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A comparative study of satellite altimetry-based and DEM-based methods for estimating lake water volume changes

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ABSTRACT

This study compared two different methods, the satellite altimetry-based and DEM (digital elevation model)-based, for estimating lake water volume changes. We focused on 34 lakes in China as the testing sites to compare the two methods for lake water volume changes from 2005 to 2020. The satellite altimetry-based method used water levels provided by the DAHITI (Database for Hydrological Time Series of Inland Waters) data and surface areas derived from Landsat imagery. The DEM-based method used the SRTM DEM data in combination with Landsat-derived lake extents. Our results showed a high degree of consistency in lake water volume changes estimated between the two methods ($R^2 > 0.90$), but each method has its limitations. In terms of temporal coverage, the satellite altimetry-based method with the DAHITI data is limited by missing water level data in certain periods. The performance of the DEM-based method in extracting lake shore boundaries in regions with flat terrains (slope $<1.5°$) is not satisfactory. The DEM-based method has complete regional applicability (100%) in the Tibetan Plateau (TP) Lake Region, yet its effectiveness drops significantly in the Xinjiang and Eastern China Plain Lake Regions, with applicability rates of 50 and 40%, respectively.

Key words: China, DAHITI, lake, SRTM DEM, water volume

HIGHLIGHTS

- Although the water volume changes derived from these methods are highly consistent, the two methods are still affected by different constraints.
- The limitations and regional applicability of the two methods were analyzed in detail.
- The DEM method is more suitable for estimating lake water volumes in the Tibetan Plateau Lake Region, and the DAHITI method is suitable for lakes with complete water level data.

1. INTRODUCTION

Lakes play an important role in the global water cycle and act as key indicators of climate change. China has more than 2,000 lakes (>1 km^2), cumulatively covering an area exceeding 80,000 km^2 (Zhang & Song 2022). These lakes show significant spatial heterogeneity in terms of water volume change, hydrological regimes, and climate interactions. Considering the spatial characteristics of natural environments and resource utilization, the geographic distribution of Chinese lakes has been categorized into five distinct regions: the Tibetan Plateau (TP), Eastern China Plain, Mongolia-Xinjiang, Northeastern China Plain, and Yunnan-Guizhou Lake Region (Wang & Dou 1998). Among these, the TP and Mongolian Regions, which together constitute more than 70% of China, have the largest lakes with individual lakes exceeding 20 km^2 in area (Liu *et al.* 2022). In particular, the TP has the largest number of lakes in China with more than 1,000 lakes in areas larger than 1 km^2 (Zhang 2018). The Xinjiang and the Eastern China Plains occupy 9.1 and 21.73% of the national total lake area, respectively (Shang *et al.* 2021).

The spatial variability in lake dynamics, increasingly influenced by both climate change and anthropogenic activities, has become more pronounced in recent years (Zhang *et al.* 2013). In the Mongolia-Xinjiang Lake Region, lakes such as Boston Lake have shrunk due to an increase in irrigation for agriculture (Liu *et al.* 2006). In the Eastern China Plains, especially in

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the Yangtze River Basin (such as Tai Lake, Poyang Lake), lakes are subject to significant hydrological alterations driven by monsoonal shifts and human interventions (Guo *et al.* 2008; Dronova *et al.* 2011; Ji *et al.* 2019). However, the TP alpine lakes are generally expanding, a trend attributed to accelerated glacial melt and increased precipitation (Zhang *et al.* 2011).

The water balance of a lake refers to the net effect of inputs (such as surface runoff inflow and precipitation) against outputs (such as surface runoff outflow and lake evaporation) (Zhang *et al.* 2013). In remote areas with harsh conditions, these variables are often not directly measurable at hydrological stations. Remote sensing technology provides a solution, enabling the estimation of lake water balance through the analysis of satellite-derived water level (from radar or laser altimeters) combined with surface area data obtained from satellite imagery (Zhang *et al.* 2013; Duan *et al.* 2018). The advent of advanced remote sensing techniques has facilitated the development of multiple methods for estimating lake water volumes, typically incorporating data from individual satellites to estimate lake levels and areas, or integrating data from multiple remote sensing sources to improve temporal and spatial coverages (Zhang *et al.* 2011; Duan & Bastiaanssen 2013; Feng *et al.* 2022). For example, Zhang *et al.* (2013) derived lake levels from ICESat-1 altimetry data and lake surface area from Landsat images and further used them to estimate the water balances of the 10 largest lakes in China during 2003–2009. Xu *et al.* (2022) used multi-mission satellite data to systematically analyze water storage changes in Inner Mongolia's major lakes.

Existing studies usually use empirical formulas to calculate the water volume change in a single area based on lake area and water level (Crétaux *et al.* 2016; Cai *et al.* 2020). The method of integrating digital elevation model (DEM) and satellite optical images is also an important technical supplement for estimating water volume change, and this method has acceptable accuracy with an overall average error of 4.98% (Yang *et al.* 2017). Most existing studies have relied on a single estimation method, with comparative analyses between different methods remaining scarce. Satellite altimetry-based estimation methods have been widely used, particularly for large lakes with comprehensive data sets such as Selin Co and Qinghai Lake. Satellite altimeters are profiling tools rather than imaging devices, and they can only observe lakes along their ground tracks, meaning that many lakes are not or only partially measured. Thus, questions remain regarding the reliability of water volume change estimates for lakes with incomplete data records. The DEM-based method has been well applied in the TP region (Yang *et al.* 2017), its suitability for lakes in other regions has not been sufficiently investigated. Moreover, comparative analyses of the two different methods are even more scarce.

To address the above-mentioned gaps, this study aimed at conducting a comparative study of satellite altimetry-based and DEM-based methods for estimating lake water volume changes in China. Specifically, we leveraged satellite altimetry-derived lake water levels provided by the Database for Hydrological Time Series of Inland Waters (DAHITI) in combination with Landsat-derived lake areas to estimate the water volume changes for 34 selected lakes from 2005 to 2020. For the DEM-based method, we used the Shuttle Radar Topography Mission (SRTM) DEM and Landsat images to estimate water volume changes in the same lakes during the same period. The objectives of this study are to (1) evaluate the two methods and examine their strengths and limitations for estimating lake water volume changes and (2) assess the regional applicability of the two methods across a large geographical region. This study is expected to help us achieve a better understanding of the performance and applicability of these two methods and potentially to synthesize these two methods for an improved estimate of lake water volume changes.

2. STUDY AREA

This study focused on 34 selected lakes in China (Figure 1) with water level time series data provided by the DAHITI at the time of writing. These lakes were selected for a comparative analysis of water volume estimation methods. The 34 lakes are distributed in three lake regions as follows: TP, Xinjiang, and Eastern China Plain Lake Region. As shown in Figure 1, The TP Lake Region includes 27 alpine lakes such as Selin Co, Nam Co, Dagze Co, Gyaring Co, and so on. Xinjiang Lake Region includes two inland lakes such as Bosten Lake and Ulungur Lake. In the Eastern China Plain Lake Region, Hulun Lake is located in the Amur River Basin; Chao Lake, Poyang Lake, Junshan Lake, and Tai Lake are distributed in the Yangtze River Basin.

