface area of about 79 767 km^2. These include 2721 lakes larger than 1 km^2. Through comparison with previous studies, we found that dramatic changes have occurred over the past decades. Reservoir construction and water diversion have changed the spatial distribution and seasonal variation of water resources and have made the river systems fragmented. Additionally, this study found that more than 200 lakes of >1 km^2 on the Mongolia-Xinjiang Plateau and the Eastern Plain have disappeared, but about 50 lakes >1 km^2 have appeared on the Tibetan Plateau. The disappearing lakes on the Mongolia-Xinjiang Plateau and the newly appearing lakes on the Tibetan Plateau could be a result of climate change; whereas the disappearance of lakes on the Eastern Plain, especially in the middle–lower reaches of the Yangtze and Huaihe River basin, reflect the impact of human activities, such as land reclamation and urbanization. The database of delineated reservoirs will be employed to estimate the total amount of sediment trapped behind dams.

Key words lakes; reservoirs; satellite images; remote sensing; hydropower; China

INTRODUCTION

There are more than 45 000 large reservoirs worldwide – defined as those impounded by dams higher than 15 m – used for water supply, power generation, flood control, etc. (White, 2000; Lehner *et al.*, 2011). These reservoirs are estimated to have a total storage capacity in the range 7000 to 8300 km^3 (Vörösmarty *et al.*, 2003; Chao *et al.*, 2008). This is equivalent to nearly 10% of the water stored in all natural freshwater lakes on Earth, and represents about one-sixth of the total annual river flow into the oceans (Downing *et al.*, 2006; Lehner *et al.*, 2011). Currently, about 20% of cultivated land worldwide is irrigated, representing some 300 million ha, which produces about 33% of the world's food supply; about 20% of the global generation of electricity is attributable to hydropower schemes, which equates to about 7% of worldwide energy usage. The benefits attributable to dams and reservoirs, most of which have been built since 1950, are considerable and the storage of water in reservoirs have improved the quality of life worldwide. However, reservoirs can disconnect rivers from their floodplains and wetlands and slow water velocity in riverine systems, converting them into a chain of connected reservoirs. Nilsson *et al.* (2005) show that, of 227 rivers assessed worldwide, 37% were strongly affected by dams and altered flows, 23% were moderately affected, and 40% were unaffected. Investigating the current waterscape is crucial and it can serve as baseline data to assess important environmental issues.

China has seen a remarkable development of dam technology over the last 60 years, with the advent of large dams, such as the Gezhouba Dam and the Three Gorges Dam on the Yangtze, and the Sanmenxia and the Xiaolangdi dams on the Yellow River. The Three Gorges Dams (TGD) is the world's largest dam in terms of installed capacity. Between 1950 and 1982, more than 18 000 dams were built in China (Milliman, 1997), where human intervention to regulate river flow is essentially a post-1949 phenomenon. Before this there were only about 20 reservoirs. However, by 2007 more than 85 000 reservoirs had been built. China is a country that is currently experiencing tremendous economic growth. Its fast-increasing demand for energy requires constant development of energy sources and China is looking for other energy sources besides the dominant source, coal. The construction of hydroelectric dams has become the first option to help the government boost the contribution of non-fossil fuel power generation in national energy consumption, due to the vast exploitable hydropower resources, especially in the upper Yangtze region.

However, a full inventory of reservoirs is either not available, or not accessible, to researchers. The objectives of this study are: (a) to investigate the current status of reservoirs and lakes in China using remote sensing techniques; (b) to estimate the storage capacity of the reservoirs using an empirical formula; (c) to examine recent changes in both the number and size of lakes; and (d) to investigate the potential causes of these changes. With this improved information on the number and size of reservoirs, our ultimate goal is to estimate the sediment retention by all the reservoirs and assess their cumulative impact on the sediment loads of large Chinese rivers.

