Satellite-based tracking of water surface variation of Poyang Lake during the last three decades

PING SONG[1,2] & YUANBO LIU[1]

1 *Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China*
ybliu@niglas.ac.cn

2 *Graduate University of Chinese Academy of Sciences, Beijing 100049, China*

Abstract Satellite-based observation provides an effective way to track water variations, since it can be used to retrieve many major hydro-physical variables, especially the water surface area. Here we used multi-satellite data to explore three-decade surface area variations of Poyang Lake, the largest freshwater lake in China. Our results revealed that the water area had declined generally in the last three decades. There existed a downtrend period of about 10 years. Generally, the decreasing trend of the decline was found to be significantly related to basin-scale climate change. Furthermore, the seasonal data demonstrated the remarkable change in surface area from over 3000 km^2 in summer to less than 1000 km^2 in winter. In the period examined, the lake surface area shrank to minimum values in 2003 and 2006. This was possibly related to land-use and land-cover change and construction of reservoirs in the basin, in addition to local climate change.

Key words remote sensing; water surface area; NDWI; Poyang Lake, China; climate change

INTRODUCTION

Water storage in freshwater lakes is vital to the biosphere, hydrosphere and anthroposphere. Freshwater lakes provide the habitats and water resources for fauna, flora and human beings. Monitoring the variations of lake water surface area is important to understand local hydrological processes and the global water cycle for better sustaining life on Earth (Alsdorf *et al*., 2007; Papa *et al*., 2008). In recent decades, remote sensing techniques have shown great potential in retrieving hydro-physical parameters. As one of the most important and intuitive hydro-physical parameters, water surface area has been widely used to track water variations of freshwater lakes (Mertes *et al*., 1995; Smith, 1997; Tan *et al*., 2006; Liao & Shen, 2008). It is valuable to understand the evolution of freshwater lakes.

Poyang Lake is the largest freshwater lake in China. It has a remarkable seasonal variation. The lake inundates a large area in the flooding period, and shrinks sharply in the dry season. Notably, it has suffered from several extreme hydrological events in the past three decades and frequent droughts in the last decade. Therefore, quantifying water surface area variations is of importance to local water management, biological diversity protection and the human environment. This study used multi-satellite multi-temporal images to track the three-decade variations of lake water surface area.

METHODS AND DATA PROCESSING

Study site Poyang Lake (28°22′–29°45′N, 115°47′–116°45′S) is located in the northern part of Jiangxi Province of China (Fig. 1). The Poyang Lake wetland is known to be an important wetland, and it has a diversity of functions related to flooding prevention, biological diversity protection and biological safety maintenance (Zhu & Zhang, 1997).

Poyang Lake is 173-km long from north to south, with a lake shore of 1200 km (http://www.poyanglake.net./pyhgk.htm). It receives inflow water mainly from five large rivers, including the Xiu River, Gan River, Fu River, Xin River and Rao River, and water discharges from the lake to the Yangtze River through Hukou (Fig. 1). There is a hydrological station at Hukou which routinely measures water level and discharge.

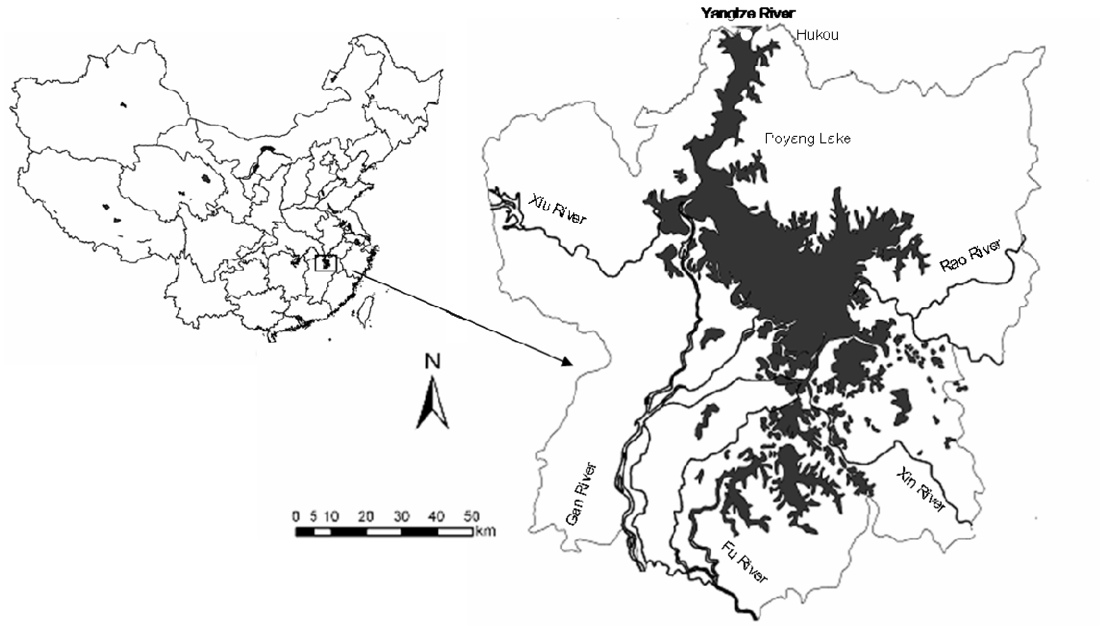

Fig. 1 Location of the Poyang Lake region in China.

