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Research Article

Changes in Glaciers and Glacial Lakes and the Identification of Dangerous Glacial Lakes in the Pumqu River Basin, Xizang (Tibet)

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Latest satellite images have been utilized to update the inventories of glaciers and glacial lakes in the Pumqu river basin, Xizang (Tibet), in the study. Compared to the inventories in 1970s, the areas of glaciers are reduced by 19.05% while the areas of glacial lakes are increased by 26.76%. The magnitudes of glacier retreat rate and glacial lake increase rate during the period of 2001–2013 are more significant than those for the period of the 1970s–2001. The accelerated changes in areas of the glaciers and glacial lakes, as well as the increasing temperature and rising variability of precipitation, have resulted in an increased risk of glacial lake outburst floods (GLOFs) in the Pumqu river basin. Integrated criteria were established to identify potentially dangerous glacial lakes based on a bibliometric analysis method. It is found, in total, 19 glacial lakes were identified as dangerous. Such finding suggests that there is an immediate need to conduct field surveys not only to validate the findings, but also to acquire information for further use in order to assure the welfare of the humans.

1. Introduction

A vast amount of studies has been conducted to increase our understanding on the changing cryosphere and its climate connection. Globally averaged temperature data show an increase of 0.85°C over the period of 1880–2012, and the total increase between the average of the 1850–1900 period and the 2003–2012 period is 0.78°C [1]. Due to rising temperatures, the areas of China's glaciers have decreased by 5–10% [2]. With the accelerated retreat of glaciers, glacial lakes have been expanding over recent decades [3, 4]; therefore, glacial lakes are also considered to be an indicator of climate change [5].

Some glacial lakes are located in valleys below glaciers and are dammed by unstable moraines formed during the Little Ice Age. Occasionally, a moraine breaks, releasing the lake's stored water and discharging large volumes of water with debris, which causes downstream flooding along the river channel. This phenomenon, generally known as a glacial lake outburst flood (GLOF), is one of the most serious disasters to occur in the Himalayan regions of China, Nepal, India, Pakistan, and Bhutan [6–10]. To assess GLOFs, remote sensing techniques are cheaper and faster than traditional field investigations and have thus been recommended for investigating glaciers and glacial lakes [11, 12].

Due to the more frequent GLOF events in the Himalayas over the past several decades, the risks to human life and property located downstream of dangerous glacial lakes have increased. Substantial progress has been achieved in different regions of the Himalayas, and several criteria have been used to identify potentially dangerous glacial lakes [13–22]. The International Centre for Integrated Mountain Development (ICIMOD), in collaboration with partners in different countries, has begun to prepare a standardized glacial inventory for the entire Hindu Kush-Himalayan region for use as a basis for GLOF risk assessment [23].

Among the river basins in the Himalayas, the Pumqu and Poiqu river basins are two of the most concentrated areas of glacial lakes. A Chinese/Nepalese joint team carried out

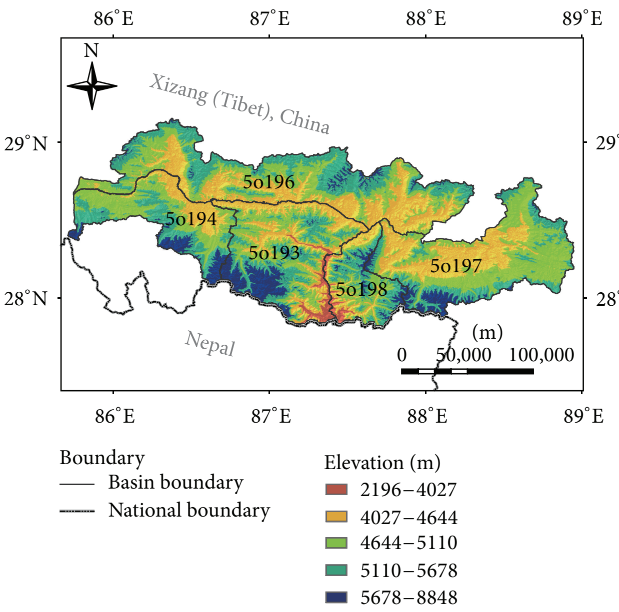

Figure 1: Location of the Pumqu river basin and its subbasins.

the first expedition to inventory glaciers and glacial lakes in the Pumqu and Poiqu river basins of Xizang (Tibet) in 1987 [24]. Later, the changes in glacial lakes in post-1986 in the Poiqu river basin were again investigated [5]. However, after another ten years [25, 26], the changes in glaciers and glacial lakes have not been studied in detail.

