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ABSTRACT

Most lakes have undergone significant changes on the Tibetan Plateau in recent decades, affecting water resources on the Tibetan Plateau and its surrounding areas. In this paper, we investigated the variations of 25 lakes in five sub-regions on the Tibetan Plateau from 1972 to 2019 based on SRTM DEM data and Landsat imagery. We used a method to derive lake-levels based on DEM and lake boundaries delineated from Landsat imagery, and then calculated the changes in lake area, level, and volume in 1972 to 2019. We also analyzed the potential impacts of temperature, precipitation, glacial and permafrost melting in lake changes during this period. The results show that the lakes tended to shrink until 2010 in southern and western plateau, after which they began to expand gradually but the overall trend is still shrinking. Limited meltwater from glaciers and permafrost and low precipitation are the main reasons for their shrinkage. The lakes in the central plateau, northwest plateau and northeast plateau tend to expand overall. The reason for the expansion of the lakes is not only precipitation but also the melting of glaciers and permafrost. Overall, the lake changes have gone through 3 phases, namely a slight decrease during 1972–2000, a rapid increase during 2000–2010, and a slowdown in the last decade (2010–2019). Multiple factors such as temperature, precipitation, the state of glaciers and permafrost have contributed to the changes in the lake.

1. Introduction

The Tibetan Plateau is the highest plateau in the world and known as the "Asian Water Tower", "Roof of the World", and the "Third Pole"(Immerzeel, Van Beek, and Bierkens 2010; Molden et al. 2016; Qu et al. 2019). Its dynamic and thermal effects on the atmospheric circulation have a huge impact on the climate of East Asia and the world, and it is a sensitive indicator of global climate change. A large number of lakes are distributed on the Tibetan Plateau and most of them are saltwater lakes, especially on the inner of the plateau. The total area of lakes on the Tibetan Plateau exceeds 5×10^4 km^2 (Zhang et al. 2019). Water clarity changes in 64 large alpine lakes on the Tibetan Plateau and the potential responses to lake expansion. The formation and disappearance, expansion and shrinking of these lakes are affected by the combined effects of multiple climate and environmental factors due to the interaction among atmosphere, biosphere, lithosphere and hydrosphere (Nistor 2019). At the same time, the changes in lake area also have an impact on local climate and sub-surface conditions (Chen, Xiao, and Zhuochao 2016). Most lakes still maintain or are close to their natural status due to the remote and harsh environments of the Tibetan Plateau. Therefore, their changes are less affected by human activities and can reflect regional climate and

environmental changes. Investigating the pattern of lake changes is of great importance to improve our understanding of the impact of climate change on water resources on the Tibetan Plateau.

Most studies have focused on the lake-area change (Zhang et al. 2018; Liu, Yao, and Wang 2019; Zhao et al. 2020; Sun et al. 2014; Lei et al. 2013; Zhang et al. 2020a; Liao, Shen, and Li 2013; Wan et al. 2014) and lake-level change (Jiang et al. 2017; Zhang, Chen, and Xie 2019; Hwang et al. 2019; Crétaux et al. 2011; Song et al. 2015; Ma et al. 2019; Phan, Lindenbergh, and Menenti 2012a; Li et al. 2014) on the Tibetan Plateau, whereas few studies have investigated on the lake-volume changes (Song, Huang, and Ke 2013; Qiao, Zhu, and Yang 2019; Zhang et al. 2017; Yao et al. 2018; Qiao et al. 2021). The natural environment of the Tibetan Plateau is very complex and harsh, especially in some high-cold and high-altitude areas not suitable for personnel to work (J. Zhang et al. 2021). Therefore, it is difficult to ensure effective monitoring of lake changes in the Tibetan Plateau during field visits, which requires other technical means. Among them, remote sensing technology is one of the main technologies for studying lake changes in the Tibetan Plateau.

A lot of studies use optical remote sensing to study the area changes of lakes on the Tibetan Plateau.

Zhang et al. (2018) use Landsat imagery to study lake area changes and their relations to climate change on the Tibetan Plateau during the past 30 years. By remote sensing images, the lake area on the Tibetan Plateau was identified using an automatic waterbody interpretation method. The lake area changes from the 1980s to 2015 were analyzed (Liu, Yao, and Wang 2019). MODIS products are also widely used in the detection of water bodies due to their wide coverage and high temporal resolution. A trend test was conducted on lake area variations from 2000 to 2018 with the use of the annual mean temperature information derived from the Moderate Resolution Imaging Spectroradiometer land surface temperature daily product (Zhao et al. 2020). Sun et al. (2014) explored the water surface variations of 629 lakes in China using MODIS data from 2000–2010 and combined the automatically extracted training data and support vector machine classification to derive the spatial distribution of these lakes.

Since 1993, radar and laser data have been available to measure lake-level (Crétaux et al. 2011; Song et al. 2015). Zhang calculated changes in lake-level using ICESat data from 2003 to 2009 and ICESat-2 data from 2018, and evaluated lake-level from 2010 to 2017 using available data to finally obtain a continuous time series of lake-level and area from 2003–2018 (Zhang, Chen, and Xie 2019). Research (Hwang et al. 2019) used Cryosat-2, SARAL, ICESat, and Jason-2 altimeters data to detect changes in lake water levels at different temporal and spatial resolutions from 2003 to 2017. Some studies also combined GRACE with ICESat data to analyze the pattern of lake level changes from 2003–2009 (Wang, Shuang, and Sun 2016). Most of these radar and laser satellites have been launched in recent years and have a limited time horizon to be studied, and some of them do not provide full ground coverage (Prins and Adriaan 2021).

Compared to area and lake-level, the water storage volume of lakes can better reflect a regional water cycle mechanism and assess the water balance within a region. Only Qinghai Lake, Nam Co and Yangzhuoyong Co currently have long-term continuous water level observations on the Tibetan Plateau (Zhang, Junli, and Zheng 2017), which is very limited relative to the more than 1000 lakes on the Tibetan Plateau. Therefore, we need remote sensing data to analyze the volume change of lakes on the Tibetan Plateau.

In this paper, the variation of lake area, lake-level and lake volume from 1972 to 2019 for a total of 25 typical lakes (area greater than 10 km^2) in 5 regions on the Tibetan Plateau is researched based on SRTM DEM data and Landsat imageries. Landsat imagery are used to extract the lake extent and calculate the lake area. A mathematical morphology-based raster calculation method for lake-level was proposed. Lake volume was calculated based on lake extent and lake-level. The annual change rate and percentage change of lake area, lake-level and volume of 25 lakes from 1972 to 2019 were calculated. The causes of the changes are discussed in terms of temperature and precipitation distribution. The study will provide basic information for agriculture and hydropower construction in South and East Asia.

2. Study area and datasets

2.1. Study area

The Tibetan Plateau (between 26°–39°N latitude and 73°–104°E longitude) is about 2,800 km long from east to west and 1000 km wide from north to south. The total area is about 2.5 million km^2. With an average altitude of more than 4,000 m, the Tibetan Plateau has complicated topographical conditions, consisting of high mountains and glaciers, prairie and gorges, rivers and lakes. On the Tibetan Plateau stands the Himalayas in southwest, the Kunlun Mountains and the Kalakunlun Mountains spread the northwest, the Gangdisi, Tanggula and Nyainqentanglha Mountains traverse the middle, and the Hengduan Mountains is its east barrier. Amidst the mountains spread a range of hills, lakes and gorges, constituting undulation alpine prairie. The central and eastern parts occupy about 50% of the Tibetan Plateau, with the surface covered by alpine prairie and meadows; its northern and western areas are covered by alpine and temperate deserts, while in the southeast Tibetan Plateau, alpine boreal, evergreen, and deciduous forests are dominant (Xue, Ma, and Li 2017). There are intensive rivers and lakes in the Tibetan Plateau. The Tibetan Plateau has the most complicated and prominent terrain on the globe and is the birthplace of ten large rivers in Asia. Many of the lakes are salt water lakes. Permafrost, snow, and glaciers cover large areas on the plateau. It contains 36,800 glaciers, amounting to a total glacial area of 49,873 km^2 and a total glacial volume of 4,561 km^3. The frozen ground of the Tibetan Plateau is about 1,740,000 km^2(Yao et al. 2007). Because of its high altitude, the air on the Tibetan Plateau is dry and thin, with strong solar radiation and low temperatures. Due to the influence of topography and monsoon, the general trend of precipitation distribution over the Tibetan Plateau is decreasing from southeast to northwest. The average annual precipitation in the northwest is the lowest, less than 50 mm, while the average annual precipitation in the southeast is the highest, generally 600 to 800 mm (Wang, Pang, and Yang 2018).

