Quaternary International xxx (2017) 1–12

Contents lists available at ScienceDirect

Quaternary International

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

Estimation of lakes water storage and their changes on the northwestern Tibetan Plateau based on bathymetric and Landsat data and driving force analyses

Baojin Qiao [a, c, *], Liping Zhu [a, b, c, **], Junbo Wang [a, b], Jianting Ju [a], Qingfeng Ma [a], Chong Liu [a, c]

[a] *Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences (CAS), Beijing, 100101, China*
[b] *CAS Center for Excellence in Tibetan Plateau Earth Sciences, Beijing 100101, China*
[c] *University of Chinese Academy of Sciences, Beijing 100049, China*

ARTICLE INFO

Article history:
Received 20 November 2016
Received in revised form
31 July 2017
Accepted 2 August 2017
Available online xxx

Keywords:
Bathymetric survey
Water storage
Lake expansion
Glacial meltwater
Glacier surging

ABSTRACT

Lake water storage changes in four lakes were analyzed based on in situ bathymetric survey data and Landsat images in the extremely dry and cold northwestern Tibetan Plateau region. The results indicated that Bangdag Co and Aksai Chin Lake, which are glacier-fed and closed lakes, showed decreasing trends from 1976 to 1996, then increasing trend from 1996 to 2015, during which period water storage increased by 1.24 km^3 and 1.37 km^3, respectively, and 65% of the water storage increase in Aksai Chin Lake during this period occurring in 2006 and 2013. Longmu Co, which is a non-glacier-fed lake, exhibited little variation from 1976 to 1996 and a slight increase of 0.1 km^3 from 1996 to 2015. The precipitation, temperature and potential evaporation (Ep) trends indicated that lake shrinkage from 1976 to 1996 was attributed to less precipitation and less meltwater at lower surface air temperatures. Decreased Ep (15.5 mm/y) contributed approximately 2% and 4% to the lake expansion of Aksai Chin Lake and Bangdag Co from 2000 to 2009. Based on the assumption of equal precipitation-evaporation for the study area, glacial meltwater contributed 76.6% to the lake expansion of Bangdag Co from 2000 to 2015. Because change in lakes' water storage showed a large difference between glacier-fed lakes and non-glacier-fed lakes from 1996 to 2015 under relatively high precipitation conditions, it is suggested that glacial meltwater exerted more influence on increasing lake water storage associated with rising temperatures.

1. Introduction

The Tibetan Plateau (TP) is known as the “Asian water tower” because many major rivers in Asia originate there (Immerzeel et al., 2010), e.g. the Yellow River, Yangtze River, and Brahmaputra River, which nourish hundreds of millions of people in Asia. There are a large number of glaciers and lakes that have considerable influence on surface runoff on the TP under warming climate. Lake water and glacial meltwater, which is located in exorheic basin, can be transmitted to fluvial systems and outflow from the TP, but for endorheic basins, glacial meltwater can directly contribute to lakes, and lake water is only removed by surface water evaporation and a portion likely becomes groundwater. On the one hand, increased glacial meltwater with rising temperatures maybe lead to glacial lake outburst floods on the southern TP, which threaten life and property as well as critical road infrastructure (Song et al., 2016). Lake expansion also floods pasture and causes a large economic loss to local herdsman. On the other hand, the changes in area and water storage of inland lakes may have significant influences on regional water and energy cycles (Yang et al., 2014). Therefore, it is important to elucidate the causes of lake changes on the TP.

Many studies have focused on the area and water level changes in TP lakes over the past decades, and inland lake area expansion has been observed via large-scale remote sensing investigations (Li

* Corresponding author. Building 3, Courtyard 16, Lin Cui Road, Chaoyang District, Beijing, 100101, China.
** Corresponding author. Building 3, Courtyard 16, Lin Cui Road, Chaoyang District, Beijing, 100101, China.
E-mail addresses: qiaobaojin@itpcas.ac.cn (B. Qiao), lpzhu@itpcas.ac.cn (L. Zhu).

http://dx.doi.org/10.1016/j.quaint.2017.08.005
1040-6182/

et al., 2014b; Phan et al., 2012; Wang et al., 2013; Song et al., 2014a, 2014b; Zhang et al., 2011b, 2014). In contrast, most lakes on the southern TP shrank slightly (Lei et al., 2014; Song et al., 2013; Wang et al., 2013; Zhang et al., 2011b). Precipitation is generally considered as the main reason for lake expansion (Lei et al., 2013; Song et al., 2014b; Zhou et al., 2015) because it has increased considerably over the past decades, especially on the central TP (Xu et al., 2008). The decreased lake evaporation is also beneficial to rapid water level increases (Ma et al., 2016, e.g. at Nam Co) due to near-surface wind speed declines (McVicar et al., 2010, 2012). However, most glaciers have experienced serious shrinkage on the TP, especially in the Himalayas (Yao et al., 2012). For example, mass balance of Dongkemadi glacier was −421.2 mm/y based on ICESat data (Ice, Cloud and Land Elevation Satellite) (Ke et al., 2015a). Increasing glacial meltwater under rising temperature conditions could make an important contribution to lake expansion (Li et al., 2014a; Meng et al., 2011; Zhang et al., 2011b, 2015; Zhu et al., 2010). For example, Zhu et al. (2010) quantified the proportions of different factors that affected the water balance of Nam Co and indicated that although precipitation played a dominant role in maintaining the water balance, the increase in glacial meltwater accounted for 50.6% of the water storage change. A comparison of the difference between changes in glacier-fed glaciers and non-glacier-fed lakes in the Tanggula Mountains indicated that glacial meltwater made a contribution to lake expansion that was equivalent to that of precipitation-evaporation (Song and Sheng, 2016). Because most lakes expansion has occurred in the inland area of the TP where permafrost is widely distributed and glaciers are less retreated, Li et al. (2014b) speculated that the main reason for inland TP lake expansion was permafrost degradation. The results of Zhou et al. (2013) indicated that the large water imbalance was explained by water seepage in Nam Co based on hydrological observations. Therefore, the reasons for lake changes on the TP are still fraught with uncertainty and need further study.

