remote sensing

Article

Temporal and Spatial Changes and GLOF Susceptibility Assessment of Glacial Lakes in Nepal from 2000 to 2020

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Abstract: Glacial lakes are a sensitive indicator of regional climate change and one of the initiators of glacier disasters. It is of great significance to understand the spatial distribution and change characteristics of glacial lakes for exploring their response patterns to climate change and assessing the glacial lake outburst flood (GLOF) susceptibility. Based on Gaofen-1/6 PMS, Sentinel-2A/2B MSI and Landsat TM/ETM+/OLI images from 2000 to 2020, we integrated geographic information technology and mathematical and statistical methods to analyze the spatial and temporal distribution of glacial lakes in Nepal and their dynamic changes, and further discriminated and evaluated the GLOF susceptibility of glacial lakes. The results show that there were 2420 glacial lakes in Nepal in 2020, mainly distributed within the 4500~5500 m, with an area of 87.21 km^2 and a water storage of 1921.72 × 10^6 m^3. The number and area of glacial lakes with each area above 0.01 km^2 in Nepal showed an increasing trend from 2000 to 2020, while 499 new glacial lakes were born, 139 lakes disappeared, the area and water storage increased by 19.46 km^2, 403.07 × 10^6 m^3, respectively. Glacial lakes at altitudes <3000 m were relatively stable, while the number and area of glacial lakes at altitudes within 4500~5500 m increased rapidly. We assessed the GLOF susceptibility of 40 moraine-dammed glacial lakes with an area above 0.2 km^2 in Nepal, and found that there were 8, 12, 14 and 6 glacial lakes with low, medium, high and very high susceptibility, respectively. Among glacial lakes with very high GLOF susceptibility, potential GLOF events of Tsho Rolpa glacial lake, Lower Barun glacial lake and glacial lake with code of GL87091E27797N will cause great harm to downstream regions. GLOFs in Nepal will be in an active status in the future, therefore, the dynamics of glacial lakes and their surroundings should be continuously monitored.

Keywords: glacial lake; outburst probability; remote sensing; Gaofen image; Nepal

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1. Introduction

Lakes are regarded as a sensitive indicator of climate change [1,2] and have an important impact on the natural environment and socio-economic development [3]. Glacial lakes, one of the types of lakes, are a natural water body that are mainly supplied by modern glacial meltwater or formed in glacier moraine's depression [4]. It can reflect the regional climate status and changes more precisely as they are less affected by human activities [5,6]. Glacial lakes are an important water resource in alpine regions, providing excellent regulation of river runoff [7]. Meanwhile, they are also one of the triggers for mountain hazards [8]. Floods and debris flows caused by glacial lake outburst pose a serve threat to the lives and properties of residents and infrastructure such as roads and bridges in the downstream areas [9–12]. Therefore, monitoring glacial lake change and assessing the glacial lake outburst flood (GLOF) susceptibility are of increasing interest to academics and local governments. It is challenging to carry out field investigations on glacial lakes due to the complex topographical conditions. Fortunately, the rapid development of remote sensing technology and the accessibility of multi-source images can help in conducting studies on glacial lake monitoring and outburst potential assessment [13].

Nepal is located at the southern part of the Central Himalayas [14] and has many glacial lakes due to the glaciation, making it one of countries most seriously affected by GLOFs in the world [15,16]. There have been at least 24 GLOF events in Nepal since the 1950s, involving many glacial lakes such as Nagma Pokhari lake (1980), Dig Tsho lake (1985), Dudh Koshi lake (1998) and Tam Pokhari lake (1998), all of which resulted in serious human casualties and the latter two caused an economic loss of Rs 156 crore [17–20]. Most recent studies on glacial lakes in Nepal focused on the individual glacial lakes (e.g., Imja lake, Thulaji lake, Lower Buran lake, etc. [21]) or on glacial lakes within parts of this region (e.g., Dudh Koshi basin [22], Tama Koshi basin [23], and the southern part of Mount Everest [24,25]), and suggested that glacier retreat due to post-Little Ice Age climate change [26,27] and human activities [28–30] are the main factors leading to glacial lake formation and expansion [31], increasing the susceptibility of GLOFs. Currently, only a few scholars have conducted studies on glacial lakes throughout Nepal. For example, Rounce et al. [15] analyzed the changes and risks of glacial lakes in Nepal from 2000 to 2015 based on Landsat ETM+/OLI images and found that 11 extremely dangerous glacial lakes and 33 dangerous glacial lakes existed in this region. Moreover, the spatial resolution of remote sensing images adopted in existing glacial lake inventory is moderate because of the influence from reference images and extraction methods [32].

