

Monitoring lake changes of Qinghai-Tibetan Plateau over the past 30 years using satellite remote sensing data

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Abstract During the years 2006–2009, lakes in the Qinghai-Tibetan Plateau (QTP) were investigated using satellite remote sensing strategies. We report the results of this investigation as well as follow-up research and expanded work. For the investigation, we mainly focused on lakes whose areas are more than 1 km². The remote sensing data that we used included 408 scenes of CBERS CCD images and 5 scenes of Landsat ETM+ images in Qinghai Province and Tibet Autonomous Region. All these data were acquired around years 2005–2006. Besides remote sensing images, we also collected 1,259 topographic maps. Numbers and areas of lakes were analyzed statistically, which were then compared with those coming from the first lake investigation (implemented between the 1960s and 1980s). According to our investigation, up to and around year 2005–2006, the total number of lakes in the QTP was 1,055 (222 in Qinghai and 833 in Tibet), accounting for more than 30 % of that of China. Thirty newborn lakes with area >1 km² were found, and 5 dead

lakes with initial area >1 km² were also found. Among those 13 big lakes (>500 km²), Yamzhog Yumco had seriously shrunk, and it has continued to shrink in recent years; Qinghai Lake had shrunk during the period, but some new researches indicated that it has been expanding since the year 2004; Siling Co, Nam Co, and Chibuzhang Co had expanded in the period. We divided the newborn lakes into six categories according to their forming reasons, including river expansion, wetland conversion, etc. The changes of natural conditions led to the death of four lakes, and human exploitation was the main reason for the death of Dalianhai Lake in Qinghai. We picked out three regions which were sensitive to the change of climate and ecological environment: Nagqu Region, Kekexili Region, and the source area of the Yellow River (SAYR). Lakes in both Nagqu and Kekexili have been expanded; meanwhile, most lakes in the SAYR have obviously been shrunk. These regional patterns of lake changes were highly related to variations of temperature, glacier, precipitation, and evaporation. Our investigation and analysis will provide references for researches related to lake changes in the QTP and the response to climate fluctuations.

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1 Introduction

The climate change of the Qinghai-Tibetan Plateau (QTP) is highly relevant to and has a strong influence on global climate change [1–4]. According to the fourth report of the Intergovernmental Panel on Climate Change (IPCC) and some related researches, the climate of the QTP has

continued to become warmer in recent years. This has been characterized by rising temperature for air and land surface, changing precipitation patterns, melting glacier and permafrost, and modern snowline depression [5–8]. The evaluation for climate change in the QTP is facing new scientific problems and challenges.

Lakes, as essential components of the hydrosphere and water cycle, are very sensitive to climatic fluctuations. This makes them important carriers of global change and regional response [9, 10]. There are a large number of alpine lakes in the QTP, and the statuses and changes of these lakes are quite different and complicated. Monitoring the number and area changes of QTP's lakes can, in some aspects, provides evidences for changes of the cryosphere [1], water cycle [2] and ecosystem [11]. Due to the QTP's remoteness, high altitude, thin atmosphere, and harsh weather conditions, it is very difficult to monitor the conditions of lakes using field observations. Instead, the use of satellite remote sensing techniques is an effective approach [12, 13]. Studies related to lakes in the QTP using remote sensing data mainly involved extracting information about lakes [14], monitoring the water level [15], searching for regional patterns of the changing lakes [16], observing the characteristics of long-term changes [12], exploring the response to climate change [10], etc.

Between the 1960s and 1980s, the first nationwide lake investigation (FLI) was conducted. A vector database (1:250,000) was built after the FLI, and the results were published with the *Chinese Lake Catalogue* [9] (CLC) and *Code for China Lake Name* [17] (CCLN). According to the FLI, number of lakes ($>1 \text{ km}^2$) in the QTP is 1,091, approximately 49.5 % of the total number in China. To determine the extent of lake changes in recent decades, we conducted a second lake investigation (SLI) from 2006 to 2009, with the support of the National Key Basic Research Special Foundation of China “Lake Water Quality, Water Quantity, and Biological Resources Investigation in China”. The SLI was conducted at the base period of 2005–2006, and a technical specification (TS) was proposed for the purpose of this investigation [18, 19]. The investigation of lakes in the QTP was an important part for the SLI. One aim of this paper is to report the results of the SLI for the QTP as well as to share the number, area, and distributions of these lakes around 2005–2006. We propose to compare the results from the SLI and the FLI, and try to discover the changes of number and area for the lakes. After the SLI, we did some follow-up and expansion work by collecting results from the latest literatures and some auxiliary data. The other aim of this paper is to share these new results. We focus on analyzing (1) the changes of big lakes ($>500 \text{ km}^2$) and the influencing factors, (2) the categories of newborn and dead lakes and the influencing factors, and (3) the characteristics of regional changes and

the response to climate change, for which we picked out Nagqu Region, Kekexili Region and the source area of the Yellow River (SAYR) as examples. Our investigation and analysis will provide references for researches related to lake changes in the QTP and the response to climate fluctuations.

2 Data

Images acquired from the China–Brazil earth resources satellite (CBERS) charge-coupled device (CCD) sensor, with 19.5 m and 16-days as their spatial and temporal resolution, were used as the main data source for the investigation. For special cases, if there were problems (e.g., cloudy days) with the CBERS data on that day, we used data from the Landsat Enhanced Thematic Mapper Plus (ETM+) instead. Most of the remote sensing data were from 2005 to 2006. Note that it was impossible to obtain good-quality data for all of the lakes during this period. Instead, we extended the time period to 2003–2008. But even with this extended time period, there were few lakes for which we could not get satisfactory data. Therefore, we also had to use data acquired from 2000 to 2003. Each lake was guaranteed to have two separate images: one was during the wet season (August or September) and the other was during the dry season (April or May). And 413 images covering all the alpine lakes in the QTP were selected for the investigation. This consisted of 408 CBERS CCD images and 5 images from Landsat ETM+. Figure 1 shows the QTP with covered images for wet and dry seasons, respectively.

In order to process the geometric correction for the remote sensing data, we collected topographic maps around the year 1975, which included 1,177 maps at the scale of 1:100,000 and 82 maps at the scale of 1:50,000 (Fig. 2). In addition, we referred to many auxiliary data during our investigation, including (1) data from the FLI (1:250,000 vector data, CLC, and CCLN); (2) books such as the *Rivers and lakes in Tibet* [20], *Salt lakes in Tibet* [21], *Salt lakes in the Qinghai-Tibetan Plateau* [22] and *Landscapes in Tibet* [23]; (3) publications that related to the characteristics of lakes in the QTP [24, 25], changes for alpine lakes [11, 14, 26], and characteristics of rivers in the QTP [27].