Most of the 27 lakes on the TP are located in the endorheic region and are less affected by human activity; however, they are extremely sensitive to climatic and cryospheric changes. The TP is a regional Earth system showing very strong interactions among its lithosphere, hydrosphere, cryosphere, biosphere, atmosphere, and anthrosphere (Yang *et al.* 2011; Yao *et al.* 2015). The inland lakes in the arid region of Xinjiang are an important link in the water resource cycle and a comprehensive reflection of the effect of climate change and human activities on water resources (Wu *et al.* 2012). Lake volumes in

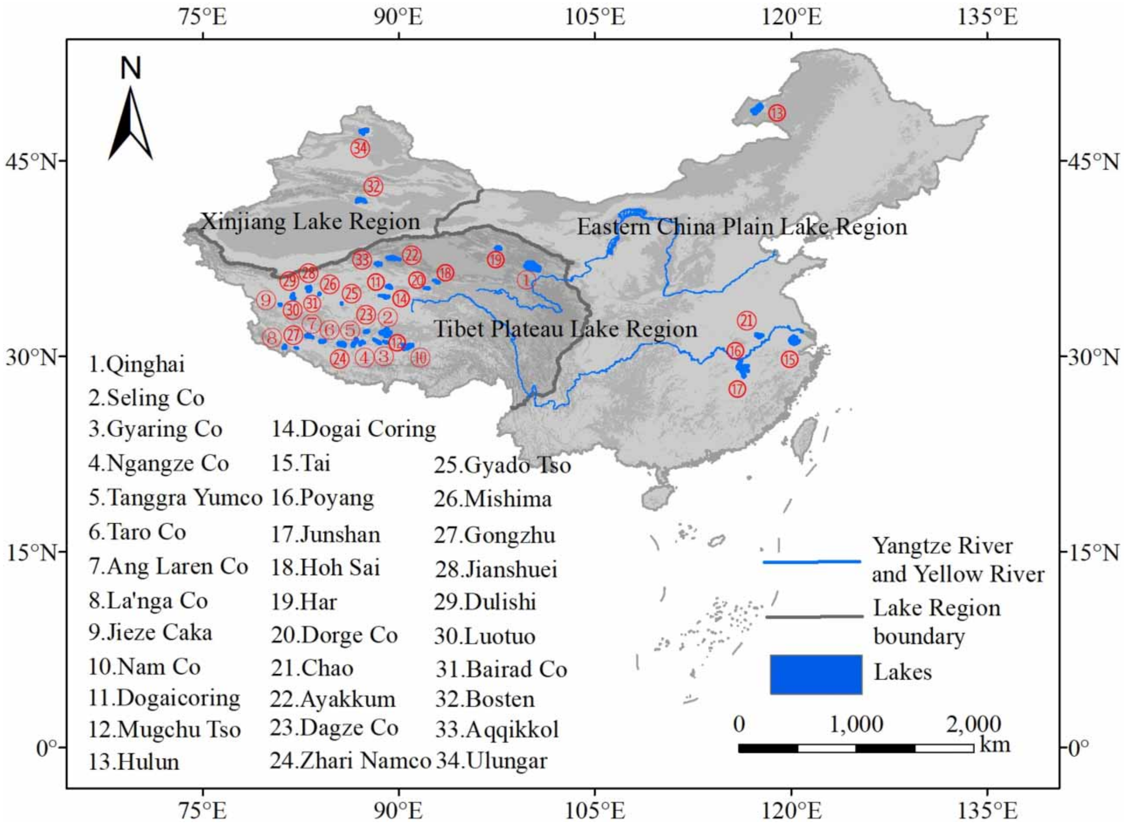

Figure 1 | Distribution map of the studied 34 lakes in China. The gray lines indicate the lake region boundaries, and the blue shaded area indicates the extent of all lakes. The circled numbers indicate all lakes studied in China.

the Eastern China Plain Lake Region show significant inter- and intra-annual variations caused by precipitation fluctuations during the summer monsoon. This phenomenon is more significant in the mid-lower reaches of the Yangtze River basin (Chen *et al.* 2011; Zheng *et al.* 2016).

3. DATA AND METHODOLOGY

We used Landsat images from 2005 to 2020 to extract the lake extents/surface areas over different periods. On this basis, we estimated lake water volume changes using two different methods: (1) satellite altimetry-based method that uses the empirical formula derived from DAHITI water level data and (2) DEM-based method that uses SRTM DEM data (Figure 2).

3.1. Landsat images and processing

Launched by NASA, the Landsat satellites have contributed greatly to our understanding of the Earth's environment. Data used in this study were downloaded from the United States Geological Survey (http://glovis.usgs.gov.landsat). These data are widely used in lake extent extraction (Crétaux *et al.* 2016; Markham *et al.* 2018). We selected 113 Landsat TM/ETM/OLI images, each with less than 5% cloud cover and acquired around October, were selected. These image dates align with DAHITI water level data within a 2-month margin. The amount of precipitation and interannual precipitation fluctuation are very small in the TP and Xinjiang (Jin *et al.* 2021). Furthermore, alpine lakes in the TP are also influenced to some extent by the supply of glacial meltwater. Therefore, the water level changes of lakes in the TP and Xinjiang Lake Region are relatively stable and the estimation results are not significantly affected by flood peak. In addition, the limited number of lakes in the Eastern China Plain Lake Region has a minimal impact on the estimation of water volume. We also consulted relevant literature to ensure that the estimated time point we chose was not during the peak flood period of the eastern lake. The times at which Landsat images were used for lake extent extraction are listed in Table 1. The normalized difference water index (NDWI) method was used to extract lake boundaries and further to calculate lake surface areas (Gao 1996). The

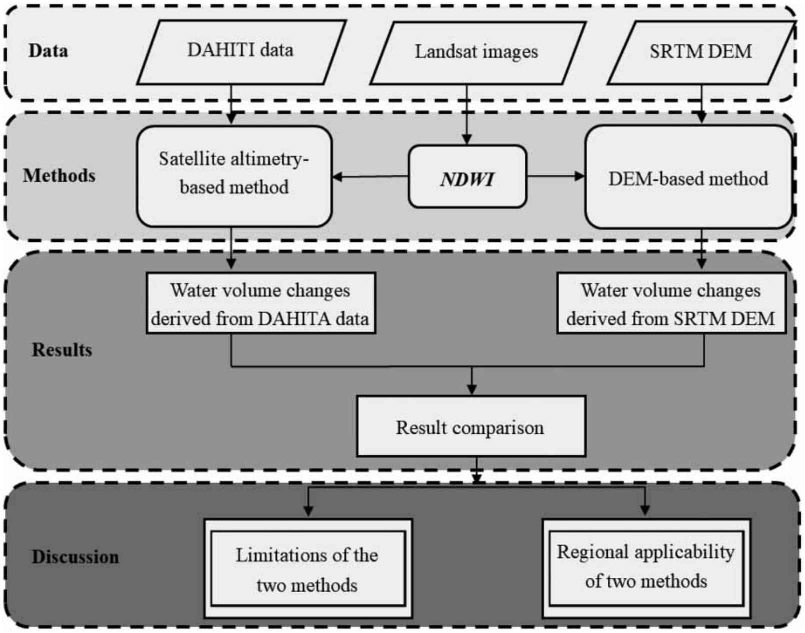

Figure 2 | The flowchart for lake water volume estimation with two different methods (satellite altimetry-based and DEM-based) in this study.