We have selected 5 regions in this area, namely the southern plateau (region A), the western plateau (region B), the central plateau (region C), the

northwestern plateau (region D) and the northeastern plateau (region E). 5 typical lakes with an area of more than 10 square kilometers were selected in each region (Figure 1, Table 1).

2.2. Datasets

2.2.1. Landsat imagery

The Landsat satellite images provided by the United States Geological Survey are selected as the optical images. Landsat has conducted the longest continuous Earth satellite observation since 1972, providing satellite images of Landsat MSS (Multispectral Scanner System) (1972–1992), TM (Thematic Mapper) (1982-), ETM+ (Enhanced Thematic Mapper) (1999-) and Landsat- 8 OLI (Operational Land Imager) (2013-). Landsat MSS images have four spectral bands, the last two of which are sensitive to the water. TM/ETM +

images have seven and eight bands, respectively, and bands 4 and 5 are sensitive to the water (Frazier and Page 2000). The spatial resolution of MSS is 60 meters, and the resolution of TM, ETM+, OLI is 30 meters. Due to the large size of the lakes selected for study, the resolution of Landsat images is adequate for the study.

Studies have shown that although lakes on the Tibetan Plateau vary dramatically in area over the course of a year, they are relatively stable from September to December, with minor lake area variations of < 2% (Li et al. 2011). We therefore selected the data from September to December (October to November if available) for the lake area analysis. Due to the limited images before 2000, it is impossible to find the images that meet the requirements every year. Instead, we selected the images every 5 years. After 2000, images were selected every year. The quality of remote sensing
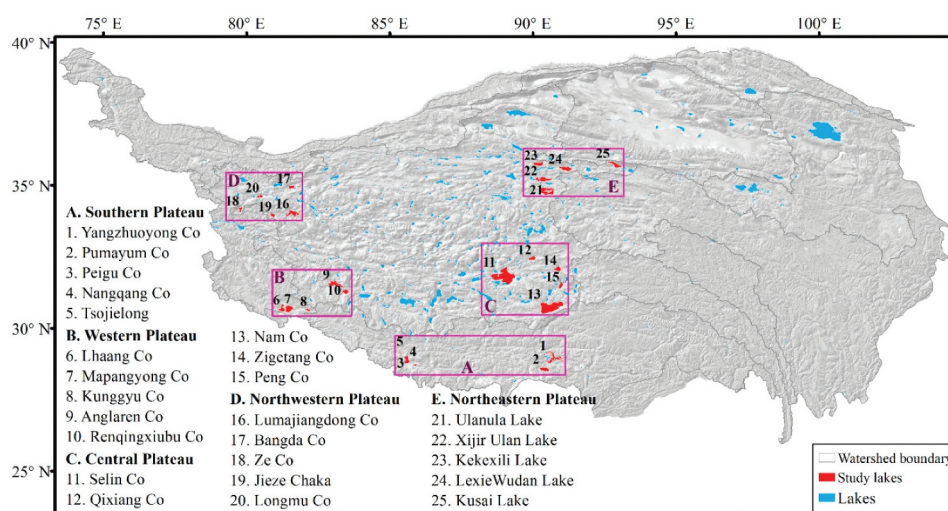

Figure 1. Map of the study area(Ma et al. 2011).

Table 1. Locations of the study lakes and the glacier and permafrost coverage in each lake's drainage basin.

Region	ID	Lake Name	Longitude (°)	Latitude (°)	Elevation (m)	Glacier coverage
A	1	Yangzhuoyong Co	90.710	28.956	4442	0.024
	2	Pumayum Co	90.395	28.567	5013	0.024
	3	Peigu Co	85.585	28.892	4627	0.057
	4	Nangqang Co	85.877	28.723	4646	0.000
	5	Tsojielong	85.399	29.122	4618	0.000
B	6	Lhaang Co	81.233	30.689	4570	0.025
	7	Mapangyong Co	81.471	30.684	4585	0.025
	8	Kunggyu Co	82.133	30.638	4784	0.008
	9	Anglaren Co	83.080	31.542	4761	0.024
	10	Renqingxiubu Co	83.448	31.278	4760	0.073
C	11	Selin Co	88.992	31.813	4539	0.008
	12	Qixiang Co	89.978	32.449	4615	0.000
	13	Nam Co	90.604	30.738	4724	0.033
	14	Zigetang Co	90.865	32.077	4568	0.000
	15	Peng Co	90.968	31.504	4529	0.000
D	16	Lumajiangdong Co	81.612	34.020	4812	0.034
	17	Bangda Co	81.557	34.944	4904	0.038
	18	Ze Co	79.779	34.159	4961	0.105
	19	Jieze Chaka	80.903	33.954	4525	0.061
	20	Longmu Co	80.457	34.614	5004	0.025
E	21	Ulanula Lake	90.478	34.801	4855	0.006
	22	Xijir Ulan Lake	90.339	35.214	4772	0.013
	23	Kekexili Lake	90.194	35.752	4870	0.025
	24	LexieWudan Lake	91.139	35.588	4886	0.034
	25	Kusai Lake	92.872	35.726	4475	0.025

images selected for each period is intact, and there is basically no or <10% cloud cover.

2.2.2. SRTM DEM

We use SRTM elevation data to calculate the lake-level and lake volume. SRTM was launched in February 2000 and obtained the digital elevation covering the earth's surface between N 60° and S 57°. Elevation data products with 30 m resolution are provided free of charge. The elevation datum of SRTM DEM data is EGM96 and the plane datum is WGS84 (Carabajal and Harding 2005). The horizontal and vertical accuracy of SRTM data are <20 m and 16 m, respectively (Farr et al. 2007). The SRTM elevation data used in this paper is the version 4.1 data provided by the Consultative Group of International Agricultural Research (CGIAR).

In this paper, SRTM DEM data were chosen to calculate the lake surface elevation. Although SRTM data is only available for 2000 and only reflects the terrain as of 2000. It is feasible to use it to calculate the lake surface elevation of lakes from 1972 to 2019, considering that the topography of the Earth is essentially unchanged over the decades.

2.2.3. ICESat altimeter data

To verify the accuracy of SRTM elevation data, ICESat altimeter data (Zwally et al. 2014) was used. The ICESat satellite was launched by NASA in January 2003. The orbital altitude of the satellite is 600 km and the orbital inclination is 94°. The GLAS on board the ICESat satellite has a footprint of about 65 m and a footprint spacing of about 172 m on the ground (Schutz et al. 2005). The distance between ICESat tracks on the Tibetan Plateau is about 70 km (Phan, Lindenbergh, and Menenti 2012b). The ICESat elevation data is based on the TOPEX/POSEIDON ellipsoid, which is about 70 cm away from the WGS84 ellipsoid (Bhang, Schwartz, and Braun 2006). The working period of ICESat is from February 2003 to October 2009. This article uses the Level-2 altimetry products created by the combination of GLAH06 and GLAH05, the version is 34. Of the 25 lakes studied, 19 lakes have ICESat data.

The ICESat altimeter data is highly accurate, but it only operated from 2003 to 2009. ICESat-2 satellite was launched in 2018, so it is not possible to research the problem of changes over a large time range. In addition, there are spaces between the tracks of the ICESat satellites, which do not allow for full surface coverage, so that changes in lakes in all regions cannot be explored. Therefore, this paper does not use ICESat data to calculate lake-level, but instead uses it as a measure of the accuracy of the SRTM data.

2.2.4. Meteorology data

We collected meteorological data from 93 ground observation stations inside and outside the Qinghai-Tibet Plateau from 1972 to 2019, including annual average temperature and annual precipitation. Meteorological data is provided by National Oceanic and Atmospheric Administration, USA and China Meteorological Data Center.

3. Methods

This paper uses SRTM and Landsat data to calculate the area, lake-level, and volume of 25 typical lakes within 5 regions on the Tibetan Plateau over the period 1972 to 2019, and counts their change rates and percentage change during 1972–2000, 2000–2010, 2010–2019, and 1972–2019. The effects of precipitation, temperature, glacier and permafrost distribution on lake variations are discussed.

