

Technical Note

Improve the Accuracy of Water Storage Estimation—A Case Study from Two Lakes in the Hohxil Region of North Tibetan Plateau

Baojin Qiao ^{1,2,†} , Jianting Ju ^{1,*}, Liping Zhu ^{1,3,4,†} , Hao Chen ¹ , Jinlei Kai ^{1,4} and Qiangqiang Kou ^{1,4}

¹ Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences (CAS), Beijing 100101, China; qiaobaojin@zzu.edu.cn (B.Q.); lpzhu@itpcas.ac.cn (L.Z.); chen hao@itpcas.ac.cn (H.C.); kaijinlei@itpcas.ac.cn (J.K.); kouqiangqiang@itpcas.ac.cn (Q.K.)

² School of Geoscience and Technology, Zhengzhou University, Zhengzhou 450001, China

³ CAS Center for Excellence in Tibetan Plateau Earth Sciences, Beijing 100101, China

⁴ University of Chinese Academy of Sciences, Beijing 100049, China

* Correspondence: jujianting@itpcas.ac.cn

† Baojin Qiao and Liping Zhu contributed equally to this work.

Abstract: Lake water storage is essential information for lake research. Previous studies usually used bathymetric data to acquire underwater topography by interpolation method, and to therefore estimate water storage. However, due to the large area of Tibetan Plateau (TP) lakes, the method of bathymetry was challenging to cover the whole region of one lake, and the accuracy of the underwater topography, in which no bathymetric data covered, was low, which resulted in a comparatively large error of lake water storage estimation and its change. In this study, we used Shuttle Radar Topography Mission (SRTM) and in situ bathymetric data to establish the underwater topography of Hohxil Lake (HL) and Lexiewudan Lake (LL) in the Hohxil Region of North TP and estimate and analyzed the changes of lake level and water storage. The results showed HL and LL's water storage was 5.12 km³ and 5.31 km³ in 2019, respectively, and their level increased by 0.5 m/y and 0.57 m/y during 2003–2018, respectively. They were consistent with those (0.5 m/y and 0.5 m/y) from altimetry data, and they were much more accurate than those results (0.077 m/y and 0.156 m/y) from bathymetric data. These findings indicated that this method could improve the accuracy of lake water storage and change estimation. We estimated water storage of two lakes by combining with multitemporal Landsat images, which had doubled since 1976. Our results suggested that the increasing precipitation may dominate the lake expansion by comparing with the change of temperature and precipitation and the increasing glacial meltwater contributed approximately 4.8% and 10.7% to lake expansion of HL and LL during 2000–2019 based on the glacier mass balance data, respectively.

Keywords: lake water storage; bathymetric data; SRTM; precipitation; glacial meltwater



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1. Introduction

The Tibetan Plateau (TP) is considered as “Water tower of Asia” and “Third Pole” with a large number of lakes, glaciers, and permafrost. Lakes are very sensitive to climate change. Most lakes of the TP have been experiencing a severe expansion in recent decades according to the evolution of lake areas and levels from satellite data, except for those lakes in the southern TP [1–7]. Lake area of the TP has increased from 40,000 ± 766.5 km² in the ~1976 to 50,000 ± 791.4 km² in 2018 [8], and lake water storage has increased by 140.8 km³ during 1990–2013 for those lakes with an area greater than 10 km² by combining Landsat images and Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) [1]. There is a large difference in climatic and hydrological conditions on the TP, and maybe there is a sizeable spatial difference causing lake change in different regions. Cause analysis of lake change has evolved from qualitative to quantitative research with the developing

remote sensing technology. Most studies suggested that increased precipitation was the primary cause of lake expansion. However, in these regions with extremely cold and dry conditions and large amounts of glaciers, glacial meltwater may have an essential contribution to lake change. After reviewing the research progress of the past decades comprehensively about the lake evolution, spatial patterns, and driving mechanisms over the TP, Zhang et al. [9] suggested that interdisciplinary lake studies will be an essential method to understand climate-cryosphere-hydrosphere interactions.

Increasing precipitation was considered as the primary cause of lake expansion. Zhou et al. [10] suggested that lake inflows, precipitation over the lake area and evaporation accounting for 49.5%, 22.1%, and 18.3%, respectively, to Selin Co expansion during 2003–2012 and according to the Water and Energy Budget-based Distributed Hydrological Model. Increasing lake water storage of the TP was consistent with increasing terrestrial water storage based on GRACE satellite, suggesting that increasing precipitation was identified as the primary cause of lake expansion [2,11]. Combining satellite and model data, it was found that increasing net precipitation, glacial meltwater, and permafrost degradation contributed respectively 74%, 13%, and 12% to lake expansion on the TP based on quantitative water mass budget [6].