formula is described as follows:

$$R_{\mathrm{NDWI}} = \frac{r_{\mathrm{green}} - r_{\mathrm{nir}}}{r_{\mathrm{green}} + r_{\mathrm{nir}}} \tag{1}$$

where R_{NDWI} indicates the water index; r_{green} and r_{nir} indicate the reflectance in the green band and near-infrared band of the Landsat image.

3.2. Satellite altimetry-based method with DAHITI data

The DAHITI data incorporate altimetry data from various satellites, such as ENVISat, Jason-1, Jason-2, and TOPEX/Poseidon. DAHITI uses an extended outlier rejection and a Kalman filter approach. The DAHITI was developed by the Technical University of Munich and now provides more than 600 water elevation time series of rivers, reservoirs, and lakes, using multi-source and multi-sensor satellite altimetry data (https://dahiti.dgfi.tum.de/en/map/) (Schwatke *et al.* 2015). Lake levels from DAHITI have been well validated in many lakes (Busker *et al.* 2019; Liu *et al.* 2019a, 2019b). Schwatke *et al.* (2015) demonstrated the water level performance of DAHITI for numerous lakes and rivers in North and South America. Comprehensive validation was performed by comparison with *in situ* gauge data and results from external inland altimeter databases. The lake-level datasets computed using the DAHITI approach yielded errors between 4 and 36 cm. At the time of our study and writing, the DAHITI database includes water level time series (2002–2021) of 83 (the number will be continuously increased) water bodies in China (including large inland lakes and rivers in the Yangtze River basin, Zhujiang River basin, and other river basins). The duration of a monitoring period is five years (the corresponding monitoring years are 2005, 2010, 2015, and 2020). To use the satellite altimetry-based method we combined DAHITI water level data with lake area data derived from Landsat images to derive a time series of water volume changes for different monitoring periods from 2005 to 2020. The water volume changes were estimated using Equation (2), as demonstrated in detail by Taube (2000):

$$V = \frac{1}{3}(H_2 - H_1)(S_1 + S_2 + \sqrt{S_1 S_2}) \tag{2}$$

where V is the volume change from elevation H_1 and area S_1 to elevation H_2 and area S_2.

Table 1 | Temporal variation trend of water volume changes (km^3) in 34 lakes estimated from the satellite altimetry-based method with the DAHITI data

Lake name	Start date	Period 1	Time 1	Period 2	Time 2	Period 3	End date	Water balance
Seling Co	09/04	+5.95	08/10	+3.41	11/15	+3.34	10/20	+12.70
Ang Laren Co					10/16	+1.08	10/20	+1.08
Zhari Namco	09/04	+1.47	10/10	−0.4	10/15	+3.52	10/20	+4.59
TangraYumco	11/05	+1.18	10/10	+0.11	10/15	+1.48	10/20	+2.77
Ngangze Co			11/09	+0.35	11/15	+0.74	11/20	+1.09
Dagze Co	09/04	+0.96	10/09	+0.69	09/15	+1.11	10/20	+2.76
Nam Co	11/05	+0.21	11/10	−0.17	11/15	+1.38	10/20	+1.42
Dogaicoring	09/04	+0.77	09/10	+0.72	09/15	+1.02	10/20	+2.51
Dorge Co					10/16	+0.04	09/20	+0.04
Junshan					11/16	+0.20	09/20	+0.2
Dogai Coring	09/04	+0.58	09/10	+0.42	10/15	+0.88	10/20	+1.88
Kusai			09/10	+1.79	11/15	+0.08	10/20	+1.87
Qinghai	09/05	+0.27	08/10	+3.78	09/15	+8.75	10/20	+12.8
Jieze Caka					10/16	+0.12	10/20	+0.12
Har	09/04	+0.42	07/10	+0.4	10/15	+1.3	10/20	+2.12
La’nga Co			10/10	−0.18	09/15	−0.22	10/20	−0.40
Taro Co			10/13	−0.33	09/15			−0.33
Gyaring Co					10/15	+0.19	10/20	+0.19
Gyado Tso					10/16	+0.07	10/20	+0.07
Mishima					10/16	+0.18	10/20	+0.18
Gongzhu					10/16	+0.04	10/20	+0.04
Jianshuei					10/18	+0.08	10/20	+0.08
Dulishi					10/16	+0.16	10/20	+0.16
Luotuo					10/16	+0.13	10/20	+0.13
Bairad Co					10/16	−0.07	10/20	−0.07
Mugchu Tso					10/15	+0.01	10/20	+0.01
Ulungar	08/05	+1.01	08/10	−0.53	10/15	+0.64	08/20	+1.12
Ayakkum	10/05	+1.25	09/10	+1.49	08/15	+2.03	10/18	+4.77
Bosten			08/10	−0.01	09/15	+1.74	10/20	+1.73
Aqqikkol			10/11	+1.25	10/15	+0.77	10/18	+2.02
Tai	11/05	+0.26	09/10	−1.19	10/15			−0.93
Hulun	10/05	−2.98	09/10	+5.60	09/15	+0.09	11/20	+2.71
Chao	11/05	+0.33	10/09	−0.12	12/16	+0.73	10/20	+0.94
Poyang	09/05	−1.15.69	08/08	−9.15	09/15	+17.74	09/20	+7.44

The starting date of each lake is 2005 and the ending date is 2020. Each monitoring cycle is five years. If the water level data of the monitoring time point were missing in the DAHITI data, the time point was extended by one year or calculated one year later. Water level data of most lakes were missing from 2005 to 2010 but were relatively complete from 2015 to 2020.

3.3. SRTM DEM and processing

The SRTM DEM is a near-global topographic database generated from satellite images (Jakob & Van 2001) at a resolution of 30 m (Rabus *et al.* 2003). The SRTM provides a global high-quality DEM which covers the Earth between latitudes 60°N and 56°S and is acquired with the same sensor in a single mission and produced with single-technique synthetic aperture radar (SAR) interferometry (Jakob & Van 2001). A great advantage is the homogeneous quality of the DEM (Rabus *et al.* 2003). Yang *et al.* (2017) assessed the accuracy of lake water volume change results calculated using the SRTM DEM and found the accuracy of this method acceptable. Therefore, these two methods in this study were not necessary to verify the accuracy.

