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Changes in glacial lakes in the Poiqu River Basin in the central Himalayas

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Abstract: The Poiqu River Basin contains 162.2 km^2 of ice and 19.9 km^2 of glacial lakes. The remote sensing data over the last 40 years have been used to identify 147 glacial lakes in the basin and clearly revealed the retreat of glaciers and the growth of glacial lakes at accelerating rates, in parallel to warming climate in the Himalayas. Based on remote sensing images and digital elevation model (DEM) analysis, the area and water changes in glaciers and glacial lakes are analyzed in detail, and a water balance equation (WBE) is proposed to account for the mechanism of lake growth. The WBE includes water supplies from rainfall runoff, ice and snow ablation, glacial retreat, and water losses due to infiltration and evaporation. As each water contribution item specifically depends on local weather and morphology, the WBE provides a direct link between glacier and glacial lake changes and climate changes under local conditions. Operation of the WBE for five major glacial lakes in the Poiqu River Basin has revealed that water from glaciers and snow cover dominates the growth of lakes. Lakes are found to vary in different ways even with similar backgrounds, depending strongly on local weather and geomorphology conditions. The WBE is not only applicable for predicting future changes in glacial lakes under climate warming conditions but is also useful for assessing water resources from rivers in the central Himalayas.

Keywords: glacier; glacial lake; global warming; water balance; Poiqu River Basin; Himalayas

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1 Introduction

Worldwide glacial retreat due to global warming has led to great changes in alpine glacial lakes (*IPCC, 2013; Mergili et al., 2013; Nie et al., 2014; Wang and Zhang, 2014; Prakash and Nagarajan, 2017*). Apart from glaciers in the Arctic and Antarctic, accounting for 45.5% and 18.8% of the total, respectively, most glaciers are distributed in Asia, mainly in central, southeast and southwest Asia, accounting for 13.8% of the total (*Mu et al., 2018*). Most glaciers retreat at increasing rates (*Solomina et al., 2016*). In the mountains of the Andes, Caucasus, Altay, and the Canadian Arctic region, glaciers have reduced in thickness by 3.6-11 m, while in the mountains of Tianshan, Alaska, Svalbard, Alps, and the Pacific coast, glaciers have thinned by up to 30 m (*Zhang, et al., 2015; 2019*). As the warming rate is much higher in Asian alpine areas, it is expected that approximately 36% of the ice will be lost by the end of this century (*Kraaijenbrink et al., 2017*).

The glacier inventory indicates that the area of glaciers in the Tibetan Plateau has reduced by 9.5% (767 km^2) in the last 40 years (*Wang et al., 2012; Nie et al., 2017*). The reduction in the south is much larger than that in the north (*Wei et al., 2014*), and the greatest changes in glacier area and length occur in the Himalayas (*Yao et al., 2012*). The retreat of glaciers in the Himalayas has led to the expansion of existing glacial lakes and the generation of new lakes (*Richardson and Reynolds, 2000; Komori, 2008; Bolch et al., 2008; Bajracharya et al., 2007; Yao, 2010; Shrestha and Aryal, 2011; Raj et al., 2013*). Approximately 4950 lakes were identified in the Himalayas in 2015, mainly of which were located between altitudes of 4000 and 5700 m, with a total area of 455.3 ±72.7 km^2, which has increased by approximately 14.1% since 1990 (*Nie et al., 2017*). In particular, in the central Chinese Himalayas, the glacial lake area has increased greatly, from 166.48 to 215.28 km^2, although the number of lakes has decreased, from 1750 to 1680 in the last 40 years (*Wang et al., 2012*). This implies that the changes in glacial lakes are mainly due to the expansion of existing lakes. Statistics show that the expansion accounts for 67% of the area increase, while the formation of a new glacial lake contributes only 33%. This expansion depends on the fact that most lakes are fed by melt water of glaciers. In fact, the lakes associated with glaciers increased by 122.1% in area during 1976-2010 in the central Himalayas, while lakes without melt water remained steady, increasing only 2.8% in area during the same period (*Wang et al., 2015*). Thus, the increase in glacial lakes is associated with the retreat of glaciers.

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Glacial retreat appears most remarkably in the south central Himalayas (*Nie et al., 2017*), where the last 30 years have witnessed a glacier length reduction of approximately 48.2 m on average and area reduction at a rate of 0.57%. In the southern Himalayas lies the Koshi River, which has attracted great attention because glaciers have decreased by approximately 19% in area in the last 40 years (*Shangguan et al., 2014; Xiang et al., 2018*), and the melt rate has been accelerating in the last decade. From 2000 to 2009, this glacial lake increased by 10% in area (0.7 km^2/a) (*Wang and Zhang, 2014*). Moreover, the Poiqu River (Bhote Koshi River), a tributary of the Sun Koshi River, is a more active location for dramatic changes in glaciers and glacial lakes. Landsat data indicate that the annual retreat rate of Poiqu was approximately 0.54% between 1976-2010, and in 1986-2001, it increased up to 1.3% per year (*Chen et al., 2007)* and has been accelerating since 2000 (*Xiang et al., 2014*). Consequently, the glacial lake increased by 47% in area (0.37 km^2/a) (*Chen et al., 2007*) in 1986-2001.

The retreat of glaciers and the growth of lakes are generally believed to be caused by rising temperatures and decreasing rainfall (*Yao et al., 2012; Xiang et al., 2014; Mir et al., 2014*). Records show that the temperature in the west Himalayas has increased by approximately 1.7°C in the last century, while the rainfall is decreasing (e.g., *Bhutiyani et al., 2009; Mir et al., 2015a; 2015b*). In particular, observations in the Tibetan Plateau indicate that there is a strong tendency of temperature rise at high elevations (*Liu and Chen., 2000*), and the rising rate increases with elevation, reaching its highest at approximately 4800 to 6200 m. (*Qin et al., 2009*), which is in the range of glacier development.

Although it is well acknowledged that glaciers and glacial lakes are sensitive indicators of climate change, most studies are merely taken at large spatial and temporal scales, and only a gross tendency is outlined for the changes (*Chen et al., 2007; Wang and Zhang, 2014; Wang et al., 2015; Wang and Jiao, 2015; Xiang et al., 2018; Zhang et al., 2019*); special cases are only concerned with lake breaks (*Xu and Feng, 1988; Chen et al., 2007; Wang et al., 2018; Nie Y et al., 2018*). In the present study, we use multisource images from the last 30 years to explore the lake variation in the Poiqu River Basin and provide a quantitative analysis of the water balance, which leads to a method for assessing glacial lake change under a warming climate and sheds new light on the mechanism of glacial lake evolution.

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2 Study area

2.1 Geomorphology of the Poiqu River Basin

Remote sensing data and field surveys indicate that the Poiqu River Basin is an area of concentration for glaciers and glacial lakes. The Poiqu River (known as the Bhote Keshi River in Nepal) is the boundary river between China and Nepal, which is located along the southern slope of the central Himalayas, between the Himalayas and Laguigang Mountains.

Within the Chinese territory, the length of the Poiqu River is 90 km, and the basin area is 2.54×10^3 km^2, dropping from a high of 5810 m at the source peak to a low of 1750 m, with an average relief of 41‰. The section from Nyalam County to Zhangmu port is approximately 25.27 km in length, the average elevation difference is 2010 m, and the average vertical drop is 79.5‰. According to the ZY-3 satellite image on August 28, 2019, the total ice area in the Poiqu River Basin is approximately 162.2 km^2, and the total glacial lake area is 19.9 km^2 (Fig. 1).

Fig. 1 Poiqu River Basin as a typical glacial lake in the central Himalayas

Geologically, the Poiqu River Basin is located in the central Himalayan terrane, which was formed by the Indian-Eurasian plate collision. The Himalayan orogenic belt has a crystalline basement complex anticline north wing (the anticline is located in Nepal). The whole basin runs through the northern Himalayan Tethyan sedimentary rock belt, high Himalayan, low Himalayan and other tectonic units, all of which are bounded by the South Tibet detachment fault (STDS) and the main central fault (MCT) (Fig. 2).

Fig. 2 Geological background of the Poiqu River Basin (Base map based on Pan, 2013)

The Sun Koshi River developed and cut through the MCT, and the Poiqu River has experienced many tectonic movements since the Pliocene; however, the difference in the local zone due to tectonic effects has been relatively reduced because of the large uplift of the plateau. The uplifted mountains continue to be eroded and denuded, while the relatively sloped gullies receive uneven amounts of loose accumulation. Under such a background, the Poiqu River is mainly characterized by alluvial and diluvial valleys, with widths of 20 m to 200 m. The riverbed twists and turns and

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develops multilevel terraces. To the south of Nyalam county, the valley bottom is narrow with steep walls, most of which are V-shaped and Y-shaped valleys. The longitudinal section of the riverbed is undulating, with multiple waterfalls and turbulence.

2.2 Climate and hydrology

The main Himalayas edge divides the Poiqu River into two climate zones: the northern zone, featured by Yalai village, is temperate and subhumid, with an average annual temperature (T_a) of 3.5°C and rainfall (R_a) of 1100 mm; the southern zone, featured by Zhangmu town, is in the subtropic monsoon climate, with T_a of 10~20°C, R_a of 2500~3000 mm, and frost-free period of 250 days, which is the area with the highest concentration of rainfall worldwide. According to weather records in Zhangmu, T_a is approximately 12°C, R_a has been 2820 mm in recent years, and more than 80% of rainfall occurs between June and September. Fig. 3 displays the 2016 daily temperature records in the study area. The average temperature is similar in Nylamu and Quxiang, where the positive temperature is concentrated between April and October, coincident with the rainy season.

The Poiqu River has 5 major tributary rivers larger than 100 km^2, i.e., Chongduipu, Keyapu, Rujiapu, Tongqu, and Dianchanggou. Rainstorms during the rainy season often cause floods in these rivers. Field surveys indicate that the average annual discharge in the Chongduipu tributary is 5.8 m^3/s, and it is 31.7 m^3/s in the Poiqu mainstream, with high seasonal fluctuations.

Fig. 3. Monthly temperature and precipitation records in the study area

3 Identification of glaciers and glacial lakes

3.1 Data sources and image processing

3.1.1 Data sources

Landform data are mainly from ALOS-12.5 m and ASTER-30 m elevation data, which are used for correcting remote sensing data and interpretation. Geological data come from geological maps of the Tibet Plateau. Remote sensing data come from the Landsat, GF-2, ZY-3, and UAV satellites, as listed in Tables 1 and 2.

Table 1 Data sources and features for interpretation of glaciers and glacial lakes

3.1.2 Image processing

Generally, we use the fusion method to integrate the multispectrum data of 4 m GF-2 and the full color data of 1 m GF-2 to create a base map for interpretation. In detail, for TM data, we use 742 band combinations and 432 combinations to highlight the colors of glaciers and glacial lakes; for the data from GF-2, we combine the 321 bands of true color and the standard 432 bands of false color images. Then, the ratios between different bands of the multispectrum data are used to create images at different gray levels.

For glaciers, reflectivity is large for green light and small for intermediate infrared light. Thus, the NDSI is employed to obtain the gray images, which is calculated as follows (Zhang *et al*., 2006):

$$NDSI=(float(b_{Green}) - float(b_{SWIR}))/(float(b_{Green}) + float(b_{SWIR})) \quad (1)$$

where B_{Green} is the green band and B_{SWIR1} is the intermediate infrared band. The index falls between -1 and 1, which can be further readjusted using ENVI software to provide the proper threshold. In this study, we set NDSI>0.35 as the threshold for glaciers.

For glacial lakes, reflectivity of blue light is large and it approaches zero for near infrared, so the NDWI is used to create the gray images, which is calculated as follows (Zhang *et al*., 2006):

$$NDWI= (p\ (Green) - p\ (NIR))/\ (p\ (Green) + p\ (NIR)) \quad (2)$$

where p(Green) and p(NIR) are the reflectivities of green and near infrared light, respectively. Similar to the NDSI, we set NDWI>0 for water, which can be used as a criterion to identify glacial lakes since there are no other water bodies in the study area.

3.2 Identification of glaciers and glacial lakes

Glaciers and glacial lakes present special shapes, colors, textures, and band combinations in the images. Fig. 4 displays the images with characteristic marks, and Table 2 lists the signs for identifying types of glaciers and glacial lakes. In practice, these elements are combined with morphology and DEM data to delineate the boundary of lakes or glaciers. Moreover, moraines, deposits, and colluvium are also identified by their marks and spectral features.

In particular, glaciers are located near mountain tops and limited to certain elevations. Glaciers usually have tongue-shaped fronts with flow lines, and the uppermost boundary coincides with the mountain edge, with ice cracks on the trailing edge, which are shown in black in the image. Glacial lakes occur below glaciers, usually elliptical or flat, with smooth boundaries.

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Fig. 4. Characteristics of glaciers and glacial lakes in the Poiqu River Basin

Table 2 Interpretation signs for glaciers and glacial lakes（Six pictures are from Google Earth images and two pictures are from GF-2 images. They are signed in the lower right corner）

3.3 Results of interpretation

A total of 147 glacial lakes and related glaciers have been identified in the Poiqu River Basin, with a glacier area of 162.2 km^2 and a glacial lake area of 19.9 km^2. Table 3 lists the types and numbers of each lakes. Most of these lakes are end moraine lakes.

Table 3 Types of glacial lakes in the Poiqu River Basin

These lakes have areas ranging between 1.66×10^{-4} ~ 5.50 km^2, and 125 lakes are smaller than 0.1 km^2. More than 60% of lakes are located at altitudes between 5000 ~ 5500 m. Lakes larger than 0.1 km^2 are mainly in the tributaries of Keyapu, Rujiapu, and Chongduipu in upper Poiqu and in Zhangzangbu in middle Poiqu. As listed in Table 4, more than half of the lake area is located in Chonduipu, approximately 9.51 km^2, and the second largest is Keyapu at approximately 5.44 km^2. These lakes account for 83% of the total area of glacial lakes. The table also lists the distance of the lake to its connected glacier, indicating that most lakes are nearly linked to the glacier and thus their changes are expected to be well correlated.

Table 4 Typical glacial lakes in tributaries of the Poiqu River Basin

Fig. 5 provides detailed distributions of glacial lakes in 4 major tributaries of Poiqu: Chongduipu tributary (Fig. 5A), Zhangzangpu tributary (Fig. 5B), Keyapu tributary (Fig. 5C) and Rujiapu tributary (Fig. 5D), where we have relatively large glacial lakes for consideration, i.e., Galongco Lake (5.50 km^2), Gangxico Lake (4.60 km^2), Jialongco Lake (0.60 km^2), Longmuqieco Lake (0.52 km^2), and Cirenmaco Lake (0.33 km^2). The features of the tributaries are as follows:

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Fig. 5 Distribution of glaciers and glacial lakes in the major tributaries of the Poiqu River Basin

1) Chongduipu lies in the western part of middle Poiqu, with a long, lobate form and U-shaped channel, which flows from northwest to southeast. Chongduipu has four tributaries, and the largest glacial Lake Galongco is located in the Jirepu tributary and supplied by the Jipuchong glacier on the southeastern slope of Mt. Shisha Pangma.