The process of calculation of lake area, lake-level and volume is shown in Figure 2. Firstly, lake boundaries from 1972 to 2019 were extracted using Landsat imagery. Then lake surface elevations were calculated by raster calculation based on SRTM DEM and lake boundaries. Finally, the volume of the lake was calculated from the lake surface elevation and lake-extent DEM data. To verify the accuracy of the lake-level from SRTM data, the lake surface elevations of the lakes were calculated using ICESat data from 2003 to 2009, and the accuracy of the lake-level was evaluated for the corresponding years.

3.1 Lake-extent delineation

Most of the downloaded remote sensing images have been radiometrically and atmospherically corrected. We geometrically corrected images with geometric distortion. Due to a malfunction of the Landsat 7 satellite, some of the images have missing bands. We used masks to repair the missing bands by interpolation. Due to the selection of spectral bands that are sensitive to the water, there is a clear reflection difference between the water and land in the image. Lake boundaries were automatically extracted using the natural breakpoint reclassification method in ArcGIS, and then the results of the automatic extraction were checked by visual interpretation. Manually edit and repair erroneous lake boundaries to obtain binary images of lakes (Li et al. 2014). Count the number of pixels in the lake area and calculate the surface area of each lake based on the resolution of the image.

3.2 Lake-level extraction

The lake surface is considered to be a horizontal surface, then the lake surface elevation is the elevation of the lake boundary. Extract the pixels of the lake boundary, remove the anomalies and calculate their average value is the lake surface elevation. Erosion calculation of a lake binary map using 3×3 structural elements, and the original binary image is superimposed and extracted to obtain a lake boundary of
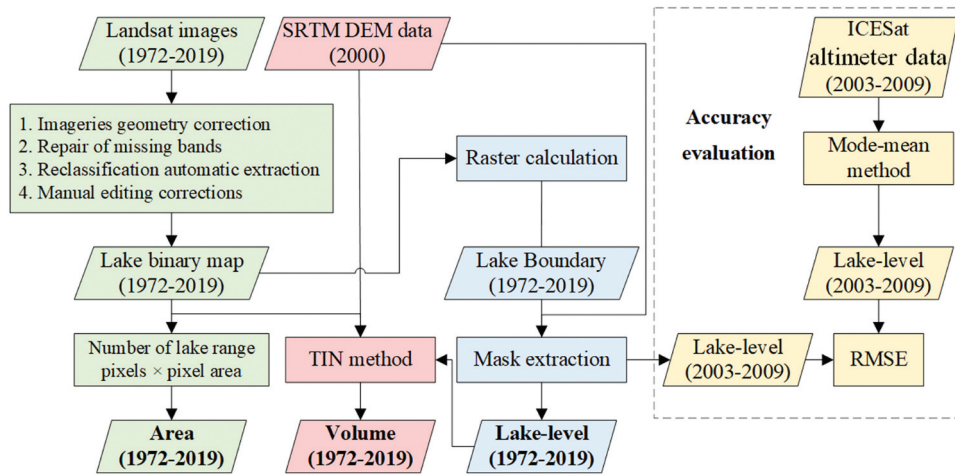
Figure 2. Flow chart for calculation of lake area, lake-level and volume.

1-pixel width. The SRTM data was mask extracted by the lake boundary to obtain the DEM of the lake boundary (Figure 3).

The boundary of a lake has n pixels, each of which has an elevation value of E_i. There are k_j pixels whose elevation values are all E_j, then $\sum^{k_j} = n$. The frequency with which the elevation value E_j appears in E_i is k_j/n. Arrange k_j/n from largest to smallest and add until it is greater than or equal to 95%. The elevation values of these pixels whose frequency of occurrence accounts for the top 95% are E_J, and there are k_J pixels that have all the elevation values E_J, $\sum^{k_J} \geq n \times 95\%$.

Only these pixels are retained for the next calculation. The remaining pixels with low frequency of occurrence may have anomalous elevation values affected by DEM accuracy or lake-level extraction accuracy. These data were removed as anomalies in order not to affect the accuracy of the lake-level extraction. The mean elevation value of the remaining pixels is calculated as lake elevation E, it can be expressed as.

$$E = \frac{\sum^{E_J} \times k_J}{\sum^{k_J}} \qquad (1)$$

After extracting the lake-level for different periods, trend and regression analyses were performed to determine the overall trend in lake surface elevation change, i.e. the annual lake-level change rate (m/a).

3.3. Accuracy evaluation of lake elevation

We used ICESat/GLAS altimeter data to evaluate the accuracy of the lake elevations calculated from the SRTM data. The GLAS points within each lake were extracted, and then the lake elevation was extracted by the mode-mean method (Li et al. 2014). The lake elevation obtained from ICESat data is then evaluated for accuracy against the lake elevation obtained from SRTM.

First calculating the elevation difference E_d between ICESat and SRTM lake elevation data for the same lakes in the same years.

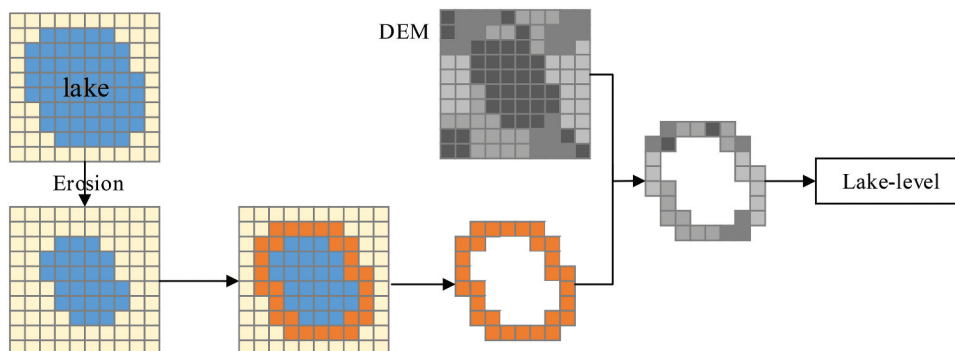$$E_d = E_{SRTM} - E_{ICESat} \qquad (2)$$

Figure 3. Flow chart for calculation of lake-level.

In the formula, E_{SRTM} is the lake-level calculated from SRTM data and E_{ICESat} is the lake-level extracted from ICESat data.

The Root Mean Square Error (RMSE) of the lake elevation is calculated as the accuracy criterion for the lake elevation.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(E_{SRTM} - E_{ICESat}\right)^2}{n}} \qquad (3)$$

In the formula, n is the total number of data.

The calculations revealed that the elevation derived using SRTM DEM is slightly higher. The RMSE of the lakes surface elevation in region A is 3.72, region B is 3.62, region C is 3.76, region is 2.28 and region E is 2.96. It can be seen that the RMSE is less than 4 m in all the regions. The RMSE of all lakes surface elevation is 3.48 m, which is far better than the so-called 5 m vertical accuracy of the SRTM. Although the SRTM DEM data can only reflect the topography in 2000, the SRTM DEM data are used to calculate the variations of lakes level elevation and lakes volume. 3.48 m RMSE is sufficient for this purpose.

3.4. Water storage change evaluation

Because most of the lake levels on the Tibetan Plateau have been on an increasing trend since 2000, the topography around any lake since 2000 can be obtained from the SRTM DEM data. Therefore, the relationship between lake volume variation and lake area and lake level variation after 2000 can be established (Song, Huang, and Ke 2013; Yang et al. 2017). Then we can estimate the lake volume variation before 2000. Qiao et al. (2021), (2019)) also proved the reliability of the estimation of lake volume variation by using SRTM data. Once lake extent S_1, S_2 and the lake level variation Δh between two years are obtained, the lake volume variation ΔV of each lake between two years can be evaluated.

$$\Delta V = \frac{1}{3} \times \left(S_1 + S_2 + \sqrt{S_1 + S_2}\right) \times \Delta h \qquad (4)$$

After calculating the volume variation of each lake, trend analysis and regression analysis are performed to determine the overall trend of the lake volume change, which is the annual lake volume change rate (km^3/a).

4. Results

4.1. Lake-level, area and volume change

We studied the changes in area, lake-level, and volume of 25 lakes from 1972 to 2019. We derived the annual change rates in lake area, lake-level, and volume for each lake during the periods of 1972 to 2000, 2000 to 2010, 2010 to 2019, and 1972 to 2019 (Table 2).