First, the lake area A_{SRTM} was extracted from the SRTM DEM data and the corresponding lake surface area A_i ($i = 1, 2, 3 \ldots$) at every 1 m increment in elevation. Therefore, A_i ($i = 1, 2, 3 \ldots$) at an elevation of i m above A_{SRTM} was calculated. Second, using Equation (3) to calculate V_i which expresses the volume between the lake surface A_{SRTM} and A_i – the volume change when the lake surface rises from A_{SRTM} to A_i – we obtained a series of (V_i, A_i) data pairs and established a regression equation (Equation (4)) between them – V_i is estimated as a function of A_i – to calculate the increase in lake volume relative to the lake surface area A_{SRTM} when the lake reaches a certain surface area.

For example, at the time t_{a}, the lake surface area increases to A_{a}. When A_{a} is substituted into Equation (4), the volume change of the lake relative to A_{SRTM} can be obtained. Assuming that the slope below A_{SRTM} is similar to that above A_{SRTM} within a certain range, the volume change when the lake shrinks from A_{SRTM} to A_{b} at moment t_{b} can be estimated using Equation (4).

Therefore, when calculating the water volume change ($V_{\mathrm{b,a}}$) of the lake between two times ($t_{\mathrm{a}} - t_{\mathrm{b}}$), it is only necessary to obtain the lake surface areas A_{a} and A_{b} of the lake at times t_{a} and t_{b}, respectively (A_{a} and A_{b} were obtained from Landsat images) and substitute them into Equation (5):

$$V_i = V_{i-1} + \left(A_i + A_{i-1} + \sqrt{A_i * A_{i-1}}\right)/3 \tag{3}$$

$$V_i = F(A_i) \tag{4}$$

$$\Delta V_{\mathrm{b,\,a}} = V_{\mathrm{b}} - V_{\mathrm{a}} = F(A_{\mathrm{b}}) - F(A_{\mathrm{a}}) \tag{5}$$

For illustrative purposes, we used Aqqikkol Lake as an example to explain the calculation procedures. Figure 3(a) represents a cross-sectional view of the lake boundary extraction process. Figure 3(b) represents a plan view of lake boundary delineation.

Equation (4) was used to calculate V_i and establish the regression equation of Aqqikkol Lake (Figure 4).

Last, by inserting A_{20} and A_{15} (obtained from Landsat images) into Equation (5), the water volume change of Aqqikkol Lake from 2015 to 2020 was estimated. Then we repeated the same procedures mentioned earlier to estimate the water volume changes of all lakes with this DEM-based method.

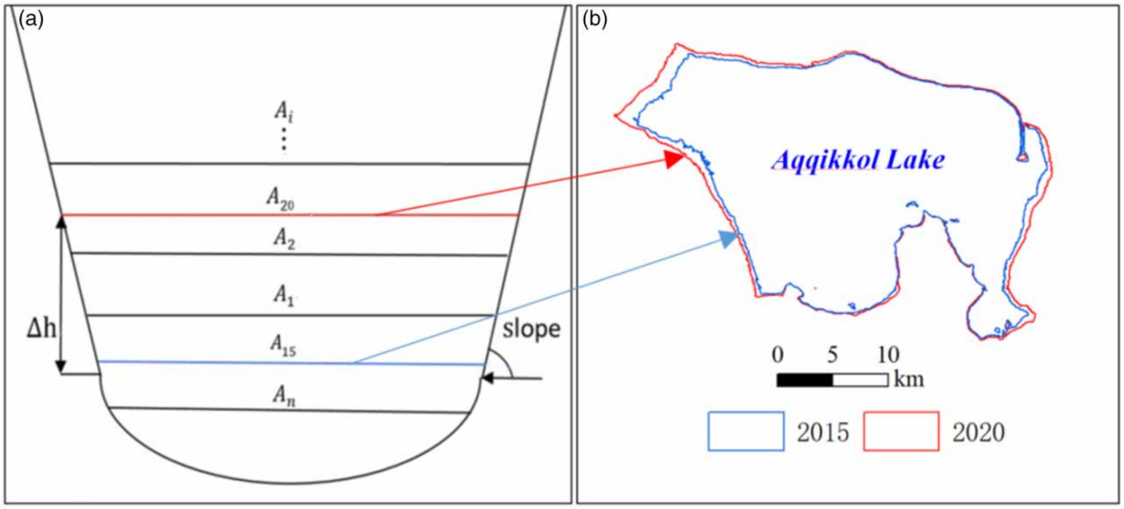

Figure 3 | Schematic diagram of the water level height difference method based on lake shore terrain simulation. The blue and red lines represent the extent of Aqqikkol Lake in 2015 and 2020, respectively.

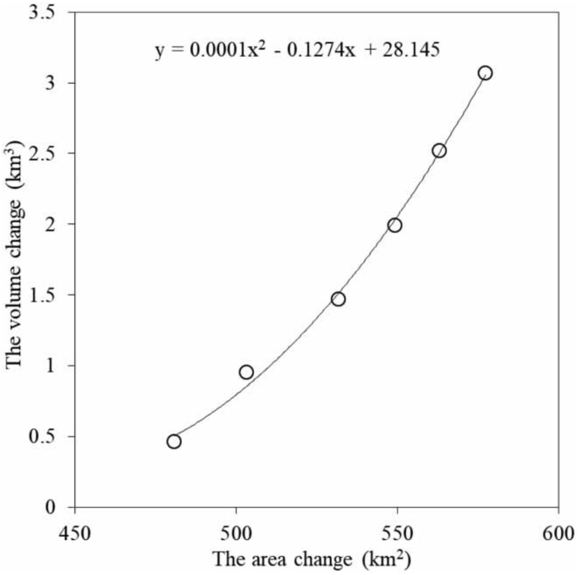

Figure 4 | Regression of lake surface area change and lake water volume change for Aqqikkol Lake.

4. RESULTS

4.1. Water volume change estimation results

We analyzed the lake water volume changes by using SRTM DEM, which has more complete estimation results relative to DAHITI missing the early water level information seriously (Table 2). The results show that the overall water volume of lakes in the study region is on the rise. From 2005 to 2020, except for the reduction of the water volume of three lakes such as La'nga Co, the total water volume of the remaining lakes has increased to varying degrees. In the three monitoring periods, the fastest increase period is from 2015 to 2020, with a total increase of 26.07 km^3 in all lakes. The slowest increase period is from 2005 to 2010 with some lakes showing a significant decrease, and the total water volume of all lakes only increased by 11.47 km^3. Therefore, the water volume growth rate of China's lakes in the past 15 years shows an accelerating trend.