Many researchers had focused on how to quantify the contribution of glacial meltwater. Comparing the difference between glacier-fed and nonglacier-fed lake water storage change, some researchers found that glacial meltwater contributed approximately 50% to lake expansion in Tanggula Mountain and northwestern TP, which is equivalent to net precipitation [12,13]. Glacial meltwater contributed 13% to lake expansion of TP based on in situ observation data and satellite data [6], 22.2% to lake expansion in the eastern of inner TP [1] and $19.3 \pm 4.5\%$ to Chibuzhang Co and Duoersuodong Co in the inner TP [14] based on the glacier mass balance. Some researchers estimated glacier mass balance with multitemporal SAR images and quantified glacial meltwater contribution to lake expansion. Glacier mass balance was approximately -0.16 ± 0.05 m w.e./y using SPOT 6/7 stereo imagery during 2000–2015/16 in the central Kunlun-Hohxil region, and glacial meltwater contributed 9.9% and 11.1% to Lexiewudan Lake (LL) and Hohxil Lake (HL), respectively [15]. Glacier mass balance of Nam Co drainage basin was calculated as -0.268 ± 0.129 m w.e./y by using TanDEM CoSSC datasets during 2000–2013/14, suggesting that glacial meltwater contributed $10.5 \pm 9\%$ to lake expansion of Nam Co [16]. Based upon high-resolution KH-9 and TanDEM-X data during 2000–2018, glacier mass balance kept a stable state (0.002 ± 0.003 m w.e./y) from in the western Kunlun Mountains, indicating that the little contribution to lake expansion [17].

Lake water storage and its change are essential to understand the lake water mass balance and its driving mechanisms. Previous studies used the Landsat image and altimetry data (e.g., ICESat and Cryosat-2) [2,6,18], bathymetric data [1,5,14], and in situ lake level observations [19] to estimate water storage change. For altimetry data, although the developed ICESat-2 covered a total of 236 lakes since 2018 compared to the 132 lakes with ICESat data [18], due to the short time scale, they are challenging to be used to analyze lake water storage and its changes on the TP for a relatively long time scale. It is also challenging to use limited in situ lake level observations to study the evolution of lake water storage with a long time scale and extensive area coverage. However, there are only several papers to research lake water storage and changes by using bathymetric data on the TP, included Nam Co [5], four large lakes in northwestern TP [20], Paiku Co [21], and Chibuzhang Co and Duoersuodong Co [14]. Bathymetric data is acquired using a sonar sensor to measure the lake's depth, e.g., Lowrance HDS5. Due to the large area of the surveyed lakes, difficult access in remote places, and frequently appeared harsh weather conditions during field survey seasons, most surveyed lakes had only sparse bathymetric routes for acquiring a rough depth distribution (or underwater topography). These results would greatly influence the interpolation accuracy of bathymetric lines of the lake, which results in large errors in estimating lake water storage and its changes.

As in previous studies with limited bathymetric data of the lakes [14,20], most survey routes covered a small proportion of the lakes, but those parts along the lake shoreline that occupy more area are particularly lacking. Fortunately, in most lakes, these parts are the expansion result of the lakes which had ever situated above the lake level in 2000, the year that the SRTM DEM topography was acquired. The SRTM DEM data may make up for the deficiency of the lake's survey bathymetric data of the lake along the shorelines at present. Thus, we use this method to improve lake water storage and its change estimations accuracy. This method is probably also useful for other lakes.

This paper will estimate lake water storage and its change by combining bathymetric data and SRTM, to improve lake water storage and change estimation accuracy. The purposes of this paper are (1) to estimate lake water storage based on bathymetric data and lake water storage change by combining Landsat images; (2) to compare the difference between lake depth and SRTM elevation data in the area of expansion since 2000; (3) to estimate lake water storage and change by combining bathymetric data and SRTM, and compare the accuracy of this method with these results only from bathymetric data; (4) to analyze the likely causes of lake expansion and estimate the contribution of glacial meltwater to lake expansion by combining glacier mass balance and climate data.

2. Study Area

As shown in Figure 1, HL and LL are two large lakes in the Hohxil National Nature Reserve Region, which is located in the northern TP. This study area is considered “no man’s land” with a cold and dry climate condition. The annual average temperature is about -10°C , and annual precipitation is 173–494 mm [22], in which 90% occurred from May to September [15]. The basin area of HL and LL are 2636 km² and 2018 km², respectively. HL received glacial meltwater from Malan glaciers with 71.04 km² in the basin, and an upstream lake is located in the western of HL, named Yinma Lake. LL received glacial meltwater from Malan glaciers with 30.86 km² and Jinyang Gangri glaciers with 28.53 km². The average glacier surface thickness showed a significantly thinning trend in recent decades [15,23], indicating that glacial meltwater may be an important water supply to HL and LL.

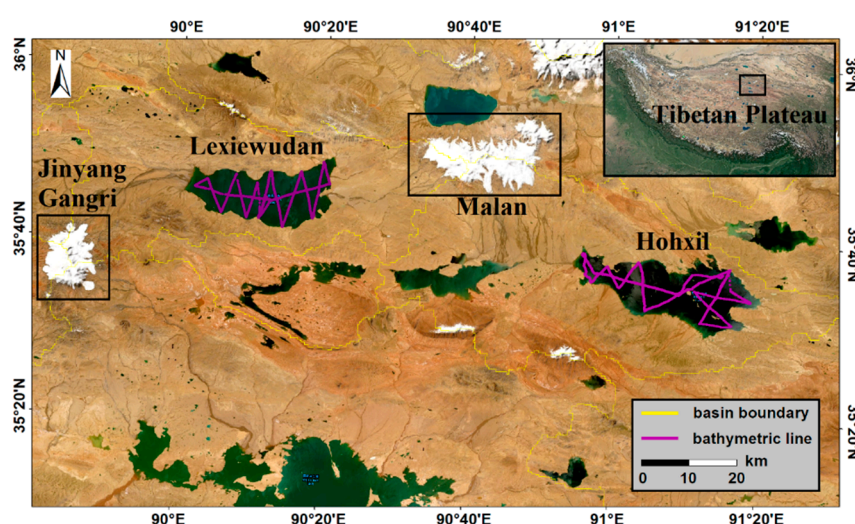


Figure 1. Location of lakes and glaciers in the Hohxil Region of North Tibetan Plateau.