Figure 4 shows the map of lake-level change rate for each lake during different time periods. As shown in Table 2 and Figure 4, lake-level tended to decrease from 1972 to 2000 for 15 lakes, with 5 lakes on the

Table 2. The annual change rates of lake area, lake-level, and volume of 25 lakes during 1972–2000, 2000–2010, 2010–2019 and 1972–2019.

| Region	ID	Lake Name	Lake-level Change rate (m/a)				Area Change rate (km²/a)				Volume Change rate (km³/a)			
			1972–2000	2000–2010	2010–2019	1972–2019	1972–2000	2000–2010	2010–2019	1972–2019	1972–2000	2000–2010	2010–2019	1972–2019
A	01	Yangzhuoyong Co	−0.130	−0.343	−4.000E-04	−0.174	−1.360	−3.808	−0.403	−1.922	−0.082	−0.209	−0.001	−0.106
	02	Pumayum Co	0.014	0.267	−0.044	0.104	0.109	0.058	−0.015	0.181	0.004	0.075	−0.013	0.030
	03	Peigu Co	−0.063	−0.133	0.040	−0.064	−0.151	−0.601	0.035	−0.225	−0.018	−0.038	0.011	−0.018
	04	Nangqang Co	−0.012	−0.041	0.013	−0.018	−0.018	−0.180	0.087	−0.054	−2.77E-04	−0.001	3.341E-04	−4.56E-04
	05	Tsojielong	0.116	−0.185	0.124	0.004	0.298	−0.344	0.162	−0.004	0.002	−0.003	0.002	5.12E-05
B	06	Lhaang Co	−0.133	−0.169	−0.031	−0.108	−0.565	−0.829	−0.457	−0.585	−0.036	−0.045	0.005	−0.029
	07	Mapangyong Co	0.057	−0.233	0.196	−0.015	−0.051	−0.246	0.364	0.025	0.023	−0.096	0.082	−0.006
	08	Kunggyu Co	−0.093	−0.112	0.075	−0.031	−0.432	−0.438	0.409	−0.080	−0.006	−0.006	0.004	−0.002
	09	Anglaren Co	−0.106	0.126	0.105	−0.027	−0.241	0.939	0.507	0.042	−0.051	0.065	0.049	−0.013
	10	Renqingxiubu Co	−0.018	0.043	0.153	0.039	0.055	0.146	0.295	0.149	−0.003	0.007	0.029	0.007
C	11	Selin Co	0.033	0.681	0.135	0.283	6.391	49.943	5.427	19.966	0.063	1.577	0.322	0.618
	12	Qixiang Co	−0.064	0.498	0.056	0.155	−0.381	2.761	0.330	0.893	−0.010	0.086	0.010	0.027
	13	Nam Co	0.052	0.379	−0.027	0.141	2.377	5.442	−0.901	2.913	0.101	0.758	−0.054	0.280
	14	Zigetang Co	0.084	0.411	0.123	0.203	0.684	2.712	0.479	1.236	0.018	0.094	0.030	0.046
	15	Peng Co	0.073	0.745	−0.086	0.237	0.582	2.884	−0.367	1.097	0.011	0.125	−0.015	0.039
D	16	Lumajiangdong Co	−0.003	0.420	0.360	0.188	−0.001	2.279	2.426	1.193	−0.001	0.156	0.142	0.071
	17	Bangda Co	−0.014	0.752	0.593	0.331	0.038	2.396	2.434	1.172	−0.001	0.091	0.085	0.042
	18	Ze Co	0.062	0.165	0.129	0.120	0.181	0.391	0.275	0.270	0.007	0.020	0.016	0.014
	19	Jieze Chaka	0.077	0.243	0.200	0.161	0.075	0.548	0.351	0.274	0.008	0.028	0.023	0.018
	20	Longmu Co	0.089	0.245	0.264	0.157	0.109	0.476	0.367	0.257	0.009	0.026	0.028	0.016
E	21	Ulanula Lake	−0.056	0.342	0.241	0.276	−1.416	8.502	5.130	6.772	−0.029	0.190	0.154	0.162
	22	Xijir Ulan Lake	−0.006	0.309	0.324	0.269	−0.275	8.102	7.166	6.585	−0.002	0.122	0.156	0.116
	23	Kekexili Lake	−0.049	0.238	0.391	0.122	−0.385	1.980	4.373	1.075	−0.015	0.075	0.137	0.040
	24	LexieWudan Lake	−0.065	0.485	0.486	0.188	0.592	4.099	2.490	1.350	−0.015	0.119	0.135	0.049
	25	Kusai Lake	−0.042	0.382	0.476	0.490	−0.103	1.873	3.419	3.068	−0.011	0.103	0.149	0.144
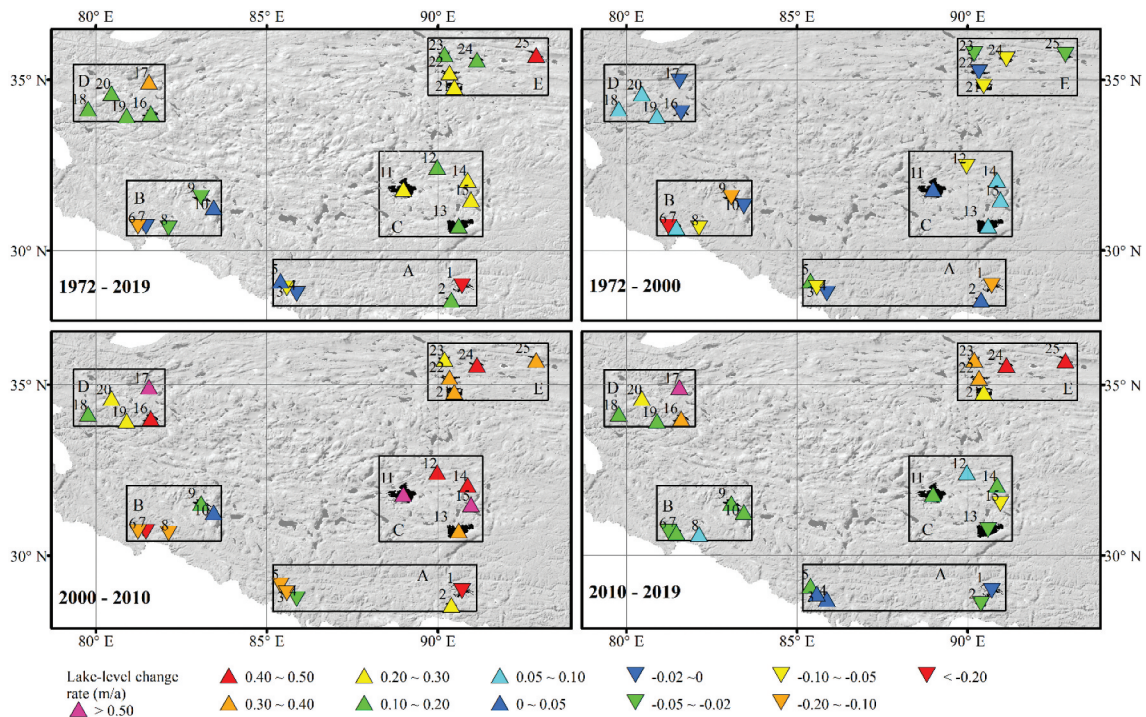
Figure 4. Spatial distribution of annual lake-level change rate of 25 lakes during the periods of 1972–2000, 2000–2010, 2010–2019 and 1972–2019.

northeastern plateau showing decreasing lake-level elevations. The largest annual decrease rate in lake-level was in Lhaang Co, at −0.133 m/a. The remaining 10 lakes showed a small increase in lake surface elevation, mostly on the central plateau and the northwestern plateau. The largest annual lake-level increase rate is Tsojielong with 0.116 m/a. The smallest change among all lakes was Lumajiangdong Co, with a decrease rate in lake-level of 0.003 m per year. On the whole, the lake-level of most of the lakes decreased and a few increased during these two decades, and the general change was relatively stable. From 2000 to 2010, only 7 lake-levels tended to decrease, all of them were located in the southern plateau and the western plateau. Yangzhuoyong Co had the largest decrease, with a lake-level decrease of 0.343 m/a. Most lakes tend to increase in surface elevation and have a significant growth rate. The lake-levels of the lakes in the central plateau, the northwestern plateau, and the northeastern plateau all tended to increase. Three lakes had annual lake-level change rate greater than 0.5 m/a. Bangda Co has the largest increase rate of 0.752 m/a. From 2010 to 2019, the number of lakes with a tendency to decrease in lake-level continued to decrease, with only 5 lakes from the southern, western, and the central plateau. Their declines were relatively small (<0.05 m/a), except for Peng Co with a higher decreasing rate of −0.086 m/a. The remaining 20 lakes all showed expansion trends in lake surface elevation. The lakes within the southern plateau all had relatively small changes, with Yangzhuoyong Co having the smallest

annual lake-level change among the 25 lakes, at −0.0004 m/a. The lakes on the southern plateau all had small changes, with the annual lake-level change in Yangzhuoyong Co having the smallest annual lake-level change among the 25 lakes.