Water volume changes derived from the SRTM DEM showed considerably spatial heterogeneity with 24 lakes in the TP Lake Region showing a marked increasing water volume trend. Among these, Selin Co and Qinghai Lake, with vast water storage capacities, showed the largest increase (both above 10 km^3) with average annual changes of 0.70 and 0.95 km^3/a, respectively. Lakes with lower water storage capacities, such as Dorge Co and Mugchu Tso, increased more slowly, with an average annual change of 0.003 km^3/a. In contrast, the Bairad Co, La' nga Co, and Gyaring Co Lakes exhibited a certain degree of shrinkage. The water volume in the Xinjiang Lake Region showed a slowly increasing trend. The annual increase in water volume in Ulunger Lake was 0.09 km^3/a, whilst the water volume changes in the East China Plain Lake Region showed fluctuating tendencies. The water volume change in Hulun Lake increased by more than 1 km^3.

Figure 5 shows the water volume change of all lakes studied. In general, the lake water volume in China is on the rise. In the TP, two lakes showed a decrease in water volume, the other inland lakes have an increased trend of water volume change. In the Eastern China Plain Lake Region, four lakes showed an increasing trend in water volume change. In Xinjiang Lake Region, the water volumes of all lakes are increasing.

4.2. Comparison of water volume change estimation with two different methods

We used two methods to estimate the water volume changes in 34 lakes and then compared their results. Overall, there is a strong correlation between the two results. For the satellite altimetry-based method with DAHITI data, not all lakes had a complete water level time series for each of the three cycles spanning 2005–2020. Nevertheless, the data from 2015 to 2020 were considerably more comprehensive, and this period was chosen for the comparative analysis of 29 lakes. Figure 6

Table 2 | Temporal trend of water volume variations (km^3) in 34 lakes estimated from the DEM-based method with the SRTM DEM data. The time point of each lake monitoring period is the same as in Table 1

Lake name	Start date	Period 1	Time 2	Period 2	Time 3	Period 3	End date	Water balance
Seling Co	09/04	+3.22	08/10	+6.40	11/15	+1.56	10/20	+11.18
Ang Laren Co	10/05	+0.68	10/10	−0.49	10/16	+1.39	10/20	+1.58
Zhari Namco	09/04	+1.21	10/10	−0.35	10/15	+2.01	10/20	+2.87
TangraYumco	11/05	+1.29	10/10	+0.11	10/15	+1.15	10/20	+2.55
Ngangze Co	10/05	+0.3	11/09	+0.27	11/15	+0.80	10/20	+1.37
Dagze Co	09/04	+1.07	10/09	+0.53	09/15	+1.21	10/20	+2.81
Nam Co	11/05	+0.47	11/10	−0.18	11/15	+0.49	10/20	+0.78
Dogaicoring	09/04	+0.73	09/10	+0.67	09/15	+0.91	10/20	+2.31
Dorge Co	08/05	+0.20	09/10	−0.20	10/16	+0.04	09/20	+0.04
Junshan	10/05	−0.01	08/08	+0.02	11/16	+0.08	09/20	+0.09
Dogai Coring	09/04	+0.29	09/10	+0.43	10/15	+0.71	10/18	+1.43
kusai	10/05	+0.85	09/10	+1.46	11/15	+0.04	10/20	+2.35
Qinghai	09/05	+0.16	08/10	+4.99	09/15	+9.05	10/20	+14.20
Jieze Caka	10/05	+0.14	10/10	+0.13	10/16	+0.13	10/20	+0.40
Har	09/04	+0.85	07/10	+0.45	10/15	+1.47	10/20	+2.77
La'nga Co	11/05	−0.1	10/10	−0.22	09/15	−0.32	10/20	−0.64
Taro Co	10/05	+0.31	10/13	−0.23	09/15	+0.84	10/20	+0.92
Gyaring Co	10/04	−0.35	10/09	−0.27	10/15	+0.29	10/20	−0.33
Gyado Tso	10/05	+0.02	10/10	+0.11	10/16	+0.09	10/20	+0.22
Mishima	11/05	+0.01	11/10	−0.03	10/16	+0.16	10/20	+0.14
Gongzhu	10/05	+0.06	10/10	+0.03	10/16	+0.11	10/20	+0.20
Jianshuei	09/05	+0.57	09/10	+1.18	09/18	+0.08	10/20	+1.83
Dulishi	11/05	+0.17	11/10	+0.18	10/16	+0.17	10/20	+0.52
Luotuo	10/05	+0.04	10/10	+0.06	10/16	+0.11	10/20	+0.21
Bairad Co	10/05	−0.02	09/10	−0.06	10/16	−0.07	10/20	−0.15
Mugchu Tso	10/05	−0.003	04/13	+0.02	10/15	+0.02	10/20	+0.04
Ulungar	10/05	+0.78	10/10	+0.002	10/15	+0.64	10/20	+1.42
Ayakkum	10/05	+1.04	09/10	+1.38	08/15	+1.94	10/18	+4.36
Bosten								
Aqqikkol	10/05	+0.31	10/11	+1.42	10/15	+0.89	10/18	+2.62
Tai								
Hulun	10/05	−2.82	09/10	+5.00	09/15	+0.08	11/20	+2.26
Chao								
Poyang								

The water volume change data for Bosten, Poyang, Tai, and Chao Lakes is missing as DEM cannot be used to estimate this change.

shows high agreement between the two results with the coefficient of determination R^2 of 0.93 and high confidence in the comparison, with most lakes falling within the 95% confidence interval, particularly those in the TP. The confidence levels for two lakes, Selin Co and Zhari Namco, were slightly lower.

The deviations in the estimated results for individual lakes were quantified using a proportional algorithm. As shown in Figure 7, the deviations for most lakes are small, but the deviations of the Gongzhu and Kusai Lakes are relatively large. This may be attributed to the small surface areas of these lakes and the minor changes in water volume, which could amplify the discrepancies between the two methods.