Study materials and data pre-processing We acquired multi-satellite data sets from which to extract water body area. The data sets include the Landsat Multi-spectral Scanner (MSS)/ Thematic Mapper (TM) (30-m resolution) and the Moderate Resolution Imaging Spectro-radiometer (MODIS) for the period from the 1970s to 2009 (Tables 1 and 2). We used the visible/near-infrared bands for the extraction of lake areas. We selected MSS band 4 (Green band: 0.50–0.60 μm, 80-m resolution) and band 7 (Near-infrared band: 0.80–1.10 μm, 80-m resolution),

Table 1 List of Landsat image acquisition dates and selected bands for water surface extraction.

Landsat sensors	Date acquired	Band selected
MSS	24 December 1973	4,7
MSS	27 April 1976	4,7
MSS	7 May 1981	4,7
TM	2 August 1984	2,4
TM	13 February 1989	2,4
TM	12 March 1993	2,4

Table 2 List of MODIS images acquired.

Year	Number of images
2000	35
2001	54
2002	33
2003	53
2004	53
2005	29
2006	32
2007	32
2008	33
2009	39

and TM band 2 (Green band: 0.52–0.60 μm, 30-m resolution) and band 4 (Near-infrared band: 0.76–096 μm, 30-m resolution). From MODIS, we used band 4 (Green band: 0.545–0.565 μm, 500-m resolution) and band 2 (Near-infrared band: 1.23–1.25 μm, 250-m resolution). The total number of MODIS Green/near-infrared bands was 393.

MODIS atmospheric product (MOD05) and land surface temperature product (MOD11_L2) corresponding to the date of the visible/near-infrared bands were used to extract precipitable water vapour (PWV) and land surface temperature (LST). They were used as proxies for precipitation and evapotranspiration of the region. All images were visualized and analysed using the ERDAS 9.2 and ENVI 4.6 software. Geometric correction, mosaic functions, subsetting and atmospheric correction were performed if necessary.

Water body extraction A water body is one of the most easily discernible objects in remote sensing due to its special spectral characteristics. Water reflectance declines from the visible to the middle-infrared bands. The water absorbs radiance almost completely in the near-infrared band. The band ratio method of near-infrared to visible band has been widely used in lake and river extraction (McFeeters, 1996; Jain *et al*., 2005; Xu, 2005; Ding *et al*., 2007; Hui *et al*., 2008). With an optimal threshold for each image, the accuracy of final results could be up to 90% (Birkett, 2000). In this study we used the Normalized Difference Water Index (*NDWI*) to delineate water from non-water areas (McFeeters, 1996). The *NDWI* is computed as follows:

$$NDWI = (G - NIR)/(G + NIR) \tag{1}$$

where G is spectral reflectance in the green band and NIR is spectral reflectance in the near-infrared band. In the case of MODIS data, we used G band (500-m resolution) and NIR band (250-m resolution). The G band was resampled into 250-m resolution using the bilinear interpolation method. The *NDWI* histogram was subsequently generated for water body delineation. An optimal threshold value was determined from the histogram through comparison with surface objects (e.g. lake banks). The segmented water surfaces were also confirmed through visual inspection. In this way, water surfaces were obtained for all the images used. Water surface was extracted from each *NDWI* image as follows:

$$a < NDWI < 1 \tag{2}$$

where a is the optimal threshold.

Because Landsat data were acquired at different seasons for a certain year, seasonal variation in lake area would lead to misrepresentation of the year. To reduce the seasonal effect, we used all the MODIS images to outline seasonal variation of the lake area. The variation was fitted with a Gaussian curve as a function of date. The curve was then used to adjust all the Landsat extracted water areas to the same date (15 September), representing high-water period, for all the years.

In addition, we also obtained daily water level data at Hukou hydrological station for the period 2000–2009.

RESULTS AND DISCUSSIONS

Figure 2 shows the reconstructed temporal variations of the water area of Poyang Lake for the recent three decades.