Overall, from 1972 to 2019, more lakes tended to increase in lake-level than tended to decrease. The lake-levels of all lakes within the central plateau, the northwestern plateau, and the northeastern plateau were trending upward. Three lakes in the southern and western plateau increased slightly, while the remaining lakes tended to decrease in surface elevation. Yangzhuoyong Co decreased the most, with a decrease in lake-level of 0.174 m per year, and the largest annual change in lake-level was Kusai Lake, with 0.490 m/a.

Figure 5 is a map of the annual lake surface area change rate of 25 lakes during different periods. As can be seen in Table 2 and Figure 5, the number of lakes that tended to decrease in area and those that tended to increase were approximately equal during 1972 to 2000, with a distribution for each region. The annual area change rate of most lakes is not significant, with Ulanula Lake shrinking the fastest, by 1.416 km^2 per year, and Selin Co expanding the fastest, by 6.391 km^2 per year. From 2000 to 2010, the change in area was similar to that of the lake-level. Yangzhuoyong Co was the fastest shrinking lake, decreasing 3.808 km^2 per year. The difference is that Selin Co's area expanded dramatically during the decade, expanding by 49.943 km^2 per year. From 2010 to 2019, the change in area remains roughly the same as at lake-level. Nam Co, which had previously been
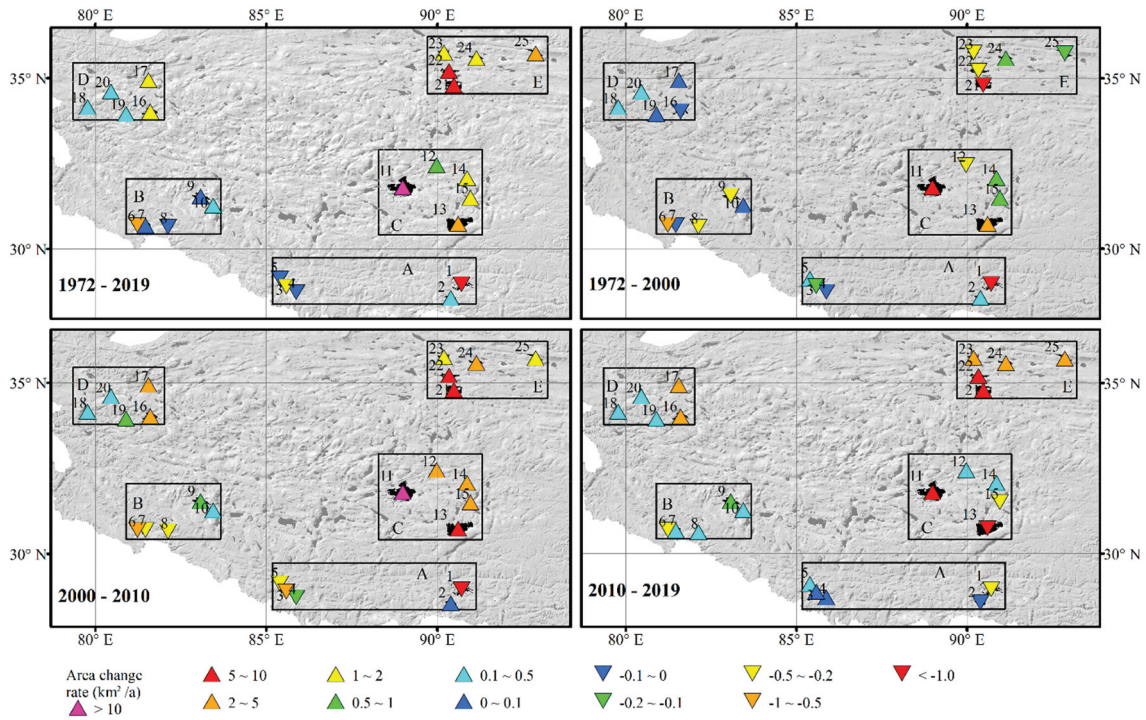
Figure 5. Spatial distribution of annual lake surface area change rate of 25 lakes during the periods of 1972–2000, 2000–2010, 2010–2019 and 1972–2019.

expanding, began to shrink at the fastest rate of 0.901 km² per year, while Xijir Ulan Lake experienced the fastest expansion at 7.166 km² per year.

Over the four decades from 1972 to 2019, most of the lakes tended to expand in area, especially on the central plateau, the northwestern plateau and the northeastern plateau. The same as the lake-level change, the largest decrease in area is Yangzhuoyong Co, which the annual area decrease rate is 1.922 km²/a. The largest increase is Selin Co, which the annual area change is 19.966 km²/a. It can be seen from the research (Li et al. 2014) and Figure 6 that the boundary line of Selin Co changes very significantly.

Figure 7 shows the annual volume change rate classification for each lake over different time periods. From Table 2 and Figure 7, it can be seen that the change in volume from 1972 to 2000 is almost the same as the lake-level. The lakes that tended to decrease in area were distributed in every region, and the volume of the lakes within the northeastern plateau all tended to decrease. The volume of Yangzhuoyong Co decreased fastest, at 0.082 km³ per year. The lakes that tended to increase in volume were mainly located in the central plateau, while Nam Co had the fastest increase in volume with an increase of 0.101 km³ per year. From 2000 to 2010, the change in volume was similar to the change in area and lake-level, while Yangzhuoyong Co continued to have the fastest volume decrease, decreasing by 0.209 km³ per year. As with the area change, Selin Co is increasing dramatically in volume, gaining 1.577 km³ per year. From 2010 to 2019, only four lakes tended to decrease in volume, located in the southern plateau and the central plateau. Nam Co changed from the
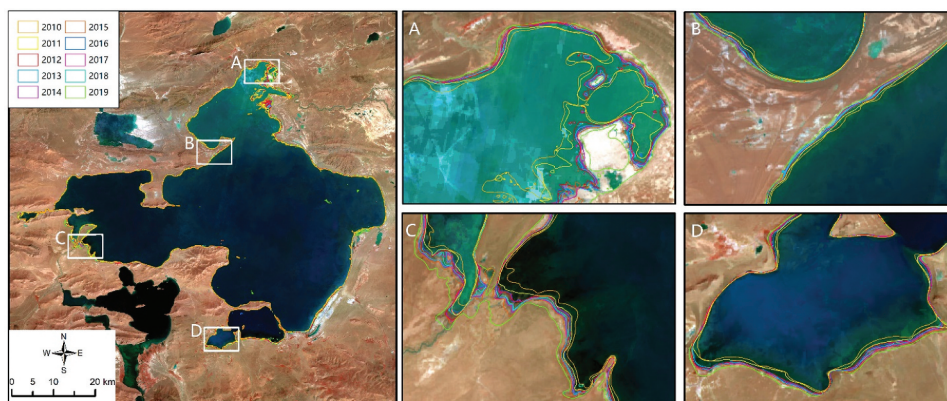