2) Zhangzangbu joins Poiqu from the east in the middle reach in the form of broad branches and V-shaped channels, which deeply cut the valley and leaves flow marks of approximately 30 m. Glaciers are mainly distributed in the upper reaches, and Cirenmaco Lake is located in a tributary in the eastern source area.

3) Rujiapu is a tributary of Tongqu and thus a secondary tributary of Poiqu. Rujiapu lies in the eastern part of the upper reaches, forming long branches and U-shaped channels. It has a 90°-turn near the mainstream, flowing from northeast to southwest, and the glacial lakes are concentrated in the southeast. Moreover, the Rujiapi tributary has four tributaries with distributions of glaciers and lakes.

4) Keyapu lies in the upper western part of Poiqu, near Chongduipu in the source area. Keyapu has broad branches and a U-shaped channel. Glaciers and glacial lakes are mainly distributed in the southeast.

Table 5 lists basic parameters of the tributaries, which are crucial for the formation and evolution of the lakes, and parameters for the major lakes in the present state, based on interpretation of 2018 images, are listed in Table 6.

Table 5 Parameters of the glacial lake tributaries

Table 6 Basic parameters for major glacial lakes in the Poiqu River Basin

4 Changes in glaciers and glacial lakes

4.1 Variations in glaciers and glacial lakes

Interpretations of the multisource images allow for detailed scrutiny of changes in glaciers and glacial lakes. In this way, we obtain the areas of glaciers and glacial lakes in recent decades.

Fig. 6 shows the total changes in glacier and glacial lake areas in Poiqu since 1977, where the dotted line means that the curve is inferred only because of the lack of data before 1999. Despite the possible uncertainty before 1999, the gross tendency of glacier loss and glacial lake growth is clear. The retreat rate of glacier area reaches 43.6%, which is approximately 2.98 km^2/a; accordingly, the glacial lake area has expanded by 169%, which is approximately 0.19 km^2/a. Since 2004, the retreat rate has reached as high as 7.2 km^2/a, while the growth rate of the lake has reached 0.44 km^2/a (in Table 7).

This finding is comparable to the results from the literature. For example, from 1975 to 2010, glaciers decreased by 19% in area (*Xiang et al., 2014*), while glacial lake area increased by 83% (approximately 0.26 km^2/a) from 1976-2010 (*Wang et al., 2015*). In 1986-2001, the glacial area increased by 47% (approximately 0.37 km^2/a) (*Chen et al., 2007*).

For comparison, glacial lakes increased by 29.7% in the entire Chinese Koshi River (including Poiqu and six other tributary rivers) in 1976-2000 (*Shrestha and Aryal, 2011; Wang et al., 2012*) at a rate of approximately 1.6 km^2/a. In the Koshi River, the glacier area has decreased by 19% (approximately 23.48 km^2/a) (*Shangguan et al., 2014; Xiang et al., 2018*), and the glacial lake area has increased by 10.6%. In 2000-2010, the glacial lake increased by 6% in area (approximately 0.72 km^2/a) (*Wang et al., 2015*). This result means that Poiqu undergoes more dramatic changes in glaciers and glacial lakes. In particular, the Galongco and Gangxico Lakes have increased up to 500% and 107%, respectively, following area decreases in their connected glaciers by 40%.

Table 7 Area variations and annual speeds of glaciers and glacial lakes in Poiqu river Basin since 1977

Fig. 6 Area variations in glaciers and glacial lakes in Poiqu

Table 8 Area variations in 5 typical glacial lakes and their glaciers since 1977

Figs. 7-10 show pictures for the five major lakes and their connected glaciers (or the so-called "mother glaciers", because they are the sources of generation for the connected glacial lakes) in different years between 1977 and 2018. It is easy to calculate the area of glaciers and glacial lakes in each stage, as listed in Table 8. (The data sources for the images in different years are listed in

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Table 1 and Table 2).

For more details, we construct the annual variation in the lakes from the historical data; Fig. 11 shows the variation in Galongco Lake since 1977, which increased abruptly from 1.77 to 5.50 km^2 between 1977 and 2018.

Fig. 7 Comparison of area change between Cirenmaco Lake and its connected glacier

Fig.8 Comparison of area change between Gangpuco Lake and its connected glacier

Fig. 9 Comparison of area change between Ganxico Lake and its connected glacier

Fig. 10 Comparison of area change between Longmuqieco Lake and its connected glacier

Fig. 11 Variation in the area of Galongco Lake (1977-2019) (The left image is from © Google Earth and the right image about the Galongco Lake is from UAV image)

The retreat-growth correlation can be seen more clearly from the large lakes mentioned above, as shown in Table 9 and Fig. 12. The gross tendency of glacial retreat and glacial lake growth is also remarkable here. Notably, there was a sudden decrease in area in 1981, simply because there was an outburst (*Xu and Feng, 1988*). Thus, historical anomalies in glacial lake areas may be caused by lake outbursts.

Table 9 Annual rates of change in 5 typical glacial lakes and their glaciers

Fig. 12 Retreat of 5 typical glaciers, growth of 5 typical glacial lakes and rates of change in the Poiqu River Basin

The five major lakes, Cirenmaco Lake, Galongco Lake, Gangxico Lake, Jialongco Lake, and Longmuqieco Lake, have increased up to 30%, 74%, 40%, 200%, and 54% at rates of 0.01 km^2/a, 0.13 km^2/a, 0.07 km^2/a, 0.02 km^2/a, and 0.01 km^2/a, respectively, from 1977 to 2018.

Corresponding to the decrease in glaciers, the variations in glacial lakes under consideration have presented three patterns in recent years:

1) Fluctuation in area, as in the case of Cirenmaco and Jialongco (Tables 8 and 9 and Fig. 12A).

Both lakes are located at relatively low altitudes (Jialongco is at 4306 m and Cirenmaco is at 4639 m), are sensitive to temperature and both experienced an outburst in this episode (in 1981 and 2002, respectively) and then increased steadily. Jialongco Lake even experienced a sudden rise during 2006 and 2008 (Fig. 13), when the local temperature reached its 50-year peak. Moreover, a field survey indicates that Jialongco has an overflow at 0.3 m^3/s in the rainy season, meaning that the lake has reached its maximum and thus fluctuates, similar to ordinary lakes undergoing seasonal changes. This finding implies that small amounts of variation in glacial lakes do not mean that the related glaciers also vary by small amounts. Dramatic change in glaciers results in a great loss of water but does not necessarily increase the size of the connected lake.

Fig. 13 Rapid rise in Jialongco Lake due to glacial loss (2002-2009)

2) Remarkable increase in area, as in the case of Galong Lake and Longmuqieco Lake (Tables 8 and 9 and Fig. 12B).

Historic remote sensing data (1954 ~ 2018) indicate that Galongco formed in the late 1960s as a result of a warming climate. Then, the lake increased steadily, with no marks of historic outburst and no overflow events based on recent UAV images. Indeed, the lake level is still 10 m below the front moraine bank, and it is only at 1 km downstream that the water flows from infiltration. Thus, the lake has had little loss of water and increases steadily. Despite no field survey data, the same case can be expected for Longmuqieco, which has similar altitude and water supply areas and connected glaciers.

3) Gentle increase in area, as in the case of Gangxico (Tables 8 and 9 and Fig. 12C). Gangxico is supplied by the back glacier. As the glacier is small, the lake grows slowly. Moreover, Gongxico is hydraulically connected near Gongco and Galongco, and its water enters Gongco in the southern area through infiltration, while the water of Gongco infiltrates into Galongco (Fig. 14). As Gongco has remained steady in last 50 years, Gongxico is also in a balanced state and

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shows a small tendency to increase.

These observations suggest that glacial lakes change in various patterns even under the same local conditions. Furthermore, little variation in glacial lake area does not necessarily mean that there are no changes in related glaciers. In this sense, glaciers are more sensitive to changes in weather or climate.

Fig. 14 Hydraulically connected glacial lakes (Galongco, Gangco, and Gangxico)

4.2 Influences of temperature and precipitation

As glaciers are sensitive to temperature, it is reasonable to consider the effects of weather on the changes in glaciers and glacial lakes. Unfortunately, weather stations are very sparse in the Himalayas, and no stations in the tributaries are under consideration; only records from nearby stations are accessible. Near the study area, we have three weather stations in Nylamu, Quxiang, and Zhangmu at altitudes of 3900 m, 3300 m, and 2200 m, which not only represent the vertical variations in weather but also the variations from north to south. Chongpudui and Rujiapu are in the northwestern and northeastern areas of Nylamu, respectively, and both rivers are similar to the whole county in terms of weather conditions, so the temperature and precipitation for lakes (i.e., Galongco, Jialongco, and Longmuqieco) in these tributaries can be interpolated from the records in Nylamu. Similarly, the weather of the Zhangzangbu (for Cirenmaco Lake) River is interpolated from the records in Quxiang.

Combining the data from the three stations may comprehensively reflect the weather features of the study area. The key factor for interpolation is the gradient of temperature (R_T) and precipitation (R_P) varying with elevation. To obtain the R_T and R_P, we take the records of Nylamu and Zhangmu in 2016. The daily R_T is defined as follows:

$$R_T = (T_N - T_Z) / (Al_N - Al_Z) \quad (3)$$

where T_N and T_Z are the daily temperatures recorded in Nylamu and Zhangmu, respectively, and Al_N and Al_Z are the altitudes of the two stations. This gives an R_T of -6.1 ℃/km. As precipitation in the study area is also governed by altitude, R_P can be obtained in a similar way, i.e., the precipitation difference divided by the altitude difference between the two stations, which gives a value of -10 mm/km. The minus symbol means a decrease with altitude. Fig. 15 displays the

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interpolated temperature and precipitation for the glacial lakes under consideration. Then, both the interpolated temperature and precipitation for the target point can be obtained in the same way:

$$T_H = T_0 - R_T\Delta H, \text{ and } P_H = P_0 - R_P\Delta H \quad (4)$$

where the subscript H means the altitude of the target points (i.e., the tributary rivers or the glacial lakes) and 0 indicates the recorded values.

Fig. 15A. Interpolated cumulative temperature

Fig. 15B. Interpolated annual precipitation

Fig. 15 Interpolated temperatures and precipitation for the glacial lakes

Based on the interpolation, the temperature rises at a rate of approximately 0.02°C/a in Poiqu, accompanied by a rainfall rate of 0.76 mm/a between 1989 and 2018.

Fig. 16 shows the temperature series in the last forty years in contrast to the areas of glaciers and glacial lakes, indicating that the temperature is negatively and positively related to glaciers and glacial lakes. Fig. 17 shows the precipitation series in contrast to the areas of glaciers and glacial lakes, indicating that the tendency of precipitation is negatively associated with glaciers but positively associated with glacial lakes. On the other hand, it is found that precipitation is well correlated with temperature, with a correlation coefficient larger than 0.5. In short, the growth of glacial lakes following the retreat of glaciers is governed by warming conditions.

Fig. 16A Changes in the area of glaciers vs. temperature

Fig. 16B Changes in the area of glacial lakes vs. temperature

Fig. 16 Changes in the area of glaciers and glacial lakes vs. temperature in Poiqu

Fig. 17A Changes in the area of glaciers vs. precipitation

Fig. 17B Changes in the area of glacial lakes vs. precipitation

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Fig. 17 Changes in the area of glaciers and glacial lakes vs. precipitation in Poiqu

Despite the remarkable fluctuation in various episodes, the weather conditions present a gross tendency in parallel to the retreat of glaciers and growth of glacial lakes. In fact, the temperature in the Tibet plateau increased at a rate of approximately 0.3-0.4°C per ten years, nearly two times the global rate. For the case of the present study, the lake area increases by approximately 40% at a rate of 0.28 km^2/a, which is clearly higher than the other regions in the Himalayas (*Nie et al., 2017*).

In the following section, we propose a procedure to calculate the water balance for typical glacial lakes, illustrating the weather effects on the changes in glaciers and glacial lakes in different ways.

5 Water balance for glacial lakes

5.1 Volume of glacial lakes

To understand changes in glacial lakes, it is necessary to find the changes in water volume in the lakes. Then, we must find the lake volume from the area. This procedure can be done using ArcGIS tools. First, we create the DEM of the lake bottom using images at the time the lake formed and the following periods. Meanwhile, we interpret the annual water level from a series of images, which record the evolution of the lake (cf. Fig. 11). In detail, we create irregular triangle nets (ITNs) under the control of contour lines and obtain the DEM since the formation of the lake. Then, the average elevation of the lake boundary (i.e., the water level) can be obtained for many years. Finally, we compare the DEM derived from the water level and the DEM before lake extension and obtain the variation in the water level with the water volume (Fig. 18). For example, Galongco has the following relationship between lake volume and area: $V_{lake} = 5.0A^{1.72}$ (10^6 m^3), where A is the lake area (in units of km^2).

Fig. 18 Terrain reconstruction of GB Lake below the water level

5.2 Water balance equation (WBE)

The observations above indicate that the expansion of glacial lakes is well related to the retreat of glaciers, which in turn relies on changes in temperature and precipitation (rainfall and snow) in recent years. Then, it is possible to propose the following water balance equation (WBE) for a glacial lake:

$$\Delta V = \Delta P + \Delta G - \Delta I - \Delta E \quad (5)$$

where V, P, G, I, and E are the water quantities of the glacial lake, the water supplies from precipitation (rainfall and snow), glacier loss and ice-snow melting, and water loss through infiltration and evaporation, respectively; Δ represents the annual increment.

In detail, the items in WBE are closely related to weather and geomorphologic conditions and can only be determined empirically.

1) Water supplies from precipitation (P_R, P_S)

This involves rainfall and snowfall. The water supply from rainfall (P_R) is governed by the hydrological process in the valley. For a given valley, the runoff depends on the rainfall process (often featured by intensity R and quantity Q_R), the drainage area contributing to the lake (S), and the geomorphologic factors such as slope θ, vegetation cover, and permeability K. In general, this can be expressed as follows:

$$P_R = f(R, Q_R, S, \theta, K) \quad (6)$$

Water supplies from snowfall (P_S) also depend on temperature T, solar radiation I_R, snow density ρ_S, and snow permeability k, in addition to the geomorphologic factors:

$$P_S = f(T, I_R, \rho_S, k, S, \theta, K) \quad (7)$$

Then, the water supplied from precipitation is as follows:

$$P = P_R + P_S \quad (8)$$

2) Water supplies from glaciers (G)

The major controlling factors are temperature T, solar radiation I_R, glacier density ρ_G, fracture density σ, and geomorphologic factors:

$$G = f(T, I, \rho_G, \sigma, S, \theta, K) \quad (9)$$

3) Water loss from infiltration (I)

Infiltration mainly depends on the permeability of the materials constituting the lake, and in the present case, the materials are mainly moraines, which are generally poorly graded in terms of grain composition and have high porosity. Infiltration also occurs underground and depends on the substrate sediment of the valley channel downstream of the lake.

$$I = f(K, GSD, J) \quad (10)$$

where GSD describes the granular features of moraines and sediments (*Li et al., 2013, 2017*) in terms of grain size distribution, and J is the hydraulic slope between the water level and seepage points.