Although the changes in lake area (Wan et al., 2014; Zhang et al., 2014, 2015) and lake level (Phan et al., 2012; Song et al., 2014a; Zhang et al., 2011b) on the TP have been widely studied, researches on lake water storage change (Lei et al., 2013; Song et al., 2013, 2014a; Yang et al., 2017; Zhang et al., 2013) are still insufficient, let along the study on the absolute lake water storage (Zhang et al., 2011a). The heat storage of the water body is depended upon the water storage, because the variation of lake heat storage is an important component to estimate evaporation for a deep lake (McMahon et al., 2013), understanding of lake water storage and its variation are very important in the analysis of water balance. However, due to the lack of bathymetric data to estimate water storage, water storage of most lakes on the TP is unknown. In Table 1, we have summarized lake change researches of TP over the past decades, and found that the studies of lake water storage are still insufficient due to the lack of bathymetric data.

The variations in lake water storage are essential responses of lakes to climatic changes, which is better response than lake area change due to different topographic conditions. For example, a lake with steep basin slopes may experience less area change than a lake in a gently sloping basin, even though the former receives more water inflow. In addition, the particle of the lake sediments is also an important factor influencing the change in lakes' levels, and a lake would increase less in a lake with coarse coast, which would allow the water to inflow into groundwater, than in lake with finer particles, given that both receive equal water inflow. Satellite radar altimetry data can be effectively used to estimate lake level changes and calculate lake water storage changes. Although some types of satellite data (e.g., Jason-1, ERS-1/2, TOPEX and ENVISAT) cover long timescales from 1991 to present, the accuracies of altitudinal data are limited due to their large footprints of several kilometers. Therefore, these data can only be used for large lakes (e.g., Nam Co, Siling Co and Qinghai Lake). ICESat has been widely used to study lake level changes (Li et al., 2014b; Phan et al., 2012; Song et al., 2013; Wang et al., 2013; Zhang et al., 2011b). Although the footprint of ICESat data is as small as 70 m, the time sequence only covers a short period (2003–2009); thus, it is difficult to accurately detect changes in water level and water storage over long timescales. However, if the bathymetric distribution and topography of a lake basin are known, it is possible to estimate the water storages under different lake area (corresponding with certain lake level altitude) conditions and construct the relationships between lake area and water storage changes. Therefore, the long-term changes in lake water storage can be estimated because the lake areas can be extracted from long-term Landsat satellite images.

The southern slope of the west Kunlun Mountains and eastern slope of the east Karakorum Mountains, which are situated in the northwestern part of the TP, contain a number of endorheic lake basins and polar-type glaciers. Despite most glaciers on the TP have experienced obviously serious decreases trend in area in recent decades (Bolch et al., 2010; Kääb et al., 2012; Wei et al., 2014; Yao et al., 2012), the mass balance of glaciers in the Pamir and Karakoram regions showed a slight mass gain (Gardelle et al., 2013), which is called the “Pamir-Karakoram anomaly”. Because precipitation in this region is generally the lowest on the TP (Zheng, 1998) and has exhibited increasing trends due to the strengthened westerlies (Yao et al., 2012), it is important to determine if the glacial meltwater in this region makes much more important contribution to fluvial system than precipitation. This is helpful for understanding the responses of lakes to recent climatic change.

In this paper, we study four lakes with bathymetric data (Gozha Co, Aksai Chin Lake, Bangdag Co and Longmu Co) on the northwestern TP as a case study to estimate water storage in 2015, and we combine these data with multi-temporal Landsat images to estimate water storage changes from 1976 to 2015. The purposes of this study are, based upon the analyses of the underwater topographic characteristics and water storage estimations, (1) to reconstruct the lake water storage and water level changes from 1976 to 2015; (2) to estimate the contribution of glacial meltwater to lake expansion; and (3) to analyze the possible linkage between lake changes and climate factors.

2. Study area

The study area is located on the northwestern TP, which is on the southern slope of the western Kunlun Mountains (WKM). There is a dense distribution of polar-type glaciers over the WKM (Huang, 1990) that are mainly affected by mid-latitude westerlies (Bolch et al., 2012). The region consists of 537 glaciers (>0.02 km^2), with a total area of 3137 km^2 in 2013. The well-known Guliya Ice Cap (over 370 km^2), which is the largest ice cap in the Kunlun Mountain ranges, is located in the eastern of the region (Ke et al., 2015b). Previous results indicated that the total glacier area of WKM decreased by 16.83 km^2 (1.53 km^2/y) from 1990 to 2011, but some individual glaciers showed advancing trends in the region (Li et al., 2013). However, according to the ICESat elevation data, glaciers in the WKM showed mass gain, with a mean rate of increase in surface elevation of 0.17 ± 0.15 m/a (Gardner et al., 2013). This rate ranged from −0.4 ± 0.2 m/y to 0.7 ± 24 m/y from 2003 to 2008, the glaciers in the northern slope of WKM showed a thickening trend, but several glaciers in the southern of WKM, which supplied Aksai Chin and Gozha Co, showed a thinning trend (Ke et al., 2015b). Lei et al. (2014) theorized that lakes expansion was not significantly associated with glacial meltwater in this region based on the results of Neckel et al. (2014) which the glaciers of WKM showed a slightly positive mass balance.