The aims of this work are (1) to investigate the changes in glaciers and glacial lakes in the Pumqu river basin based on remote sensing data acquired in 2013 and (2) to identify potentially dangerous glacial lakes in the Pumqu river basin by integrating the latest criteria from recent reports.

2. Data and Methodology

2.1. Study Area. The Pumqu river basin is situated in the southwestern region of the Tibet Autonomous Region of China (Figure 1). This basin is bounded in the north by the Mimanjinzhu Range and in the south by the world's highest mountain range, the Himalayan Range. The basin extends into the Biakuco continental lake in the west. The Yap Mountains separate the Pumqu and Poiqu river basins. The eastern part of the basin extends to Mountains Qumo, Xaya, and Joding, which border the Nyangqu river, a tributary of the Yarlungzangbo river. The total drainage area of the Pumqu river basin is 25,307 km^2. The Pumqu river flows through Nepal and into the Ganges through the Kosi. Based on hydrological maps and the guidelines of the world glacier inventory (WGI), the Pumqu river basin is subdivided into five subbasins (Figure 1), which also represent a glacier code basis.

2.2. Methods. The Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) are instruments on board the Landsat 8 satellite, which was launched in February of 2013. In total, we acquired five series of Landsat 8 OLI/TIRS images with no or low cloud cover in June, 2013. The images used in this study are Level 1 GeoTIFF Data Products, which were preliminarily calibrated. Digital elevation model (DEM) data with a resolution of 90 meters from the Shuttle Radar Topography Mission (SRTM) were used to obtain topographic information [27].

Glacier and glacial lake datasets collected in the 1970s and 2001 were used as historical data [25, 26]. The original data obtained in the 1970s included aerial photos and digital topographic maps based on aerial surveys from 1974 to 1983. The topographic maps from the 1970s were produced from aerial surveys, and two levels of maps 1 : 100,000 and 1 : 50,000, respectively, were adopted [25]. The original data for 2001 included sixteen images from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and two images from the China-Brazil Earth Resources Satellite (CBERS), and their spatial resolutions were 15 m and 30 m, respectively. In this study, panchromatic images (band 8) from Landsat 8 OLI were registered with digital topographic maps using the software of Earth Resource Data Analysis System (ERDAS) Imagine. The registration accuracy was within 15 m (one pixel) in most areas. Furthermore, the images of other bands were resized to 15 m and were registered using the reference information from the panchromatic band.

A manual interpretation method was used to outline the glaciers and glacial lakes based on false color composite (FCC) images (6, 5, and 3 bands). DEM data were used to determine the divide line of the conjunct glaciers. The accuracy of manual interpretation has been demonstrated as optimal for identifying glaciers and glacial lakes because it allows for the consideration of both spectral characters and information regarding texture, patterns, shapes, and shadows. Finally, the spatial attributes of glaciers and glacial lakes were calculated using the topological analysis function of ArcInfo software based on the DEM data, while the physical attributes were duplicated from the historical data in the 1970s and 2001. The volumes of glacier and glacial lake were calculated based on the areas [28, 29]

$$V_g = \left(-11.32 + 53.21 A_g^{0.3}\right) A_g \times 10^{-3}, \quad V_l = 0.104 A_l^{1.42}, \tag{1}$$

where V_g and A_g represent the volume (km^3) and area (km^2) of glacier, while V_l and A_l represent the volume (km^3) and area (km^2) of glacial lake, respectively. It should be noted that these two formulas were developed in another research field and were not validated in this study. Therefore, the volumes can only be considered as a reference.