METHODS AND DATA COLLECTION

Remotely-sensed data provide a means of delineating reservoir boundaries over a large area at a given point in time. Landsat Thematic Mapper (TM) and ETM+ imagery, mainly acquired after the monsoon season (September–October), for the period 2005 to 2008, were used in this study. Ideally, contemporary data for the same year should be used for a study of this nature, but the limited availability of cloud-free data for the region necessitated the use of data from multiple years and seasons. A total of 556 images, including 432 TM images and 123 ETM+ images, were employed and processed in 2011.

The hydrological data used in this study, such as reports on reservoir construction and water regulation, were primarily obtained from official published sources, such as the *Bulletin of Changjiang Sediment*. Some data on reservoir capacity were obtained from previous field investigations and published research results. Some other ancillary data sources, as well as information from the Internet about the capacity of individual reservoirs, were also used. We treated this information in a very conservative manner, i.e. only using values which appeared in multiple sources. During the screening process, only reliable data were identified for subsequent use.

The waterbody delineation can be divided two phases, namely, waterbody detection and reservoir classification (see Yang & Lu, 2012). In the first step, a density slicing and multi-threshold approach was used to classify the pixels of satellite images into two categories: water and non-water. In the second step, with the assistance of secondary data and high-resolution satellite data from the Google Earth Image Service, visual interpretation was used to classify waterbodies into three main classes: lakes (lakes and ponds), reservoirs and rivers.

It should be noted that because of the low resolution of Landsat TM/ETM+ images and effects caused by mixed pixels and shadow removal, the accuracy of smaller waterbodies could not be guaranteed and thus the delineated waterbodies of <0.0036 km^2 were excluded. An empirical relationship between surface area and storage capacity of reservoirs was used as the basic principle for area-based estimation of reservoir storage capacities.

RESULTS

Reservoir spatial distribution

This study identified 89 691 reservoirs, covering about 26 755 km^2 of the land surface of China. The number of delineated reservoirs is very close to the officially reported number of 86 353 (MWRC, 2009). Figure 1 shows the variation of dam density across China. It shows a clear east-to-west gradation in the distribution of dams: most of the reservoirs are located in the eastern regions. Figure 1 indicates that the reservoirs are mainly distributed in the Yangtze River basin, the Pearl River basin and some river basins in South China, which are flat agricultural regions, such as the Sichuan Basin, the Poyang Lake Plain around Poyang Lake and the Taihu Lake Plain around Taihu Lake. Few reservoirs are located in China's vast western regions, such as the Tibet Plateau and the Mongolia and Xinjiang plateaus.

An empirical relationship between surface area and storage capacity of reservoirs (Lehner & Doll, 2004; Liebe *et al.*, 2005; Sawunyama *et al.*, 2006; Lehner *et al.*, 2011) was employed to estimate reservoir storage capacity. The established formula is as follows:

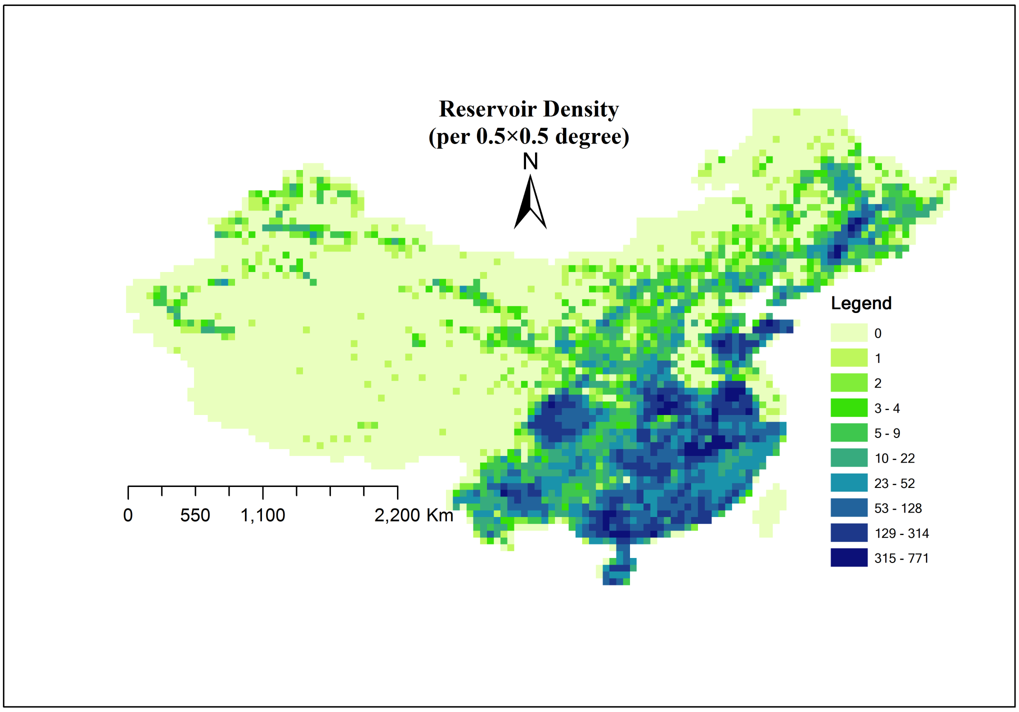

Fig. 1 A map of reservoir (>0.0036 km^2) density (the numbers of reservoirs per 0.5 × 0.5 degrees) delineated from satellite images.

Table 1 Number and estimated capacity of reservoirs across China.

Water resources region	No. of reservoirs	Total storage capacity (km^3)	Runoff[a] (km^3)	Water regulation (%)
Yangtze River	42 873 (42 710)[a]	237 (231)[a]	951.3	24.9
Songhua River	5 016 (2 240)[b]	103 (58.4)	76.2	135
Liaohe River	1 309 (1 254)	38 (39.3)	14.8	257
Haihe River	1 041 (2 063)	33 (32)	22.8	145
Yellow River	2 747 (2 731)	65 (82.7)	66.1	98
Huai River	9 806 (8 944)	58(62)	62.2	93
Pearl River	17 740 (16 442)	107 (109.6)	333.8	32
Rivers in Southeast	6 295 (7 172)	56 (56.7)	--	--
Rivers in Southwest	1 897 (2 009)	57 (42.5)	--	--
Rivers in Northwest	967 (788)	16 (15.9)	--	--
Total	89 691 (86 353)	770 (500)		

[a] Data from China Statistical Yearbook(2009).
[b] According to Dai *et al.* (2009), the number of reservoirs in the Songhua River Basin is 6551.

$$C = 17.19 \times A^{1.172} \, (r^2 = 0.8802) \quad (1)$$

where C is reservoir storage capacity for individual reservoirs in 10^6 m^3, and A is reservoir surface area in km^2. The number and estimated storage capacity of the reservoirs identified is shown in Table 1.

The flows of most of the large rivers have been severely impacted by anthropogenic modifications and regulation, except for the Yangtze (24.9%) and Pearl River (32%). Taking the Yellow River as an example, the estimated total reservoir capacity of 65 km^3 is comparable to the river's long-term annual water dischrage of 66.1 km^3 year^{-1}, meaning that almost 100% of the runoff is regulated. If the recent (reduced) runoff is used, the degree of regulation would be much higher (Ran & Lu, 2012). Impoundment by some major dams, such as Sanmenxia, Liujiaxia and

Longyangxia, has caused a sharp decline of the runoff of the Yellow River (Xu *et al*., 2010). The situation is worse, in northern China, where in areas such as the Liaohe River basin and the Haihe River basin, the estimated reservoir capacity is almost twice as large as the annual runoff. Rapid urbanization and high population density in these areas are the major drivers of dam construction. Since the 1950s, water withdrawal and consumption in China have increased by about 5-fold because of a doubling of the population and increased irrigation and industrial activity. In the narrow eastern coastal zone and the very densely populated North China Plain, the concentration of people is a key driver of water regulation.