3. Methods

3.1. Estimation of Water Storage and Its Change

Lake bathymetric data was surveyed by using Lowrance HDS5 equipment, which measured lake depth with a vertical accuracy of 0.01 m. The numbers of total bathymetric points of HL and LL were 0.73 and 0.61 million, respectively, in October 2019, and the route lines are shown in Figure 1. Previous studies used the bathymetric data to establish

underwater topography and estimate water storage [14,20], by using the Topo to Raster tool to interpolate underwater topography with those depth data and the lake shoreline derived from Landsat images (method 1). The depth of lake shoreline was assigned as 0. Then the isobaths were established and the water storage was estimated by using Area and Volume tool based on underwater topography. Area and Volume is a tool to calculate the area and volume of a raster, triangulated irregular network, or terrain dataset surface above or below a given reference plane. Therefore, we can use this tool to establish the relationship between lake area and water storage or lake depth and water storage based on underwater topography, which the lake depth was smaller than the maximum depth of 2019. To improve water storage estimation accuracy, we establish the underwater topography by combining bathymetric data and SRTM 1 (method 2). The SRTM 1 data were chosen because the resolution of 30 m is much higher and the accuracy is better than SRTM 3 data. Because both lakes have expanded since 2000, the lake depth in the flooded area could be acquired by SRTM 1, to augment the depth data for establishing underwater topography.

3.2. Lake Area from Google Earth Engine

Google Earth Engine (GEE) is a cloud platform to process satellite images and other earth observation data for high-performance computing with high efficiency. This platform has been used to analyze large and long time scale urban land, flood events, wetland inundation dynamics, vegetation cover change, and lake area change, and so on [24–28]. In this study, all Landsat 4, 5, and 8 images with less than 30% cloud during September–October in the study region were screened out using the GEE platform. First, these images were removed with a large cloud covered and high-quality images were selected with less cloud. We used the method of Normalized Difference Water Index (NDWI) to extract the water body and calculated the water body area based on the threshold algorithm. Generally, we selected 0 to 1 as the threshold. The median area of those areas from different images after the NDWI calculation was chosen as the lake area in that year, and we calculated the lake area from 1976 to 2019.

3.3. Climate Effects

Climate data provide essential information to analyze the cause of lake change. However, reanalysis datasets may have large errors as there is no meteorological station in the study area. The nearest meteorological station is located in the east of HL approximately 200 km away, named Wudaoliang in No. 109 national highway. In this study, we analyzed the changing trend of annual average temperature (AAT), annual average minimum temperature (AAMT), and annual precipitation (AP) using the data from the Wudaoliang meteorological station from 1990 to 2018.

4. Results

4.1. Climate Change

As shown in Figure 2, AAT showed a significantly increasing trend (0.06 ± 0.01 °C/y, $p < 0.01$) with a noticeable variation. The average temperature was -4.6 °C during this full period. The average temperature was -5.0 °C during 1990–2005, and -4.1 °C during 2006–2018. The highest AAT occurred in 2016 with -3.7 °C, and the lowest temperature occurred in 1997 with -6.2 °C. AAMT also showed an increasing trend (0.08 ± 0.01 °C/y, $p < 0.01$), which was much faster than that AAT (Figure 2). The average AAMT was -10.4 °C during 1990–2018, -11 °C during 1990–2004 and -9.7 °C during 2005–2019. The lowest AAMT was -12 °C in 1997 and the highest was -9.1 °C in 2009 and 2011. As shown in Figure 2, precipitation showed a significantly increasing trend (4.6 ± 1.2 mm/y, $p < 0.01$) with fluctuation from 1990 to 2018. The average AP was 328.8 mm during this period. The average precipitation was 297.8 mm during 1990–2007 and 379.5 mm during 2008–2018. The highest precipitation occurred in 2018 with 480.6 mm, and the least precipitation was in 1993 with 232 mm.

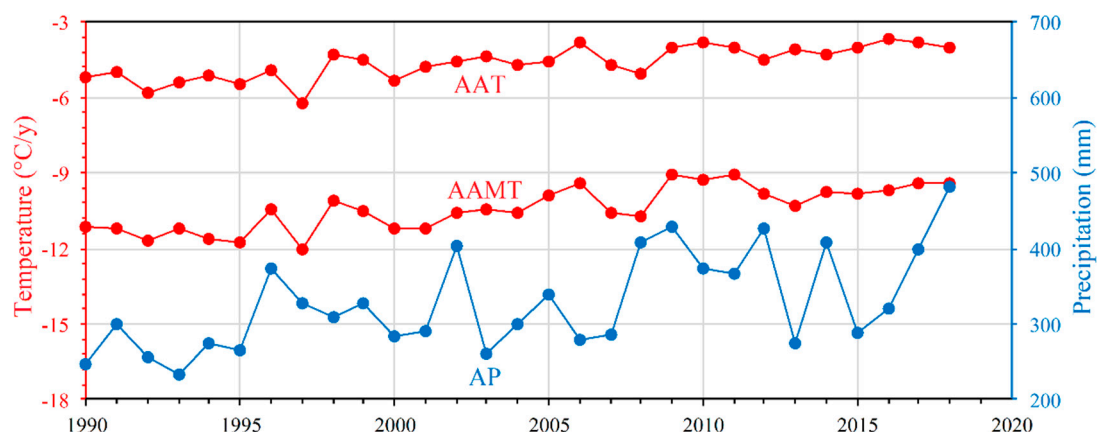


Figure 2. Changes of precipitation and temperature during 1990–2018, including annual average temperature, annual average minimum temperature, and annual precipitation.