To identify potentially dangerous glacial lakes, a bibliometric analysis was adopted to define criteria. First, reports associated with the identification of dangerous glacial lakes published over the last 10 years were collected. Second, overview and review papers were removed, so that only original and independent research papers were used to derive the index of identification. Third, a two-dimensional table was established based on the indices and their frequencies. Correlated indices were combined, such as the area and

Table 1: Summary of glacier inventories in the Pumqu river basin for the 1970s, 2001, and 2013 periods.

Subbasin	Number of glaciers			Areas of glaciers (km^2)			Changing ratio of area (%)		Ice reserve (km^3)		
	1970s	2001	2013	1970s	2001	2013	1970s–2001	1970s–2013	1970s	2001	2013
5o193	358	333	314	689.05	654.47	545.02	−5.02	−20.90	78.52	74.73	55.32
5o194	110	113	112	294.09	281.88	279.66	−4.15	−4.91	32.50	29.01	27.25
5o196	58	37	18	13.37	4.20	1.99	−68.59	−85.12	0.43	0.09	0.04
5o197	226	222	214	280.85	259.48	252.57	−7.61	−10.07	21.23	19.72	18.21
5o198	247	195	181	184.48	130.57	104.16	−29.22	−43.54	10.27	7.32	5.24
Total	999	900	839	1461.84	1330.60	1183.40	−8.98	−19.05	142.95	130.87	106.06

Table 2: Summary of glacial lake inventories in the Pumqu river basin for the 1970s, 2001, and 2013 periods.

Subbasin	Number of glacial lakes			Areas of glacial lakes (km^2)			Increasing ratio of area (%)		Lake volume (10^6 m^3)		
	1970s	2001	2013	1970s	2001	2013	1970s–2001	1970s–2013	1970s	2001	2013
5o193	62	61	72	9.15	9.65	10.13	5.41	10.73	200.54	221.15	215.54
5o194	16	15	15	7.08	7.94	7.47	12.09	5.42	313.99	357.05	333.37
5o196	37	36	55	9.35	9.91	10.71	6.00	14.53	285.63	306.68	313.07
5o197	25	24	36	6.63	7.46	11.39	12.46	71.84	171.75	205.86	333.04
5o198	59	60	76	9.40	12.15	13.05	29.22	38.82	218.37	315.44	334.40
Total	199	196	254	41.61	47.09	52.75	13.18	26.76	1190.28	1406.18	1529.42

volume of a glacial lake or the gradient ratio of a downstream channel and the slope of a dam. Fourth, it was assumed that the frequently used indices were more important. These indices were ordered based on their importance, and the most important indices were selected as the final criteria. Weight of each criterion was calculated based on its frequency of usage. Finally, all weights of criteria that are conformed to the properties of glacial lake were accumulated as the dangerous degree. A glacial lake with the larger degree is more dangerous.

3. Results

3.1. Distribution and Change of Glaciers and Glacial Lakes. The number and areas of glaciers throughout the entire basin and in each sub-basin of the study area were calculated for the 1970s, 2001, and 2013 periods (see Table 1). The glaciers were primarily distributed in the southern region, and the average area of the glaciers was small. The number of glaciers in the Pumqu river basin was 999 in the 1970s, 900 in 2001, and 839 in 2013. The glacier areas were 1,462 km^2 in the 1970s, 1,330 km^2 in 2001, and 1,183 km^2 in 2013. Over the past four decades, the number of glaciers decreased by 160, while the glacier area decreased by 278.44 km^2 (19.05%). It is found that similar findings are obtained as compared with the previous study.

It is found that small glaciers decreased faster than larger glaciers in the past four decades (Figure 2). Such findings are consistent with those found from the previous study [25]. However, the rate of changes in areas of glaciers during the period of 2001–2013 is more significant than those for the period of the 1970s–2001. Meanwhile, the glaciers in the southwest region were relatively stable (5o194 sub-basin).