In addition, when the lake is "saturated", i.e., the capacity reaches the maximum due to the limitation of the local landform, the lake will not increase in area, and the water supplies exceeding the capacity will be lost through overflow. In such a case, the supply is balanced by the loss.

4) Water loss from evaporation (*E*)

Theoretically, evaporation is controlled by temperature, solar radiation, lake area *A*, wind speed *v*, surface saturated vapor pressure *p*, and turbulent energy ε (Lu *et al*., 2017):

$$E = f(T, I_R, v, p, \varepsilon) \tag{11}$$

However, for the present case, the effect due to evaporation is much smaller and is usually ignorable compared with the other contributing terms.

5.3 Practical operation of the balance equation

In practice, each item introduced in the WBE can be empirically estimated, especially in the present case, where we suffer from a severe lack of basic solar radiation and local weather data. In the following section, we provide a practical routine for the calculations.

1) Water supplies from rainfall and snow

In principle, the supply is equal to the runoff drainage to the lake, which is calculated using the standard hydrologic method for each rainfall event, depending on the temporal process and spatial distribution of the rainfall over the drainage area. However, for the case of glacial lakes, we have only annual area variation and weather data from nearby stations, and it is impossible to perform standard hydrograph calculations; instead, we reduce the calculation to the runoff of the slope (*Gao et al., 2019*):

$$P_R = \alpha S R_a \tag{12}$$

where P_R is the runoff and employed here as the water supply from rainfall, *S* is the drainage area contributing to the lake, R_a is the annual rainfall, and α is the coefficient, depending on local conditions of the drainage slope, such as the material properties and vegetation cover, which is empirically determined as follows (Liang *et al*. 2018):

$$\alpha = 0.065 + 0.0086\theta + 0.33\text{ALs} \tag{13}$$

where θ is the slope angle, and ALs varies among arid, semiarid, semihumid, and humid areas. As the Poiqu River Basin is located in the semiarid area but has sufficient moisture content in air, ALs can be taken as the upper limit of 0.75. Then, α is mainly governed by the slope gradient of the drainage area to the lake.

2) Melt water from ice and snow melt

There have been various methods used in glacial hydrology (*Braithwaite and Olesen, 1989*). Physical models have incorporated many influencing factors, such as temperature and radiation intensity; thus, these models have high calculation accuracy. However, they do not apply to areas lacking a sufficient database, as in the case in the Himalayas. Instead, empirical methods are widely employed, among which the Degree-Day Model (DDM) is generally most used to calculate the melting of glaciers and snow cover (*Kayastha et al., 2005; Zhang et al., 2006; Pradhananga et al., 2014*). The DDM is practical, simple and well-accepted, considering the influence of the degree-day factor (DDF) and the normal accumulated temperature. Following the method, the melted thickness of the glacier (M) is determined by the production of DDF and the positive cumulative temperature in a certain period (PDD, in units of d·°C):

$$M = DDF \cdot PDD \tag{14}$$

where DDF is in units of mm·d^{-1}·°C^{-1}, and varies with elevation (*Liu et al., 2014*). PDD can be directly calculated from the daily temperature record, i.e., the cumulative temperature of the days with temperatures higher than 2°C. In fact, the PDD involves two components applied to the melt of snow cover and glaciers, PDD_S and PDD_G. In other words, only the residual cumulative temperature PDD_G applies to glacial melting.

Then, the melt water quantity is the production of M and the glacier area (A_G):

$$G = M \cdot A_G \tag{15}$$

Similarly, this also applies to the water supply from snow cover melting. DDF is generally hard to obtain, but in Poiqu, we may make a reference to the results in the nearby area, 80 km away at Mt. Everest. According to previous studies, the DDF is 16.9 for the Kunbu glacier at an altitude of 5350 m (86°52′E，27°59′N) (*Kayastha et al., 2005*), and the DDF is 8.21 for the Rongbu glacier at the same altitude (*Liu et al., 2014*). Then, we take the average value, 12.6, as the overall DDF for glaciers in Poiqu, and for individuals, we make some corrections depending on the slope orientations of the glaciers. For the west-oriented slope (e.g., Cirenmaco Lake), the melt is relatively more intense than the east-oriented slope (e.g., the Galongco and Gangxico Lakes); for the cases of Jialongco and Longmuqieco, the slopes are north-oriented, the sunshine is shielded, and the melt is relatively weak. Based on these results, we obtain a corrected DDF for each glacier (Table 9).

According to studies on the snow cover of the Dokriani Glacier in the Indian Himalayas (78°50′E, 28°50′N) (*Singh et al., 2000*), the DDF for snow is approximately 30% less than that for glaciers. As this is geographically similar to the Poiqu area, a reduction rate of 30% can be used for determining the DDF of snow cover for the glaciers and glacial lakes under consideration, as listed in Table 6.

On the other hand, not all meltwater can reach the connected lake; some infiltrates into the bed through the crevasses. This creates a loss of water supplies from melt water, and a reduction coefficient, R_c, is considered when the water supplies are estimated (cf. Table 5).

3) Evaporation

The Poiqu River is located at high altitude, where the stored water is in a liquid state only in July and August. It is reasonable to assume that the evaporation is very weak in this area and can be ignored in the estimation of water balance. For this estimation, we take Gongco Lake as the

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reference. The lake is located in the tributary of Chongduipu, similar to Galongco and Gangxico, and at similar altitudes (5173, 5075 and 5218 m, respectively). However, it is distinctive in that the Gangco does not receive a water supply from glaciers; the major water supplies come from rainfall. Notably, Gongco has not increased in area, remaining at approximately 2.1 km^2 in recent years. It is possible that the water supplies are balanced by the water losses due to infiltration and evaporation. Since Gongco receives seepage flow from Gangxico and simultaneously feeds Galongco through seepage, the supplies from rainfall can be considered balanced by evaporation. However, according to the estimation, water supplies from rainfall are generally very small compared with those from the meltwater of glaciers and snow cover. Therefore, evaporation is negligible in the Poiqu River.

4) Infiltration

Water loss due to infiltration is controlled by the permeability of the moraine bank of the lake and the sediment in the valley channel. As it is inaccessible to most glacial lake areas, we can only trace the marks of infiltration through remote sensing images (including UAV and Google Earth) (cf. the case of Galongco in Fig. 19).

For the permeability coefficient K, we conducted experiments on material samples from the moraines and sediments, and it was found that K (cm/s) is well related to the grain size distribution (GSD) of the loose granular materials:

$$K=0.003D_c^{1.5}-29.46\mu^{2.5}-0.0196 \ (R^2=0.9892) \tag{16}$$

where D_c and μ are GSD parameters (Li *et al*., 2013; 2017), which can be directly obtained from the granulometric analysis of moraine and sediment samples for each lake. Then, the infiltration discharge can be calculated by Darcy's law:

$$Q = KJA \tag{17}$$

where J is the hydraulic slope and A is the infiltration area. For a given valley, the water loss from infiltration is $I = QT$, with T as the effective time for infiltration, which is mainly the rainy season when the valley has flow water.

Based on the discussions above, we obtain a working list of parameters for calculating the WBE (Table 10).

Table 10 Parameters for the water balance calculation of glacial lakes

5.4 Calculations

5.4.1 Exemplification of Galongco

Now, we apply the WBE to the five major lakes to see how the area has increased in recent decades. For this procedure, we first take glacial Lake Galongco in 2006 as an example to show the calculation process.

1) Geomorphologic background and related parameters

As mentioned above, Galongco Lake is located in a small tributary of Chongduipu, at an altitude of 5075 m, in an area 5.5 km^2, and the drainage area to the lake, including slopes around

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the lake, is 22.33 km^2. Two glaciers are directly connected to the lake in the northwestern and western parts of the upstream area, with a total area of 13.5 km^2 according to the GF-2 satellite images in 2018.

In 2006, the lake area was 3.93 km^{2,} and the glacier area was 13.06 km^2 (Fig. 19). Based on the DEM, the angle of the draining slope is estimated to be 23.7 ° on average, and thus, the runoff coefficient is 0.56 according to Eq. (13).

Following the background of the lake and glaciers, the DDFs for glaciers and snow cover are 12.6 and 8.3, respectively, and the reduction coefficients for glaciers and snow cover are 0.61 and 0.56, respectively (cf. Table 9).

Fig. 19 Galongco Lake and the connected glaciers in 2006

2) Weather conditions

The weather conditions are interpolated from the records in Nylamu; the annual temperature and precipitation in 2006 are shown in Fig. 20 according to this interpolation.

Fig. 20 Temperature and precipitation of Galongco Lake in 2006

Following the instruction above, the rainfall and snowfall in 2006 were 1.5 mm and 1545 mm, respectively, and the cumulative temperature was 282.3°C. Based on the DDM, the cumulative temperature for snow cover melt is 128.3°C, and thus the cumulative temperature for glacial melt is 153°C.

3) Infiltration

According to samples of moraine materials in the lake tributary, the GSD parameter μ is 0.03 and D_C is 11.2 mm, which yields a permeability coefficient K of 0.088 cm/s. According to Google Earth images, the infiltration area is approximately 8426 m^2, and the hydraulic slope is 0.13, which gives a discharge of infiltration of 0.96 m^3/s. Considering that only July and August have positive temperatures higher than 2°C, infiltration only occurs in these months.

4) Water supplies and losses

Based on the parameters described above and using formulas (6)-(9), we obtain the water supplies and losses:

(i) the water supply from rainfall (P_R) is 1.56×10^5 m^3;

(ii) the water supply from glacial melting (P_S) is 1.90×10^6 m^3;

(iii) the water supply from snow melting (G) is 8.11×10^6 m^3; and

(iv) the water loss from infiltration is (*I*)5.92×10^6 m^3.

Therefore, the WBE provides a water supply of 4.25×10^6 m^3 to the lake in 2006, which accounts for the area increase of 0.33 km^2.

In the same way, we can calculate the water balance for other years. Notably, for some years, no data are available for glaciers or lakes (e.g., only three sets of data are available between 1988 and 2004); for these situations, we use an extrapolation method. Considering that the changes in glaciers and glacial lakes have steady near-linear tendencies in recent years, we can assume that both glaciers and glacial lakes in the years between 1988 and 2004 vary linearly, with the average rate determined by the slope of the line linking the points of 1988 and 2004. Thus, we can infer the area of glaciers and glacial lakes in those years. Specifically, for Galongco, the variation rate of glaciers between 2004 and 2018 is -0.36 (R^2=0.8956), and the variation rate of glacial lakes is 0.15 (R^2=0.8779), which provides a baseline for extrapolation in recent years.

Using the methods above, we obtain the water balance for Galomngco between 1988 and 2018, as listed in Table 10, and the symbols in Table 11 are listed as follows:

T_c – cumulative temperature;

T_{cG} – cumulative temperature for glacial melting;

T_{cS} – cumulative temperature for snow melting, which is T_c - T_{cG};

M_G –melt thickness of a glacier;

W_G – water supply from glaciers;

W_{snow} – water supply from snow cover; and

W_{total} –total quantity of water supplies.

Table 11 Water balance for Galongco Lake between 1988 and 2018

5.4.2 Water balance for typical lakes

Similarly, we can perform balance calculations for other lakes, from which we obtain the variation in water quantity for the lakes since 1988 using the parameters listed in Table 6. Table 12 displays the comparison between the calculated water quantity and the observed quantity for the five selected lakes.

Table 12 Comparison between the calculated water quantity and the observed quantity

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The calculations generally agree with the observations, but it is noted that great discrepancy occurs in the case of Jialongco, the lowest lake among the five samples at an altitude of 4306 m, which experienced an outburst in 2002 and sudden rise during 2006 and 2008 due to dramatic changes in the connected glacier (cf. Fig. 13). As the WBE does not consider the glacial dynamics and dramatic changes in local conditions, the calculation cannot incorporate the sudden changes. This means that the WBE operation should be further improved to incorporate the water variations due to catastrophic processes.

However, the gross agreement between the calculation and observation does suggest that the WBE has provided a practical and functional framework for understanding the characteristics of changes in individual glacial lakes. Moreover, it provides a practical method for quantitatively assessing the growth of glacial lakes. In particular, the calculation reveals that the lakes in Poiqu have undergone different water supply balance proportions, which makes it possible to distinguish among the local conditions of the lakes.

Table 13 lists the average fraction of water supplies from glaciers, snow, and rainfall over the calculation period. It is obvious that lakes at relatively low elevations (i.e., below approximately 5000 m) are mainly supplied by glaciers, and lakes at high elevations are mainly supplied by snowfall. For all these lakes, the water supplies from rainfall are much smaller, even below 5%, and this can almost be ignored considering the accuracy of the estimation. This clearly reflects the altitude effect on glaciers. At low altitudes, the cumulative annual temperature is positive and directly melts the glaciers. At high altitudes, glaciers are covered by snow, and the positive temperature mainly acts on snow cover. Indeed, several years have shown near-zero cumulative temperatures for Gangxico Lake and Longmuqieco Lake, which results in a small fraction of glacial ablation.

Table 13 Fractions of various water supplies to the lakes

Then, the WBE not only provides a method to account for the water supplies to glacial lakes but also reveals differences between lakes. Although glaciers are sensitive to temperature, the lake grows in various ways depending on local conditions, especially altitude and basin circumstances (e.g., morphology and moraine materials).

6 Discussions

Based on the present study, we can remark on some of the problems concerning changes in

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glaciers and glacial lakes under warming conditions.

1) Changes in temperature and precipitation have been recognized as effecting ice and snow melt and leading to serious consequences for both nature and society (Immerzeel *et al*., 2012; Immerzeel *et al*., 2013). Recently, the estimation of ice thickness distribution indicated that the present-day glacier area in highly mountainous Asia will decrease by half at an accelerating rate, approximately one decade ahead of schedule, as suggested in previous studies (Farinotti *et al*., 2019). A detailed analysis in the present study proves that changes in glaciers and glacial lakes in Poiqu are at remarkably high levels compared with other regions in the Himalayas (Nie *et al*., 2017). In particular, although the glaciers are generally in their retreat phase, water supplies from glaciers are still dominant in the central Himalayas. However, it is also noted that the fluctuation of temperature and precipitation in local areas does not present a clear-cut tendency in parallel with the retreat of glaciers or growth of glacial lakes. Changes in individual glaciers and glacial lakes are dominated by local conditions but not global changes.

2) Mass balance for glaciers and ice caps is of great importance in Earth's hydrological cycle and response to climate change (*Aizen and Aizen, 1997; Haeberli et al., 1999; Valentina Radić and Hock, 2013; Lambrecht and Mayer, 2009; Huss, 2011; Huss and Hock, 2018*). The results of this study provide a detailed scenario of water balance for individual lakes through operation of WBE for typical glacial lakes, revealing details in water supplies from precipitation, glaciers, and snow cover and water losses from infiltration. The WBE provides the mechanism for lake growth and agrees well with the observations and image interpretations, and the calculation for individual lakes has made up for the deficiencies in previous studies, which only gave an overall view of lake expansion at the regional scale (e.g., Nie *et al*., 2017). In addition, the WBE operation has also discovered that glacial lakes under similar background conditions may vary in different ways, depending on local elements at small scales, which would be inevitably neglected in studies at large scales. The lake may remain at their greatest sizes (e.g., at the maximal area of extension) even if the glaciers undergo dramatic changes.