4.2. Comparison of SRTM DEM to Bathymetric Data

The two lakes have expanded since 2000. Lake underwater topography in the flooded areas acquired by SRTM DEM, which provided global topography data in 2000. As shown in Figure 3a,b, the Landsat image data from October 2000 showed the shorelines at that time, while the yellow boundary of two lakes showed the present lake shoreline as acquired from Landsat image in 2019. The flooded area is between the lake shoreline boundaries of 2000 and 2019. There are 9755 and 1259 in situ bathymetric data (red point) of LL and HL in the newly flooded area, respectively. Assuming that the SRTM DEM data is accurate, the in situ bathymetric data and inferred water depth from SRTM DEM data for each pixel should be consistent in 2019. However, due to erosion and sedimentation effects, the lake topography in the littoral zone might have changed.

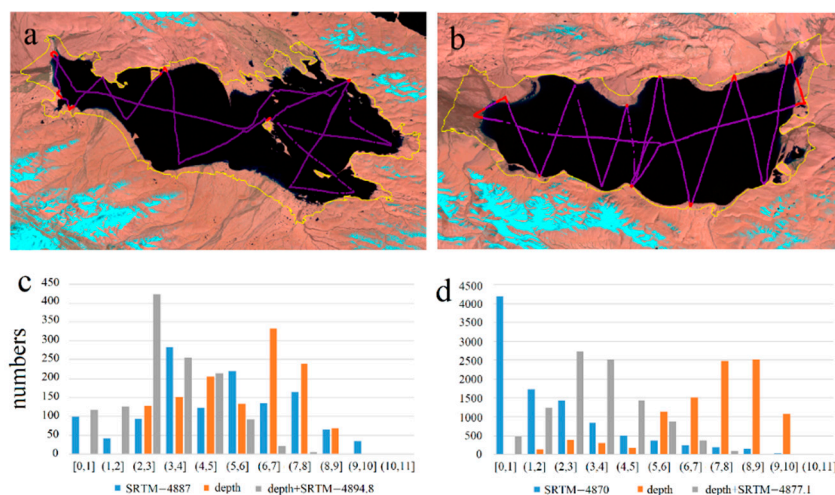


Figure 3. Comparison of the data between Shuttle Radar Topography Mission (SRTM) and bathymetric data. (a), lake boundary of Hohxil Lake (HL) in 2000 and 2019; (b), lake boundary of Lexiewudan Lake (LL) in 2000 and 2019; (c), three cases of HL, included SRTM–4887 in HL, depth, depth+SRTM–4894.8 in HL; (d), three cases of LL, included SRTM–4870, depth, depth+SRTM–4877.1.

To keep the data in the same order of magnitude, subtract the minimum value from each set of data. The histogram of three cases for two lakes (the values of bathymetric depth, SRTM, and combined bathymetric depth and SRTM) is shown in Figure 3c,d. The value of SRTM and depth of HL distributed more evenly, and the value of SRTM and depth of LL distributed mainly in 4870–4871 m (0–1 m), and 7–9 m, respectively. As shown

in Figure 3c, the values (SRTM + depth) of HL ranged from 0 to 8.5 which corresponds to 4894.8–4903.3, and approximately 80% of these values fell into 4896.8 m (2–2.5 m) to 4899.3 m (4–4.5 m). The values (SRTM + depth) of LL ranged from 4877 m (0–0.5 m) to 4886 (8.5–9 m), and approximately 60% of these values fell into 4878.6 m (1.5–2 m) to 4882.1 m (5–5.5 m) (Figure 3d). These results indicated that the accuracy of most values is better than 3 m. Due to the effect of erosion by lake water, lake depth estimated would be deeper than that from SRTM when lakeshore was flooded. In order to account for this effect, we selected 4882 m and 4900 m as a threshold to calculate lake depth of expanding area of LL and HL, respectively. Using these data and bathymetric data to establish underwater topography and estimate lake water storage and change.

4.3. Characteristics of Underwater Topography

As shown in Figures 4 and 5, the underwater topography and isobaths line were established based on bathymetric data. There were two main regions of HL with relatively large depths, which are located in the eastern and western of HL. The largest depth of bathymetric data was 42 m. The main lake basin of LL located in the middle of this lake with the largest depth of 44.5 m. Isobaths of 5 m of HL and LL by method 2 (Figures 4c and 5c) were closer to the shoreline than method 1 (Figures 4a and 5a). In other words, the average depth by method 2 was higher than that by method 1. Due to this, we just added these depths of the flooded area from SRTM, which was less than 10 m; other isobaths (>10 m) derived from the two methods were still consistent. Underwater topography from method 1 was smooth in whole lakes, but method 2 was rough in the flooded area. We thought that soil erosion in the flooded area was an important cause.