Despite the presence of more than 42 000 dams in the Yangtze River basin and nearly 18 000 dams in the Pearl River basin in South China, it would seem that dams have a lower net impact on the annual water discharge in these two river basins, because the water discharge at the Datong gauging station on the Yangtze River has not yet shown a significant change (Yang *et al*., 2006; Xu & Milliman, 2009). The Three Gorges Reservoir (TGR) with a total capacity of 39.3 km^3, the world's largest, began to impound water in June 2003. However, because its storage capacity is less than 5% of the Yangtze's annual discharge, its impact on the Yangtze water discharge has been minor (Xu & Milliman, 2009). Nevertheless, dam construction has drastically altered annual and seasonal sediment discharge in the upper and lower Yangtze River basin (Lu & Higgitt, 1998; Lu *et al*., 2003; Walling, 2006; Xu & Milliman, 2009).

Lake spatial distribution

We delineated more than 180 000 lakes and natural ponds which cover about 79 767 km^2 of the land surface of China (Fig. 2). The distribution of lakes in China is uneven. Traditionally, China is divided into five geographic zones in terms of the frequency of lakes, namely, the Tibetan Plateau (TP) covering Qinghai Province and the Tibet Autonomous Region; the Yunnan-Guizhou Plateau (YGP) covering Yunnan, Guizhou, Sichuan and Chongqing provinces; the Mongolia-Xinjiang Plateau (MXP) covering Inner Mongolia, Xinjiang Uygur and Ningxia Hui autonomous regions, Gansu, Shaanxi and Shanxi provinces; the Northeast Plain (NP) covering Liaoning, Jinlin and Heilongjiang provinces; and the Eastern Plain (EP) covering all the remaining provinces (Fig. 3). Among them, the Eastern Plain and Tibet Plateau contain the largest number of lakes, which account for nearly 85% of the total lake area in China, and form two dense lake clusters in East and West China respectively.

Table 2 summarises the distribution of lake area across China. It can be seen that more than 50% of the lakes are located in the Tibetan Plateau, covering 42 136 km^2 of the land area. Likewise, the Eastern Plain contains about 25% of the lakes. Despite the large area covered by the Mongolia-Xinjiang Plateau, only 15.3% of the lakes are located there. A similar trend for the lakes larger than 1 km^2 can be observed.

Of the 2721 lakes >1 km^2, 1140 out are located in the Tibetan Plateau and 601 lakes >1 km^2 are distributed in the Eastern Plain. Although, the Mongolia Plateau also has nearly 600 large lakes, their total surface area (10 710 km^2) is rather less than that of the large lakes in the Eastern Plain (17 980 km^2), as average lake size in the Mongolia Plateau is much smaller than that in the Eastern Plain.

Table 2 Regional distribution of lake area in China.

Lake region	All lakes Area (km^2)	Percentage (%)	Lakes (>1 km^2) Number	Area (km^2)
TP	42 136	52.8	1140	40 333
YGP	1 205	1.5	36	1 066
MXP	12 165	15.3	574	10 710
NP	4 058	5.1	370	3 050
EP	20 203	25.3	601	17 980