In this study, based on multi-source satellite remote sensing images such as Gaofen-1/6 PMS, Sentinel-2A/2B MSI and Landsat TM/ETM+/OLI images, we produced an inventory of glacial lakes in Nepal for 2000, 2010 and 2020 to analyze their distribution patterns and dynamic changes. Meanwhile, mathematical and statistical methods were used to assess the GLOF susceptibility of glacial lakes, with the aim of providing a scientific basis for the management and prevention of GLOF disasters in Nepal. Among them, in 2020, Gaofen-1/6 PMS images with a spatial resolution of 2 m were used to extract glacial lakes throughout Nepal, this will help to comprehensively understand and grasp the number and spatial distribution characteristics of glacial lakes.

2. Study Area

Nepal (80°04′~88°12′ E, 26°22′~30°27′ N) is located at the northern part of the South Asian subcontinent and the southern foot of the Central Himalayas [14], bordered by China's Tibet Autonomous Region to the north and surrounded by India to the east, west and south, with a national boundary of about 2400 km and a land area of about 14.7×10^4 km^2 (Figure 1). The terrain of Nepal is high in the north and low in the south. There are four major terrain areas from north to south: the Himalayan mountains, mountain valleys, hills and the Terai plains [33,34]. There are eight peaks with an altitude of over 8000 m a.s.l within the Himalayan mountains, such as Mount Everest, Kangchenjunga and Lhotse [35]. The climate in Nepal is distinctly different due to huge topographical differences, including an alpine climate (northern), a temperate climate (central) and a subtropical climate (southern). The northern part of Nepal is alpine with snow all year round and the lowest temperature reaching −41 °C, the central valley has a mild climate, and the southern plain is hot all year round with the highest temperature of 45 °C in summer. In 2020, Nepal had a population of about 30 million, 80% of whom were agricultural. Arable land covers 22.11% of the total land area around this country (3.25×10^4 km^2). (https://www.fmprc.gov.cn/web/gjhdq_676201/gj_676203/yz_676205/, accessed on 20 March 2022).

As an important barrier between the Qinghai-Tibet Plateau and the South Asian subcontinent, the Himalayas have large differences in its northern and southern parts [36,37]. Nepal, located in the southern part of the Himalayas, is significantly influenced by the South Asian Monsoon and receives abundant precipitation. The formation of glacial lakes relies on glacial meltwater supply, and the number of glaciers in Nepal in 2020 was 3486, with a total area of 4179.69 km^2. According to the High Asia Glacier Lakes Inventory, there were 1232 glacial lakes, with a total area of 73.06 km^2 in Nepal in 2018, which were mainly distributed in 11 administrative districts including Mahakali, Seti, Karnali, Rapti, Dhawalagiri, Gandaki, Bagmati, Janakpur, Sagarmatha, Koshi and Meggi [32]. Because the northern high mountains are on the Mediterranean-Himalayan seismic belt [38], geological activities are active, leading to frequent natural disasters such as earthquakes, avalanches, landslides, and GLOFs [39,40].