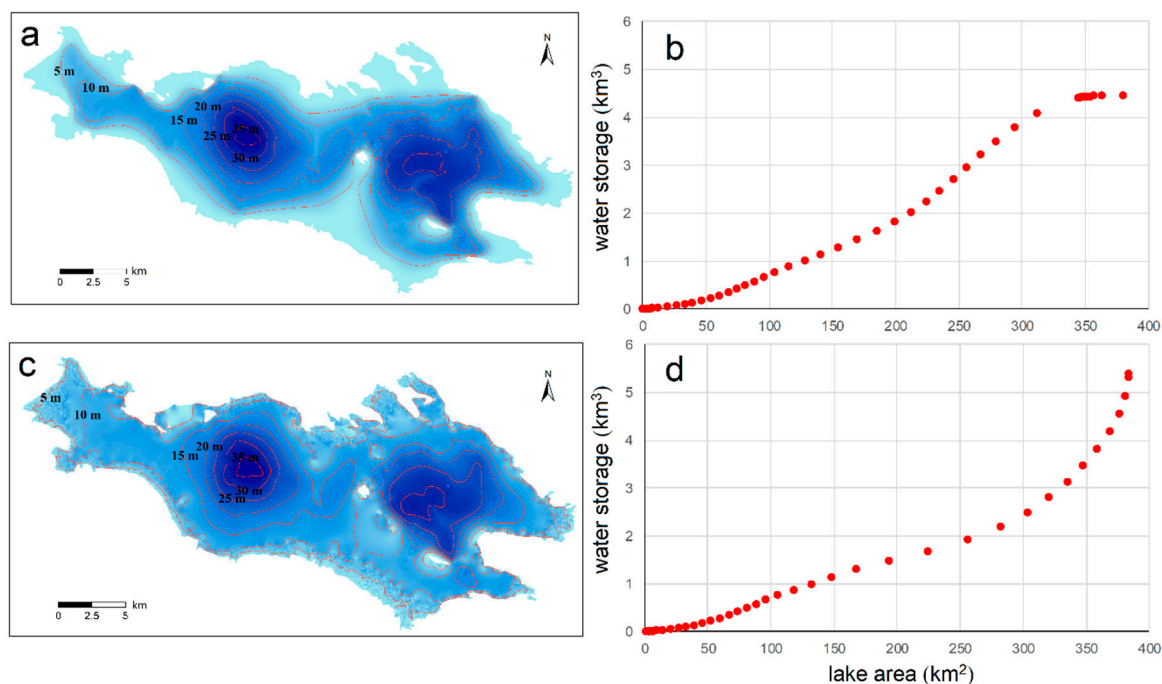


Figure 4. Accuracy comparison of underwater topography from two methods in HL. (a), underwater topography based on bathymetric data; (b), the relationship between lake area and water storage based on bathymetric data; (c), underwater topography based on bathymetric data and SRTM; (d), the relationship between lake area and water storage based on bathymetric data and SRTM.

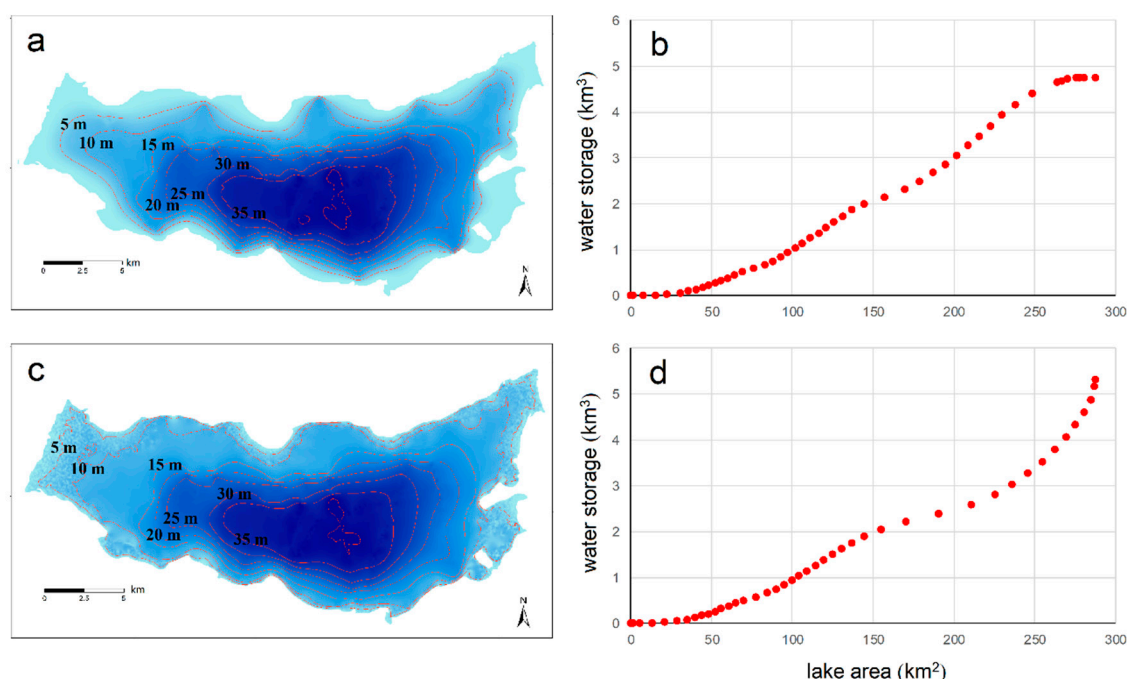


Figure 5. Accuracy comparison of underwater topography from two methods in LL. (a), underwater topography based on bathymetric data; (b), the relationship between lake area and water storage based on bathymetric data; (c), underwater topography based on bathymetric data and SRTM; (d), the relationship between lake area and water storage based on bathymetric data and SRTM.