3 Method

Previous publication of this investigation has explained the general rules which the TS provided for the extraction of lake boundaries, as well as rules for determining the number, area and names for lakes in China [18]. However, conditions for lakes in the QTP were so complicated that

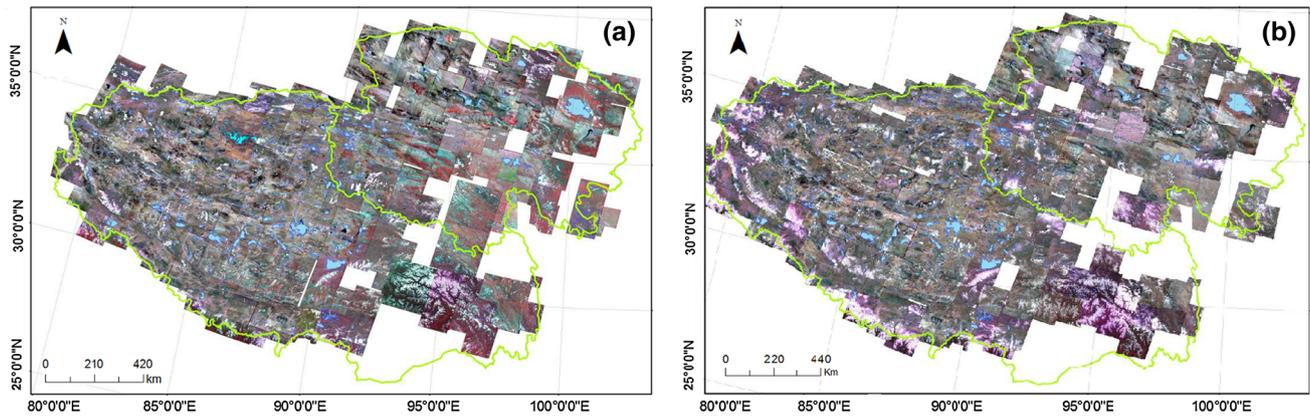


Fig. 1 Coverage of remote sensing images for **a** wet season and **b** dry season

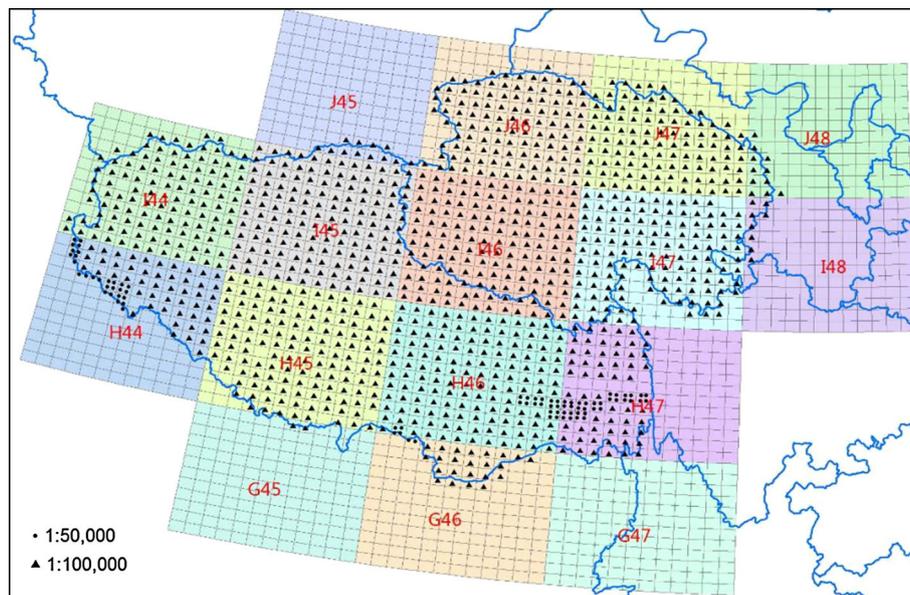


Fig. 2 Topographic maps collected for geometric correction of remote sensing data

we had to refer to additional materials which provided special rules for interpreting different types of alpine lakes (freshwater lake, saltwater lake, salt lake, half-extinct lake, extinct lake, etc.) [28].

General procedures for the SLI mainly included data pre-processing and lake interpretation. A longitude/latitude grid covering the QTP was created at the scale of 1:100,000 (longitude 30' × latitude 20'), and a 2 × 2 km² grid was delineated. All the scanned topographic maps were geographically rectified using the grids, with the root mean square (RMS) error <10 m. These geo-rectified maps were subsequently used for geometric correction of the remote sensing images. All images were geo-rectified to an Albers Equivalent Conical Projection with the RMS error <30 m, and no orthorectifications were implemented to the images. Although there have been many methods for auto-

extraction of waterbodies [29, 30], in order to strictly control the precision, we chose to manually interpret and extract the lake boundaries. For ordinary lakes, the water surface boundary was treated as the lake boundary, and the total area of all parts (including the area of water surface, islands, bottomlands, etc.) within the lake boundary was considered as the lake area. For questionable lakes like seasonal-changing lakes or salt lakes with salt crusts, we checked and compared their statuses on both wet-season and dry-season images. If the bottomlands with seasonal-covered water or the salt crusts were located outside the water surface boundaries on both wet/dry-season images, we would not consider them as components of the lake. Otherwise, if they were located inside the water surface boundaries on wet-season images but outside for the dry-season ones, we took the median lines of the water surface

boundaries on wet/dry-season images as the lake boundaries.

Besides these normal lakes, during the investigation, we determined two special types of lakes: newborn lakes and dead lakes. The definitions and criteria of these two types are shown in Table 1. We discovered these two types by investigating all the images one by one when compared to results from the FLI.

4 Results

4.1 Number of lakes

According to the SLI, the number of lakes ($>1 \text{ km}^2$) in the QTP was 1,055, 30 % of the total number in China [18], including 222 in Qinghai (QH) and 833 in Tibet (TB). Table 2 shows comparisons of the numbers recorded by the CLC, CCLN and the SLI. The number of QTP's lakes ($>1 \text{ km}^2$) recorded by CLC is 1,091, with 272 in QH and 819 in TB, while the number recorded by CCLN is 1,041, with 261 in QH and 780 in TB. It is necessary to point out that, for the big lakes ($>1,000 \text{ km}^2$), the total number was 3 both in the CLC and CCLN. However, there was only one

Table 1 Definition and criterion for newborn and dead lakes [18, 19]

	Definition	Criterion
Newborn lake	Non-existent during the FLI, but had developed gradually and existed during the SLI	Had no record in the CLC or CCLN, and used to be land or non-lake waterbody, and turned out to be a lake during the SLI
Dead lake	Existed during the FLI, but no longer existed during the SLI	Had record in the CLC or CCLN, and used to be a lake, and had dried up or disappeared due to other reasons during the SLI

Table 2 Statistical numbers and comparisons for QTP's lakes recorded by the CLC, CCLN and SLI

		$>1,000 \text{ km}^2$	500–1,000 km^2	100–500 km^2	50–100 km^2	10–50 km^2	1–10 km^2	Total
CLC	QH	3	5	17	13	45	189	272
	TB	2	5	40	57	158	558	819
	Subtotal	5	10	57	70	203	745	1,091
CCLN	QH	3	5	19	15	48	171	261
	TB	2	5	38	57	151	527	780
	Subtotal	5	10	57	72	199	698	1,041
SLI	QH	1	5	18	13	53	132	222
	TB	2	5	51	56	185	534	833
	Subtotal	3	10	69	69	238	666	1,055*

* Does not include 34 lakes whose areas were greater than 1 km^2 during the FLI but were less than 1 km^2 during the SLI

left according to the SLI. This excluded Chaerhan Salt Lake and Kunteyi Dry Salt Lake. The reason for this disagreement is that ten salt lakes (including Dabuxun Lake, Niese Lake, Beihuobuxun Lake, etc.) were given one single name (called Chaerhan Salt Lake in the CLC), while in the SLI we interpreted them separately. Kunteyi Dry Salt Lake, which was actually a salt flats without any water, was not considered in the SLI. Table 3 shows the numbers of newborn and dead lakes in the SLI. There were, in total, 30 newborn lakes in the QTP, including 8 in QH and 22 in TB. Also, five lakes vanished during our investigation, including two in QH and three in TB.

4.2 Area and spatial distribution of lakes

Table 4 depicts comparisons of area for QTP's lakes recorded by the CLC, CCLN, and SLI (there was no statistics in the CLC for lakes whose areas are between 1 and 10 km^2). Our investigation results hypothesized that the total area of QTP lakes ($>1 \text{ km}^2$) was $41,831.72 \text{ km}^2$, $>50 \%$ of the total area of Chinese lakes. For more details, the total area of lakes ($>10 \text{ km}^2$) was $39,778.59 \text{ km}^2$, and for 1– 10 km^2 lakes, it was $2,053.13 \text{ km}^2$; the total area of newborn lakes was 202.63 km^2 , and for dead lakes, it was 7.16 km^2 in earlier topographic maps when they exist.