Figure 6. Lake boundary variations of Selin Co from 2010 to 2019.
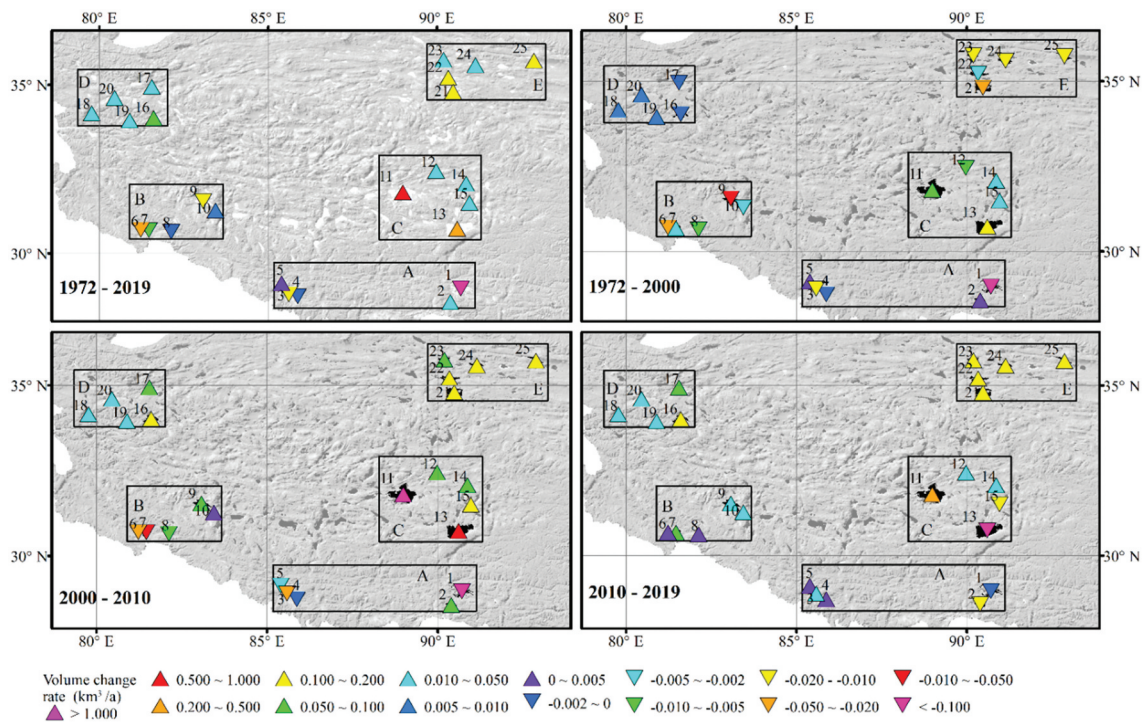
Figure 7. Spatial distribution of annual lake volume change rate of 25 lakes during the periods of 1972–2000, 2000–2010, 2010–2019 and 1972–2019.

fastest growing to the fastest shrinking lake in terms of volume, decreasing in volume by 0.054 km³ per year. The remaining 21 lakes all tended to increase in volume, with Selin Co still increasing the fastest, but significantly less than in the previous decade, with an increase of 0.322 km³ per year.

Overall, the majority of lakes tended to increase in volume from 1972 to 2019, with lakes in the central plateau, the northwestern plateau and the northeastern plateau all trending toward increasing volume. The lakes that tended to decrease in volume were concentrated in the southern plateau, the western plateau, and similar to the change in area, the fastest decreasing and increasing lakes were Yangzhuoyong Co and Selin Co.

Lakes in the same area do not have the same trend of change, and two lakes in close proximity may also have opposite trends, such as Yangzhuoyong Co and Pumayum Co, Peigu Co and Tsojielong.

Table 3 shows the percentage increase in lake-level, area and volume of the lakes over time for each region. Region A and region B showed

smaller change rates. The lake-level, area and volume of the lakes in both regions showed a decreasing trend during 1972 to 2000 and 2000 to 2010, with the exception of the area of the lakes in region B, which edge up by 0.002% from 2000 to 2010. Especially the volume of the lake, the lakes in region A shrank by 33.20% in and 25.41% in region B during the period 1972 to 2000. The shrinking trend slowed from 2000 to 2010, with a 29.59% reduction in region A and a 4.98% reduction in region B. The changes in region C and region D were similar, with lake area, lake-level, and volume all tending to increase since 1972. Lakes in region C had the smallest percentage growth in the last decade. Unlike area and lake-level, volume increased by the largest percentage from 1972 to 2000, lake volume more than tripled, at 277.36%, and by a slightly smaller percentage from 2000 to 2010, 235.31%, which also more than tripled. The area, lake-level, and volume of the lakes in region D increased to the same extent, with a small increase from 1972 to

Table 3. Lake area, lake-level and volume percentage increase in each region.

Region	Lake-level percentage increase				Area percentage increase				Volume percentage increase			
	1972–2000	2000–2010	2010–2019	1972–2019	1972–2000	2000–2010	2010–2019	1972–2019	1972–2000	2000–2010	2010–2019	1972–2019
A	−0.002%	−0.016%	0.013%	−0.003%	−3.16%	−3.95%	0.50%	−6.20%	−33.20%	−29.59%	2.37%	**−49.00%**
B	−0.039%	−0.010%	0.030%	−0.017%	−2.75%	0.002%	1.65%	−0.76%	−25.41%	−4.98%	34.68%	−5.97%
C	0.023%	0.105%	0.020%	0.167%	6.44%	12.32%	1.75%	24.80%	277.36%	235.31%	15.30%	**1894.95%**
D	0.020%	0.064%	0.056%	0.164%	1.45%	7.05%	6.25%	17.56%	20.43%	67.39%	40.80%	274.24%
E	−0.021%	0.066%	0.090%	0.154%	−4.19%	14.28%	13.69%	27.63%	−30.65%	142.88%	75.85%	243.74%
Sum	−0.004%	0.042%	0.042%	0.093%	1.38%	8.35%	4.17%	16.66%	−1.26%	98.41%	29.70%	205.39%

2000, a sharp expansion of the lakes beginning during 2000 to 2010, and a slowdown in the growth of the lakes in the last decade. As already mentioned, this was largely the result of the dramatic increase in area and volume of Selin Co during this period. Region E, which shrank slightly from 1972 to 2000 but began to expand after 2000, and had the largest percentage increase in area of the five regions, 14.28% from 2000 to 2010 and 13.69% from 2010 to 2019.

From 1972 to 2019, the lake-level, area and volume of lakes in regions A and B shrank, with all other regions tending to increase. Lakes in region B had the largest percentage reduction in lake-level, by 0.017%, and lakes in region A had the largest percentage reduction in both area and volume, shrinking by 6.20% in area and 49% in volume. Lakes in region E had the largest percentage expansion in area, at 27.63%. The percentage of lake-level increase in lakes within region C, D, and E was about the same at 0.16%, with the largest in region C at 0.167%. Lakes in regions D and E both more than tripled in volume, while lakes in region C had a huge increase in volume, increasing nearly 19 times.

Total lake-level and volume decreased slightly for the 25 lakes from 1972 to 2000, with a slight increase in area. The percentage increase in lake-level was the same for 2000 to 2010 and 2010 to 2019, and the percentage increase in area and volume was higher for 2000 to 2010 than 2010 to 2019. Total lake-level, area, and volume increased during 1972 to 2019, with 25 lakes tripling in total volume. Overall, during 1972 to 2019, the lakes can be divided into three phases of change, with lakes shrinking slightly before 2000, expanding dramatically between 2000 and 2010, and slowing down in the last decade.

4.2. Related climate variables change

From the reference (Zhang et al. 2013), it is known that temperature and precipitation are the important factors influencing changes in lakes on the Tibetan Plateau. Precipitation can directly supply lake water volume, and temperature affects the state of glaciers, permafrost, etc., as well as evaporation. To obtain the changes in temperature and precipitation in the study area, we used meteorological data for analysis and calculation. Since temperature and precipitation are greatly influenced by altitude, there is a relationship between temperature and altitude, with a decrease of 6°C for every 1 km increase in altitude. Since the study lakes are mainly located at an altitude of 4,500 m, the temperature at 4,500 m was first calculated based on the altitude of the station. However, for precipitation, there is no exact correspondence, and we can only calculate directly based on site precipitation. Then the annual average temperature and annual precipitation of the 93 ground observation stations were Kriging interpolated respectively, and the annual temperature and precipitation distribution maps of the Tibetan Plateau were obtained by mask extraction, as shown in Figures 8 and 9. Combining the reference (Li et al. 2014) and Figures 8 and 9, it can be seen that the overall annual average temperature and precipitation on the Tibetan Plateau showed an increasing trend from 1972 to 2019.