3) Furthermore, WBE operation is crucial to gain a better understanding of water supplies for glacierized river basins. Near the study area, there are many rivers originating in the high Asian mountains, such as the rivers of Yarlong Zangbo (Brahmaputra), Indus, Ganges, Nujiang (Salween) and Lancangjiang (Mekong), but the quantification of water sources is usually highly uncertain

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because of a lack of understanding of the hydrological regimes and runoff calculations (Winiger *et al.*, 2005; Bookhagen and Burbank, 2010; Immerzeel and Bierkens, 2012; Miller *et al.*, 2012; Lutz *et al.*, 2014; Hassan *et al.*, 2017). The proposed WBE calculation has revealed the variety of water supplies from glaciers, snow cover, and precipitation for individual glacial lakes; thus, this calculation is expected to be applicable for estimating glaciohydrologic processes in large glacierized rivers.

4) Admittedly, the WBE for glacial lakes is proposed here only at the annual scale, which makes it difficult to be accurate when considering individual lakes during a given period. This is mainly due to the lack of data and ignorance of specific water supply and loss processes. For example, runoff should be calculated for the tributary watershed using records for individual rainfall events, which strongly depend on the watershed conditions (i.e., conditions of slope, channel, vegetation, and soils or sediments, especially moraines for the lakes) and the rainfall pattern. However, in the study area, and even in the Himalayas, only annual (and usually incomplete) weather records are available at several points, and it is only possible to provide a gross estimate of the runoff simply by the production of rainfall and watershed area. Similarly, water quantities from other sources can only be best estimated for accuracy in terms of order of magnitude.

On the other hand, the WBE does not consider the dynamical processes of glaciers (Copland *et al.*, 2011; Dowdeswell *et al.*, 1995), such as glacial surging, its hydrologic consequences or the possible dramatic changes in morphology, such as the collapse of lakes or other surface processes (e.g., icefalls, landslides, or debris flows due to earthquakes or extreme weather events), which may bring dramatic changes that overwhelm the steady, gentle changes that occur over tens or even hundreds of years. Therefore, the model cannot explain the sudden changes in glaciers and glacial lakes, as in the case of Jialongco. In addition, the parameters involved for these items are highly uncertain in practice, and systematic and detailed scrutinization is required to improve the accuracy of the operation.

7 Conclusion

This study employed multisource images and identified 147 glacial lakes in the Poiqu River in the central Himalayas and explored the detailed changes in major glacial lakes. Tracing the evolutions of glaciers and glacial lakes over the last 40 years, we find that the glaciers have undergone increasing retreat while the glacial lakes grew and expanded. The major lakes have increased by up to 30% ~ 200% in area, at rates between 0.01 km^2/a and 0.13 km^2/a, which make the Poiqu River an area of high levels of glacier and glacial lake changes in recent decades.

Detailed analysis of individual glacial lakes indicates that the lake grows in various patterns, depending on local conditions of weather and geomorphology, or even occasional dramatic events such as a lake outburst, icefall, or glacial surging. As these events are always inaccessible and usually cannot be identified from images, abnormalities in glacial lake growth may provide hints for those catastrophic occurrences. Meanwhile, small variations in lakes do not necessarily imply no changes in glaciers and lakes.

Based on the changes in glacial lake area and DEM analysis, we abstracted the water change in the lakes and proposed a WBE that governs the growth of the lake. As each item of the water contribution specifically depends on local weather and morphology, the balance equation provides a direct link between glacier and glacial lake changes and climate changes under local conditions.

Operation of the WBE for the five major glacial lakes in the tributaries of Poiqu River has shown that individual lakes vary in different ways and receive water supplies from glaciers, snow cover, and precipitation in different fractions. The results clearly reveal the altitude effect on changes in glaciers and glacial lakes. At low altitudes, temperature is more effective for glacier ablation, and lakes are mainly supplied by melted water from glaciers. At high altitudes, temperature acts more on snow cover, and melted snow becomes the major water supply to lakes. The difference between water supplies from glaciers and snow cover is as high as 50%, according to the present cases. This implies that it is insufficient to apply weather or climate conditions to individual glacial lakes at a large scale to determine climate effects on glacial lake changes.

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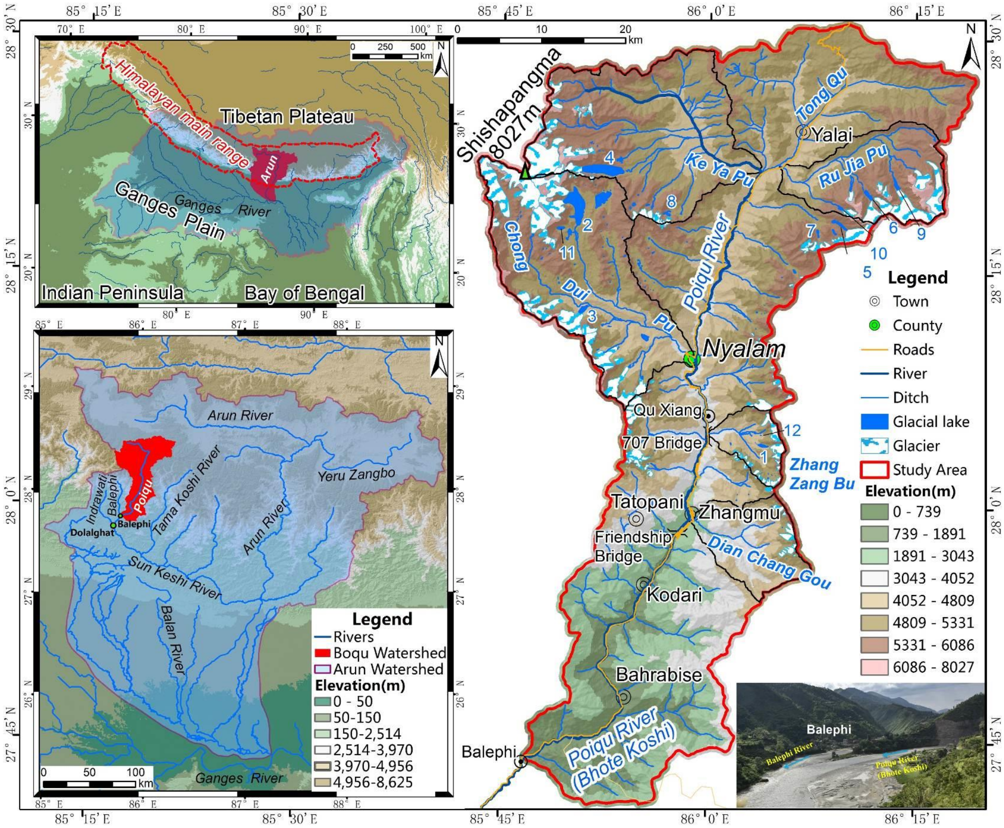

Fig. 1 Poiqu River Basin as a typical glacial lake in the central Himalayas

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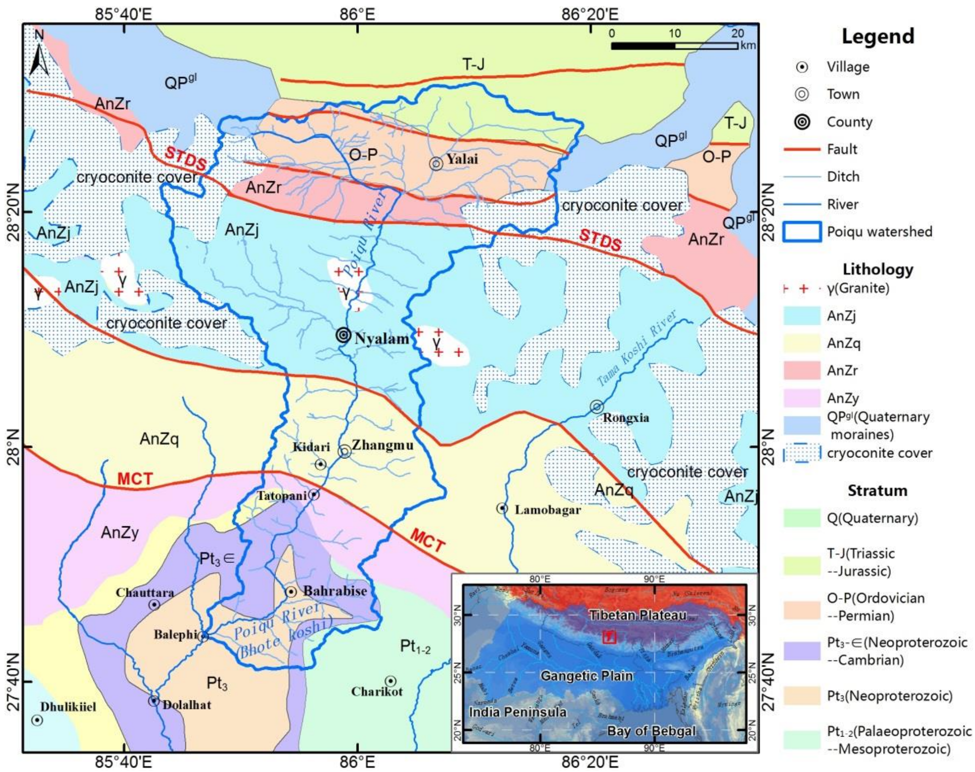

Fig. 2 Geological background of the Poiqu River Basin (Base map based on Pan, 2013)

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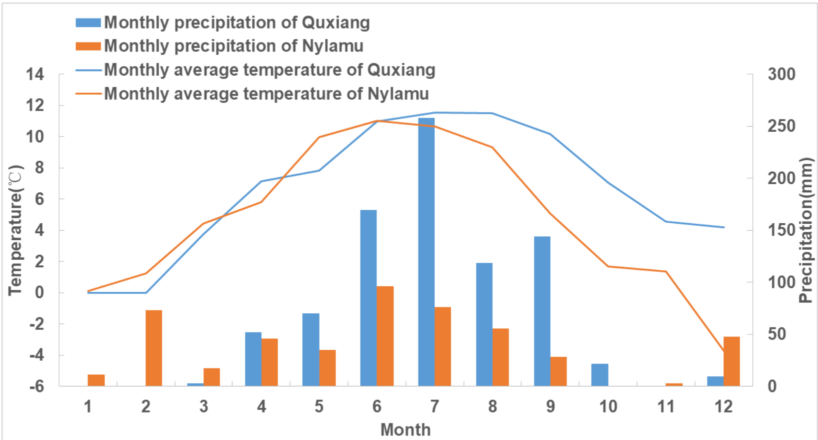

Fig. 3. Monthly temperature and precipitation records in the study area

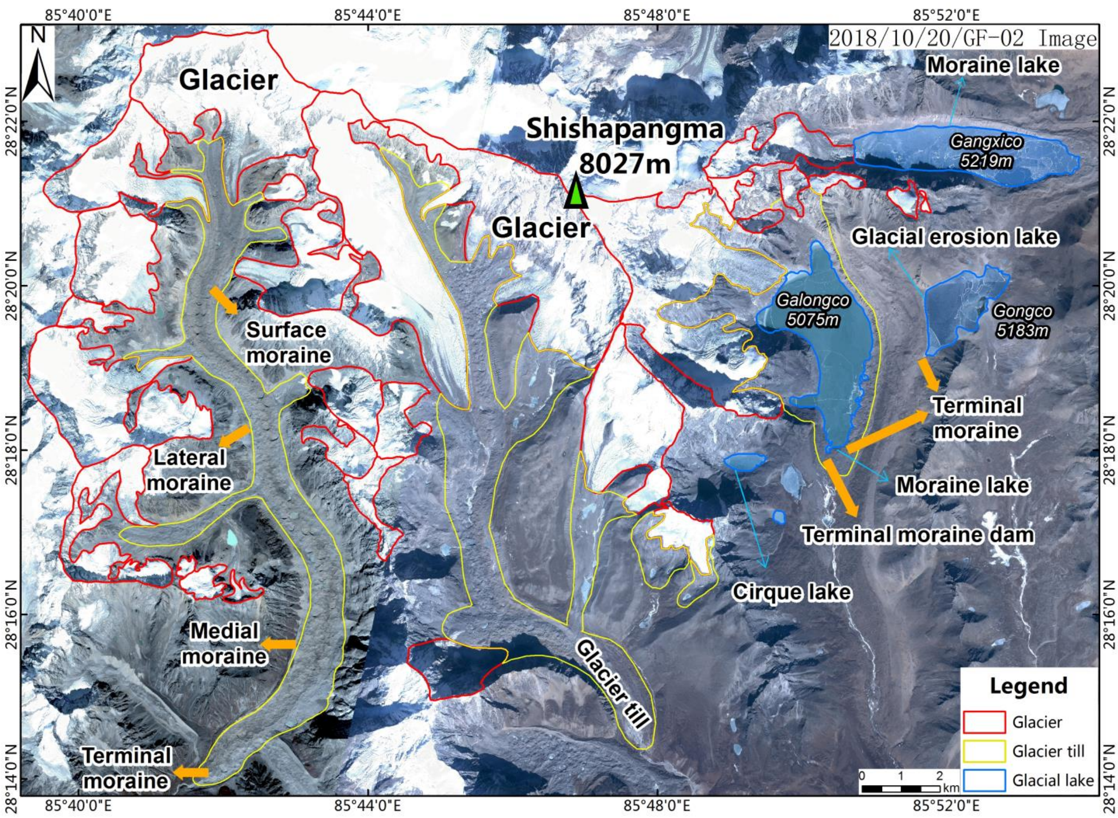

Fig. 4. Characteristics of glaciers and glacial lakes in the Poiqu River Basin

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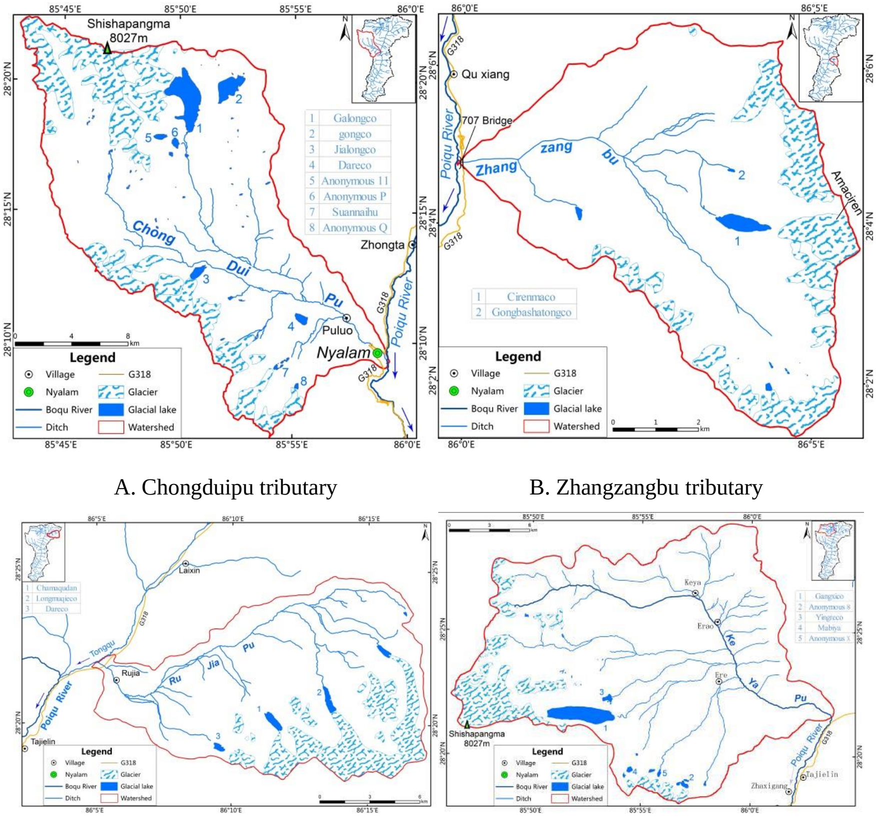