Figure 3 illustrates the spatial distribution of all alpine lakes ($>1 \text{ km}^2$) in the QTP. Note that there were, in total, 13 big lakes ($>500 \text{ km}^2$) according to the SLI, which included five in QH (Qinghai Lake, Eling Lake, Hala Lake,

Table 3 Numbers of newborn and dead lakes

		10–100 km^2	1–10 km^2	Total
Newborn lake	QH	2	6	30
	TB	3	19	
Dead lake	QH	0	2	5
	TB	0	3	

Table 4 Statistical area and comparisons for QTP’s lakes recorded by the CLC, CCLN and SLI (km²)

		>10 km ²	1–10 km ²	Total
CLC	QH	18,940.1	–	–
	TB	17,583.6	–	–
	Subtotal	36,523.7	–	–
CCLN	QH	19,743	514	20,257
	TB	23,343.6	1,583.5	24,927.1
	Subtotal	43,086.6	2,097.5	45,184.1
SLI	QH	12,796.97	417.90	13,214.87
	TB	26,981.62	1,635.23	28,616.85
	Subtotal	39,778.59	2,053.13	41,831.72

Wulanwula Lake and Zhaling Lake), seven in TB (Selin Co, Nam Co, Zharinanmu Co, Dangreyong Co, Yamzhog Yumco, Pangong Co and Anglaren Co), and one Chibuzhang Co belonging to both QH and TB. Distribution of newborn and dead lakes is also shown in Fig. 3, for which we use two different symbols to represent these two types without considering their area and shape.

5 Discussions

5.1 Changes of big lakes and the influencing factors

The QTP is a sensitive and valuable region for the research of global climate change. Of greater importance, it is more

valuable to learn the changes of big lakes for exploring the climate change. We first analyzed the changes of big lakes during the base period of the SLI, and then we extended the analysis to years after the SLI referring to the latest publications. We also tried to determine the influencing factors for the changes. Table 5 depicts the area changes of all the 13 big lakes, in which we use $\Delta t = \frac{(S_{TR}-S_{CLC})}{S_{CLC}} \times 100\%$ to calculate the changing rate of each lake. This is called the expansion rate (ER) if Δt is positive and shrink rate (SR) when Δt is negative.

- (1) Shrank lakes and the influencing factors: During the SLI, Yamzhog Yumco and Qinghai Lake had shrunk seriously with reduced areas of 184.82 and 85.10 km², respectively. Hala Lake and Zharinanmu Co had shrunk also. Yamzhog Yumco lies north of the Yarlung Zangbo River and south of the Himalayas, and it is an enclosed-basin lake which depends mostly on glacial water and precipitation recharge. In addition to our results, several other researchers also provided solid evidences for the shrinkage of Yamzhog Yumco. For instance, in [31–33], they analyzed the changes of water level and area of Yamzhog Yumco and the response to climate change using topographic maps, remote sensing data, meteorological data and hydrological data, and results showed that the main reason for the shrinkage of Yamzhog Yumco was that potential evaporation was greater than precipitation throughout most of the basin due to

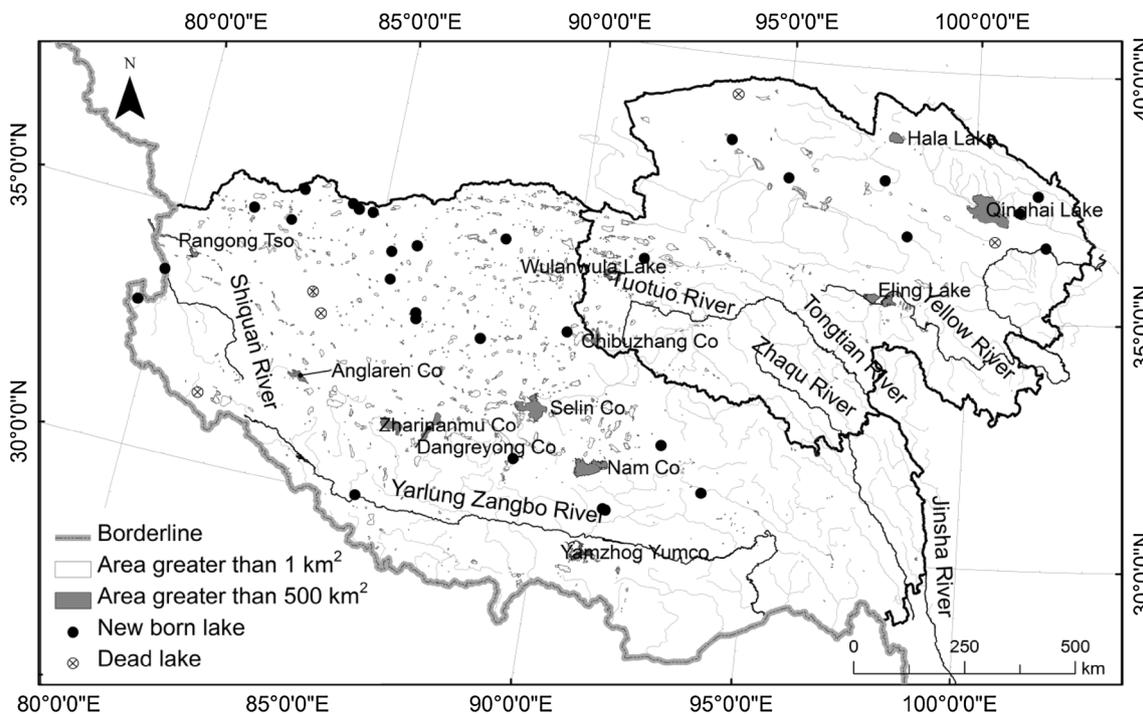


Fig. 3 Distributions of lakes in the QTP (>1, >500 km², newborn lakes and dead lakes)

Table 5 Changes of area for all the 13 big lakes (>500 km²)

Name	Code	Lon. (E)	Lat. (N)	CLC-lake area (km ²)	SLI-water area of wet season (km ²)	SLI-water area of dry season (km ²)	SLI-lake area (km ²)	Changed area (km ²)	Changing rate (%)
Qinghai Lake	R63B002	100.19°	36.89°	4,340.00	4,232.32	4,206.41	4,254.90	−85.10	−1.96
Eling Lake	D63A101	97.7°	34.9°	610.70	628.47	587.9	629.75	19.05	3.12
Hala Lake	R63F101	97.59°	38.29°	601.70	596.39	591.06	596.39	−5.31	−0.88
Wulanwula Lake	S63B101	90.48°	34.81°	544.50	566.96	566.89	566.96	22.46	4.12
Zhaling Lake	D63A102	97.26°	34.93°	526.00	523.89	510.57	526.62	0.62	0.12
Chibuzhang Co	T63F201	90.26°	33.46°	476.80	515.68	514.33	515.68	38.88	8.15
Selin Co	T54B002	88.99°	31.81°	1,628.00	2,129.02	1,965.26	2,129.02	501.02	30.78
Nam Co	T54B001	90.61°	30.74°	1,961.50	2,086.86	2,023.38	2,040.90	79.40	4.05
Zharinanmu Co	T54B101	85.15°	30.99°	996.90	990.26	987.08	990.26	−6.64	−0.67
Dangreyong Co	T54B102	85.89°	31.23°	835.30	840.82	409.53	840.82	5.52	0.66
Yamzhog Yumco	U54B101	90.71°	28.96°	835.30	620.78	620.98	650.48	−184.82	−22.13
Pangong Tso	T54B103	79.25°	33.68°	604.00	626.01	641.75	627.19	23.19	3.84
Anglaren Co	T54B104	81.24°	31.29°	512.70	507.53	556.86	542.89	30.19	5.89