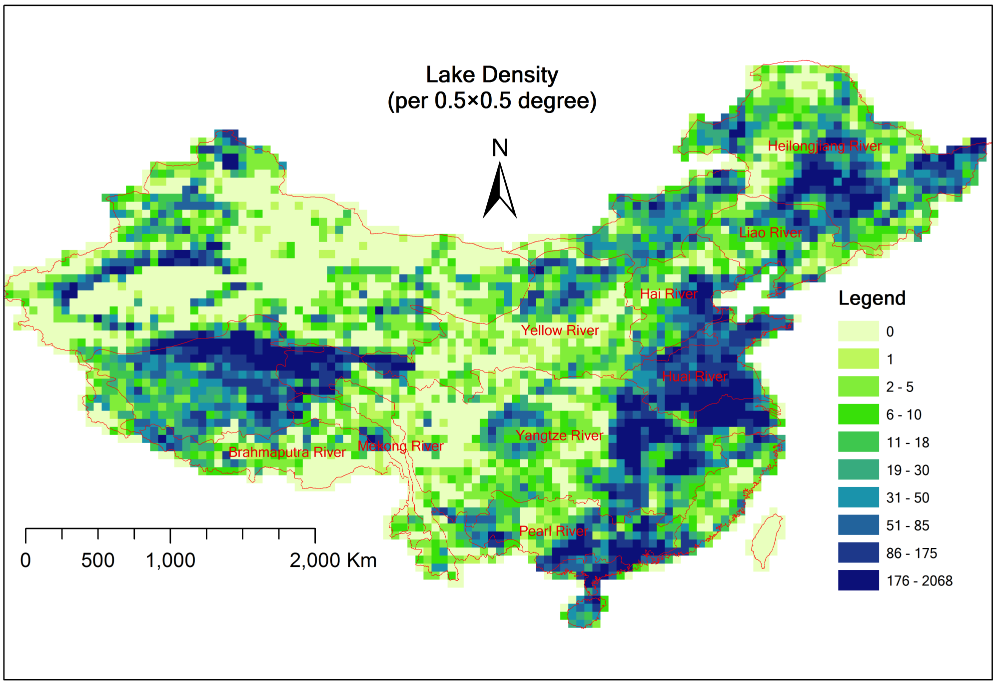

Fig. 2 A map of lake (>0.0036 km^2) density (the numbers of lakes per 0.5 × 0.5 degrees) delineated from satellite images.

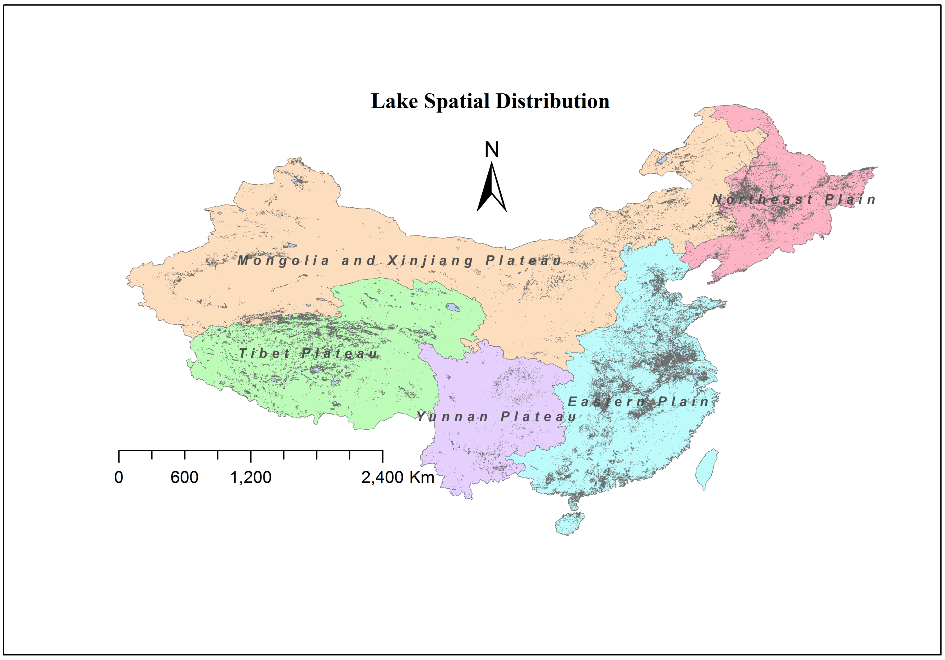

Fig. 3 Lake spatial distribution with respect to five geographic zones.