Three-decade variation of Poyang Lake During the last 30 years, the water area of Poyang Lake decreased strongly at a rate of 93 km^2/year. The rate of decline rate increased to 166 km^2/year in the last 10 years. In general, water surface area was 6000 km^2 in 1973, and it reduced to less than 4000 km^2 after 2000. The decreasing trend may be related to global warming. It coincided with the faster increase of surface temperature, which began at the end of the 1970s. A profound understanding of the changes of lake water area needs integrated investigation of precipitation, evapotranspiration, runoff and human activities at the basin-scale in the last 30 years.

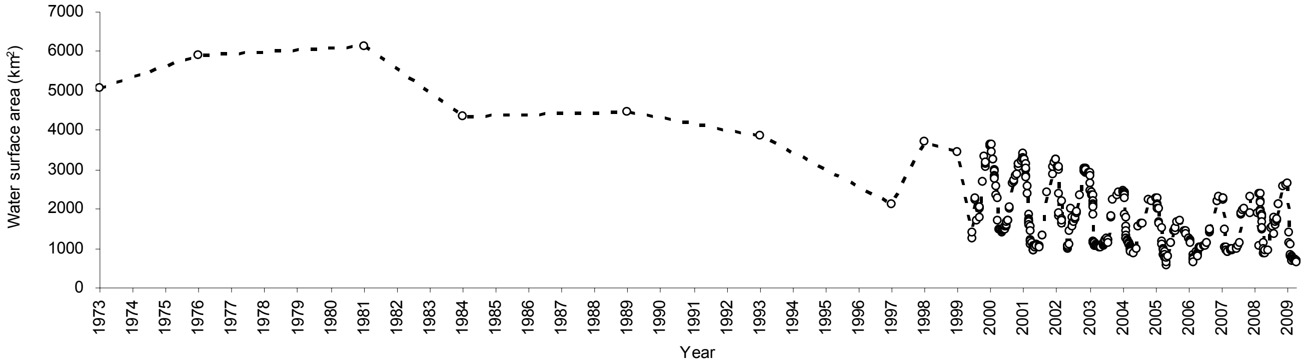

Fig. 2 Variations over three decades, 1973–2009, of water surface area in Poyang Lake, China. The variations were derived from multi-satellite images, including Landsat MSS/TM and MODIS data.

Recent one-decade variation of Poyang Lake In the last 10 years, 2000–2009, Poyang Lake suffered from unprecedented frequent drought. Therefore, it is necessary to delineate in detail the lake area variation and its relationship with other hydrological variables. The MODIS data offer the possibility to reconstruct the annual trend and seasonal variation. This quantitative delineation of lake area provides a basis for exploring the relationships among land-cover change, basin-scale water storage and precipitation.

Since 2000, the lake area has decreased significantly, at an average rate of 166 km^2/year. The lake area decreased to less than 1000 km^2 in the dry periods of 2003 and 2006. The reductions may be related to land-use and land-cover change, and reservoir construction in the basin, in addition to local climate change.

Figure 3 shows the fluctuations of water level at Hukou from 2000 to 2009 for the same dates as water areas were extracted from multi-temporal images. The water level fluctuations are similar to those of water surface area after 2000 (Fig. 2). For example, a strong increase of lake area, from 1703 to 2402 km^2, is found between 28 October and 12 November 2008 (Fig. 2). The increasing lake areas and water levels were closely correlated with heavy precipitation events during the period in this region. Further investigation is necessary to reveal the hydrological processes. Statistically, there existed a strong cubic relationship between lake area and water level (Fig. 4). It demonstrated that water level could reflect the variation of lake area, but it had a relatively large variance.

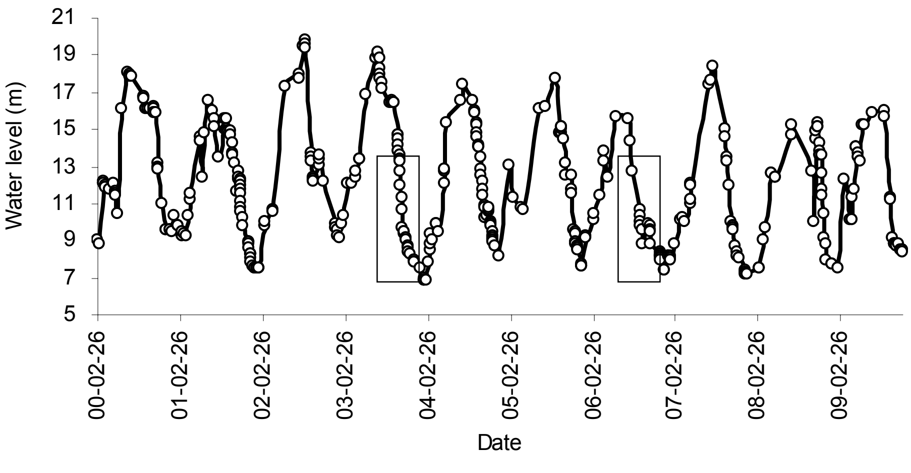

Fig. 3 Water level fluctuations between 2000 and 2009, with the same date of visible/near-infrared bands.