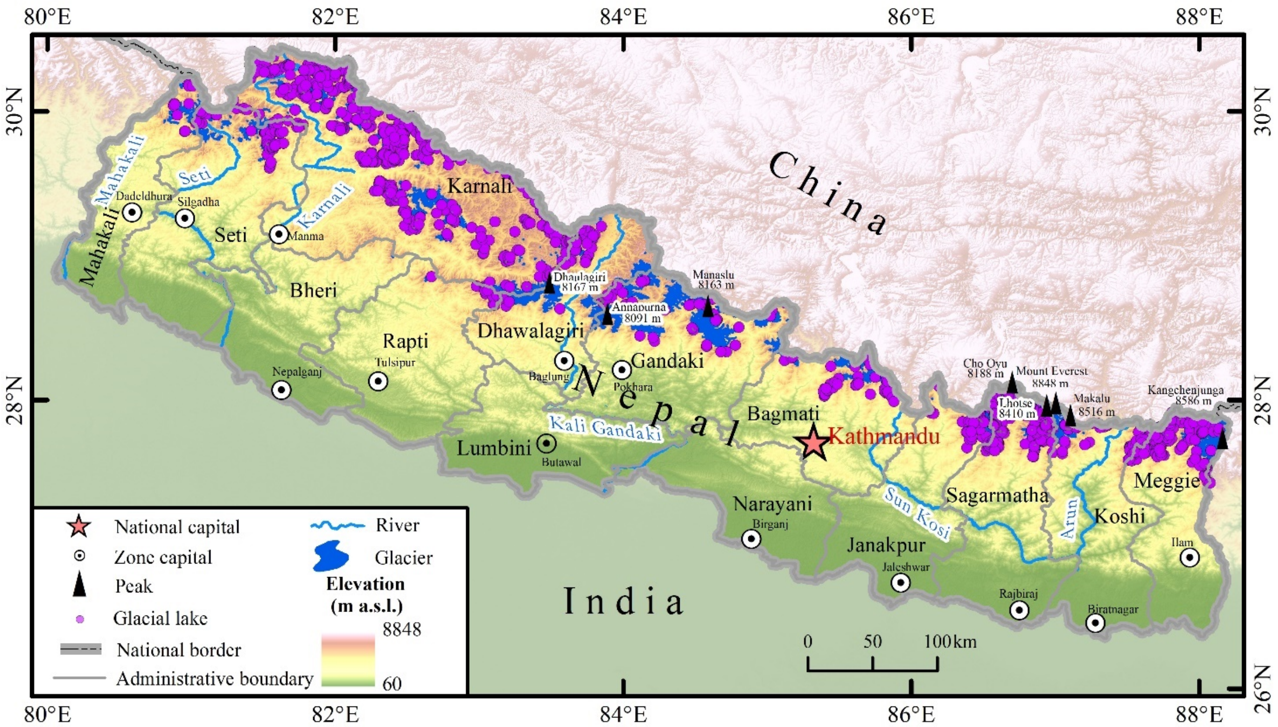

Figure 1. Location of Nepal and the distribution of glacial lakes in Nepal.

3. Data and Methods

3.1. Data

In this study, satellite images used to interpret glacial lakes and their mother glaciers in Nepal include Gaofen-1/6 PMS images in 2020 (85 scenes), Landsat TM images in 2000 and 2010 (37 scenes), Landsat ETM+ images in 2000 (13 scenes), Landsat OLI images in 2020 (16 scenes) and Sentinel 2A/2B MSI images in 2020 (21 scenes). Additionally, the acquisition time is concentrated between May and October. The selected Gaofen-1/6 PMS images with the spatial resolution of 2 m were downloaded from the website of China National Space Administration's Earth Observation and Data Center (https://www.cheosgrid.org.cn, accessed on 15 November 2021). The Landsat TM/ETM+/OLI images were obtained from the United States Geological Survey (https://earthexplorer.usgs.gov/, accessed on 17 November 2021). We produced the fused image containing the visible band and the panchromatic band of the Landsat ETM+/OLI images to improve the spatial resolution of the image (from 30 m to 15 m) and retain its multispectral information. The Sentinel 2A/2B MSI images were acquired from the Copernicus Open Access Hub (https://scihub.copernicus.eu/apihub/, accessed on 20 November 2021), which have a spatial resolution of 10 m. All the above images were preprocessed by orthorectification, geometric fine-tuning and atmospheric correction.

We used the 3D scene maps in the ArcGIS Earth and LocaSpaceViewer software to judge the type of glacial lake [4], as well as to extract the width and the mean slope of moraine dam. The SRTM DEM V3 obtained from USGS (https://earthexplorer.usgs.gov/, accessed on 28 January 2022) was adopted to extract the lake elevation and slope of the mother glacier tongue. Moreover, the High Asia Glacier Lakes Inventory [32] and the Randolph Glacier Inventory (RGI) v6.0 were used as important reference data to assist in the identification and extraction of glacial lakes and their mother glaciers.

