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Delineation of lakes and reservoirs in large river basins: An example of the Yangtze River Basin, China

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ABSTRACT

One of the major impediments to water resources management in developing countries has been the fragmented nature of available data on the surface area, size and distribution of natural lakes and artificial reservoirs. In this study we used a parsimonious method based on remote sensing techniques to identify and extract water bodies in the Yangtze River Basin and classify them into three main categories: natural lakes, artificial reservoirs and rivers. This method combines data from the best available free sources, resulting in higher data quality. Using Landsat TM/ETM+ images, we delineated nearly 43,600 reservoirs and 42,700 lakes and estimated a total quantity of 0.7 million smaller (surface area <0.0036 km^2) reservoirs and 0.5 million smaller lakes. The combined surface area of the reservoirs was ca. 8600 km^2 with a total storage capacity of ca. 288 km^3, and the total surface area of natural lakes was ca. 16,200 km^2, with a total storage capacity of only 46 km^3. These results indicate that the 43,600 reservoirs are capable of storing a volume of water equaling nearly 30% of the annual mean runoff in the Yangtze basin, but there is considerable geographic variation in the potential surface water impacts. Capacity–area ratios, which are strong indicators of the general hydrologic effects of reservoirs, range from 22,600 $m^3\ km^{-2}$ in the Jinshajiang tributary to 347,500 $m^3\ km^{-2}$ in the Poyang Lake Region. The greatest river flow impacts may occur in the Hanjiang tributary, where the reservoir capacity is equivalent to up to 90% of the mean annual runoff. The results of this study show that the Yangtze River Basin, which was previously dominated by natural lakes, has become dominated by reservoirs as a result of reservoir construction and the shrinkage of natural lakes.

1. Introduction

Water is often regarded as the most essential natural resource, yet freshwater resources are directly threatened by human activities and stand to be further affected by anthropogenic climate change (Vörösmarty et al., 2010). Humans have built dams and impoundments for various purposes, including flood control, water supply, irrigation, recreation and hydropower (Lehner et al., 2011). To effectively manage water resources for competing uses, the storage capacities of reservoirs need to be accurately estimated. The issue of storage capacity will likely increase in importance in the future due to the increasing number of severe droughts (e.g., the drought in the Yangtze River Basin in May 2011) possibly associated with global warming and the growing population pressure (Jackson et al., 2001). For example, large dams have contributed to a 12–16% increase in global food production (Lehner et al., 2011). Recent projections suggest that 70% more food will be needed by 2050 (nearly 100% more food in developing countries such as China and India) to cope with a 40% increase in the world's population. Part of this additional food will be produced on irrigated lands that require 11% more water than current irrigated lands, much of it likely from reservoirs (Lehner et al., 2011). Thus, accurate assessments of water resources both in terms of quantity (e.g., surface area and storage capacity) and quality (e.g., turbidity) are important for producing wetland inventories, estimating water resource availability, and assessing the relationship between water and sediment discharges (Frazier and Page, 2000; Lu and Siew, 2006).

Scientific research has provided critical assessments of the impacts caused by reservoirs; however, inadequate data and assessment tools at regional and global scales have hindered the advancement of new and rigorous studies. Although several researchers and organizations have created their own georeferenced global or regional datasets of dams and reservoirs (ILEC, 1988–1993; Birkett and Mason, 1995; Vörösmarty et al., 1997; MSSL–WCMC–UNEP, 1998; Lehner and Doll, 2004; Lehner et al., 2011), these attempts are primarily based on data from the national archives of developed countries because national dam inventories are typically unavailable in developing countries. Therefore, the development of a parsimonious approach that can be used to rapidly delineate reservoirs in developing countries is urgently needed for reservoir studies. Recent developments in remote sensing,

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including increases in data quality and resolution, can support reservoir studies (Lehner and Doll, 2004). For example, Landsat Thematic Mapper (TM)/Enhanced Thematic Mapper Plus (ETM+) imagery has been employed in recent studies to delineate water bodies in Zimbabwe (Sawunyama et al., 2006), India (Mialhe et al., 2008), Ghana (Annor et al., 2009) and the Yellow River of China (Ran and Lu, 2012).

The Chinese Yangtze River Basin and its tributaries are being dammed at a dazzling pace. Nearly 45,000 reservoirs have been constructed to meet the large demand for water that has resulted from population growth and rapid economic development. The reservoirs serve more than 30% of China's population and support approximately 40% of the country's industrial and agricultural production (Dai et al., 2010). Along with the Amazon (Nazareno and Lovejoy, 2011) and the Mekong (Kummu et al., 2010; Wang et al., 2011), the Yangtze is considered a hotbed of hydropower development.

Focusing on the Yangtze River Basin, this study aimed to (a) explore the advantages of using remote sensing techniques to delineate water bodies across the entire Yangtze River Basin, (b) establish empirical formulas to quantify the storage capacity of reservoirs and lakes and (c) assess the magnitude and distribution of the potential impacts of reservoirs on the surface water component of the hydrologic cycle at the basin-wide scale.