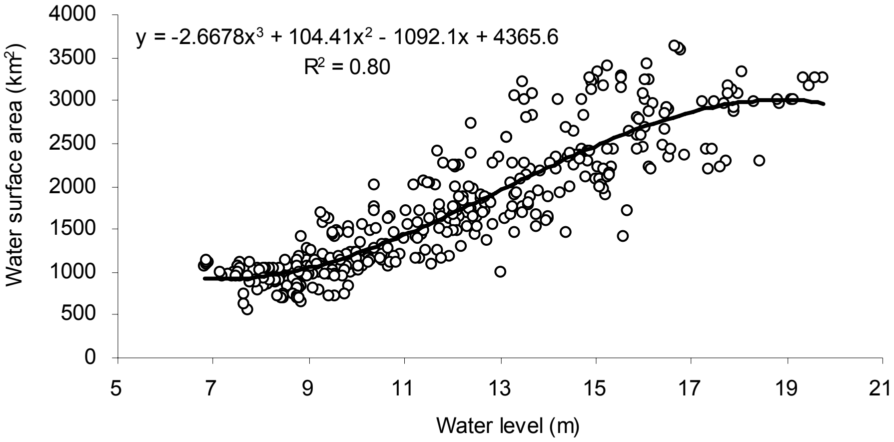

Fig. 4 Statistical relationship between water surface area and water level.

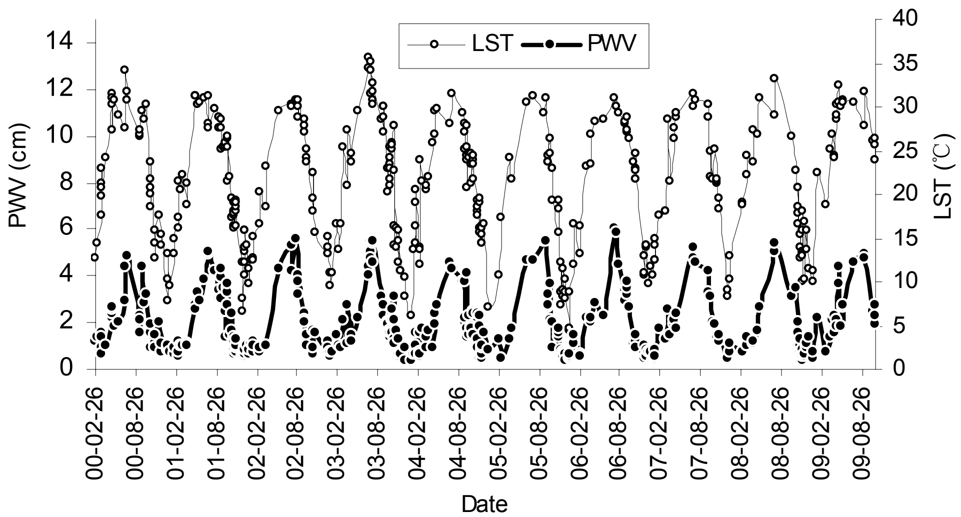

Fig. 5 PWV and LST fluctuation between 2000 and 2009, with the same date of visible/near-infrared bands.

The variation of lake area is sensitive to local precipitation, evapotranspiration and river discharge. Here we used PWV and LST as proxies for precipitation and evapotranspiration (Fig. 5). For the same area, a high PWV implies a high precipitation, and a high LST is assumed to be related to high evapotranspiration. In general, PWV and LST had significant relationships with water surface area. In particular, at the end of 2003, PWV had relatively low values of less than 5 cm, and LST was relatively low, with values of approx. 5°C. This suggests that the 2003 drought might be related more to precipitation (or lack of) than the high temperature (evapotranspiration). However, LST values were about 10°C in the late autumn and early winter of 2006, which is notably higher than that in the same period of other years. It implies that the 2006 drought might result from the warm seasons rather than reduced precipitation.

CONCLUDING REMARKS

With multi-satellite multi-temporal data, we reconstructed the surface-area variation of Poyang Lake in the past three decades. The water area has declined generally. However, the lake area has become notably smaller since 2000. It has suffered from more drought events in the recent decades.

The lake area showed a significant relationship with the water level at Hukou. The changes in lake area resulted from the water balance of the Poyang Lake Basin. The 2003 drought might be more related to precipitation than the high temperature (evapotranspiration), and the 2006 drought might result from the warm seasons rather than less precipitation. However, comprehensive analysis through incorporation of meteorological and hydrological data is necessary to reveal the changes of lake area in the recent decades.

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