ISPRS Journal of Photogrammetry and Remote Sensing 92 (2014) 26–37

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

journal homepage: www.elsevier.com/locate/isprsjprs

Review Article

Remote sensing of alpine lake water environment changes on the Tibetan Plateau and surroundings: A review

Chunqiao Song [a], Bo Huang [a,b,*], Linghong Ke [c], Keith S. Richards [d]

[a] Department of Geography and Resource Management, The Chinese University of Hong Kong, Shatin, Hong Kong
[b] Institute of Space and Earth Information Science, The Chinese University of Hong Kong, Shatin, Hong Kong
[c] Department of Land Surveying and Geo-Informatics, The Hong Kong Polytechnic University, Kowloon, Hong Kong
[d] Department of Geography, University of Cambridge, Cambridge CB2 3EN, United Kingdom

ARTICLE INFO

Article history:
Received 16 September 2013
Received in revised form 26 February 2014
Accepted 3 March 2014

Keyword:
Tibetan Plateau
Lake
Remote sensing
Glacial lake
Climate change

ABSTRACT

Alpine lakes on the Tibetan Plateau (TP) are key indicators of climate change and climate variability. The increasing availability of remote sensing techniques with appropriate spatiotemporal resolutions, broad coverage and low costs allows for effective monitoring lake changes on the TP and surroundings and understanding climate change impacts, particularly in remote and inaccessible areas where there are lack of *in situ* observations. This paper firstly introduces characteristics of Tibetan lakes, and outlines available satellite observation platforms and different remote sensing water-body extraction algorithms. Then, this paper reviews advances in applying remote sensing methods for various lake environment monitoring, including lake surface extent and water level, glacial lake and potential outburst floods, lake ice phenology, geological or geomorphologic evidences of lake basins, with a focus on the trends and magnitudes of lake area and water-level change and their spatially and temporally heterogeneous patterns. Finally we discuss current uncertainties or accuracy of detecting lake area and water-level changes from multi-source satellite data and on-going challenges in mapping characteristics of glacial lakes using remote sensing. Based on previous studies on the relationship between lake variation and climate change, it is inferred that the climate-driven mechanisms of lake variations on the TP still remain unclear and require further research.

1. Introduction

The Tibetan Plateau (TP, hereinafter), which is known as "the Roof of the World" and "the Third Pole" of Earth, consists of a large number of alpine lakes, with the total area surpassing 44,990 km^2 (Jiang and Huang, 2004). As the alpine hydrologic environment has been minimally disturbed by human activities, such as agricultural irrigations and settlements, it is deemed as an important indicator of climate change. During the past decades, climate changes, characterized by rapidly rising temperature, as well as changing precipitation and evaportranspiration, have substantial impacts on water storage of the inland lakes over the plateau. In particular, the rapidly rising temperature has accelerated glacier retreating and permafrost thawing, which is considered to be tightly associated with accelerated lake expansions (Yao et al., 2007; Ye et al., 2008, 2007; Zhu et al., 2010). Recently there are rapidly growing literatures focusing on the alpine lake changes and their response to climate change.

Traditionally, the lake water balances are measured by the "direct" meteorological or hydrological stationed observations (Chu et al., 2012b; Meng et al., 2012; Qi and Zheng, 2006; Zhang et al., 2011a), which detect changes in lake water level and shoreline at local spatial and temporal scales. This method is limited to a few lakes due to the remoteness and unavailability of most Tibetan lakes. The increased availability of remote sensing platforms with adequate spatial and temporal resolutions, near global coverage and low financial costs provide the potential of observing lake water environments at larger spatial extent and longer timescales. This paper therefore reviews the potential of optical images and satellite altimetry data for monitoring the spatiotemporal variability of alpine lakes on the TP. The distribution characteristics of the alpine lakes were firstly introduced; Then, we analyze merits and demerits of a variety of available satellite data and their applicability for plateau lakes; Thirdly, the commonly used semi-automated or automated algorithms of determining lake water body from multi-spectral and topographic data are introduced and the

* Corresponding author. Address: Department of Geography and Resource Management, The Chinese University of Hong Kong, Shatin 999077, Hong Kong.
E-mail address: bohuang@cuhk.edu.hk (B. Huang).

http://dx.doi.org/10.1016/j.isprsjprs.2014.03.001
0924-2716/

uncertainties are discussed; Finally we summarized applications of remote sensing techniques on change detection on lake extent and water level, glacial lake detection and outburst modeling, monitoring lake ice phenology, and relations of lake and climate. Besides, we discussed the advantages and limitations of remote sensing methods for lake water environment detection at different spatial and temporal scales, and concluded several aspects of challenges and problems that need to be solved.

2. Overview of the Tibetan lakes

The Tibetan Plateau, located in central Asia, is the highest and most extensive plateau on Earth with an average altitude more than 4000 m (Fig. 1). There are more than 1500 lakes on the plateau, 312, 104, 7 and 3 (statistics in 2011) of which cover surface areas larger than 10 km^2, 100 km^2, 500 km^2 and 1000 km^2, respectively. The total area of Tibetan lakes accounts for about 49% of the total lake area in China (Bian et al., 2006; Ma et al., 2010). This region is featured by rather complex topography and climate patterns. The highland is divided into many different broad basins or valleys by many high mountain ranges, such as the Himalayas, Kunlun Mts., Qilian Mts., Gangdise Mts., and Nyainqêntanglha Mts. In summer, the climate of the plateau is mostly influenced by some airflows of tropospheric tropical easterlies, subtropic westerlies, and southwestern monsoon from the Indian Ocean (Liu et al., 2008), which bring abundant precipitation during June–September. In winter, the climate is dominated by cold and dry westerlies. With diverse climatic and topographical patterns, these alpine lakes over the TP show strong spatial and temporal variability and different responses to climate change.