the increasing temperature. In the following years after this investigation, some new researches showed evidence for the current status of Yamzhog Yumco. They pointed out that this lake has been keeping shrinking these years, and the area was merely 600.26 km² till April, 2010 [15, 34–36]. Qinghai Lake lies in the northeast of Qinghai Lake Basin, and water from surface runoff and precipitation is its main source of recharge. The Buha River, whose water puts into Qinghai Lake, mainly depends on the glacier from the Qilian Mountain for recharge. Results obtained by some other researches reached the same conclusion that Qinghai Lake had kept shrinking over the past three decades. On the other hand, they also verified that the water level and area started to increase since 2004 [37, 38]. This phenomenon has been proven by other studies [12]. Ref. [39] claimed that the most likely reason for the expansion of Qinghai Lake was the increasing precipitation and decreasing evaporation due to the summer monsoon.

- (2) Expanded lakes and the influencing factors: there were seven big lakes which had expanded over the past 30 years (Table 5). Selin Co had the highest ER which was 30.78 %, while Nam Co and Chibuzhang Co had also expanded notably. Instead of Nam Co, Selin Co has become the biggest lake in the QTP [40]. Selin Co lies north of Gangdise, with the Zhajiazangbu River, rising from Geladandong Glacier and Tanggula Mountains in north Tibet, as its largest source of recharge. Therefore, the change of lake area was directly related to the change of the glacier. Most of the researches agreed that the main reason of the

expansion was the melting glacier and permafrost due to the continuous increase of temperature [41, 42]. Of greater importance, the north part of Selin Co enlarged more obviously than other directions, which could be directly related to the shrinkage of Geladandong Glacier in the north [16, 43, 44]. The area of Selin Co had enlarged to 2,323.6 km² as of October, 2010, which was larger than the 2,129.02 km² in this investigation. As for the reason of Nam Co and Chibuzhang Co's expansion, the increase of water from melting glacier is still the main cause [45–47]. To some extent, the expansions of Selin Co, Nam Co, and Chibuzhang Co represent the variation tendency of lakes in the Nagqu Region, and we will give further explanation below. Eling Lake and Zhaling Lake are usually recognized as “sisters” lying at the Yellow River Source. According to the SLI, Eling Lake expanded by an area of 19.05 km², which was more serious when compared to Zhaling Lake. Other studies considered that Eling Lake had first shrunk and then expanded over the past 30 years [48]. It took until the year 2000 as the “turning point.” The rising water level after 2000 was because of the construction of a hydroelectric station [49]. We also showed that Wulanwula Lake expanded 22.46 km² around the year 2005, while some evidence showed that this lake experienced a stage of shrinkage from 1976 to 2000 due to the dry climate [8, 50]. Moreover, our results showed that Pangong Co and Anglaren Co have enlarged a small amount. Note that the area of dry season is greater than that of wet season for these two lakes. However, this result is not consistent with some

other studies. Since we have not looked into the data after 2005, we will not discuss this disagreement in this paper.

5.2 Categories of newborn and dead lake and the influencing factors

The newly forming and vanishing of alpine lakes in the QTP could directly reflect the changes of climate, rivers, glaciers and the content of salt in the lakes. In this research, we divided the newborn lakes into six categories based on the auxiliary data like landscapes, vegetation cover, rivers, etc. The six categories are: (1) River expanded to lake; (2) Wetland converted to lake; (3) Saline-alkali or sandy land converted to lake; (4) Gobi Desert converted to lake; (5) Glacier meltwater became lake; and (6) Seasonal lake with water in wet season, but saline alkali land in dry season. Distributions of these six types of newborn lakes are depicted in Fig. 4. We coded newborn lakes in QH and TB as Q01-Q08 and X01-X22, respectively. The newborn lakes were not very large; the largest one was Q05 in Haixi County with 38.93 km². Therefore, instead of considering their shape and area, we use different symbols to represent different types of newborn lakes (Fig. 4). For further explanation, Fig. 5 shows examples for these six types,

using earlier topographic maps and images from the SLI to show the forming process of the newborn lakes. Note that lakes of Type 1 always formed along big rivers as well as their branches. The reasons for the formation of Type 1, Type 5, and Type 6 are very straightforward. However, it is difficult to explain the reason for Type 3 and Type 4, because it is nearly impossible to convert saline-alkali, sandy land, or gobi into lakes under normal climate conditions. We temporally attribute this strange phenomenon to the mistakes when making topographic maps in earlier years.

Distributions of the five dead lakes are also shown in Fig. 4, including Salt Lake, Dalianhai Lake in QH and Riazhi Co, Kalie Co, and a lake without name in TB. From comparing earlier topographic maps and the images during this investigation, we conclude that the vanishing of Dalianhai was closely related to human exploitation, while the drying up of the other four lakes was related to strong evaporation (Fig. 6).

5.3 Characteristics of regional changes and the response to climate change

- (1) Changing characteristics of lakes in the Nagqu Region. The Nagqu Region, being the main part of

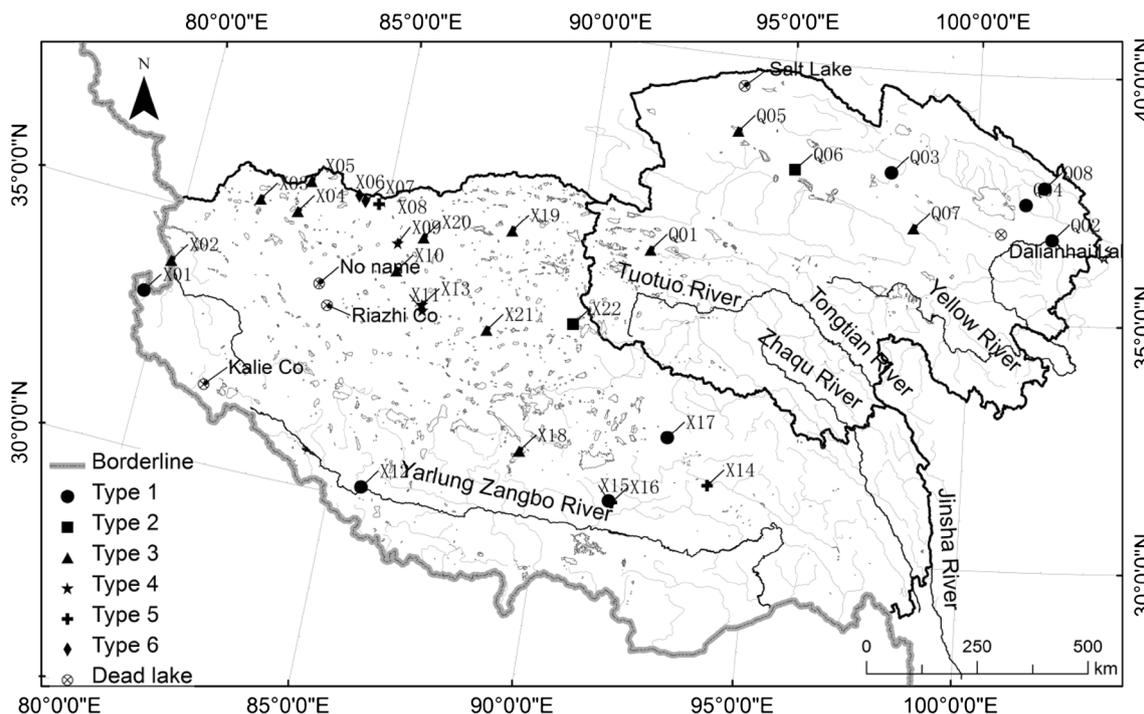


Fig. 4 Distributions of newborn and dead lakes. *Type 1* river expanded to lake; *Type 2* wetland converted to lake; *Type 3* saline-alkali or sandy land converted to lake; *Type 4* gobi desert converted to lake; *Type 5* glacier meltwater became lake; *Type 6* seasonal lake with water in wet season, but saline-alkali land in dry season