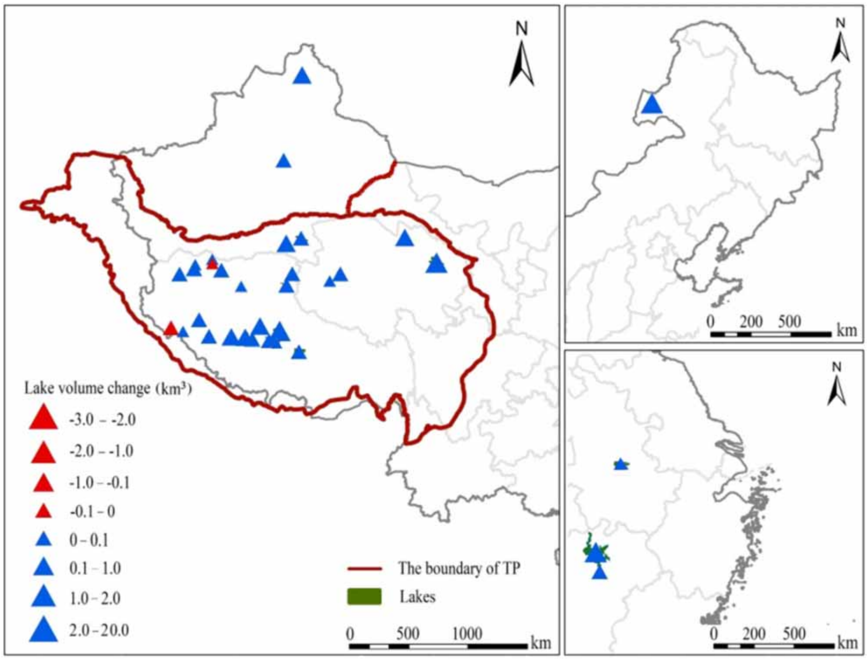

Figure 5 | Spatial distribution of lake water volume change from 2015 to 2020 based on DEM. Lakes that cannot have their water volume changes estimated using DEM-based methods are represented using estimation results based on satellite altimetry-based methods. The red and blue color triangles indicate a decrease and increase in lake volume, respectively. The red line indicates the boundary of the lake region. Tai Lake is not shown in this figure as it lacks DAHITI data and DEM-based methods cannot be used to estimate its water volume change.

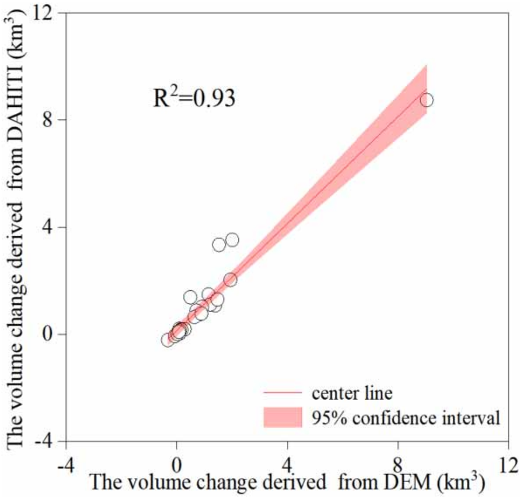

Figure 6 | Correlation analysis and confidence interval map of water volume change estimated by two different methods. The white circles represent the calculation results of every lake studied. The red strip indicates the confidence interval of 95%.

5. DISCUSSION

5.1. Limitations of the two methods

5.1.1. Limitations of the DEM-based method with the SRTM DEM data

The vertical accuracy of SRTM DEM data is reported to be 3–5 m (Bhang *et al.* 2006), while the horizontal accuracy is 3–6 m (Passini & Jacobsen 2007). Its mean absolute error (MAE) is measured at 3.60 m, ranking second among all global public

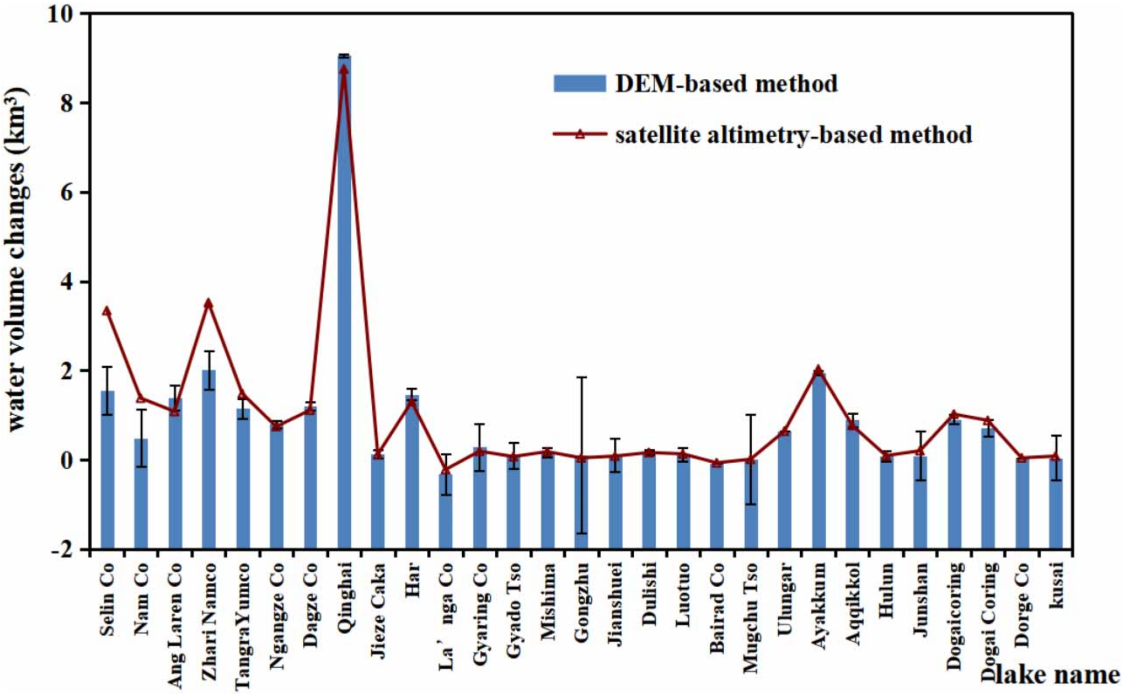

Figure 7 | Deviation of the estimated results of water volume changes in 29 lakes. The blue histogram and red line represent the estimated results using the DEM-based method and satellite altimetry-based method with the DAHITI data, respectively. The black short line represents the deviation of water volume changes obtained using the two methods.

DEMs (Liu *et al.* 2019a, 2019b). The high accuracy of SRTM DEM data has led to its widespread application in lake volume estimation studies (Yang *et al.* 2017; Liu *et al.* 2024). It is necessary to point out that we used the same SRTM DEM data to estimate the water volume changes of all lakes for different monitoring periods. Lake water volume changes are estimated based on variations in the lake level and area at different time periods. In short, the vertical errors present in SRTM DEM data can impact the estimation of lake water volume changes, although generally within acceptable margins. Yang *et al.* (2017) validated the accuracy of lake water volume change estimates using SRTM DEM by comparing them with depth measurement data. They found that the results were highly accurate. Liu *et al.* (2024) demonstrated the great utility of SRTM DEM in monitoring lake water storage changes through mapping inundated bathymetry. However, the lakeshore terrain plays a critical role in the applicability of the DEM-based method. The precision of contour line extraction is directly influenced by the slope of the lakeshore. For example, as shown in Figure 8(a) and 8(b), the lakeshore to the northeast and southwest of Chao Lake is relatively flat, whereas that in the eastern and northern mountainous areas is relatively steep. By comparing the extraction results of the contour line with the terrain slope binary map, it was found that the extraction of the contour line in areas with terrain slopes >1.5° – such as the eastern and northern shores of Chao Lake – was more accurate (within the range of the purple dashed lines in Figure 8(c). In contrast, in flat terrain areas with a slope <1.5°, the contour lines are confusing. Through extensive experiments, we set the slope condition (threshold) of the DEM method for estimating the lake water volume to >1.5°.