The most dominant feature for these high-altitude and closed lakes is the cold-arid climate condition. These lakes are mainly supplied by precipitation runoff, as well as meltwater from glacier and snow cover within adjacent catchments; and lake water leaves through evaporation and seepage. For a small proportion of lakes, the groundwater runoff becomes an important supplement for water balance. In the northern Changtang Plateau, with low precipitation and strong evaporation, many small lakes largely depend on seasonal snowpack meltwater, thus show stronger intra-annual and inter-annual variability, or even dry up in some years. There are also a few freshwater or mildly saline lakes, mainly distributed in the northeastern TP (e.g. Gyaring Lake and Ngoring Lake in the Yellow River Source) and South Tibet (e.g. Yamzhog Yumco, Mapam Yumco) where the annual rainfall is relatively plentiful.

There are a large number of small-size glacial lakes distributed in glaciated regions of high mountains. Two types of typical glacial lakes are known on the TP and surroundings: lakes dammed by an end moraine and lakes dammed by a glacier (Ding and Liu, 1991). The moraine-dammed lakes are mainly distributed in the Himalaya, the middle and eastern Nyainqentanglha Mts. and sections of the Hengduan Mts. in the southeastern TP (Fig. 1), while the supraglacial lakes are mainly scattered over the Karakoram Mts., the Pamir and the western Tianshan mountains. Recently with accelerated global warming, the glacial lakes and frequently occurred glacial lake hazards have attracted increasing attention.

3. Characteristics of satellites or sensors available for monitoring lake

So far, there have been a number of remote sensing satellites being put into practice. This section presents a brief overview on characteristics of space-borne sensors applied in lake studies with a focus on the Tibetan Plateau. Table 1 summarizes characteristics of some typical satellites and sensors. These satellites or sensors can be divided into three groups according to their application objectives: for monitoring lake surface extent, water level changes, and water properties, including lake ice, temperature, and organic contents.

Lake waterbody or basin inundation area can be retrieved from optical remote sensing imagery. Medium-resolution satellite images have become available for lake environmental studies since the early-1970s, with the launches of sensors: Landsat Multispectral Scanner (MSS), Landsat Thematic Mapper (Pitman et al.) and Enhanced Thematic Mapper Plus (ETM+), System Pour l' Observatoire de la Terre (SPOT), TERRA ASTER, the China – Brazil Earth Resources Satellite (CBERS). Other optical sensors with meter and sub-meter spatial resolution, such as Quickbird, IKONOS, and GeoEye-1 provide satellite imagery comparable to aerial photography, suitable for fine extraction of lake shorelines. However, the high costs, narrow swath size, and long revisit intervals of a few months limit their applications on large-scale environment monitoring. For medium or high resolution optical imagery, the frequent

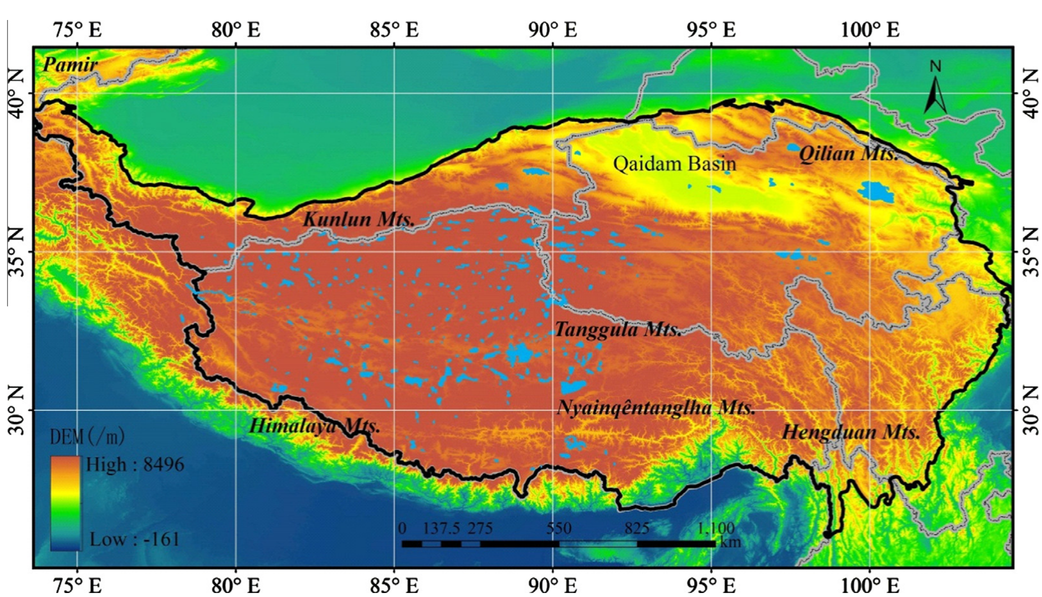

Fig. 1. Spatial distribution of alpine lakes and topographic characteristics of the Tibetan Plateau.