4.4. Comparison of the Results from Two Methods

According to the underwater topography from bathymetric data (method 1), the average depth and water storage of HL in 2019 were 11.6 m and 4.44 km³, respectively. The average depth and water storage of LL in 2019 were 16.3 m and 4.72 km³, respectively. Figures 4b and 5b showed the relationship between lake area and water storage of HL and LL based on method 1. The rate of HL water storage with increasing lake area was 0.011 km³/km² during 50–200 km² of the lake area, and 0.021 km³/km² during 200–310 km², and 0.003 km³/km² during 340–365 km². The rate of LL water storage with increasing lake area was 0.019 km³/km² during 50–150 km² of the lake area, and 0.026 km³/km² during 150–250 km², and 0.006 km³/km² during 260–280 km².

According to the underwater topography from bathymetric data and SRTM (method 2), the average depth and water storage of HL were 14 m and 5.39 km³ in 2019, respectively, and LL was 18.5 m and 5.31 km³ in 2019, respectively. Total water storage calculated by method 2 exceeded that calculated with method 1. The rate of increase of lake water storage calculated by method 2 was significantly faster than that by method 1 when the lake area of HL was larger than 300 km² and LL was larger than 250 km². Water storage of HL in 300 km² lake area by method 2 was approximately 2.6 km³, which was less than that in 300 km² lake area by method 1 with 4 km³ water storage. Water storage of LL in 250 km² lake area by method 2 was approximately 3.4 km³, which was less than that in 250 km² lake area by method 1 with 4.4 km³ water storage. This result indicated that average water depth was much larger by method 2 than method 1, especially for flooded lake area since 2000.

4.5. Lake Water Storage and Change during 1976–2019

As shown in Figure 6a, the lake area of HL had little variation before 2005. The smallest area was 296.11 km² in 1995, and the lake area increased quickly since 2005 with a rate of 4.84 km²/y. The average increasing rate of the HL area was 4.1 km²/y during 2000–2019. Lake area of LL had a decreasing rate before 1995, and then kept a stable state

during 1995–1999 and increased quickly with an increasing rate of $3.38 \text{ km}^2/\text{y}$ during 2000–2019.

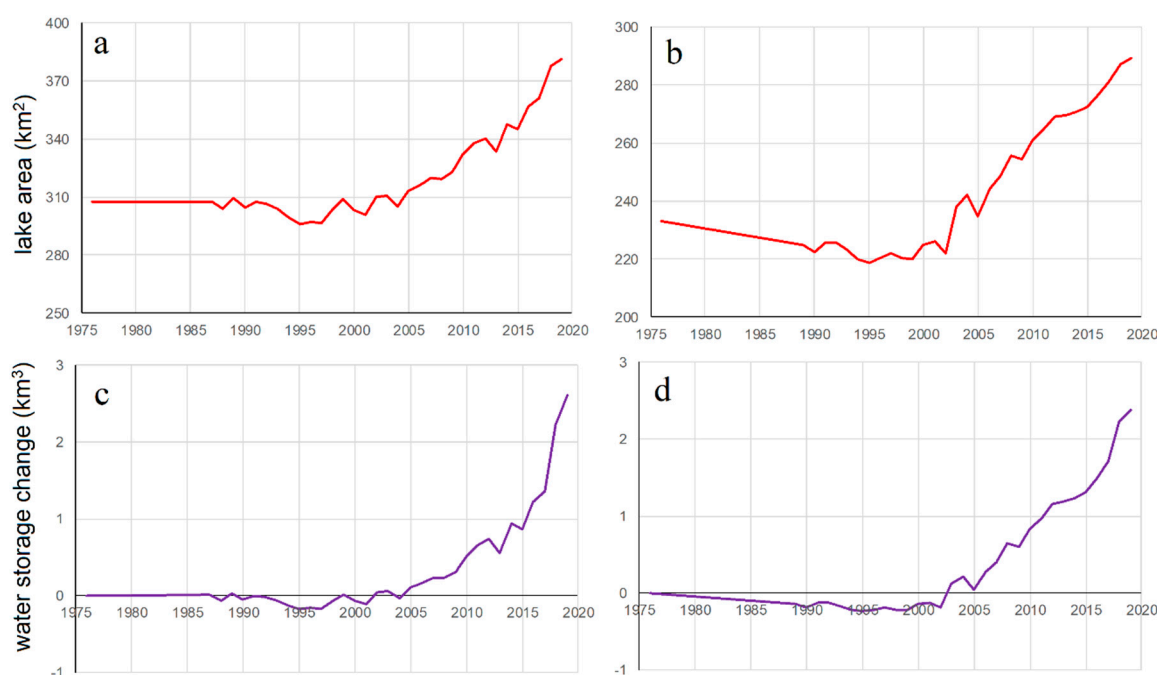


Figure 6. Lake area and water storage change during 1976–2019 based on underwater topography Landsat images. (a), lake area change of HL; (b), lake area change of LL; (c), water storage change of HL; (d), water storage change of LL.