In summary, the shorelines of most lakes with steep terrains can be accurately fitted using the DEM-based method (Figure 9(a), Gongzhu Lake), but those with relatively flat terrains are difficult to extract accurately. In addition, some large lakes have defects and only a portion of the shoreline can be accurately obtained. For example, the eastern and southern shores of Bosten Lake (Figure 9(b)) are close to mountain ranges, and the contour lines can effectively extract the lakeshore boundary. However, the contour lines deviate severely from the lakeshore boundary on the relatively flat plains to the west. In this situation, it is difficult to establish regression equations that accurately simulate changes in lakeshore topography, leading to an inability to accurately estimate the water volume changes in these lakes.

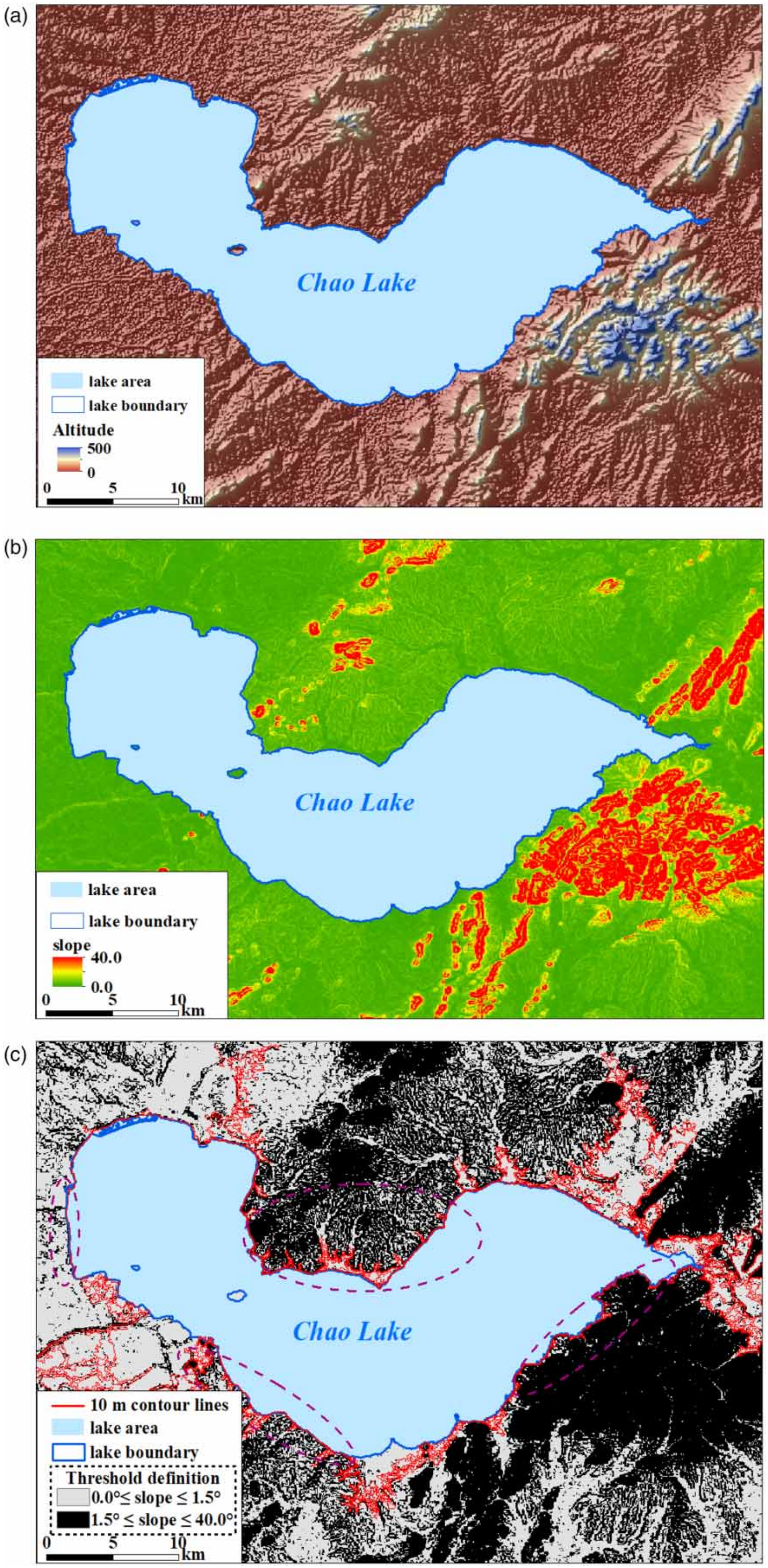

Figure 8 | Threshold setting for extracting the contour lines of the Chao Lake shore. (a,b) represent the surrounding terrain and slope of Chao Lake, respectively. (c) represents the slope threshold setting for accurately extracting the lake shore using contour lines (gray and black areas represent areas with slopes $<$ and $>$1.5°, respectively). The red lines represent the contour lines, and the area circled by the purple dashed line represents the relatively accurate area of the lake shoreline extracted by the contour lines.

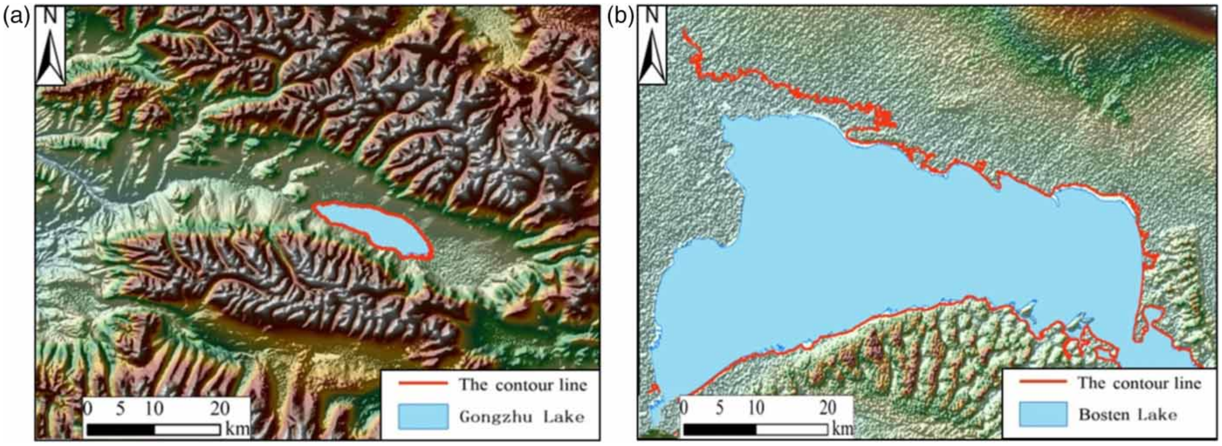

Figure 9 | The contour line cannot describe the lake shore extent. (a) Gongzhu Lake and (b) Boston Lake. The blue area and red line represent the lake extent and contour line of the lake shore, respectively.