A. Chongduipu tributary

B. Zhangzangbu tributary

C. Rujiapu tributary

D. Keyapu tributary

Fig. 5 Distribution of glaciers and glacial lakes in the major tributaries of the Poiqu River Basin

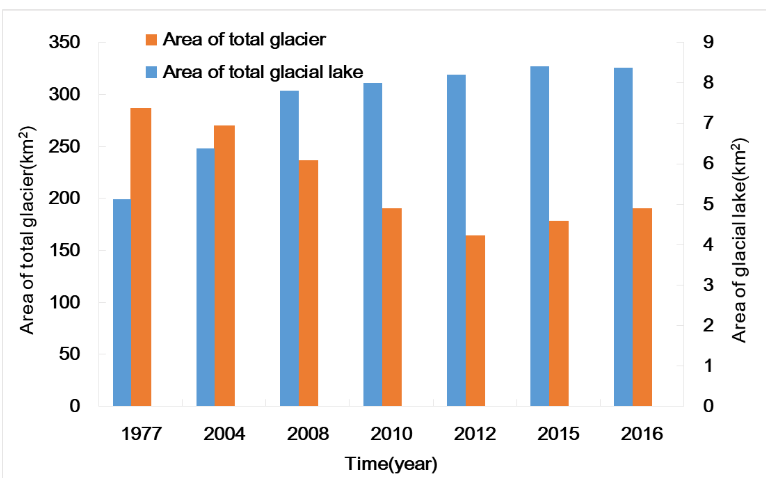

Fig. 6 Area variations in glaciers and glacial lakes in Poiqu

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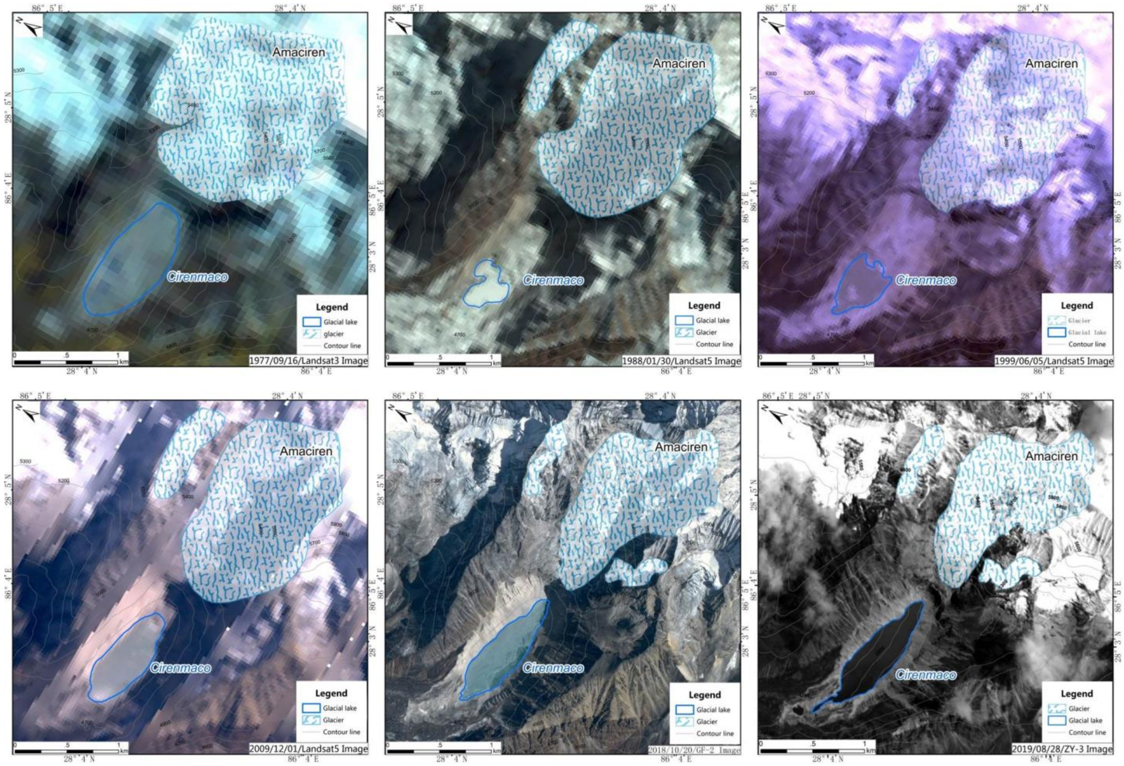

Fig. 7 Comparison of area change between Cirenmaco Lake and its connected glacier

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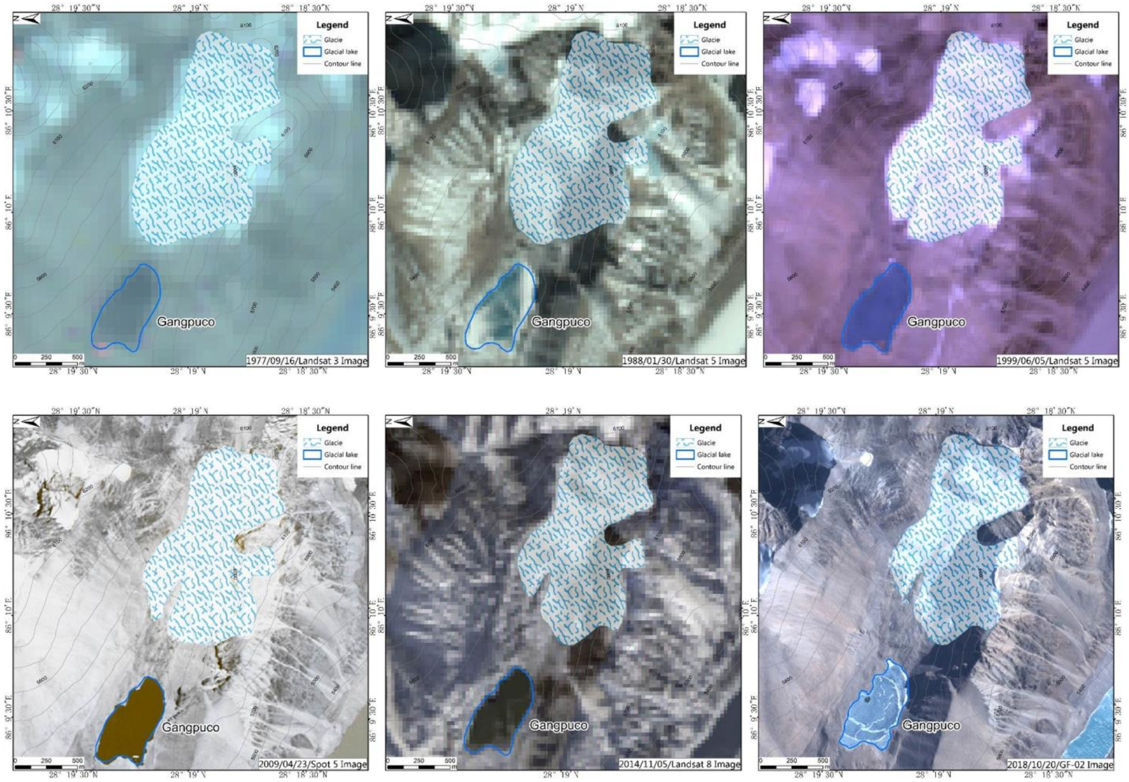

Fig.8 Comparison of area change between Gangpuco Lake and its connected glacier

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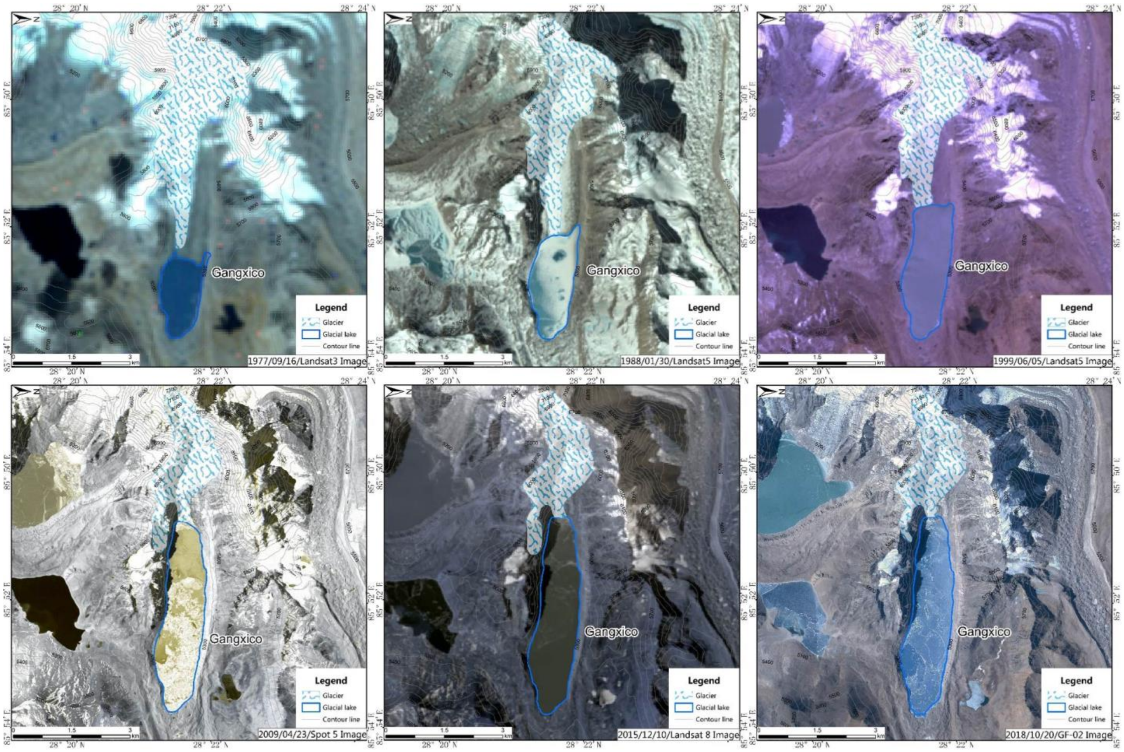

Fig. 9 Comparison of area change between Ganxico Lake and its connected glacier

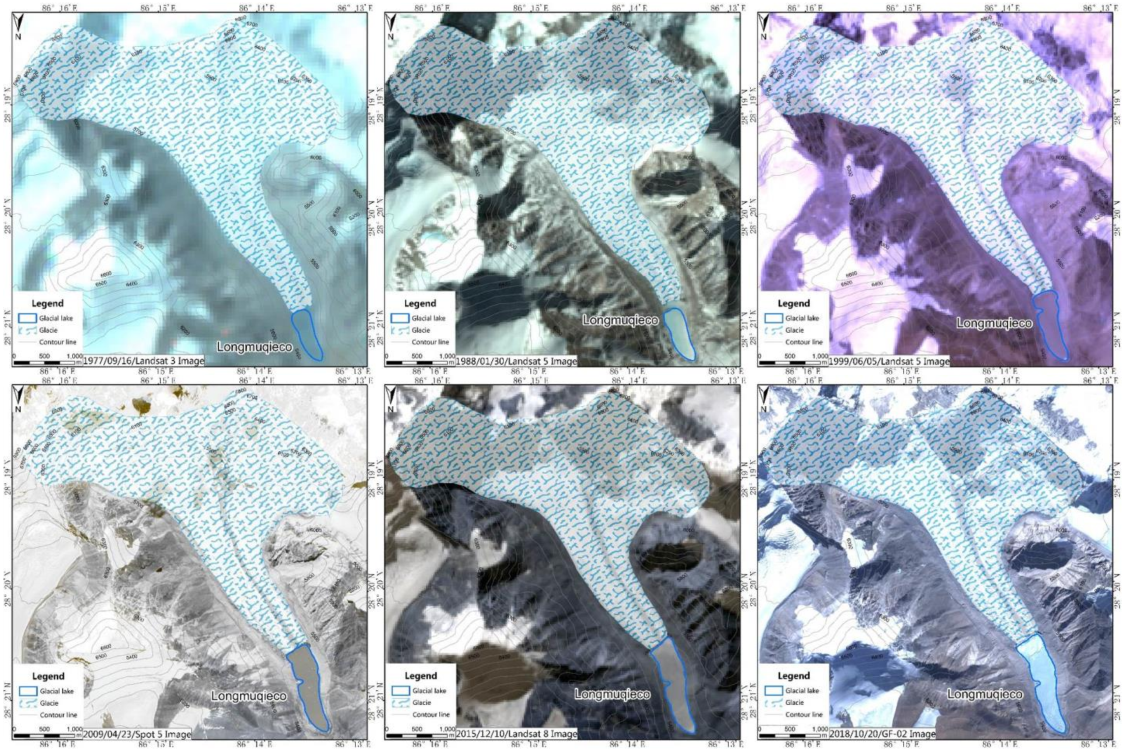

Fig. 10 Comparison of area change between Longmuqieco Lake and its connected glacier