Based on the coordinates of the center point of each lake, we extracted the annual average temperature and annual precipitation of the lake from 1972 to 2019,
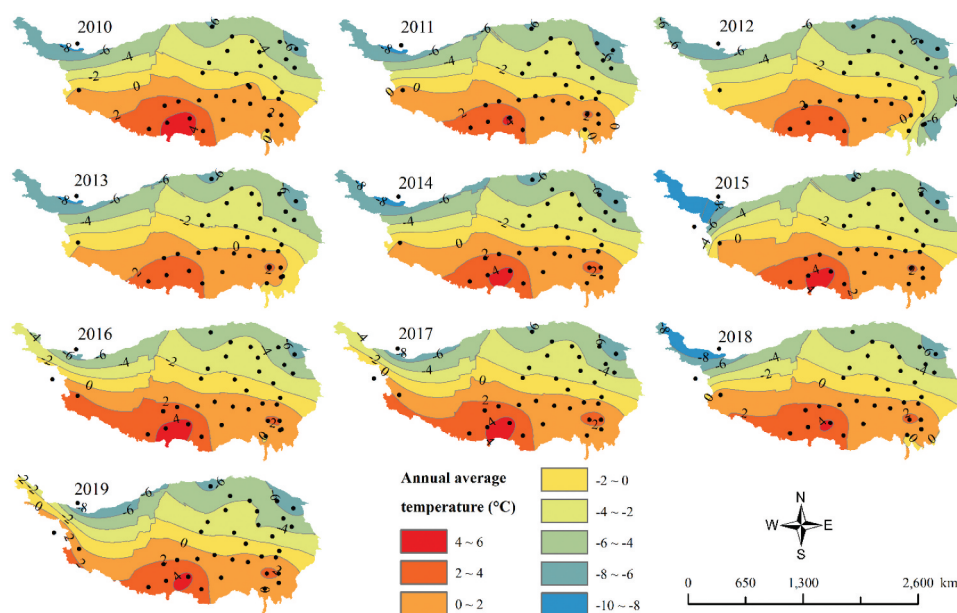

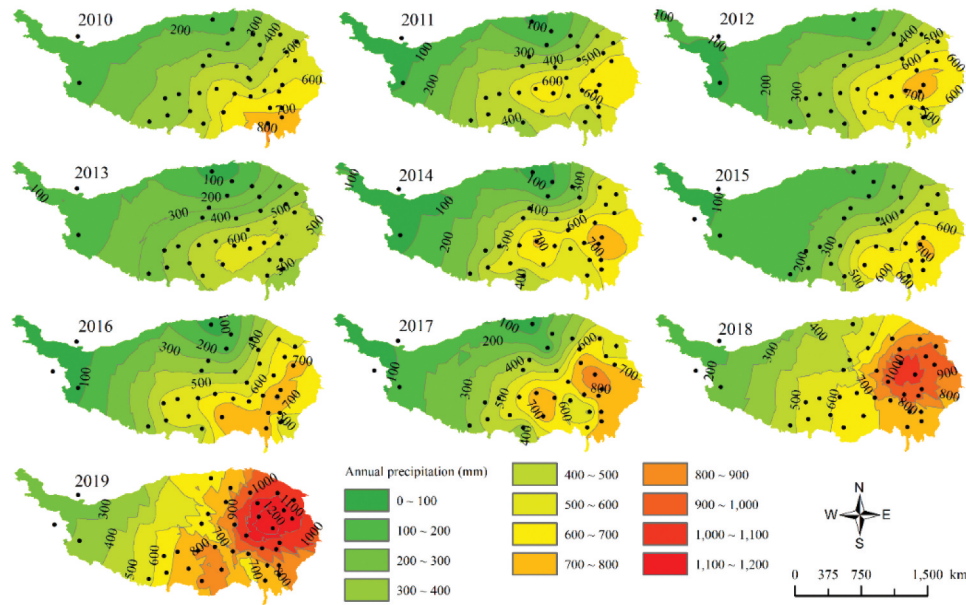**Figure 8.** Spatial variations of annual average temperature from 2010 to 2019 across the Tibetan Plateau.

Figure 9. Spatial variations of annual precipitation from 2010 to 2019 across the Tibetan Plateau.
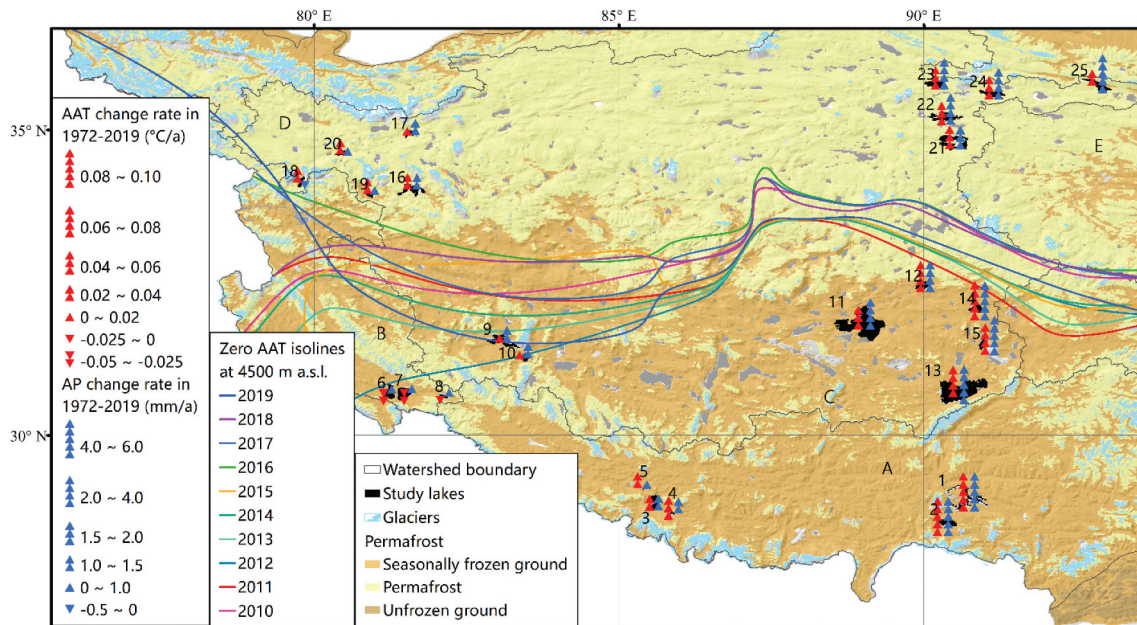

Figure 10. Annual rate of change in Annual Average Temperature (AAT) and Annual Precipitation (AP) of 25 lakes during 1972 to 2019.

and then analyzed the annual change rate of annual average temperature and annual precipitation for each lake by regression analysis, as shown in Figure 10. Also continuing from reference (Li et al. 2014), we generated the 0°C annual average temperature isolines at 4,500 m a.s.l. Figure 10 also shows the spatial distribution of glaciers and permafrost and seasonal frozen ground.

From Figure 10, it can be seen that except for Ze Co, the precipitation of the other 24 lakes has tended to increase from 1972 to 2019, but not all of them have tended to increase in terms of volume of the lakes. 8 of the 25 study lakes had opposite trends in precipitation

and volume changes. Lhaang Co, Mapangyong Co and Kunggyu Co tended to decrease in temperature, while the other lakes tended to increase in temperature.

We also calculated the annual average temperature and annual precipitation for each region, and regression trend analysis yielded the annual rates of change in annual average temperature and annual precipitation for each period in the 5 regions (Table 4). The mean annual average temperature and annual precipitation were also calculated for each period (Figure 11).

The Tibetan Plateau has decreasing temperatures from south to north at 4,500 m a.s.l., influenced by

Table 4. Annual change rates of AAT and AP in the 5 regions during the period of 1972–2000, 2000–2010, 2010–2019 and 1972–2019.