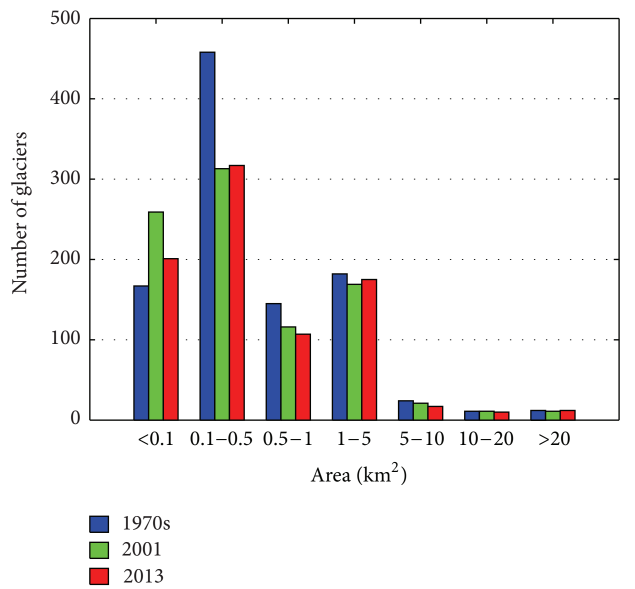

Figure 2: Changes in number and areas of glaciers for the 1970s, 2001, and 2013 periods.

Table 2 presents the number and areas of glacial lakes in the Pumqu river basin for the 1970s, 2001, and 2013 periods. The expansion of glacial lake is very clear in the past four decades. The number of glacial lakes was almost not changed during the period of 1970s–2001, while the area of glacial lakes was increased by 13.18%. In the past decade, more than 50 glacial lakes have newly formed, and the area of glacial lakes increased by 26.76% over the past four decades. Similar to the changes in glaciers, the rate of changes in area of glacial

Table 3: Integrated criteria for identifying potentially dangerous glacial lakes.

Index	Criteria	Frequencies	Weight
Type of glacial lake	End moraine-dammed lake	10	0.15
Area of lake	Larger than 0.2 km^2	10	0.15
Distance between lake and its mother glacier	Smaller than 500 m	10	0.15
Average slope of glaciers	Larger than 7 degree	7	0.10
Slope of the downstream	Larger than 20 degree	7	0.10
Top width of dam	Less than 60 meters	7	0.10
Area of glacier	Larger than 2 km^2	6	0.09
Slope between lake and its mother glacier	Larger than 8 degree	5	0.07
Change of lake area	Larger than 10% of decade	4	0.06
Elevation of lake	Higher than 5000 meters	2	0.03

lakes during the period of 2001–2013 is more significant than those for the period of the 1970s–2001. Similar results were also obtained in the Poiqu river basin [5].

On the other hand, the number of glacial lakes was stable, while the areas were expanded from the 1970s to 2001 periods. The number of glacial lakes with areas less than 0.1 km^2 was decreased, while that with areas between 0.5 and 1.0 km^2 was increased from the 1970s to 2001 periods (Figure 3). However, both the number and areas of glacial lakes have significantly risen since 2001 (Figure 3). There were many new glacial lakes with areas less than 0.1 km^2, and the number of glacial lakes with larger areas was increased for the period of 2001–2013.

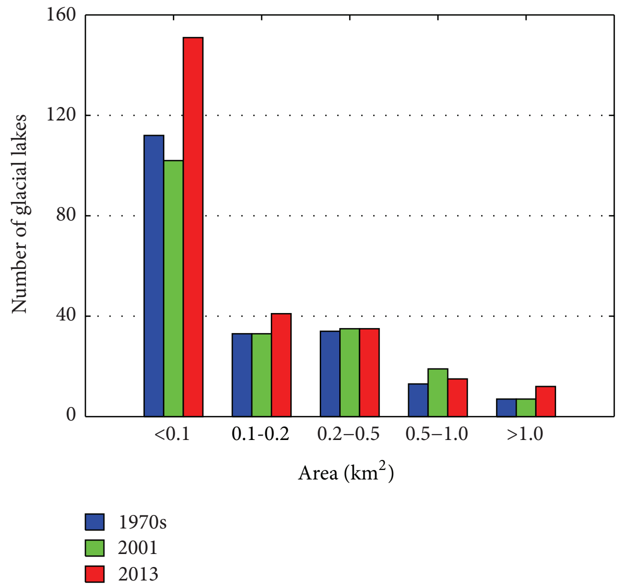

Figure 3: Changes in number and areas of glacial lakes for the 1970s, 2001, and 2013 periods.