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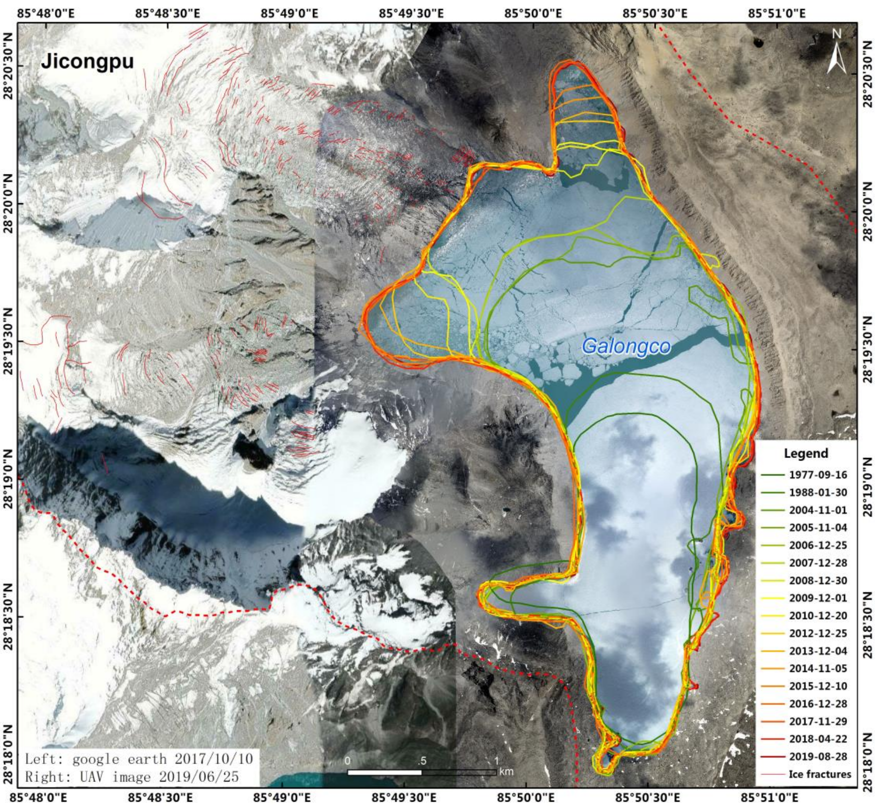

Fig. 11 Variation in the area of Galongco Lake (1977-2019) (The left image is from © Google Earth and the right image about the Galongco Lake is from UAV image)

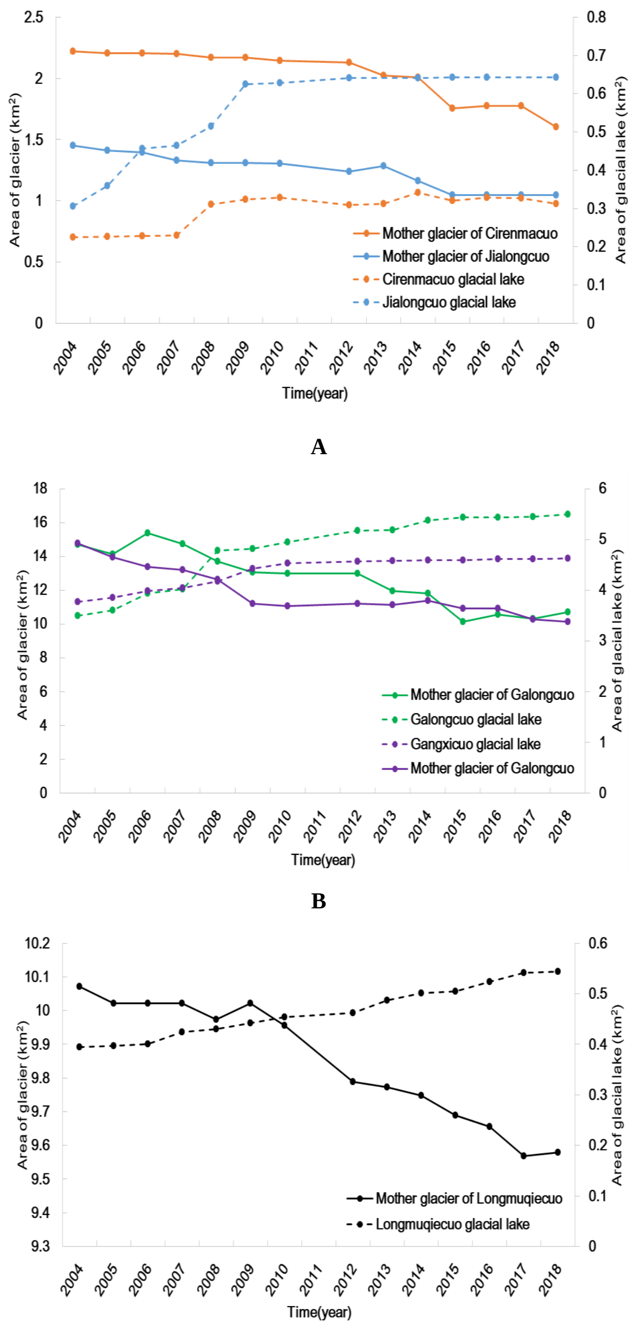

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Fig. 12 Retreat of 5 typical glaciers, growth of 5 typical glacial lakes and rates of change in the Poiqu River Basin

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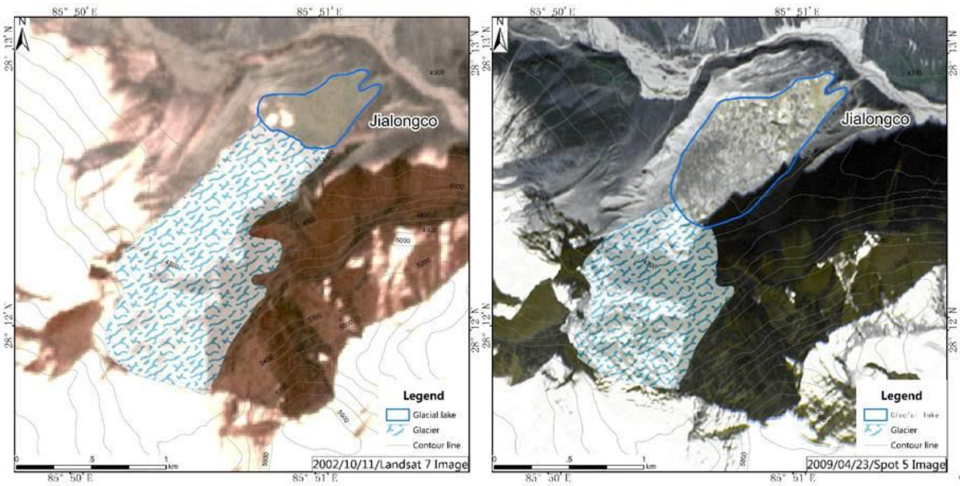

Fig. 13 Rapid rise in Jialongco Lake due to glacial loss

(2002-2009)

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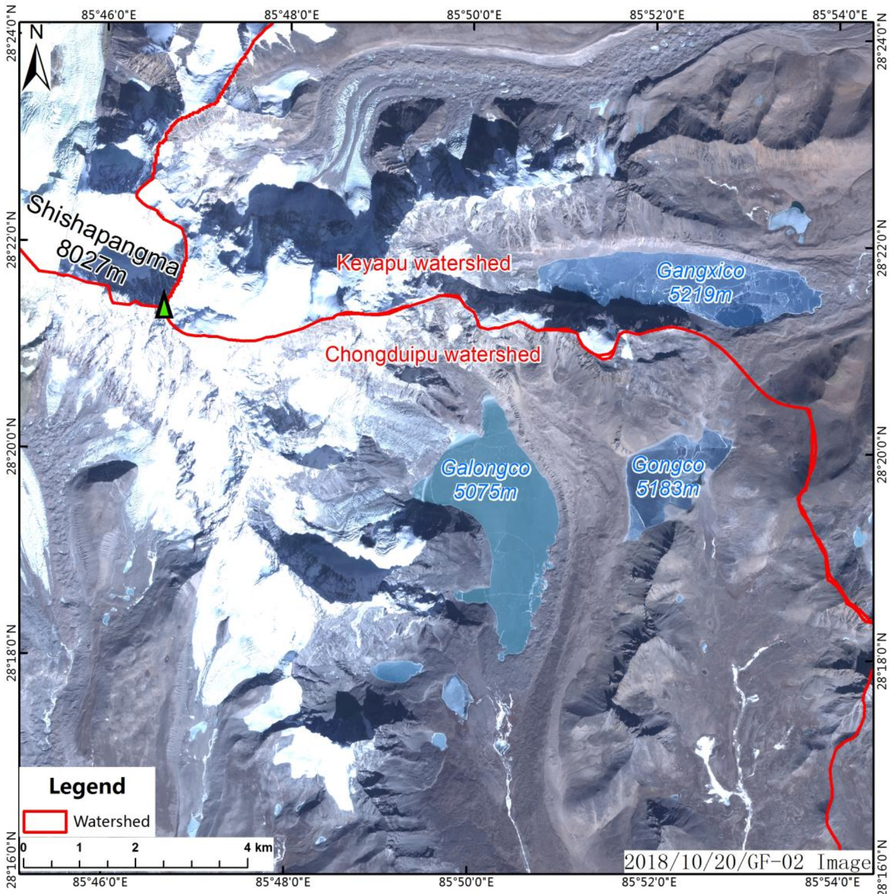

Fig. 14 Hydraulically connected glacial lakes (Galongco, Gangco, and Gangxico)

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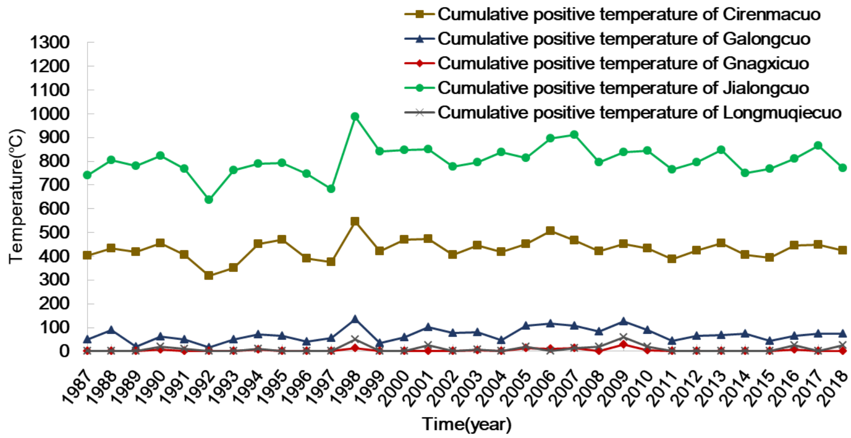

Fig. 15A. Interpolated cumulative temperature

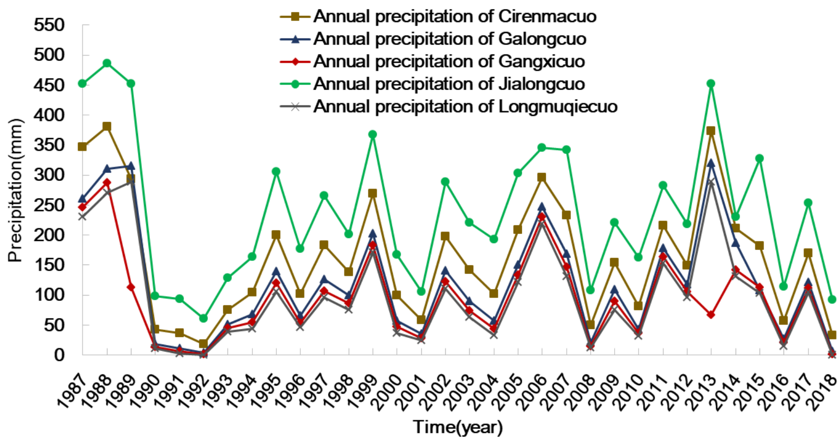

Fig. 15B. Interpolated annual precipitation

Fig. 15 Interpolated temperatures and precipitation for the glacial lakes

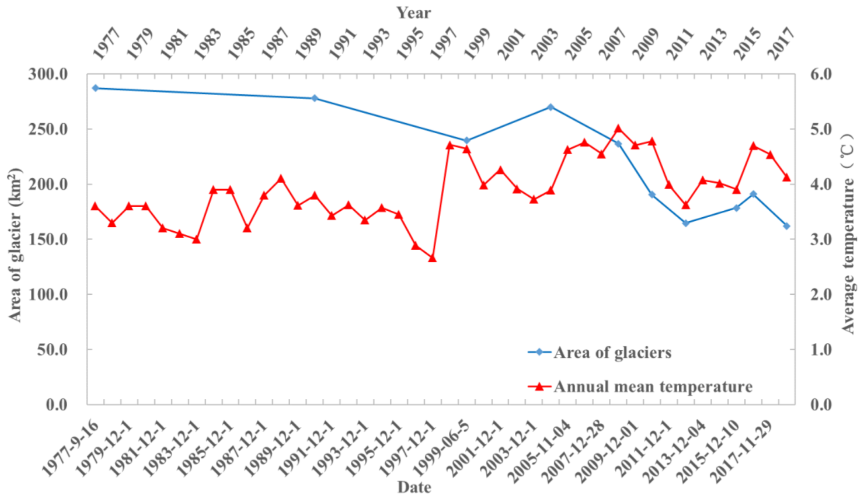

Fig. 16A Changes in the area of glaciers vs. temperature

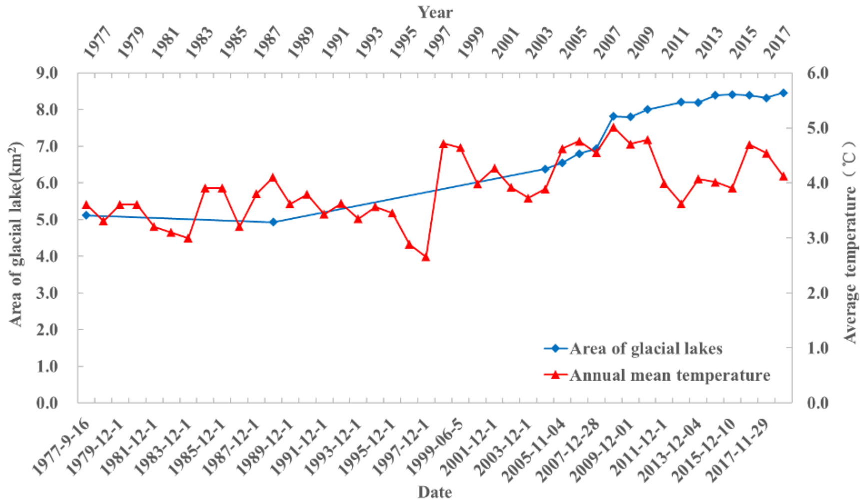

Fig. 16B Changes in the area of glacial lakes vs. temperature

Fig. 16 Changes in the area of glaciers and glacial lakes vs. temperature in Poiqu