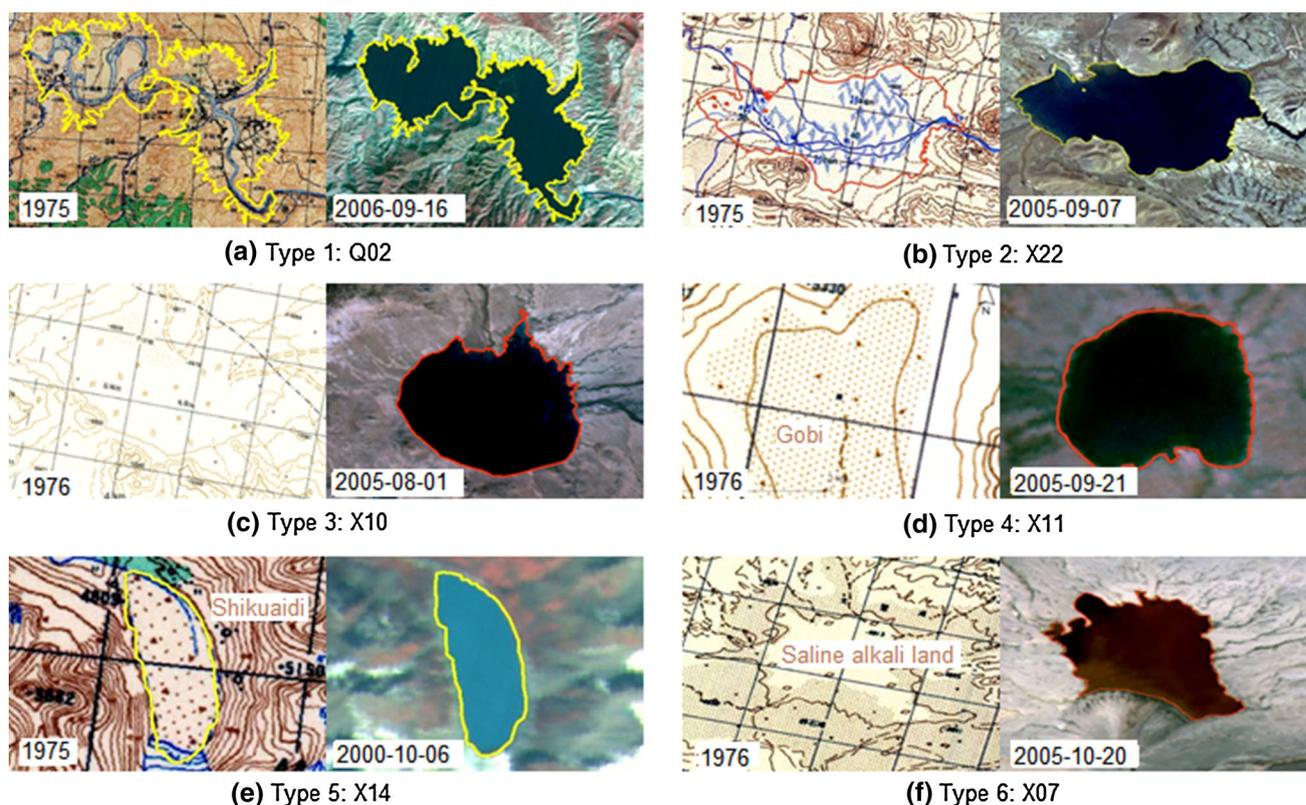


Fig. 5 Examples of different types of newborn lake. **a** river expanded to lake; **b** wetland converted to lake; **c** saline-alkali or sandy land converted to lake; **d** gobi desert converted to lake; **e** glacier meltwater became lake; **f** seasonal lake with water in wet season, but saline-alkali land in dry season

north Tibetan Plateau, is surrounded by Kekexili, Tanggula Mountains, and Gandise-Nyainqentanglha Mountains. The Nagqu Region includes 11 counties, and the average elevation is above 4,500 m with high-lying west and low-lying east. A large number of inland lakes and modern glaciers are seated in this region. The changes of lakes in Nagqu are mainly controlled by natural factors, which consequently makes this region better reflect the environmental changes of the QTP.

Figure 7 depicts the distribution and area changes of 61 lakes ($>30 \text{ km}^2$) in Nagqu. Most lakes are located in five counties, i.e., Nima, Bange, Shenzha, Anduo, and Naqu. We classify the expanded lakes into three categories according to their ER: $>50 \%$, $10 \%-50 \%$, and $<10 \%$. Among all the 61 lakes, there were only three diminished lakes whose names and SRs are Bange Co (-2.62%), Angzi Co (-3.47%), and Gemu Co (-8.68%). Table 6 lists further information for the severely expanded lakes (ER: $>50 \%$). Yagedong Co reached the highest ER of 179.93 %, followed by Guojialun Lake (99.88 %) and Yibuchaka Lake (95.13 %). For these three lakes, further comparisons of their statuses on earlier topographic

maps and images during this investigation are illustrated in Fig. 8. Note that a large amount of water grew at the west of Yagedong Lake as is shown on the 2005-07-09 image, which made no sense on the topographic map; Guojialunqu Lake, which used to be a group of several lakes in 1975, turned into a large lake whose area was 69.26 km^2 ; Yibuchaka Lake had an obvious expansion at the south part of the lake comparing to the topographic map, nearly twice as big as is in 1975.

- (2) Changing characteristics of lakes in Kekexili Region. The Kekexili Region is located in between the Tanggula Mountains and the Kunlun Mountains, north of the QTP. It is a junction for the inland lakes in the Qiangtang Region and the north source of the Yangtse River. We focus on investigating lakes ($>10 \text{ km}^2$) in Kekexili Nature Reserve (KKNR, $89.25^\circ\text{--}94.05^\circ\text{E}$, $34.19^\circ\text{--}36.16^\circ\text{N}$). The distribution and area changes of 35 lakes ($>10 \text{ km}^2$) in the KKNR are shown in Fig. 9 (excluding those lakes in Bange County and the Nagqu Region, since they have been discussed previously). There were five shrunk lakes in total (Mirror Lake/ -0.37% , Yishan Lake/ -2.89% , Kekao Lake/ -3.63% , Telashi Lake/ -5.46% and