3.2. Identification of Potentially Dangerous Glacial Lakes. Many researchers have reported indices for the identification of potentially dangerous glacial lakes [29–31]. In this work, study areas located in the Tibet Plateau regions were selected and analyzed to obtain suitable criteria for the Pumqu river basin [13–22]. The indices and criteria used in these ten papers are listed in Table 3. The glacial lake type, the distance between the mother glacier and the glacial lake, the glacial lake area, the average slope of the glacier, the slope of the downstream region, the dam width, the mother glacier area, the slope between the lake and its mother glacier, the change in lake area, and the lake elevation were adopted as indices based on the literature analysis. Note that the values within the criteria represented most of the previous reports.

According to the statistics shown in Table 3, all studies agreed that an end moraine-dammed lake with an area larger than 0.2 km^2 for which the distance between the lake and its mother glacier is less than 500 m is dangerous. However, the lake area was used in seven cases, while the lake volume was used in six cases. It is difficult to obtain the lake volume, which is calculated from the lake area via empirical equations [29]. Thus, these two indices were combined as the lake area.

Most of the studies argued that the average slope of the glacier, the slope of the downstream region, and the dam width are important factors. Half of the studies considered the area of the mother glacier, the slope between the lake and its mother glacier, and changes in the lake area. Only two studies considered the glacial lake elevation, because a higher elevation indicates a greater potential energy once the dam is broken.

In addition to the above-mentioned indices, the number of mother glaciers and the height and stability of the dam were each used in two studies. The number of mother glaciers can be reflected by the area of mother glaciers, while it is challenging to determine the height and stability of a dam from remote sensing data. Therefore, these two indices were excluded in the integrated criteria in this work.

To identify potentially dangerous glacial lakes in the Pumqu river basin, the criteria and their weights in Table 3 were adopted. The SRTM DEM data were used to obtain the slope of the glacier, the slope of the downstream region, the slope between the lake and its mother glacier, and the lake elevation. The areas and changes in glaciers and glacial lakes were obtained from the datasets for the 1970s, 2001, and 2013 periods, while the width of the dam and the distance between the lake and its mother glacier were measured from the OLI images.

The total weight of each lake was calculated based on the criteria and weights in Table 3. The dangerous degrees were

Table 4: Number of glacial lakes with different hazard levels in each subbasin.

Subbasin	Number of glacial lakes	Hazard level (total weight)				
		1 (0–0.19)	2 (0.2–0.39)	3 (0.4–0.59)	4 (0.6–0.79)	5 (0.8–1.0)
5o193	72	11	37	19	4	1
5o194	15	0	0	8	4	3
5o196	55	15	31	8	1	0
5o197	36	2	3	11	9	11
5o198	76	8	23	21	20	4
Total	254	36	94	67	38	19

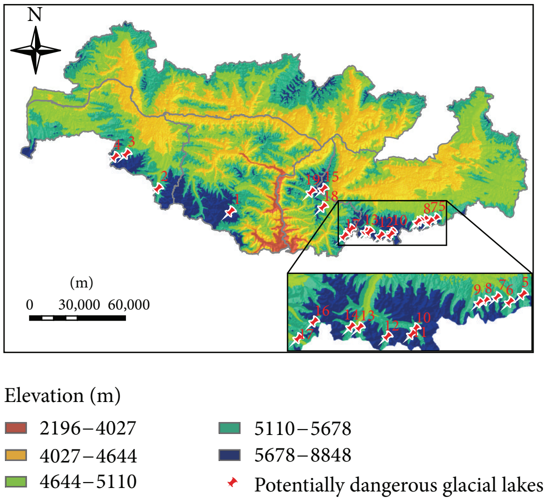

Figure 4: Distribution of potentially dangerous glacial lakes in the Pumqu river basin (the ID is according to Table 4).