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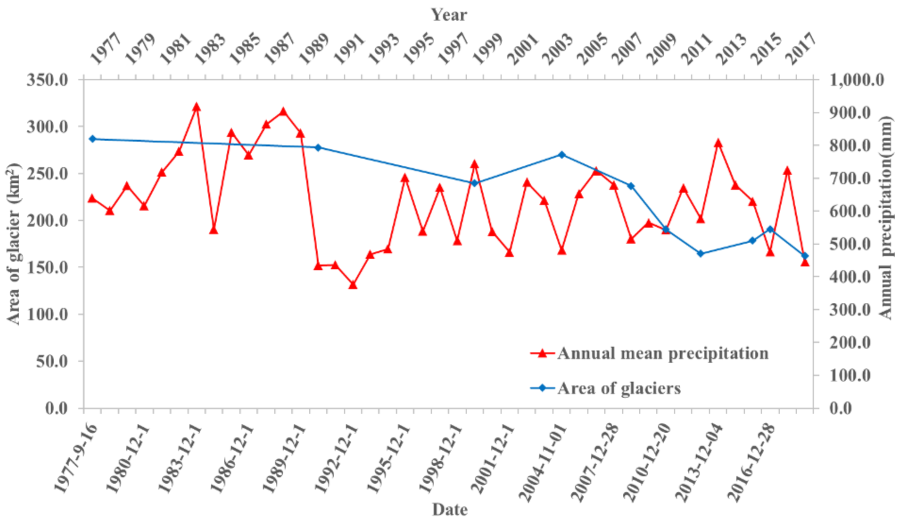

Fig. 17A Changes in the area of glaciers vs. precipitation

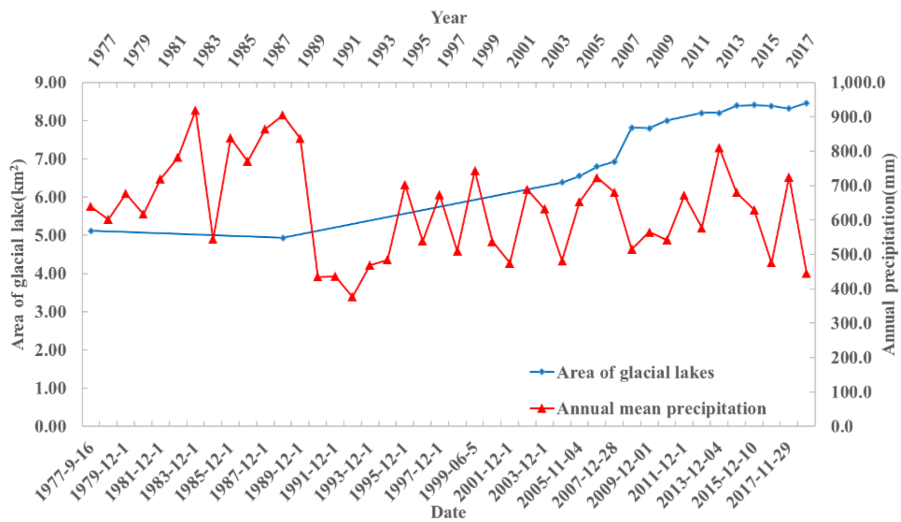

Fig. 17B Changes in the area of glacial lakes vs. precipitation

Fig. 17 Changes in the area of glaciers and glacial lakes vs. precipitation in Poiqu

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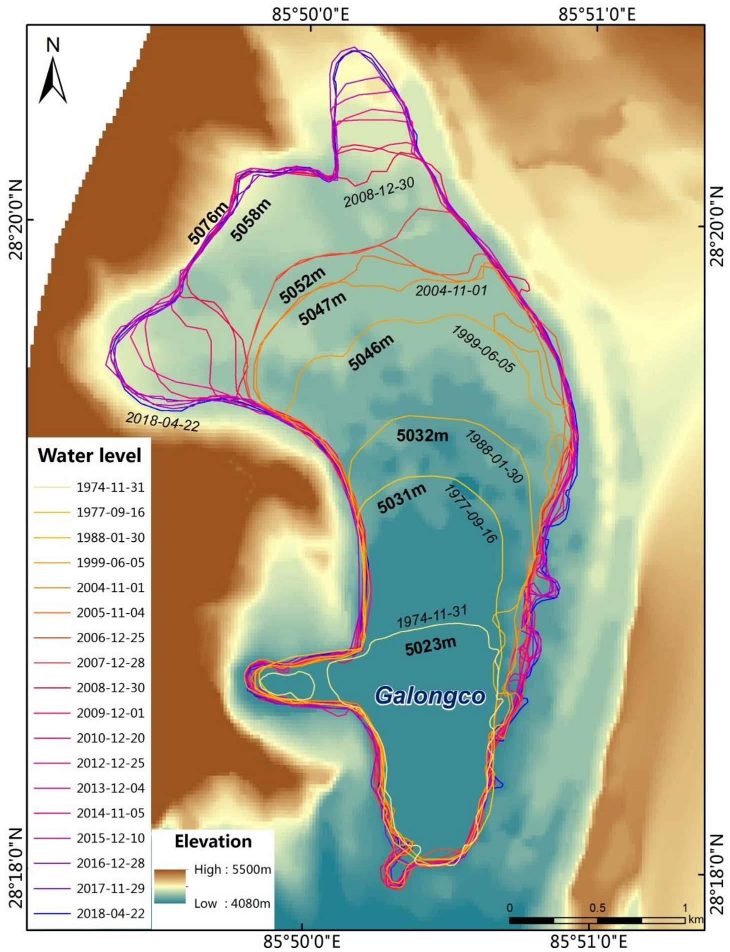

Fig. 18 Terrain reconstruction of GB Lake below the water level

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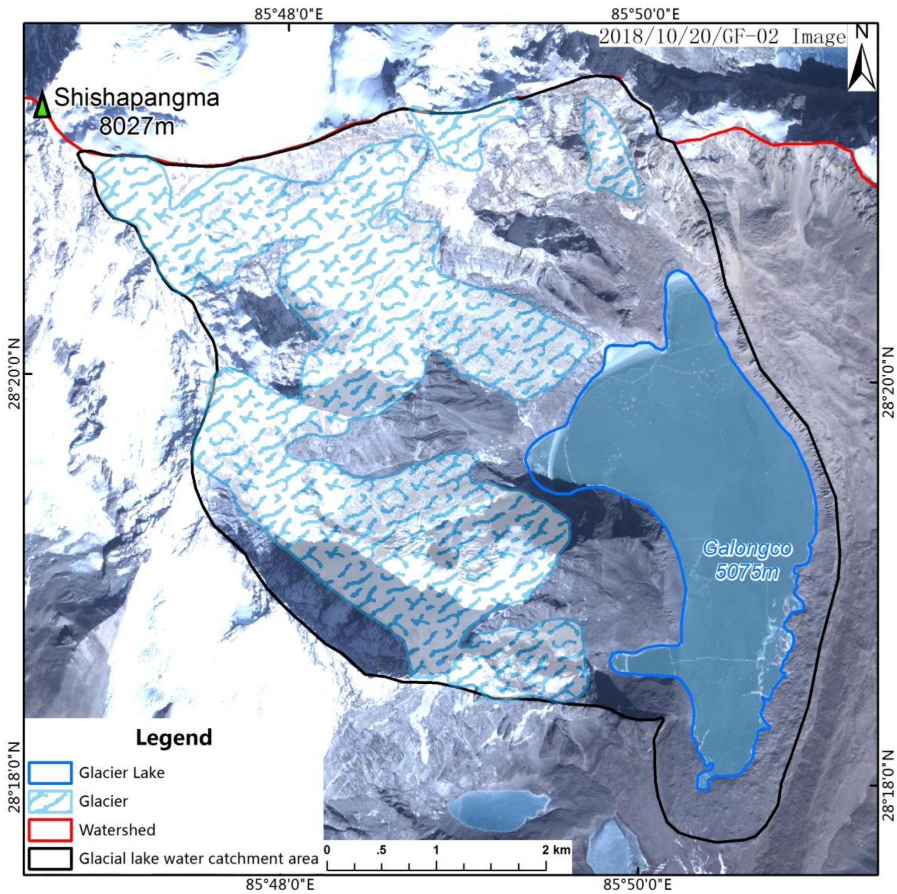

Fig. 19 Galongco Lake and the connected glaciers in 2006 (The image is from GF-02 image)

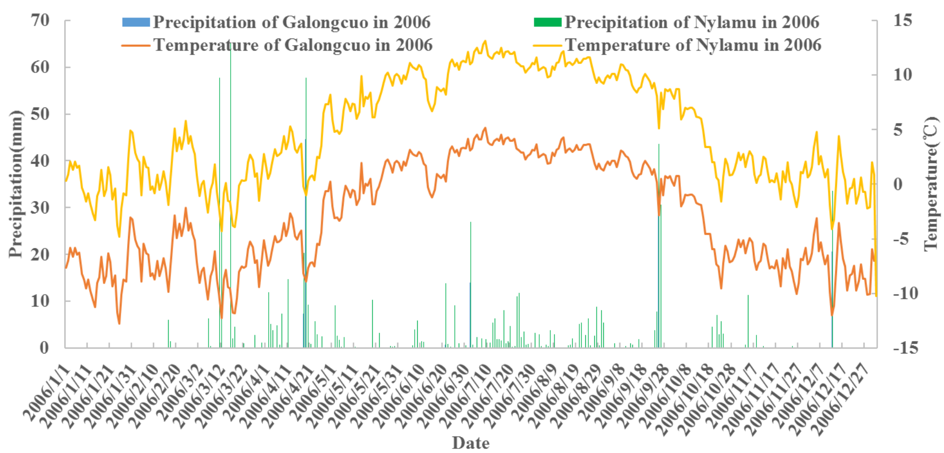

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Fig. 20 Temperature and precipitation of Galongco Lake in 2006

Table 1 Data sources and features for interpretation of glaciers and glacial lakes

Satellites	Spot number	Date	Sensors	Spectrum features	Spatial Resolution(m)
Landsat 3	LM21510401977259AAA01	1977-09-16	MSS	4 bands, from visible to near infrared	Multi-Spectral (60m)
Landsat 5	LT51410401988030BKT00	1988-01-30	TM	7 bands, from visible to near infrared	Multi-Spectral (30m)
Landsat 7	LE71410402004306PFS00	2004-11-01	ETM	7 bands, from visible to intermediate infrared Micron Panchromatic	Multi-Spectral (30m) Panchromatic (15m)
Landsat 7	LE71410402005308PFS00	2005-11-04			
Landsat 7	LE71410402006359SGS00	2006-12-25			
Landsat 7	LE71410402007362SGS00	2007-12-28			
Landsat 7	LE71410402008365SGS00	2008-12-30			
Landsat 7	LE71410402009335SGS00	2009-12-01			
Landsat 7	LE71410402010354PFS00	2010-12-20			
Landsat 7	LE71410402012360PFS00	2012-12-25			
ASTER GDEM	ASTGTM_N27E085/ N27E086/ N28E085/ N28E086	2009	ASTER	14 bands, 3 visible/ near infrared, 6 short-wave infrared, 3 thermal infrared band	visible/ near infrared (15m), short-wave infrared (30m), 3 thermal infrared (90m)
SPOT-5	S5G1B201004230520204YZYZMX S5G1J201004230520206YZYZMX S5G1A201004230520201YZYZMX	2010-04-23	HRG_s	5 bands, 1 Panchromatic, 1 short-wave infrared, 3 Multi-Spectral	Panchromatic (2.5m), Multi-Spectral (10m), short-wave infrared (20m)
Landsat 8	LC81410402013338LGN00	2013-12-04	OLI	7 bands, from visible to intermediate infrared, 2 thermal infrared, Panchromatic, Cirrus	Multi-Spectral (30m), Multi-Spectral(30m), Cirrus, Thermal infrared (100m), Panchromatic (15m)
Landsat 8	LC81410402014309LGN02	2014-11-05			
Landsat 8	LC81410402015344LGN00	2015-12-10			
Landsat 8	LC81410402016363LGN00	2016-12-28			
Landsat 8	LC81410402017333LGN00	2017-11-29			
Landsat 8	LC81410402018112LGN00	2018-04-22			
GF-2	L1A0003537778/GF2_PMS2_3537778	2018-10-20	MSS	4 bands, from visible to near infrared, Panchromatic	Panchromatic (1m), Multi-Spectral (4m)
GF-2	L1A0002952275/GF2_PMS2_2952275	2018-01-22			
GF-2	L1A0002952269/GF2_PMS2_2952269	2018-01-22			
GF-2	L1A0002951335/GF2_PMS2_2951335	2018-01-22			
GF-2	L1A0002951338/GF2_PMS2_2951338	2018-01-22			
UAV	SONY Alpha 7 III (4)	2019-05-30	Visible light		
ZY-3	52252940901110452051A 52252931103010521012U	2009/01/11 2011/03/01	TLC	4 bands, from visible to near infrared Foresight, back sight, Panchromatic	Foresight, Backsight (3.5m); Orthophoto (2.1m), Multi-Spectral (3.5m)

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Table 2 Interpretation signs for glaciers and glacial lakes（Six pictures are from © Google Earth images and two pictures are from GF-2 images. They are signed in the lower right corner）

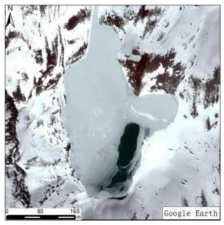
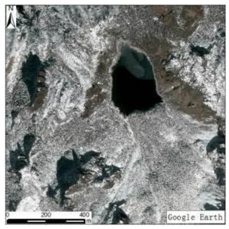
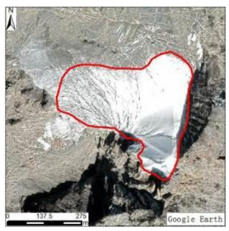
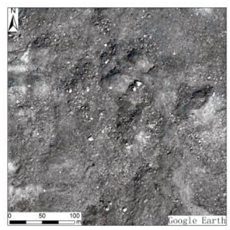
Types	**Moraine lake**	**Ice surface lake**	**Cirque lake**	**Glacial erosion lake**
Images				
Signs	Formed by pool eroded by glacier.	Occurring in the melted area of glacier covered by surface moraines.	Forming in the cirque, with steep rocky walls.	Having gentle bank with residual boulders.
Types	**Valley glacier**	**Cirque glacier**	**Hanging glacier**	**Moraine**
Images				
Signs	Located in low-lying gorges, with white or blue tone and irregular plane shapes, having thick front tongue.	In chair-shaped hollow in the source slope, in moderate size between 1 - 10km^2.	Hanging isolatedly on slope near the peak, thin and small.	Moraine is glacially formed accumulation of unconsolidated glacial debris (regolith and rock).