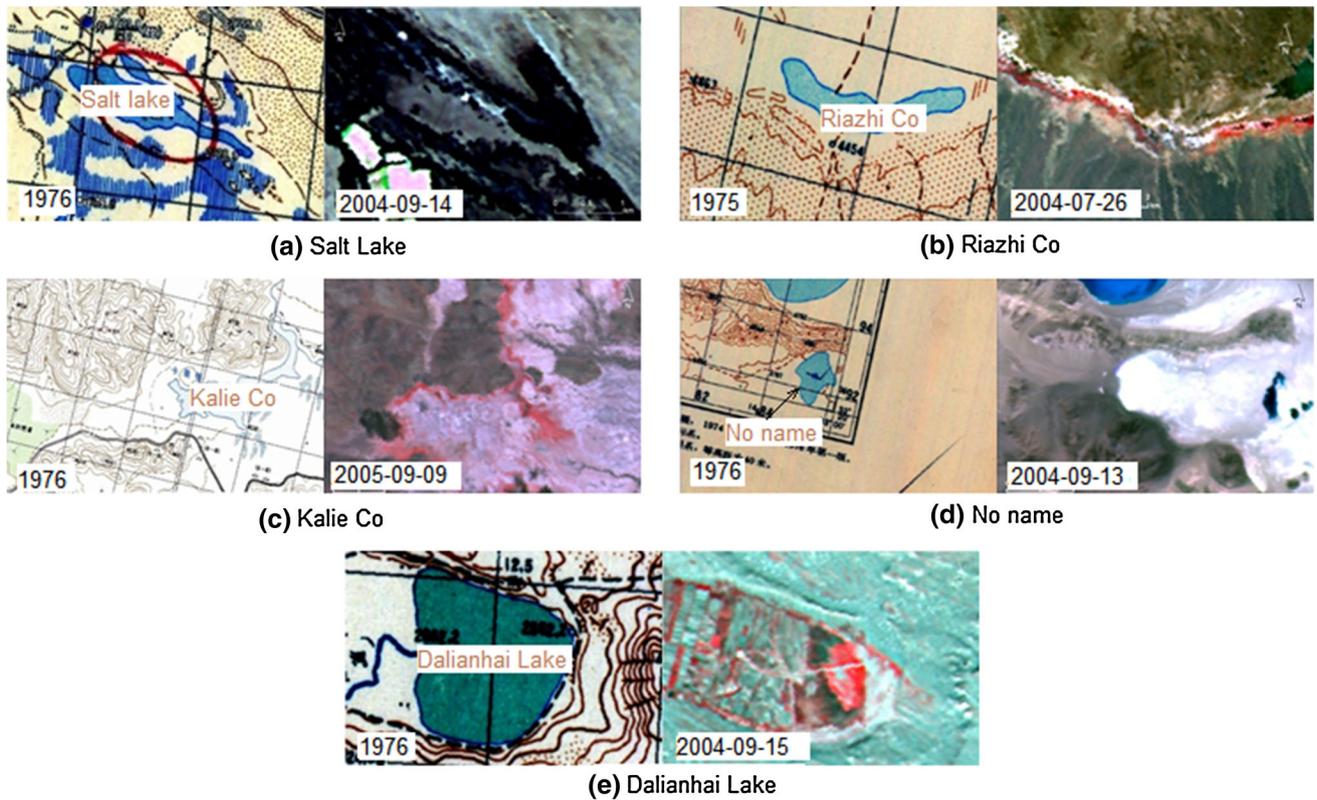


Fig. 6 Dead lakes. Vanishing of a–d was due to the strong evaporation; vanishing of e was due to human exploitation

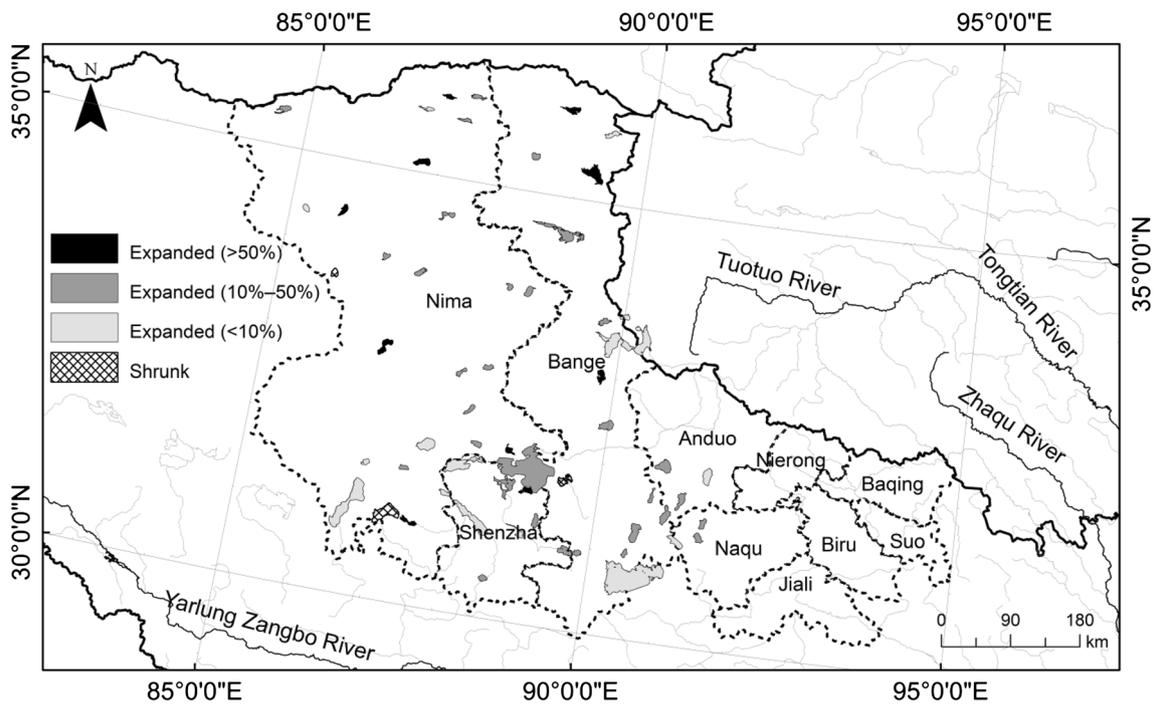
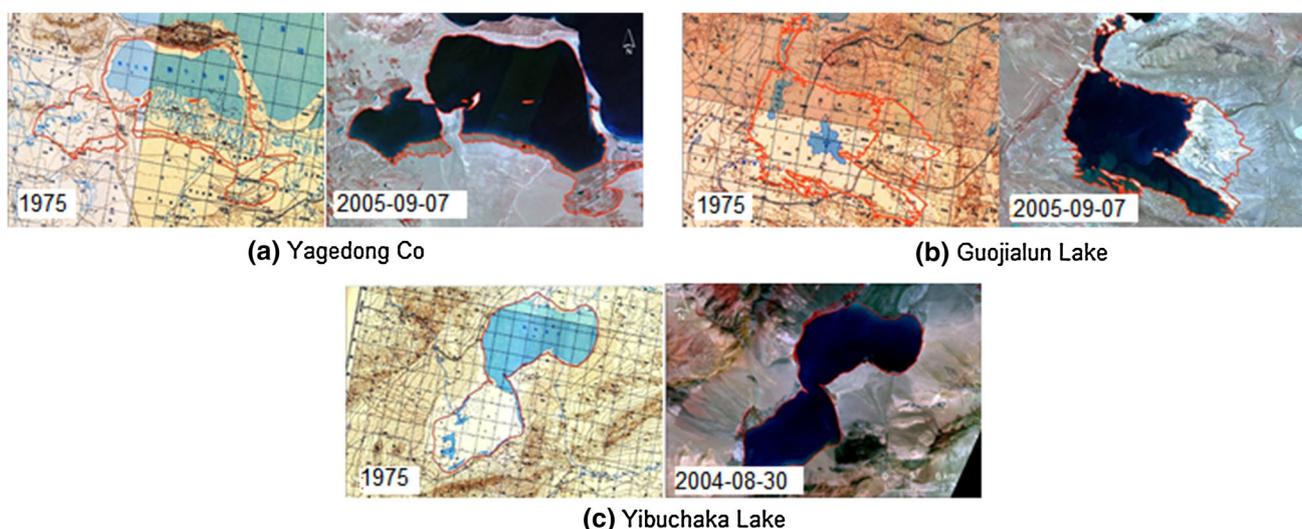