3.2. Methods

3.2.1. Glacial Lake Extraction and Error Analysis

The lake identification methods based on remote sensing images mainly included the water index method [41], NDWI~NDSI combination threshold method [42], artificial visual interpretation [43], supervised classification and deep learning based on SAR images [44], most of which are suitable for extracting water bodies in the plain areas or individual water bodies [45]. The distribution area of the glacial lakes in Nepal has complex terrain and is easily affected by snow, resulting in the poor performance of automated extraction methods. Therefore, in this study, artificial visual interpretation was used to draw the boundaries of glacial lakes based on the color, shape, texture and other features of the glacial lake on the image. When encountering the challenge of mapping glacial lakes caused by mountain shadows, cloud cover or seasonal ice cover, we usually used multi-source images from different periods or with different spatial resolutions to assist in the identification, improve the accuracy and completeness of the identification, and finally validate them by high-resolution ArcGIS Earth images. Images from different satellite have different spatial resolutions, so the minimum areas of glacial lakes extracted for each year are different. The minimum area of glacial lakes for 2020 from the Gaofen-1/6 PMS and Sentinel-2A/2B MSI images was 0.0001 km^2, while that for 2000 and 2010 from the Landsat TM/ETM+ images was 0.01 km^2. The use of high-resolution images with meter spatial resolution was to map the more real conditions of the glacial lakes in Nepal to compensate for the deficiencies of previous remote sensing images with medium spatial resolution. Because of the low spatial resolution of historical images and the late launch of satellites carrying high spatial resolution sensors, changes in glacial lakes with areas larger than 0.01 km^2 were analyzed in this paper. This ensured that the analysis results are credible to a certain extent.

The extraction accuracy of glacial lakes and glaciers can be affected by the quality, spatial resolution and geometric registration of remote sensing images [46,47]. However, verifying the accuracy of glacial lakes and glaciers is challenging because of the difficulty of obtaining high-quality remote sensing images and the topographic complexity of the glacial lake and glacier distribution area in Nepal. In addition, interpretation by referring to remote sensing images is also one of the factors leading to errors, and 50% of a mixed pixel will be included or excluded when delineating glacial lakes and their mother glaciers. In this study, the methods proposed by Wang et al. [48] were used to calculate the area errors of glacial lakes and glaciers:

$$u_a = \frac{\lambda^2 \times p}{2\sqrt{\lambda^2 + \lambda^2}} = \frac{\lambda \times p}{2\sqrt{2}} \quad (1)$$

where u_a is the area error (km^2) of the glacier and glacial lake, λ is the spatial resolution of satellite images (2 m for Gaofen-1/6 PMS, 10 m for Sentinel-2A/2B MSI, and 30 m, 15 m, and 15 m for Landsat TM/ETM+/OLI, respectively), p is the perimeter (m) of the glacial lake and glacier. The results showed that the area error of glaciers in 2020 caused by Gaofen-1/6 PMS was $\pm$171.81 km^2, accounting for $\pm$4.11% of the total glacier area. The area error of glacial lakes in 2020 caused by Gaofen-1/6 PMS, Sentinel 2A/2B MSI and Landsat OLI images was $\pm$5.28 km^2, and the area error of glacial lakes in 2010 and 2000 caused by Landsat TM/ETM+ image were $\pm$13.98 km^2 and $\pm$14.17 km^2, respectively.

3.2.2. Glacial Lake Water Storage Calculation

All glacial lakes in Nepal are located in high-altitude areas, making field investigation extremely difficult. Therefore, only a few glacial lakes, such as the Lower Barun lake and the Imja Tsho lake, have measured water depth data [21,49]. In this paper, the glacial lake area-volume calculation formula proposed by Qi et al. [50] was adopted to obtain the water storage of each glacial lake. This formula is feasible to calculate the water storage of glacial lakes in Nepal because it is deduced from 35 measured glacial lakes in the Himalayan region.

$$V = \begin{cases} 40.67 \times A^{1.184} - 3.218 \times Ratio_{(mxw/mxl)} & A > 0.1\ km^2 \\ 557.4 \times A^{2.455} + 0.2005 \times Ratio_{(mxw/mxl)} & A < 0.1\ km^2 \end{cases} \quad (2)$$

where V is the water storage (10^6 m^3) of the glacial lake, A is the area (km^2) of the glacial lake, and the $Ratio_{(mxw/mxl)}$ is the ratio between the width and length of the smallest circumscribed rectangle of the glacial lake.