Table 3 Types of glacial lakes in the Poiqu River Basin

Types	Moraine lake	Glacier-eroded lake	Glacier-surface lake	Cirque lake
Numbers	19	84	20	24
Percentage	13%	57%	14%	16%
Area (km^2)	15.2	1.7	0.40	2.0

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Table 4 Typical glacial lakes in tributaries of the Poiqu River Basin

Tributaries	Lakes	Types	Longitude E (°)	Latitude N(°)	Area (km^2)	Altitude (m)	Distance to mother glacier (km)
Chongduipu	Galongco	EM	85.8382	28.3222	5.5	5076	0.18
	gongco	ER	85.8693	28.3293	2.13	5183	without glacier
	Jialongco	EM	85.8475	28.211	0.6	4382	0
	Dareco	ER	85.9229	28.1816	0.48	4372	without glacier
	Anonymous 11	EM	85.8197	28.2975	0.29	5092	0.1
	Anonymous P	V	85.8307	28.2936	0.28	5009	without glacier
	Suannaihu	EM	85.9059	28.1507	0.13	4507	1.5
	Anonymous Q	EM	85.9198	28.1386	0.1	4882	0
Dajilingpu	Paquco	EM	86.1575	28.3035	0.6	5306	0
	Tananco	EM	86.151	28.2953	0.17	5337	0
Duogapu	Tuzhuoco	EM	86.1032	28.2532	0.12	5208	0.1
Gangpu	Gangpuco	EM	86.1586	28.321	0.22	5539	0.5
Karupu	Longjueco	V	85.9155	28.2595	0.25	5103	without glacier
Keyapu	Gangxico	EM	85.8708	28.36	4.6	5219	0
	Anonymous 8	EM	85.9488	28.3141	0.31	5223	0.2
	Yingreco	EM	85.8907	28.3712	0.27	5225	without glacier
	Mabiya	EM	85.9079	28.3234	0.15	5419	0.4
	Anonymous X	EM	85.9304	28.3213	0.11	5319	0
	Chamaqudan	EM	86.1921	28.3352	0.54	5420	0.3
Rujiapu	Longmuqieco	EM	86.2259	28.3468	0.52	5342	0
	Dareco	EM	86.1314	28.2941	0.21	5233	0.2
Zhangzangbu	Cirenmaco	EM	86.0664	28.067	0.33	4639	0.29

Note: EM-- End moraine-dammed lake; ER--Glacial erosion lake; V—Glacial valley lake.

Table 5 Parameters of the glacial lake tributaries

Tributaries	Area (km^2)	Glacier number	Average slope	Elevation difference (m)	Moraine (km^2)	Glacier area (km^2)	Lake area (km^2)
Chongduipu	372.77	55	23.7°	4277	64.1	68.66	10.44
Zhangzangbu	49.92	14	29.3°	2941	9.2	8.28	0.42
Rujiapu	354.89	13	21.9°	2636	7.1	27.33	1.63
Keyapu	163.96	25	18.7°	3807	29.2	27.5	5.87

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Table 6 Basic parameters for major glacial lakes in the Poiqu River Basin

Major lakes	Tributaries	Water supply area (km^2)	Connected glacier (km^2)	Distance to glacier (km)	Water level altitude (m)
Galongco	Chongduipu	29.61	10.71	0.18	5076
Jialongco	Chongduipu	5.61	0.88	0	4382
Longmuqieco	Rujiapu	19.30	9.58	0	5342
Cirenmaco	Zhangzangbu	5.10	1.61	0.29	4639
Gangxico	Keyapu	15.91	3.38	0	5219

Table 7 Area variations and annual speeds of glaciers and glacial lakes in Poiqu river Basin since 1977

Year	Area（km^2）		Annual speeds of change from 1977 to 2016（km^2/a）		Annual speeds of change from 2004 to 2016（km^2/a）	
	Glacier	Glacial lake	Glacier	Glacial lake	Glacier	Glacial lake
1977	287.00	5.12	-2.46	+0.08	-6.60	+0.17
2004	270.10	6.38				
2008	236.70	7.82				
2010	190.4	8.00				
2015	178.4	8.41				
2016	190.9	8.38				

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Table 8 Area variations in 5 typical glacial lakes and their glaciers since 1977

Date	Cirenmaco		Galongco		Jialongco		Gangxico		Longmuqieco	
	Area of Glacier (km^2)	Area of Glacial Lake (km^2)	Area of Glacier (km^2)	Area of Glacial Lake (km^2)	Area of Glacier (km^2)	Area of Glacial Lake (km^2)	Area of Glacier (km^2)	Area of Glacial Lake (km^2)	Area of Glacier (km^2)	Area of Glacial lake (km^2)
1977/9/16	2.58	0.57	17.15	1.66	1.81	0.10	6.13	1.82	10.6	0.22
1988/1/30	2.24	0.12	14.91	2.07	1.47	0.15	5.49	2.53	10.25	0.24
1999/6/5	2.04	0.19	14.78	2.98	1.48	0.20	5.12	3.31	10.19	0.35
2002/12/1						0.24				
2002/12/1						0.30				
2004/11/01	2.22	0.23	14.72	3.50	1.45	0.31	4.92	3.77	10.07	0.39
2005/11/04	2.21	0.23	14.12	3.60	1.41	0.36	4.65	3.86	10.02	0.40
2006/12/25	2.21	0.23	45.37	3.93	1.39	0.46	4.46	3.99	10.02	0.40
2007/12/28	2.20	0.31	14.73	4.01	1.33	0.46	4.40	4.04	10.02	0.42
2008/12/30	2.17	0.32	13.71	4.78	1.31	0.51	4.22	4.17	9.97	0.43
2009/12/1	2.17	0.32	13.05	4.81	1.31	0.63	3.73	4.41	10.02	0.44
2010/12/20	2.14	0.33	12.98	4.95	1.30	0.63	3.68	4.54	9.96	0.45
2012/12/25	2.13	0.31	12.99	5.17	1.24	0.64	3.74	4.56	9.79	0.46
2013/12/04	2.02	0.31	11.96	5.18	1.28		3.71	4.58	9.77	0.49
2014/11/05	2.01	0.34	11.81	5.38	1.16	0.64	3.79	4.59	9.74	0.50
2015/12/10	1.75	0.32	10.15	5.43	1.05	0.64	3.64	4.60	9.69	0.50
2016/12/28	1.77	0.33	10.54	5.44	1.05	0.64	3.64	4.61	9.66	0.52
2017/11/29	1.78	0.33	10.31	5.45	1.05		3.42	4.62	9.67	0.54
2018/4/22	1.61	0.31	10.71	5.50	1.05	0.64	3.38	4.63	9.58	0.54

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Table 9 Annual rates of change in 5 typical glacial lakes and their glaciers

Glacial lake	Annual speed of change 1997-2018 (km^2)		Annual speed of change 2004-2018 (km^2)	
	Area of Glacier	Area of Glacial lake	Area of Glacier	Area of Glacial lake
Cirenmacuo	-0.018	-0.006	-0.044	+0.006
Galongco	-0.167	+0.093	-0.286	+0.143
Jialongco	-0.018	+0.013	-0.029	+0.024
Gangxico	-0.066	0.068	-0.110	0.061
Longmuqieco	-0.015	0.008	-0.035	0.011

Table 10 Parameters for the water balance calculation of glacial lakes

Glaciers	Runoff coefficient	R_c for snow cover	R_c for glacier	DDF (snow)	DDF (glacier)	Drainage area to lake (km^2)
Cirenmaco	0.60	0.60	0.53	8.30	12.60	9.77
Galongco	0.56	0.56	0.50	8.30	12.60	22.33
Gangxico	0.54	0.54	0.47	8.30	12.60	19.1
Jialongco	0.61	0.61	0.56	6.70	9.60	5.76
Longmeqieco	1.00	1.00	1.00	7.40	11.60	19.47

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Table 11 Water balance for Galongco Lake between 1988 and 2018

Year	Glacier area (km^2)	Rainfall (mm)	Runoff (10^{4}m^3)	T_c (℃)	T_{cG} (℃)	M_G (mm)	W_G (10^{4}m)	Snowfall (mm)	T_{cS} (℃)	W_{snow} (10^{4}m^3)	W_{total} (10^{4}m^3)	Infiltration (10^{4}m^3)
1987	21.3	16.5	18.4	210.4	12.4	112.4	119.9	253.5	198.0	226.4	364.7	404.5
1988	21.0	1.5	1.7	233.4	0.0	0.0	0.0	309.0	241.4	276.0	277.7	414.4
1989	20.6	7.4	8.3	204.0	0.0	0.0	0.0	308.0	240.6	275.1	283.4	424.2
1990	20.2	0.0	0.0	252.8	101.0	919.1	930.5	194.3	151.8	16.3	946.8	434.1
1991	19.9	5.4	6.0	214.5	85.8	780.3	775.9	164.8	128.8	5.4	787.4	444.0
1992	19.5	2.3	2.6	142.1	67.4	613.5	598.9	95.6	74.7	0.0	601.4	453.8
1993	19.2	0.0	0.0	190.8	76.5	696.2	667.0	146.3	114.3	46.1	713.1	463.7
1994	18.8	4.1	4.6	257.9	107.2	975.5	917.0	192.9	150.7	57.0	978.6	473.5
1995	18.4	23.3	26.0	253.5	118.4	1077.6	993.6	172.9	135.1	103.7	1123.3	483.4
1996	18.1	7.1	7.9	207.2	78.5	714.6	646.0	164.7	128.7	52.2	706.0	493.2
1997	17.7	19.2	21.4	199.3	84.6	770.0	682.1	146.8	114.7	95.0	798.6	503.1
1998	17.4	13.0	14.5	326.1	121.9	1109.1	962.5	261.4	204.2	77.6	1054.6	512.9
1999	17.0	27.3	30.5	218.4	81.1	737.6	626.7	175.8	137.3	157.0	814.3	522.8
2000	16.6	3.0	3.3	257.0	88.5	805.2	669.6	215.7	168.5	48.9	721.8	532.6
2001	16.3	8.2	9.2	256.2	69.4	631.6	513.8	239.1	186.8	24.4	547.4	542.5
2002	15.9	0.0	0.0	229.1	93.3	849.2	675.5	173.8	135.8	125.5	801.0	552.3
2003	15.5	22.9	25.6	260.6	129.7	1180.6	917.8	167.5	130.9	49.8	993.1	562.2
2004	14.7	21.0	23.4	235.8	164.3	1495.3	1100.2	91.5	71.5	41.7	1165.4	572.0
2005	14.1	24.7	27.6	266.2	147.0	1337.5	944.5	152.6	119.2	112.3	1084.4	581.9
2006	15.4	14.0	15.6	282.3	116.0	1055.3	810.8	212.9	166.3	190.2	1016.6	591.8
2007	14.7	7.5	8.4	285.7	143.9	1309.5	964.7	181.5	141.8	162.1	1135.2	601.6
2008	13.7	8.6	9.6	249.1	147.9	1346.1	923.3	129.5	101.2	11.3	944.2	611.4
2009	13.1	3.6	4.0	261.5	142.3	1294.8	845.0	152.6	119.2	94.0	942.9	621.3
2010	13.0	2.9	3.2	258.4	165.7	1508.3	978.6	118.6	92.7	35.5	1017.3	631.1
2011	12.7	41.2	46.0	205.0	128.3	1167.4	738.7	98.2	76.7	122.5	907.3	641.0
2012	13.0	14.5	16.2	240.3	152.2	1384.8	899.7	112.8	88.1	91.8	1007.7	650.8
2013	12.0	8.9	9.9	258.1	164.6	1497.7	895.5	119.7	93.5	278.5	1184.0	660.7
2014	11.8	35.0	39.1	235.9	160.8	1463.5	864.3	96.1	75.1	67.3	970.8	670.5
2015	10.2	0.6	0.7	211.0	129.3	1176.5	597.2	104.6	81.7	157.6	755.5	680.4
2016	10.5	10.4	11.6	248.0	168.0	1528.3	805.9	102.4	80.0	14.8	832.4	690.3
2017	10.3	12.0	13.4	221.5	147.8	1345.4	693.5	94.3	73.7	98.1	805.0	700.1
2018	10.7	4.2	4.7	260.6	181.3	1649.9	883.4	101.5	79.3	1.9	890.0	710.0

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Table 12 Comparison between the calculated water quantity and the observed quantity

	Cirenmaco			Galongco			Gangxico			Jialongco			Longmuqieco		
Year	MV	TV	ER（%）	MV	TV	ER（%）	MV	TV	ER（%）	MV	TV	ER（%）	MV	TV	ER（%）
1988	0.180	0.224	24.44	0.369	0.367	-0.54	0.355	0.363	1.75	0.087	0.105	20.69	0.247	0.252	2.50
1999	0.412	0.346	-16.02	0.526	0.551	4.94	0.523	0.565	8.60	0.121	0.353	191.74	0.464	0.455	-1.80
2000		0.425			0.568			0.571		0.157	0.392	149.04		0.457	
2001		0.474			0.579			0.586			0.427			0.459	
2002		0.498			0.58			0.633		0.187	0.459	145.45		0.516	
2003		0.492			0.594			0.648		0.273	0.481	76.19		0.535	
2004	0.571	0.519	-9.11	0.598	0.619	3.68	0.655	0.673	2.43	0.281	0.51	81.49	0.576	0.540	-6.00
2005	0.579	0.551	-4.84	0.538	0.654	21.56	0.684	0.688	0.57	0.37	0.543	46.76	0.582	0.545	-6.17
2006	0.581	0.608	4.48	0.566	0.683	20.67	0.729	0.714	-2.00	0.557	0.569	1.97	0.591	0.555	-6.00
2007	0.590	0.694	17.63	0.63	0.708	12.38	0.748	0.739	-1.29	0.574	0.607	5.57	0.653	0.597	-7.86
2008	0.991	0.763	-23.11	0.72	0.739	2.64	0.797	0.763	-4.25	0.684	0.645	-5.70	0.670	0.609	-8.71
2009	1.062	0.766	-27.87	0.713	0.758	6.31	0.901	0.797	-11.56	0.954	0.675	-29.25	0.701	0.656	-6.43
2010	1.090	0.807	-25.96	0.687	0.777	13.10	0.954	0.847	-10.80	0.962	0.706	-26.61	0.734	0.761	3.86
2011		0.826			0.8			0.888			0.74			0.785	
2012	0.986	0.854	-13.39	0.691	0.815	17.95	0.967	0.898	-6.90	0.997	0.768	-22.87	0.757	0.790	4.13
2013	1.002	0.882	-11.98	0.689	0.836	21.34	0.973	0.910	-6.30		0.795		0.827	0.796	-3.88
2014	1.169	0.957	-18.14	0.761	0.866	13.80	0.980	0.928	-5.20	0.997	0.82	-17.75	0.869	0.805	-7.00
2015	1.042	0.986	-5.37	0.803	0.884	10.09	0.983	0.944	-4.00	0.999	0.84	-15.92	0.880	0.820	-6.67
2016	1.094	0.987	-9.78	0.915	0.888	-2.95	0.991	0.952	-3.90	1	0.854	-14.60	0.940	0.826	-12.67
2017	1.081	1.006	-6.94	0.945	0.896	-5.08	0.993	0.984	-0.90		0.882		0.993	0.893	-10.00
2018	1.000	1.055	5.5	1	0.903	-9.70	1.000	1.000	0.00	1	0.915	-8.50	1.000	0.906	-9.40

Illustration: MV- Measured Value, TV-Theoretical Value, ER- Error Rate

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Table 13 Fractions of various water supplies to the lakes

Glacial lakes	Elevation （m）	Supply			Loss
		Glacier （%）	Snow （%）	Rainfall （%）	Seepage Flow （%）
Cirenmaco	4642	78.3	17.3	4.4	95.4
Galongco	5075	88.0	11.1	0.9	93.3
Gangxico	5218	23.9	73.8	1.7	0.0
Jialongco	4374	81.2	11.5	7.3	76.5
Longmuqieco	5358	29.9	70.1	0.0	15.0