DISCUSSSION

Changes in the number of reservoirs and lakes

Reservoir construction to support human activities has played a key role in the changes in China's waterscape. Prior to 1949, China had no more than 40 small hydropower dams and only a small number of large-scale reservoirs. After 1949, reservoir construction expanded rapidly. The expansion can be divided into three phases. The first (from the 1950s to the 1970s) represented a major expansion of the nation's hydropower industry. From the 1950s to the 1970s, China experienced a "great leap forward" in terms of hydraulic engineering and water conservancy projects, leading to the construction of most of China's reservoirs. By the end of the 1970s, the state-organized campaigns for electricity generation, irrigation, and flood control has resulted in the building of nearly 80 000 reservoirs, more than half of which were located in the Yangtze basin (National Bureau of Statistics of China, 1993). During the second phase (from the 1980s to the 1990s), less than 4500 reservoirs were built, but the growth of large reservoirs was greater than in the first phase, reflecting the emphasis of the government on large reservoir projects. The same trend continued during the next phase, after the 1990s. By 1992, when the Three Gorges Project was approved for construction, China already had 369 large reservoirs. By 2009, when the Three Gorges project was completed, the number of large reservoirs had increased to 529 (MWRC, 2009). The large number of hydropower plants on the large rivers, such as the Yangtze, the Pearl and the Yellow rivers has dramatically changed the distribution of water resources. For example, due to reservoir construction, 80 km^3 of water is impounded in the upper reaches of the Yangtze and the amount is expected to increase to 180 km^3 when some planned/under construction hydropower plants (such as Xiangjiaba, Xiluodu, Wudongde and Baihetan) become operational.

Table 3 Number and surface area of lakes larger than 1 km^2 (Wang & Dou, 1998).

Lake region	Number	Area (km^2)
TP	1 091	44 993
YGP	60	1 199
MXP	772	19 700
NP	340	3 955
EP	696	21 172

Note: According to Wang & Dou (1998), the data were primarily collected during the period extending from the 1960s to the 1980s.

The information on lake numbers and size and the total area of lakes in different regions provided by the current study were compared with equivalent information provided by previous studies (Wang & Dou, 1998; Ma *et al*., 2010). Table 3 shows the number and surface area of lakes >1 km^2 documented by Wang & Dou (1998). By comparing the information presented in Table 3 with that provided by Table 2, it can be seen that dramatic changes in both lake number and lake surface area have occurred since the 1980s. The total number of lakes of >1 km^2 declined from 2959 to 2721 and the total surface area decreased from 91 019 km^2 to 73 139 km^2, a loss of about 20% of total surface area. Ma *et al*. (2010) report similar findings: 243 lakes >1 km^2 have disappeared in recent decades. With respect to the five geographic lake regions, the changes show two important trends. First, in the Tibet Plateau, the number of lakes of >1 km^2 shows an *increase* of 49 lakes, although the total surface area decreased slightly; secondly, in the other four lake regions, both lake number and surface area *decreased* by varying degrees. The greatest reduction occurred in the Mongolia-Xinjiang Plateau, with a loss of nearly 9000 km^2 of lake area, whilst the second largest decrease occurred in the Eastern Plain lake region which lost 96 large lakes representing a surface area of 3192 km^2. Much of this reduction occurred in the middle and lower reaches of the Yangtze and in the Huaihe River basin.

According to Ma *et al.* (2010), the causes of the uneven spatial distribution of changes in lake number and lake area vary in different lake regions. The reduction in lake numbers in the Mongolia-Xinjiang Plateau has been mainly caused by climate change, because this area is characterized by an arid and sub-arid climate (242.5 mm annual precipitation; Yang *et al*., 2003). Air-temperature records indicate a warming trend beginning in the 1950s with an abrupt change occurring in the mid- and late-1980s, resulting in an average annual increase of 0.0221°C from the 1950s to 2000 (Guo *et al*., 2005), accompanied by mean annual potential evaporation of

2205.6 mm (Yang *et al.*, 2003). In addition, agriculture in this region depends heavily on irrigation and the effective area of irrigated land has been continuously increasing (Ma *et al.*, 2010), which has made the situation worse. It should be noted that, although the total surface area declined slightly, the number of lakes increased significantly in the Tibet Plateau. The changes could also reflect climate change over past decades, with the areas at altitudes above 4000 m having warmed 0.3°C per decade. As a result of this warming, glaciers on the Tibet Plateau have been melting at an alarming rate (Xu *et al.*, 2009), leading to increased river flows.