Fig. 7 Distributions and area changes of 61 lakes (>30 km²) in Nagqu Region

Table 6 Detailed information for expanded lakes (ER >50 %) in Nagqu Region

Name	Code	Lon. (E)	Lat. (N)	CLC-lake area (km ²)	SLI-lake area (km ²)	Changed area (km ²)	Changing rate (%)
Yagedong Co	T54D378	89.01°	31.56°	34.80	97.41	62.61	179.93
Guojialun Lake	T54F834	88.69°	31.99°	34.65	69.26	34.61	99.88
Yibuchaka Lake	T54D310	86.71°	32.93°	88.00	171.71	83.71	95.13
Maergaichaka Lake	T54D315	86.75°	35.12°	80.00	144.04	64.04	80.05
Yagen Co	T54D231	89.79°	33.01°	108.00	174.04	66.04	61.15
Duogecuorenqiang Co	T54F215	89.24°	35.32°	207.50	328.84	121.34	58.48
Yuye Lake	S54F302	88.78°	36.01°	82.30	126.36	44.06	53.54
Zhenquan Lake	S54B306	86.96°	35.92°	42.40	64.75	22.35	52.72
Maerxia Co	T54F328	84.52°	30.53°	63.80	96.46	32.66	51.19
Buruo Co	T54F313	85.77°	34.40°	59.70	89.91	30.21	50.60

**Fig. 8** Statuses for **a** Yagedong Co (ER = 179.93 %), **b** Guojialun Lake (ER = 99.88 %) and **c** Yibuchaka Lake (ER = 95.13 %) on earlier topographic maps as well as on images during this investigation

Cuoridama Lake/−5.90 %). All the other lakes have expanded. Again, we classify the expanded lakes into three categories according to their ER: >50 %, 10 %–50 %, and <10 % (Fig. 9). Table 7 lists the further information for some of the expanded lakes (ER: >10 %). We use the code in CCLN to denote those lakes without names. Note that the ERs for Maan Lake, S63005, Xiaokusai Lake, and Lianhu are all greater than 50 %.

(3) Changing characteristics of lakes in the SAYR. The Yellow River originates from the Yueguzonglie Basin, north of the Bayan Har Mountains [51], and it is one of the most important regions for water supplies in China. The SAYR is located in the southeast of the QTP, which is also a region sensitive to the change of ecological environment. We focus on

analyzing lakes (>10 km²) being located in a rectangle area (99.40°–99.85°E, 34.20°–35.40°N). As is shown in Fig. 10, there are many lakes in this region but most of which are small. Two big lakes, named Zhaling Lake and Eling Lake, are seated in this region. Since we have discussed them previously, we will not cover them again here. Note that most lakes in the SAYR had been shrunk, with SRs ranging from 40 % to −1 % (Fig. 10; Table 8).

(4) The response of regional changes to climate change. According to the fourth report of IPCC, the temperature and precipitation has been keeping rising in a fluctuating way in the QTP, and the temperature has risen by 1.5 °C over the past 50 years [52, 53]. Moreover, IPCC illustrated that the rising rate for QTP's temperature was 0.16 °C per decade, and the

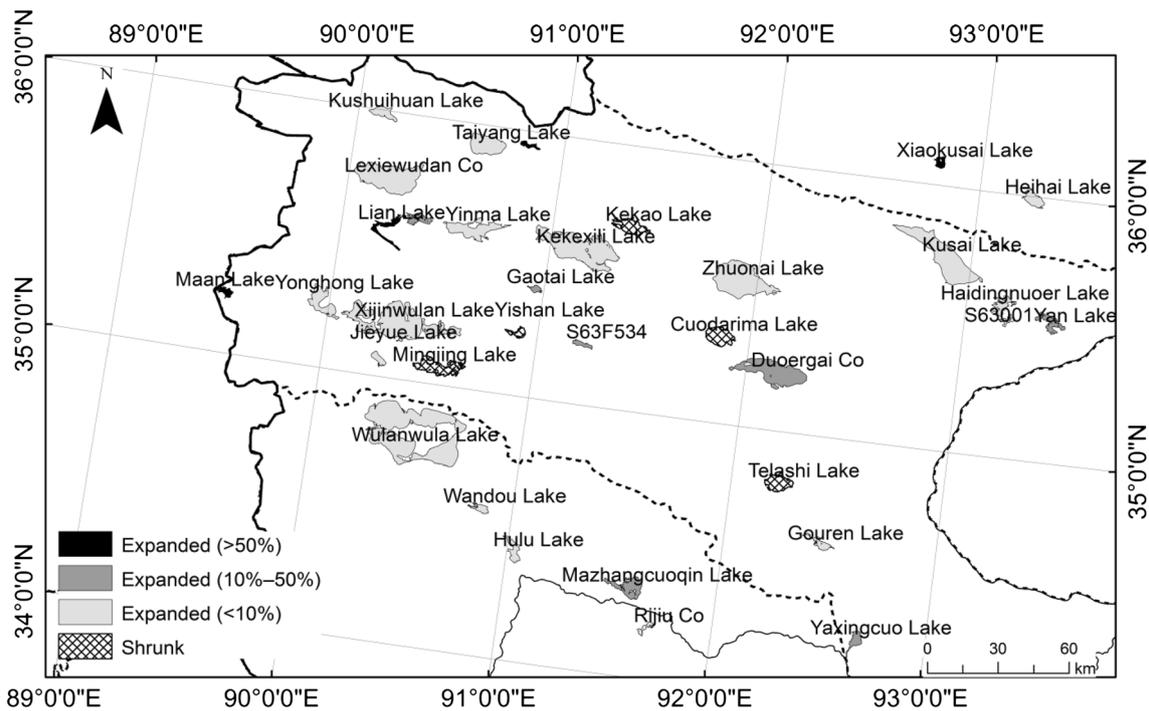


Fig. 9 Distributions and area changes of 35 lakes (>10 km²) in the KKNR

Table 7 Detailed information for expanded lakes (ER >10 %) in the KKNR

Name	Code	Lon. (E)	Lat. (N)	CLC-lake area (km ²)	SLI-lake area (km ²)	Changed area (km ²)	Changing rate (%)
Maan Lake	S63F510	89.51°	35.23°	8.08	17.17	9.09	112.54
S63005	S63F509	90.83°	35.95°	7.00	12.80	5.80	82.84
Xiaokusai Lake	R63F503	92.80°	36.09°	9.20	16.70	7.50	81.56
Lian Lake	S63B310	90.22°	35.56°	26.30	39.82	13.52	51.39
S63004	S63F508	90.33°	35.60°	7.50	11.01	3.51	46.86
Yelus Lake	F63A201	92.13°	35.22°	144.10	204.92	60.82	42.21
S63022	S63F534	91.21°	35.23°	12.57	16.83	4.26	33.90
Yaxi Co	F63A303	92.68°	34.25°	19.30	25.02	5.72	29.65
Salt lake	S63D308	93.41°	35.53°	32.80	41.55	8.75	26.67
Mazhangcuoqin Lake	F63B301	91.59°	34.34°	58.80	73.44	14.64	24.90
Moon Lake	S63F315	90.38°	35.61°	15.00	17.25	2.25	15.03
Gaotai Lake	S63F502	90.96°	35.41°	9.60	10.74	1.14	11.92

increase of precipitation mainly happened in the northeast of the QTP [6]. Meanwhile, related researches showed that the temperature and precipitation have been increasing at the middle, east and north parts of the QTP over recent decades, and the rising temperature may have led to the increasing precipitation [1, 54, 55]. Ref. [7] concluded using data from weather stations that during 1965–2000, precipitation in the northwest and middle of the plateau was increasing while it was decreasing in the

northeast. The area decrease of Qinghai Lake during our investigation could be a direct response to the decrease of precipitation in the northeast of QTP, and the increase of lake area after 2004 could be evidence for the subsequently increase of precipitation in this area. In addition, the remote sensing retrieved information (e.g., land surface temperature (LST), glacier area, snowline, etc.) can be responded for climate change. It has been observed by remote sensing data that the LST has been rising, glaciers have been