Region	Annual AAT change rate (°C/a)				Annual AP change rate (mm/a)			
	1972–2000	2000–2010	2010–2019	1972–2019	1972–2000	2000–2010	2010–2019	1972–2019
A	0.058	0.212	0.032	0.059	7.888	**−8.015**	9.962	3.291
B	−0.259	0.762	0.083	−0.008	0.562	12.993	0.452	1.066
C	0.006	0.326	0.039	0.065	0.707	1.046	**21.121**	3.519
D	−0.136	0.476	0.139	0.036	−0.012	8.710	3.527	0.580
E	−0.142	0.565	0.013	0.043	−1.568	8.928	20.151	3.528
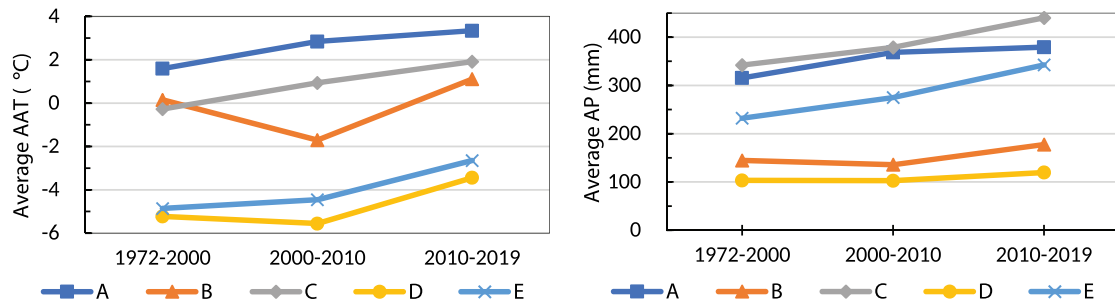
Figure 11. The mean AAT and AP during the period of 1972–2000, 2000–2010 and 2010–2019.

latitude. The annual average temperatures in the southern plateau are greater than 0°C, in the western plateau and the central plateau around 0°C, in the northwestern plateau and the northeastern plateau below 0°C. On the whole, the average annual temperature of the southern plateau is greater than that of the western and central plateau, and greater than that of the northwestern and northeastern plateau. Precipitation on the Tibetan Plateau decreases from southeast to northwest. The annual precipitation is 300 to 450 mm in the central plateau, 300 to 400 mm in the southern plateau, 200 to 300 mm in the northeastern plateau, 100 to 200 mm in the western plateau and the northwestern plateau.

From 1972 to 2000, both temperature and precipitation tended to decrease in the northwestern plateau and the northeastern plateau, decrease in the western plateau, and increase in the other regions. From 2000 to 2010, the southern plateau tended to decrease in precipitation. Precipitation in the western plateau, the central plateau, the northwestern plateau and the northeastern plateau increased during this period. Temperature and precipitation trends were increasing in all 5 regions from 2010 to 2019, with the central plateau and the northeastern plateau experiencing substantial increases in precipitation. From 1972 to 2019, temperature and precipitation tended to increase in all regions except for a small decrease in the annual average temperature in the western plateau.

5. Discussion

5.1. Influence of climatic factors

The climate of the Tibetan Plateau is influenced by the atmospheric circulation system of the Indian summer monsoon and the mid-latitude westerlies. Glaciers and snow in the region can melt into water under warmer conditions (Huss and Hock 2018; Shea and Immerzeel 2016). Precipitation is the dominant factor controlling historical lake volume, particularly during the wet season (June to September)(Kraaijenbrink et al. 2017). Many studies (Kraaijenbrink et al. 2017; Wang et al. 2017; Yao et al. 2012) have examined the importance of precipitation changes, and temperature changes on the different responses of water volume changes in the past decades.

From 1972 to 2000, lakes volume and regional precipitation variation were inconsistent in the southern, western and northwestern plateaus. From 2000 to 2010, the trends in precipitation and volume within the western plateau were reversed, while the other regions have consistent trends during this period. The volume of lakes in all 5 regions likewise tended to increase from 2010 to 2019. From 1972 to 2019, temperature tended to increase except for the western plateau. Rising temperatures could melt glaciers, which could cause lakes connected with glaciers to expand. But some of the lakes connected with glaciers shrank during this period, such as Yangzhuoyong Co, Peigu Co in the southern plateau. Taken together, while climate change plays an important role in lake

change, it is not fully positively correlated, a finding consistent with reference (Li et al. 2014).

5.2. Influence of other factors

In addition to climatic factors, the water balance of lakes on the Tibetan Plateau is also influenced by a variety of factors such as glaciers, snow water equivalent, permafrost melting, surface runoff, groundwater and human activities. The water balance of lakes is a rather complex subject, which needs to be analyzed and evaluated by a combination of factors.

As can be seen from Figure 10, the southern plateau, the western plateau and the central plateau are south of the 0°C annual average temperature isolines.20 of the 25 lakes have glacial distribution in their drainage basins, and the recharge sources of lake water include glacial meltwater. Studies (Zhao et al. 2004; Yao et al. 2012; Cheng and Wu 2007) have shown that the continuous increase in temperature in the southern plateau led to rapid glacier shrinkage and the effect of glacier melt on the changes of glacial lakes, also known as Yangzhuoyong Co, Pumayum Co, and Peigu Co, gradually became smaller. Where Yangzhuoyong Co and Peigu Co tend to shrink, Yangzhuoyong Co was affected by the hydroelectric plant, while Peigu Co water volume tended to shrink mainly due to the low latitude and high temperature in the region, resulting in limited meltwater provided by glaciers (Chipman 2019; Zhang et al. 2020b). The western plateau is at the same latitude as the central plateau, but receives much less precipitation than the central plateau. Although precipitation tends to increase, the annual precipitation is only about 100 mm. The basins of the lakes in the western plateau are distributed by glaciers, and the temperature in the region tended to decline, resulting in a decrease in glacial meltwater, which shrunk the lakes. In addition to Nam Co, the other 4 lakes in the central plateau have almost no connection with glaciers. The annual precipitation in the central plateau is the largest of the 5 regions, and precipitation is the main reason for the increase in lake volume (Wang, Zhou, and Zhang 2018; Chen et al. 2021; Dai et al. 2018). The northwestern plateau and the northeastern plateau are located in the northern region on the Tibetan Plateau, where glaciers is sensitive to temperature, especially with the massive melting of glaciers after 2000 (Yao et al. 2012). The lakes in this region are associated with glaciers, especially Ze Co, which has a glacier coverage in its drainage basin greater than 0.1 (Table 1), and glacial meltwater is one of its major recharge sources, although there is a slight decrease in precipitation, but the lake expanded.

Human activities are also a factor that affects the changes in lake volume. For instance, Yangzhuoyong Co has shrunk drastically in recent decades, one of the reasons is that there is a hydroelectric plant pumping water to generate electricity (Shi 1995; Chen and Liu 2020). Changes in surface runoff in the region can also lead to variations of lakes. The 2011 outburst of Zonag Lake led to the expansion of Kusai Lake and the rise of water level (Liu et al. 2019).

6. Conclusions

In this paper, a method is used to extract the lake-level and then calculate the lake volume variations based on SRTM DEM data and Landsat images. This paper focuses on the changes in the lake over the decades rather than to obtain accurate lake surface elevation and volume values, so 3.48 m RMSE is acceptable. It is possible to study the changes of the lake using SRTM DEM data. This approach extends the time span for monitoring lake variations.

Based on this algorithm, a total of 25 typical lakes (area >10 km^2) in 5 regions on the Tibetan Plateau were studied. The annual change rate and percentage change of their lake area, lake-level and volume during 1972–2019 were calculated. The lakes in the southern plateau and western plateau were shrinking during 1972 to 2019, which was shrinking before 2010 and began to expand slightly in the last decade. Yangzhuoyong Co in the southern plateau had the highest annual shrinkage rate. The increase in lake area and volume within the central plateau is significantly greater than in other regions. In particular, the increase from 2000 to 2010 was very large. Selin Co in the central plateau had the largest annual expansion rate in area and volume, especially after 2000, when the lake expanded dramatically. Lakes within the northwestern plateau have tended to expand, and lakes within the northeastern plateau tended to shrink until 2000 and began to expand after 2000. The lakes in both regions have been on an expansionary trend for nearly four decades. The changes in lake area, lake-level and volume are similar, but not identical. This is due to the lakes as irregularly shaped objects, their area, water level and water volume is not a simple multiplicative relationship. Lakes in the same region may not have the same trend of variations. On the whole, lake variations have gone through three stages, a slight decrease during 1972 to 2000, a rapid increase between 2000 and 2010, and a slowdown in the last decade (2010 to 2019).

Data availability statement

The Landsat satellite images can be queried and downloaded from the website of the United States Geological Survey (https://www.usgs.gov/). The SRTM elevation data used in this paper is the version 4.1 data provided by the Consultative Group of International Agricultural Research (http://srtm.csi.cgiar.org/). ICESat altimeter data can be

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