In the Eastern Plain lake region, the important causes of waterscape change are land reclamation and lake isolation. For example, in the late 1940s, lakes covered a total area of about 35 123 km^2 in the middle and lower reaches of the Yangtze River. About 12 000 km^2 of lake area were drained for farming from the 1950s to the 1970s (Jiang *et al.*, 2006). In many cases, whole lakes were drained. Due to urbanization, land reclamation remained common from the 1980s to 2000, leading to a further decrease in lake number and surface area during this period, although the total surface area decreased only slightly over the two decades. After 2000, the rate of reduction slowed down and the number and area of lakes decreased only slightly; however, it is too late to save the natural lakes that have disappeared.

Future trends in reservoirs and lake development

China is a country currently experiencing very rapid economic growth. The rapidly increasing demand for energy requires constant development of energy sources and China is looking for other energy sources besides coal, the dominant source. Thus, the construction of hydropower dams has become the first option to help the government boost the contribution of non-fossil fuels to national energy consumption, due to the vast exploitable hydropower resources, especially in the upper Yangtze River and Pearl River regions. To take advantage of these hydropower resources, China has accelerated hydropower development in recent years, after a more limited development from the 1950s to 2005. In 2008, hydropower generated 563 TWh, which was equivalent to about 16% of China's total electricity generation. Because the potential hydropower capacity (estimates range up to 600 GW, but currently the technically exploitable capacity is about 400 GW) is only 25–30% utilized, and there remains much potential for further hydropower development. In comparison, utilization of potential hydropower in the USA is currently 80% and in Norway, Iceland, and other countries, it stands at over 90%. In 2009, the National Development and Reform Commission set a 300GW target for 2020 in the 17th Five-Year Plan. In terms of the scarcity of fossil fuels, hydropower is currently the best alternative to fossil fuels.

Figure 4 shows the distribution of hydropower dams in China. It can be seen that most of China's planned hydropower stations are located in Central and Southwest China, and particularly on the Upper Yangtze, Upper Mekong, the Pearl River and other rivers in Southwest China. At present, most of the hydropower dams in operation are located in the Yangtze and Pearl river basins. In terms of the distribution of hydropower resources, China has planned 13 foci for hydropower development, namely, the Jinshajing River, the Yalongjiang River, the Daduhe River, the Wujiang River, the upper reaches of the Yangtze River, the Nanpanjiang River and Hongshuihe River, the Lancangjiang River, the upper reaches of the Yellow River, the mainstream of the Yellow River, West Hunan, Fujian-Zhejiang-Jiangxi, the Northeast, and the Nujiang River. If the hydropower resources available in these areas are completely developed, the installed capacity will amount to 275.77 GW.

The rapid increase of water impoundment and major water diversions could dramatically change the spatial distribution of water resources and could result in a series of environmental problems, including: insufficient water in the middle and lower reaches of many rivers, variation in seasonal water discharge and severe waterscape fragmentation. For example, in April to June, 2011, the middle and lower reaches of the Yangtze River were hit by a severe drought. When the central government requested the Three Gorges Reservoir to release water to reduce the water shortage, a total of over 50 km^3 of water, a volume larger than the Three Gorges reservoir's maximum storage, was still impounded by the many other large reservoirs used for power