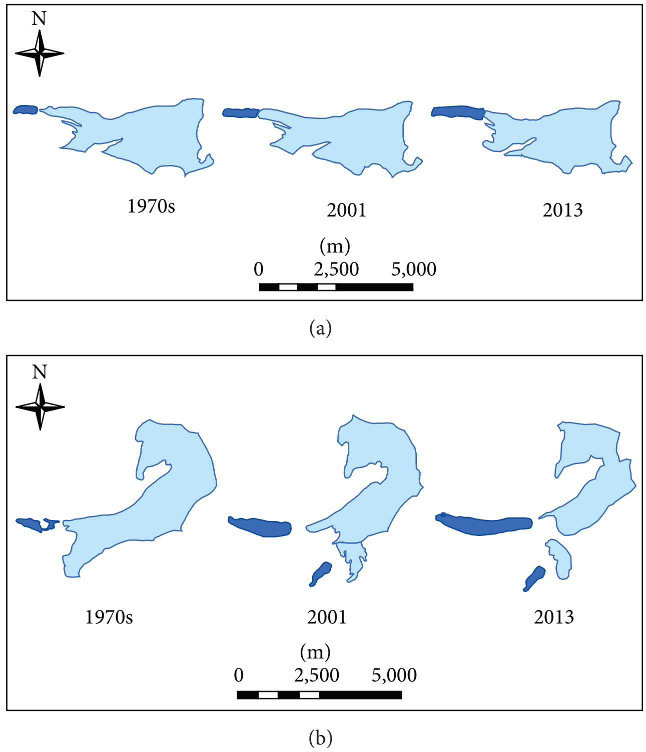

Figure 5: Morphological changes in two dangerous glacial lakes, (a) Gelhaipuco Lake and (b) Coqong Lake. (Dark blue represents glacial lakes while light blue represents glaciers.)

divided into five levels with equal interval (e.g., 0.2), and those lakes with highest hazard level were considered as potentially dangerous. Totally, there are 19 glacial lakes with the highest hazard level (Table 4), almost all of which are in the southern basins (particularly in sub-basin of 5o197), where glaciers and glacial lakes are densely located (Figure 4). The potentially dangerous glacial lakes are recommended for further detailed investigations and field surveys because a potential breakout could have catastrophic effects on human life and property in China and Nepal. For information to the field work, the basic attributes of these lakes were listed in Table 5.

Figure 5 shows two examples of the morphological changes of potentially dangerous glacial lakes (Gelhaipuco Lake and Coqong Lake). Their locations and other characteristics are presented in Table 5 the ID of Gelhaipuco is “19” and Coqong Lake is “16,” respectively. Figure 5 clearly shows the relationship between glacial lake expansion and mother glacier shrinkage in different periods.

4. Discussion

4.1. Accuracy of Glacier and Glacial Lake Data. The glaciers and glacial lakes were mapped by manual interpretation, which has been considered the most accurate method for outlining glaciers and glacial lakes. However, the original datasets had different spatial resolutions. The uncertainty of the glacier and glacial lake areas depends on the register accuracy and the spatial resolution of the remote sensing data. The register accuracy is one pixel in most study areas, although the error can reach two pixels in very rugged regions. In the 1970s, the original data were obtained from topographic maps with map scales of 1 : 100,000 and 1 : 50,000, indicating a spatial resolution of 50 m and 25 m, respectively. For the 2001 data, the resolutions of the ASTER and CBERS images are 15 m and 30 m. For the 2013 data, the OLI image resolution has been enhanced to 15 m. Therefore, the uncertainty can be calculated based on the register error ($R \times R$) and the error induced by the spatial resolution ($2 \times R \times R \times \sqrt{1}$), where R is the spatial resolution [32, 33]. For the lowest resolution (50 m), the register error is 0.0025 km^2 and the spatial resolution error is 0.005 km^2 for the glacier and glacial

Table 5: Potentially dangerous glacial lakes in the Pumqu river basin.