5.1.2. Limitations of the satellite altimetry-based method with the DAHITI data

The satellite altimetry-based method with the DAHITI data integrates multi-source satellite data, and the monitoring period for each satellite is different. This resulted in partially missing water level data for some lakes which affected the lake water volume change estimation for some lakes in the TP Lake Region. Based on the data of the 'water balance' column in Tables 1 and 2 (the total water balance over the past 15 years), there is a marked difference in the total water balance of 21 of the lakes. These lakes limited water level data from DAHITI for the past 15 years, making it impossible to estimate the results of water volume changes during this period. Therefore, missing water level data is an extremely unfavorable factor for exploring the temporal variation characteristics of lake volumes using satellite altimetry data.

In addition, for water volume estimation in a single lake, the limited DAHITI water level data may also affect the value of the estimation results. Table 3 shows the deviation between the estimated results for Junshan and Dulishi Lakes. The deviation for Dulishi Lake is 0.01 km^3, while that of Junshan Lake is 0.12 km^3. Junshan Lake is located in the Eastern China Plain Lake Region, and its daily water level changes significantly owing to seasonal precipitation changes and human activities. However, the time difference between the water level and area is approximately two months, leading to a notable deviation in the estimation results. In contrast, the water level time series for Dulishi Lake is relatively complete, and the estimated results had a small deviation.

5.2. Regional applicability of two methods

The DEM-based method has the advantage for estimating lake water volume changes without temporal constraints and can be applied to inland lakes worldwide because of the coverage of DEM data. However, the DEM-based method is highly dependent on lakeshore terrain. For some lakes with complete water level time series, such as the Hulun and Poyang Lakes, the satellite altimetry-based method is more suitable for monitoring the water volume change. However, the limited satellite altimetry-derived water levels from the DAHITI data constrain the applicability of this method.

As summarized in Table 4, the two methods demonstrate different regional applicability. The DEM-based method has a good applicability rate of 100% in the TP Lake Region which has a greater lakeshore slope, while in the Xinjiang and Eastern China Plain Lake Region with flatter lakeshore slopes, the water volume changes of some lakes cannot be estimated as there

Table 3 | Several examples of studied lakes with the large time offset between water level time and area extraction time

Lake name	Time of water level	Time of area	Time offset (day)	Water volume offset (km^3)
Junshan	21/11	05/10	47	0.12
Dulishi	14/10	20/10	6	0.01

The date in the table represents the time point of the lake in a monitoring period.

Table 4 | Regional applicability of the two methods for 34 lakes

Lake region	Lake name	DAHITI applicability	Missing period (year)	DEM applicability
TP Lake Region	Gyado Tso, Mishima, Gongzhu, Dulishi, Luotuo, Bairad Co, Ang Laren Co, Dorge Co, Jieze Caka	Missing data	05–15	Available
	Taro Co	Missing data	16–20	Available
	Seling Co, Zhari Namco, TangraYumco, Nam Co, Dogaicoring, Dogai Coring, Qinghai, Dagze Co, Har	Available	Complete	Available
	Ngangze Co,	Missing data	05–08	Available
	kusai, La'nga Co	Missing data	05–09	Available
	Aqqikkol	Missing data	05–10	Available
	Gyaring Co	Missing data	05–14	Available
	Jianshuei	Missing data	05–17	Available
	Ayakkum	Missing data	18–20	Available
	Mugchu Tso	Missing data	05–14	Available
Eastern China Plain Lake Region	Tai	Missing data	16–20	Unavailable
	Chao, Poyang	Available	Complete	Unavailable
	Junshan	Missing data	05–15	Available
	Hulun	Available	Complete	Available
Xinjiang Lake Region	Bosten	Missing data	05–09	Unavailable
	Ulungar	Available	Complete	Available

Those with relatively complete DAHITI data and accurate extraction of lakeshore terrain are represented by 'complete' and 'available'. Lakes with partially missing DAHITI data or lakes whose shores cannot be accurately extracted by DEM-based methods are represented by 'missing data' and 'unavailable'. In addition, the period of missing DAHITI water level data for lakes is also indicated.

are applicability rates of only 50 and 40%, respectively. In contrast, the lack of long-term water level data across a period of 10 years for 10 lakes, such as Gongzhu Lake, greatly restricts the use of DAHITI data for estimating volumetric changes in these lakes.

In summary, these two methods, along with their limitations and advantages, are technical complements. Therefore, when assessing lake water volume changes over a large region and over a long time series, more suitable methods can be selected based on the different lake region types. For lakes in regions that lack water level data for a certain period, the DEM-based method can be prioritized to estimate water volume changes during this period. For lakes with a relatively flat lakeshore terrain in the region and the availability of altimeter observations, satellite altimetry-based methods can be used to estimate water volume changes.

6. CONCLUSIONS

This study used and compared two different methods, the satellite altimetry-based method with the DAHITI data and the DEM-based method with the SRTM DEM data, to estimate the water volume change results of 34 lakes in China. This study discussed the limitations and regional applicability of the two methods. The estimation results obtained using the two methods were highly consistent, with an R^2 of 0.93. However, both methods have advantages and limitations. The satellite altimetry-based method with the DAHITI data can only obtain lake water volume changes during the time period having altimetry data. In addition, for the eastern lakes, the huge daily change in lake water levels requires that the water level and lake range monitoring time points, i.e., the corresponding date, must be completely consistent. The DEM-based method with the SRTM DEM data can be used to estimate the water volume change of any closed lake in any region since 2000; but its accuracy is dependent on the lake shore topography. In our studied lakes in China, extracting accurate lake shorelines is challenging for lakes with slopes less than 1.5°. Because of the accuracy of lake shore extraction, the DEM-based method with the SRTM DEM is more suitable for estimating lake water volumes in the TP Lake Region (with an applicability rate of 100%); however, its applicability is lower in Xinjiang and Eastern China Plain Lake Region (with an applicability rate of 50 and 40%, respectively). Owing to the limited water level data for some lakes, the satellite altimetry-based method with the DAHITI data is more suitable for lakes with more complete water level data. A strategic selection of methods is recommended for analyzing lake water volume changes over extensive regions and timeframes. The DEM-based method is recommended for lakes with steeper shorelines and missing water level data. The satellite altimetry-based method with the DAHITI data is better suited for lakes with flatter shore terrain and comprehensive water level data. By combining these two methods, more complete and accurate estimates of lake water volume changes can be achieved.

This study provides valuable insights for researchers to effectively integrate these methods and obtain more complete and accurate estimates of lake water volume changes, especially when estimating changes over large spatial regions and long time series to understand the underlying patterns. Future researchers can further enhance the effectiveness of these methods by incorporating additional data. The new SWOT mission (launched at the end of 2022) promises to significantly advance lake monitoring capabilities. It is interesting and relevant to evaluate the actual performance of SWOT data for estimating lake water volume changes.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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