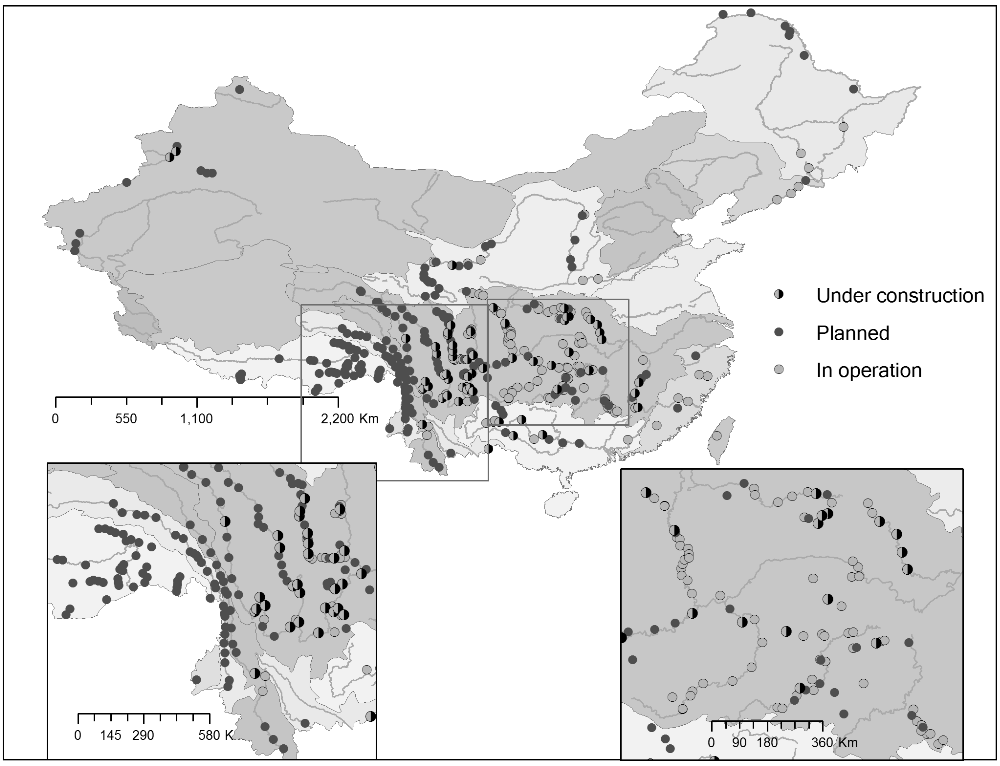

Fig. 4 The spatial distribution of the hydropower dams (>2.5×10^4 KW) in China. The left hand enlargement shows the planned hydropower dams on the Mekong River, Yangtze River and other rivers in Southwest China. The right hand enlargement shows the distribution of hydropower dams in the middle reaches of the Yangtze basin.

generation. The cumulative effects of these reservoirs on the large scale hydrological regime of the river cannot be ignored (Lu *et al*., 2011).

CONCLUSIONS

Dramatic changes have occurred to the reservoirs and lakes in China in recent years. Numerous reservoirs with a total storage capacity of 770 km^3 have appeared, but 238 lakes larger than 1 km^2 have disappeared. Reservoir construction is the key driver of waterscape changes, although the changes can be attributed to a variety of reasons. Reservoir construction has also changed the existing distribution of water resources and their seasonal distribution and caused fragmentation of the waterscape. Other human activities, such as land reclamation and urbanization have also caused the disappearance of nearly 100 large lakes in South China. The changes of lake size and lake surface area in North China and the Tibet Plateau can be attributed primarily to glacier melting as a result of climate change. With China's continuous economic growth, dam construction is expected to continue in the future and the changes will intensify in the coming decades.

This study has demonstrated that remote sensing is an effective method for identifying major water bodies (larger than 0.0036 km^2) including both reservoirs and lakes. Using information on all the delineated reservoirs, it will be possible to assess the cumulative impact of these reservoirs on water flow, sediment retention, carbon burial and river fragmentation across China.

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