ID	Subbasin	Longitude	Latitude	Elevation (m)	Area (m^2)
1	5o193	87°02.83′E	28°04.16′N	5597.03	746 023
2	5o194	86°34.91′E	28°11.95′N	5069.80	1 381 460
3	5o194	86°22.81′E	28°23.72′N	5469.70	925 628
4	5o194	86°18.23′E	28°22.64′N	5347.70	3 748 580
5	5o197	88°21.24′E	28°01.42′N	5150.85	538 032
6	5o197	88°19.25′E	28°00.37′N	5104.19	380 862
7	5o197	88°17.26′E	28°01.04′N	5237.12	508 882
8	5o197	88°15.47′E	28°00.67′N	5240.75	581 487
9	5o197	88°14.45′E	28°00.36′N	5244.71	372 990
10	5o197	88°04.42′E	27°56.96′N	5479.38	1 348 830
11	5o197	88°04.03′E	27°56.16′N	5566.11	853 070
12	5o197	88°00.27′E	27°55.83′N	5331.51	1 147 950
13	5o197	87°55.82′E	27°57.16′N	5017.86	1 094 160
14	5o197	87°54.49′E	27°57.07′N	5183.23	952 025
15	5o197	87°38.39′E	28°11.68′N	5352.83	545 510
16	5o198	87°48.64′E	27°57.87′N	5259.75	454 416
17	5o198	87°46.21′E	27°55.61′N	4918.94	1 084 740
18	5o198	87°38.39′E	28°05.62′N	5197.41	693 135
19	5o198	87°33.68′E	28°10.70′N	5024.18	1 013 480

lake areas. These errors are very small and can thus be ignored. However, the presence of very small glacial lakes and water ponds in different periods can lead to a larger uncertainty for the number of glacial lakes. Therefore, glacial lakes with an area larger than 0.02 km^2 were analyzed in this work to obtain consistent datasets for the past four decades.

One issue that may influence the accurate classification/interpretation of glacial lakes is the fact that glacial lake areas are always larger in the summer due to the high and concentrated precipitation during the summer monsoon. High temperatures in summer also result in more water supplies (primarily melt water from glaciers, snow cover, and permafrost terrains) in glacial lakes. Therefore, when using remote sensing images for long-term monitoring of glacial lakes, one must take temporal consistency into account [34]. In this study, the dates of remote sensing images acquisition were inconsistent with three periods of 1970s, 2001, and 2013, which may lead to the uncertainties in glacial lake area.

4.2. Changes in Glacier and Glacial Lake. Temperature and precipitation are major factors controlling glacier change and glacial lake activities and are also direct causes of GLOFs. Annually averaged air temperature and precipitation data from 1971 to 2012 were acquired at the Dingri meteorological station (Figure 6). The temperature data were measured in the air 2 m above the surface, and the precipitation data include rainfall, snowfall, large-scale precipitation, and convective precipitation. The meteorological data indicate an increasing trend in air temperature but not an obvious trend in precipitation (Figure 6). Besides the trends of temperature, the monthly maximum air temperature data were collected for the evaluation of glacier melting (Figure 7). Because

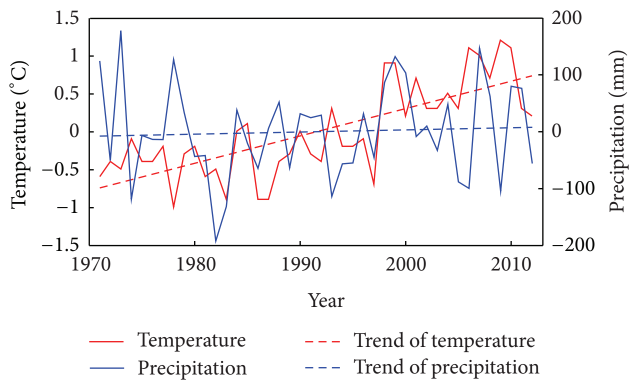

Figure 6: Anomalies in air temperature and precipitation from 1971 to 2012 at the Dingri meteorological station.

the elevation of Dingri station is 4300 m and the mean elevation of glacial lake is 5100 m, which can be considered as the elevation of end of glaciers, the air temperatures were corrected based on −0.6°C per 100 m according to the observations at the nearby meteorological station. However, the average air temperature was also higher than 0°C from May to September (the figure was not shown here). Therefore, both the temperature and its trend indicate the glaciers were accelerated in melting in summer. In agreement with the previous reports [25, 26], it can be concluded that climate warming is the main reason for glacier recession in the Pumqu river basin and, hence, glacial lake expansion. Statistics also showed that with the rising temperatures and increased variability of precipitation, the frequency of GLOF events is expected to increase [35].