According to the established underwater topography based on bathymetric data and SRTM by method 2, we had calculated water storage and changes of two lakes from 1976 to 2019 by combining multitemporal Landsat images. As shown in Figure 6c, lake water storage of HL showed a little variation with an average value of 2.47 km^3 during 1987–2005, and then the increasing rate of water storage was $0.09 \text{ km}^3/\text{y}$ during 2005–2012. In 2012, water storage was 3.24 km^3 , and water storage decreased by 0.18 km^3 during 2012–2013. The water storage rate increased by $0.34 \text{ km}^3/\text{y}$ during 2013–2019, which was the faster rate during the study period. The average increasing rate of HL was $0.14 \text{ km}^3/\text{y}$ during 2000–2019. Lake water storage of HL in 2019 (5.12 km^3) had doubled since 2000 (2.44 km^3), and lake water storage of HL had increased by 2.61 km^3 from 1976 to 2019.

As shown in Figure 6d, lake water storage HL had a slightly decreasing trend during 1989–1995, little variation with an average value of 2.73 km^3 during 1995–1999. During 2000–2019, then lake water storage had a quickly increasing rate with $0.13 \text{ km}^3/\text{y}$, and water storage in 2019 (5.31 km^3) had doubled since 2000 (2.8 km^3). The average increasing rate of two lakes was consistent during 2000–2019, and the increasing rate of LL was stable during this period, but the increasing rate of HL during 2000–2012 was much slower than that during 2013–2019. Lake water storage of LL had increased by 2.37 km^3 from 1976 to 2019. The lake area increasing rate for LL ($3.38 \text{ km}^2/\text{y}$) was 82% of HL ($4.1 \text{ km}^2/\text{y}$) during 2000–2019, but the lake water storage increasing rate of LL ($0.13 \text{ km}^3/\text{y}$) was 93% of HL ($0.14 \text{ km}^3/\text{y}$). These results also suggest that lake area change was not consistent with lake water storage change due to the different topography around the lake.

5. Discussion

5.1. Comparison of Lake Water Storage Changes between Bathymetric and Altimetry Data

Lake area–water storage relationship can be established according to underwater topography derived from in situ bathymetric data (Figures 4a and 5a). The lake area of HL was greater than 350 km^2 , lake water storage increased little with increasing lake area, and lake depth also increased little. The increasing rate of water storage in the lake area greater

than 350 km² was far less than that in the lake area 200–300 km². Lake area had increased by 67 km² from 2003 (311 km²) to 2018 (378 km²) based on Landsat images. The water level and water storage just increased by 1.15 m (0.077 m/y) and 0.39 km³ (0.026 km³/y) based on underwater topography from bathymetric data. Water storage of LL also increased little with increasing lake area in the lake area larger than 250 km². Lake area of LL had increased by 49 km² from 2003 (238 km²) to 2018 (287 km²) based on Landsat images, and water level and water storage just increased by 2.34 m (0.156 m/y) and 0.59 km³ (0.039 km³/y) based on underwater topography from in situ bathymetric data, respectively.

We used altimetry data to calculate lake level and lake water storage changes and compared them with those from method 1 and 2. Altimetry data provided high accuracy for detecting lake level changes and then estimating water storage change, especially for ICESat and ICESat-2. The rate of lake level increase of HL and LL lake level was 0.38 m/y and 0.5 m/y during 2003–2015 based on ICESat data and linear fitting [15]. The results of Zhang et al. (2019a) suggest that both of HL and LL were 0.5 m/y during 2003–2018 based on ICESat and ICESat-2, and water storage had approximately increased by 0.17 km³/y or 2.58 km³ and 0.13 km³/y km or 1.96 km³. There is a large difference between the results using in situ underwater topography and altimetry data to estimate lake level and water storage changes. Lake level and water storage of HL by method 2 (in situ bathymetric and SRTM data) had increased by approximately 7.5 m and 2.75 km³ from 2003 to 2018 with an average rate of 0.5 m/y and 0.18 km³/y, respectively, and LL was 8.5 m and 2.28 km³ with an average rate of 0.57 m/y and 0.15 km³/y, respectively. The underwater topography in the flooded area by method 2 was much rougher than method 1, and isobaths of 5 m by method 2 were closer to the shoreline than method 1. The results from method 2 were consistent with that from Zhang et al. [18], indicating that the method 2 was better suitable to estimate water storage and change than method 1. These results indicated that lake depth distribution based on in situ underwater topography had a large error due to the insufficiency of bathymetric data around the lake shoreline, especially for the flooded area since 2000. These results suggested that much more bathymetric data is needed in future bathymetric work.