2. The study area

The Yangtze (Changjiang) River in southern China lies between 91°E and 122°E and 25°N and 35°N, has a basin 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, including the Jinshajiang, Minjiang, Jialingjiang and Wujiang rivers, extends ca. 4300 km to Yichang from the headwaters in the Himalayan Mountains, with a drainage area of ca. 1.0×10^6 km^2. At Yichang, the Yangtze River exits the Three-Gorges Dam and enters the 950-km middle reach (Yichang to Hukou). Three large water bodies join the Yangtze River in this section: Dongting Lake, the Hanjiang River and Poyang Lake. The 930-km lower reach extends from Hukou to the river mouth approximately 20 km north of Shanghai and has a drainage area of 1.2×10^5 km^2. The long-term mean annual precipitation in the Yangtze Basin is approximately 1070 mm but the spatial and temporal distributions of rainfall are highly uneven (Xu and Milliman, 2009). Annual precipitation ranges from 500 mm in the west to 2500 mm in the east. Because most of the basin is affected by the southeast monsoon in the summer season, most precipitation occurs from May to October.

According to the records at Datong, the Yangtze River annually transports approximately 1035 km^3 yr^{-1} of water (1951–1990) to the estuary (Chen et al., 2001). The seasonal variability of water discharge is relatively small in comparison with that of the large rivers in northern China, such as the Yellow River. The annual water discharge from the upper Yangtze River, recorded at the Yichang station, averaged 451 km^3 yr^{-1} between 1882 and 1987, amounting to approximately half of the total discharge to the estuary. Monthly mean discharge has varied from 218 km^3 in August 1954 to 17.4 km^3 in February 1963 (Chen et al., 2002).

3. Data and methods

3.1. Data sources and data preprocessing

In this study, Landsat Thematic Mapper (TM) and ETM+ images, mostly acquired shortly after the monsoon season (September and October) from 2005 to 2008, were used to delineate the boundaries of water bodies in the basin. Ideally, this should be performed with data collected during a single year; however, a lack of sufficient cloud-free regional data necessitated the use of multi-annual and multi-seasonal data. In total, 94 cloud-free images were used, including 10 Landsat ETM+ images and 84 Landsat TM images (Fig. 2). The images were acquired from the United States Geological Survey (USGS) (http://glovis.usgs.gov/, last accessed in October 2011).

Additionally, very high-resolution satellite data, such as IKONOS and QuickBird images from the Google Earth mapping service, were acquired for selected areas to improve and validate the classification of water bodies. 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) and used to determine the backwater region of each cascade reservoir.

3.2. Water body detection and classification

The methodology for this study can be divided into two phases: water body detection and water body classification (Fig. 3). In the first step, a density slicing, multi-threshold approach was used to classify the satellite images into two categories: water and non-water. In the

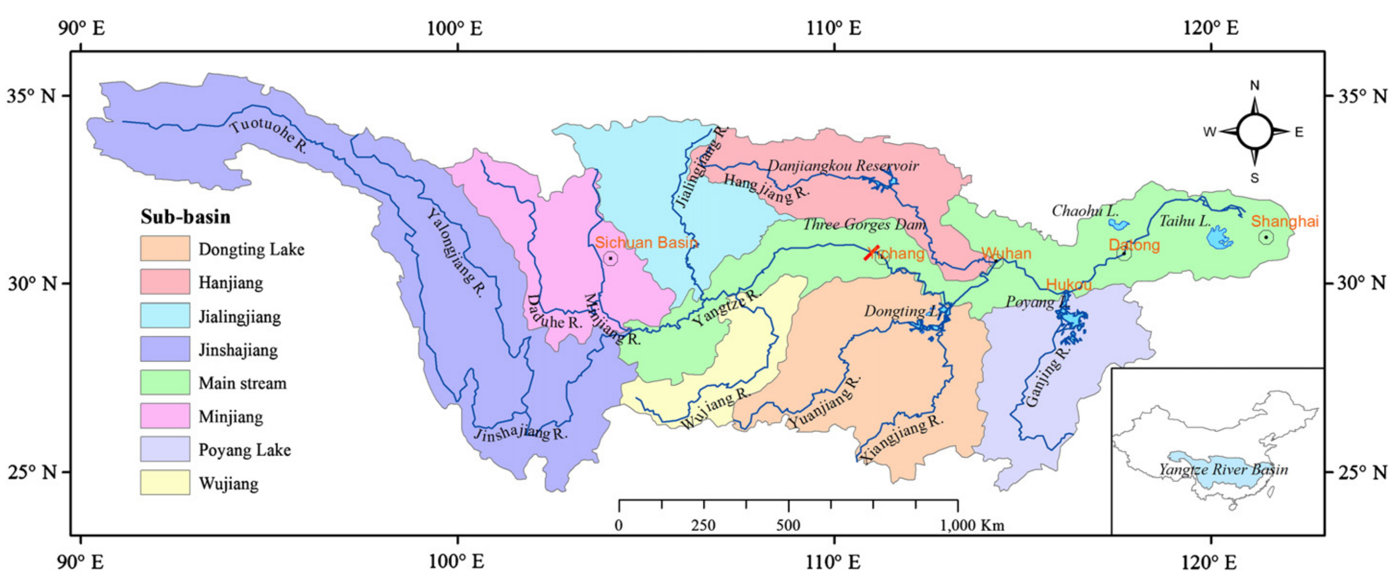

Fig. 1. Geographical setting of the Yangtze River and its sub-basins.