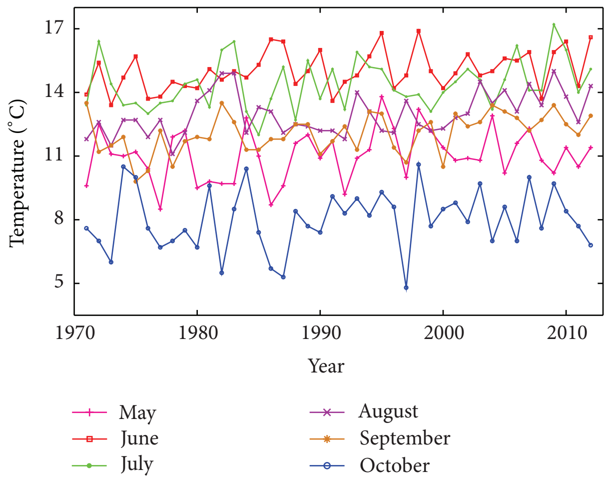

Figure 7: Monthly maximum air temperature from 1971 to 2012 at the elevation of 5100 m.

4.3. Potentially Dangerous Glacial Lakes. Potentially dangerous glacial lakes were identified based on our literature analysis, as well as remote sensing and DEM data. A sudden increase in temperature can lead to rapid glacier melting (even glacier calving) based on previous reports of historical GLOF events [16, 36, 37]. High temperatures can also destabilize surrounding sediments (e.g., the moraine dam). With the increased temperatures in the Pumqu river basin, the possibility of GLOF events has risen. Moreover, the interannual fluctuations in precipitation for the period of 2000–2012 were significantly larger than those for the period of 1971–2000. The standard deviation of precipitation for the period of 1971–2000 was 81.23 mm, while it grew up to 85.55 mm for the period of 2000–2012. These extremes in temperature and precipitation have been persistently increasing under the background of global changes. Thus, these potentially dangerous glacial lakes should receive more attention.

Note that the moraine dam properties, such as the presence of bedrock, ice, and pipes, cannot be interpreted by remote sensing data with a resolution of 15 m [38]. Therefore, we recommend that a field survey should be carried out in the next few years to obtain a more reliable evaluation of the dangerous lakes identified in this work. For confirmed dangerous lakes, substantial mitigation measures should be immediately implemented to reduce the risk of outburst. This work has provided basic information regarding potentially dangerous glacial lakes, which is very useful to the organization of field work.

5. Conclusion

This study used remote sensing images supplemented by DEM data to update the inventory of glaciers and glacial lakes in the Pumqu river basin, Tibetan Plateau. The changes in glaciers and glacial lakes over the past four decades were also analyzed. The results indicate that there are currently 839 glaciers and 254 glacial lakes in the study area, with total area of 1183.4 km^2 and 52.75 km^2, respectively. Between the 1970s and 2013 periods, the number of glaciers decreased by 160, while the glacier area decreased by 276.57 km^2 (19.05%). The glacial lake area rose by 11.14 km^2 (26.76%), and the number of lakes increased by 55. The retreat of glaciers and expansion of glacial lakes (both in number and area) were particularly significant during the period of 2001–2013.

Based on a literature analysis, integrated criteria were established for the identification of potentially dangerous glacial lakes. Based on these criteria and their weights, 19 potentially dangerous glacial lakes were identified, most of which are located in the southern part of the basin. The outlet of the Pumqu river basin is the boundary between China and Nepal, so that potential GLOFs could have a catastrophic effect on lives and properties in the downstream communities. Therefore, a field survey is recommended to investigate the dangerous glacial lakes identified in this work and to conduct mitigation measures for highly dangerous glacial lakes.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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