5.2. Lake Water Storage Change and Its Linkage with Climate Change

Annual precipitation showed a quickly increasing trend in the TP, e.g., nearly 90% of the meteorological station showed an increasing trend during 1961–2001 [29]. Annual precipitation during 1996–2015 was approximately 21% greater than that of 1976–1996 [30]. Generally, the water cycle of an endorheic lake in the TP is primarily affected by precipitation, evaporation, glacial meltwater, and permafrost degradation. Increasing precipitation was considered the primary cause of lake expansion in the TP due to a significantly increasing trend in past decades [2,6,11]. In this study region, precipitation showed a significantly increasing trend since 1990, but both of the two lakes' water storage had a decreasing trend before 2000, the likely reason was that low level of precipitation could not offset the loss of evaporation. After 2000, annual precipitation had risen quickly and high precipitation had offset and exceeded the loss of evaporation. Thus, lake water storage had increased quickly during this period. Both AAT and AAMT had a rising trend since 1990, rising temperature could accelerate the melting of glaciers, and increasing glacial meltwater supplied to lakes, which would be a positive effect on lake expansion.

5.3. The Contribution of Glacial Meltwater to Lake Expansion

Glaciers of the TP are experienced severe shrinkage as diagnosed by different methods in past decades, except for the Karakoram mountains [23,31–33]. Glacier mass had decreased by 15.6 ± 10.1 Gt/y during 2003–2009 by using ICESat data, which represented approximately 80% glacier area of TP [23], when assuming that 1 Gt = 1 km³ with the density of water is 1000 kg/km³. The total glacier mass of the TP had decreased by 16.3 ± 3.5 Gt/y during 2000–2016 based on multitemporal ASTER DEMs [34]. Even though most studies had suggested that increasing precipitation was the primary cause of

the TP's lakes expansion, increasing glacial meltwater also had a positive contribution to lake expansion, e.g., ~10.5% to Nam Co during 2000–2013/14 [16], 9.9% and 11.1% to HL and LL during 2000–2015 [15], 13% to lakes of TP [6].

Glacier mass balance of the study region was -0.77 ± 0.35 m water equivalent per year (w.e/y) with a glacier area of 1491 km² based on ICESat data during 2003–2009 [23]. However, glacier mass balance of this region was calculated to -0.16 ± 0.05 m w.e/y by utilizing high-resolution SPOT-6/7 stereo imagery and SRTM during 2000–2015/16 [15], and this result was consistent with Brun et al. [34] from multitemporal ASTER DEMs (-0.15 ± 0.04 m w.e/y). There was a considerable difference among these results from different methods or data, and altimetry data just covered a part of the glacier surface, but DEMs from ASTER or SPOT could cover the total glacier surface with much more accuracy. There were some differences among these results. We used the glacier mass balance results of Malan glaciers (-0.2 ± 0.07 m w.e/y) and Jinyang Gangri glaciers (-0.02 ± 0.07 m w.e/y) from Brun et al. [34] to estimate the contribution of glacial meltwater to lake expansion of these two lakes. The results suggested that increasing glacial meltwater was approximately 0.13 km³ and 0.27 km³ in the basin of HL and LL during 2000–2019, respectively. Lake water storage of HL and LL had increased by 2.68 km³ and 2.52 km³ during the same period, suggesting that increasing glacial meltwater contributed approximately 4.8% and 10.7% to lake expansion of HL and LL during 2000–2019. The contribution of glacial meltwater to lake expansion in this study had a little difference with Zhou et al. [15], in which they suggested glacial meltwater contributed 11.1% and 9.9% to HL and LL, respectively. This may be attributed to the considerable difference of changing rate of water level in HL between from Zhou et al. [15] and from our study and Zhang et al. [15], i.e., 0.3 m/y versus approximately 0.5 m/y during 2003–2018.

6. Conclusions

Some previous researchers used bathymetric data to establish underwater topography and estimated lake water storage and its change. However, bathymetric data did not cover the whole area of the lake, especially for the flooded areas near the shoreline and estimation of lake water storage and its change had a large error. SRTM provided elevation data for the flooded area since 2000. To improve water storage and its change estimation accuracy, we established the underwater topography by combining bathymetric data and SRTM data. The underwater topography was rough in the flooded area where the SRTM data was added as depth data. An increasing rate of HL and LL lake level was 0.5 m/y and 0.57 m/y during 2003–2018, respectively. These results are consistent with the results from ICESat and ICESat-2 data (0.5 m/y and 0.5 m/y), indicating that the results of 0.077 m/y and 0.156 m/y from method 1 using only bathymetric data was poor. These results suggested that this method could improve the accuracy of lake water storage and change estimation.

According to the underwater topography derived from bathymetric data and SRTM, lake water storage of HL and LL was 5.12 km³ and 5.31 km³ in 2019, respectively. We also estimated lake water storage change by combining multitemporal Landsat images during 1976–2019, lake water storage of HL and LL had increased by 2.61 km³ and 2.37 km³ from 1976 to 2019, respectively. Both of the two lakes showed a little decreasing trend before 2000 and later a water storage increase rate for HL and LL of 0.14 km³/y and 0.13 km³/y during 2000–2019, respectively. Analyzing the changing trend of AAT, AAMT, and AP based on the nearby meteorological station, we suggested that the increasing precipitation perhaps was the primary cause of lake expansion. Increasing glacial meltwater contributed approximately 4.8% and 10.7% to lake expansion of HL and LL during 2000–2019 based on the glacier mass balance data from multitemporal ASTER DEM.

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