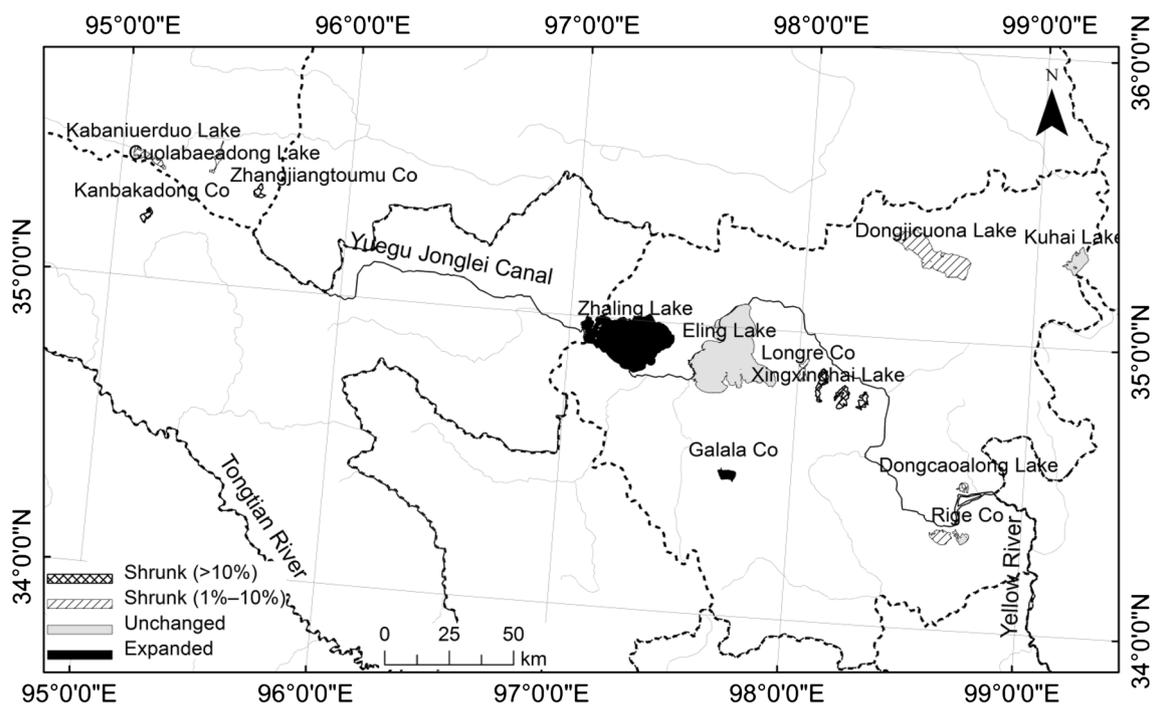


Fig. 10 Distributions and area changes of 16 lakes (>10 km²) in the SAYR

Table 8 Detailed information for diminished lakes (SR <−10 %) in the KKNR

Name	Code	Lon. (E)	Lat. (N)	CLC-lake area (km ²)	SLI-lake area (km ²)	Changed area (km ²)	Changing rate (%)
Kanbakadong Co	R63F315	95.13°	35.21°	11.72	19.50	−7.78	−39.89
Ayongnaima Co	D63A305	98.29°	34.78°	14.38	22.70	−8.32	−36.65
Zhangtoujiangmu Co	D63B306	95.61°	35.33°	13.72	20.00	−6.28	−31.38
Ayongwuerma Co	D63A301	98.20°	34.79°	27.17	37.60	−10.43	−27.73
Xingxinghai Lake	D63A303	98.10°	34.83°	26.28	29.30	−3.02	−10.31

melting, and the modern snowline has been depressing over recent decades, which have strongly proved that the climate of the QTP has been changing [7, 56, 57].

We have learned from previous analysis that, while most lakes in the Nagqu Region and the Kekexili Region have expanded, most lakes in the SAYR have shrunk. This phenomenon, on one hand, shows that changes of lakes could be considered as indicators for climate change; on the other hand, it reveals that the responses had different regional and temporal patterns. For example: (a) For the Nagqu Region: Ref. [58] analyzed the changes of lakes in the southeast of Nagqu and the response to climate change using meteorologic data from 1975–2005, which claimed that the expansion of lakes was a direct response to the features of climate change such as the increasing temperature and precipitation, decreasing evaporation, and melting glacier and permafrost. The latest researches

showed that most of the lakes in Nagqu are still enlarging recently, and this may be further evidence for the variations of temperature, precipitation and glacier in the middle of QTP [13, 59, 60]. (b) For the Kekexili Region: The majority of lakes, which depend on glacial water, precipitation, and river for recharge, have expanded over the past 30 years, as response to the increased precipitation in the north of QTP and also to the increased water from melted glaciers in the Kunlun Mountains [12]. Meanwhile, some salt lakes like Telashi Lake and Kekao Lake which lie in enclosed basins have shrunk significantly due to high temperature and strong evaporation [50]. (c) For the SAYR: The ecological environment has worsened in recent years, characterized by increasing evaporation, decreasing runoff, melting glacier, and grassland degeneration [61, 62], thus, the shrinkage of lakes in the region has strongly indicated these terrible influences [63, 64].

6 Conclusions

We investigated the number and area changes of lakes ($>1 \text{ km}^2$) in the QTP over the past 30 years, using satellite remote sensing data which included CBERS CCD and Landsat ETM + during the period of 2005–2006. Furthermore, we discussed the influencing factors, regional characteristics, and the response to climate change referring to the latest research progresses. It is an effective strategy to investigate and monitor alpine lakes using satellite remote sensing data, especially for areas like the QTP, where it is difficult or even impossible, to conduct field observations. The results of the research have shown that: (1) Up to around 2005, there were 1,055 lakes ($>1 \text{ km}^2$) in the QTP including 222 in QH and 833 in TB, which accounted for more than 30 % of the total number in China. These lakes covered an area of $41,831.72 \text{ km}^2$, accounting for more than 50 % of the total area of lakes in China. We also discovered 30 newborn lakes ($>1 \text{ km}^2$) and 5 dead lakes whose area used to be greater than 1 km^2 ; (2) Among 13 big lakes ($>500 \text{ km}^2$), Yamzhog Yumco and Qinghai Lake had severely shrunk up to our investigation period. The latest researches indicated that Yamzhog Yumco has continued to diminish in recent years, but Qinghai Lake has been expanding since the year 2004 (due to the melting glacier of Qilian Mountain and the increasing precipitation around the basin). Siling Co, Nam Co, and Chibuzhang Co in the Nagqu Region had expanded during our investigation, since the temperature had been increasing which led to the melting of glaciers; (3) We classified newborn lakes into six categories: (i) river expanded to lake, (ii) wetland converted to lake, (iii) saline alkali or sandy land converted to lake, (iv) Gobi Desert converted to lake, (v) glacier meltwater became lake, and (vi) seasonal lake with water in wet season, but saline alkali land in dry season. Newborn lakes were small with the largest one no more than 40 km^2 . There were five dead lakes in total, and most of them dried up because of the strong natural evaporation; (4) we discussed the changes of lakes in the Nagqu Region, the Kekexili Region, and the SAYR as well as the response to climate change. Overall, most lakes in Nagqu and Kekexili have expanded; meanwhile, most lakes in the SAYR have shrunk. These regional patterns of lake changes were highly related to variations of temperature, glacier melt, precipitation, and evaporation.

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