3.2.3. GLOF Susceptibility Assessment of Glacial Lake

At present, the models to assess GLOF susceptibility of a glacial lake include the logistic regression model [51], fuzzy comprehensive evaluation model [52–55], hierarchical matrix graphic model [56] and event tree model [57]. Considering the difficulty of obtaining each indicator and the accuracy of evaluation, the fuzzy comprehensive evaluation model was adopted to assess the dangerous glacial lakes in Nepal. The model realizes the transformation from qualitative description to quantitative evaluation based on the affiliation theory of fuzzy science, which means that fuzzy mathematics is used to make an overall evaluation of things or objects restricted by many factors. The factors leading to the collapse of glacial lakes are very complex, such as snow/ice/rock avalanches, heavy rainfall, earthquakes and thawing of ice cored moraines [58], etc. After comprehensively referring to the existing evaluation indicators [43,54,59–61], we selected the area of the glacial lake, the width of the moraine dam, the mean slope of the moraine dam, the area of the mother glacier, the slope of the ice tongue and the distance between the lake and glacier terminus to construct an assessment index system of glacial lakes in Nepal. Among them, the area of the glacial lake dictates the upper limit of the glacial lake outburst disaster. The area of the mother glacier, including the area of its accumulation and ablation zone, can suggest the intensity of the snow and ice avalanche. The distance between the lake and the glacier terminus reflects the magnitude of the impact from the ice/snow avalanche into the glacial lake. The mean slope of the moraine dam determines the stability of the moraine dam. The slope of the ice tongue reflects the potential of the ice tongue breakup [52].

The glacial lakes that have experienced an outburst in Nepal are mainly moraine-dammed lakes [19], therefore only the GLOF susceptibility assessment of moraine-dammed lakes was carried out in this paper. Additionally, the area of the glacial lake was another important indicator for outburst potential assessment, as smaller glacial lakes cause less impact even if they burst. We selected 0.2 km^2 as the area threshold of dangerous glacial lakes by referring to the results from Liu et al. [43]. Then, the value of each indicator of the glacial lake that meets the above standards was calculated. First, we constructed the fuzzy consistent matrix (FCM) (Table 1), which shows the relative weights of the six indicators in pairs, and the weight coefficient of each indicator was calculated by the FCM method [55]. The relative weights of six indicators were 0.115, 0.147, 0.171, 0.183, 0.191 and 0.195, respectively. According to the historical records of glacial lake outbursts in Nepal and expert opinions, the main cause of glacial lake outbursts in this region is snow/ice avalanches. Therefore, indicators such as the distance between the lake and glacier terminus and the slope of the glacier tongue have a greater weight.

$$W_i = \frac{1}{n} - \frac{1}{2a} + \frac{1}{na}\sum_{k=1}^{n} A_{ik} \quad (3)$$

$$a = (n-1)/2 \quad (4)$$

where W_i is the weight of the ith indicator, n is the total number of indicators, A_{ik} is the value calculated by the FCM method in Table 1.

Table 1. Fuzzy consistent matrix.

Indicators	F1 [a]	F2 [b]	F3 [c]	F4 [d]	F5 [e]	F6 [f]
F1	0.5	0.5	0.6	0.5	0.7	0.9
F2	0.5	0.5	0.7	0.5	0.6	0.8
F3	0.4	0.3	0.5	0.6	0.8	0.8
F4	0.5	0.5	0.4	0.5	0.5	0.7
F5	0.3	0.4	0.2	0.5	0.5	0.6
F6	0.1	0.2	0.2	0.3	0.4	0.5

[a] Area of the glacial lake. [b] Width of the moraine dam. [c] Mean slope of the moraine dam. [d] Area of the mother glacier. [e] Slope of the ice tongue. [f] Distance between the lake and glacier terminus.

According to rough set theory [62], six indicators for each glacial lake were arranged in ascending order and divided equally into four groups at 25% intervals. Then, the susceptibility value (SV) of each group was assigned 0.25, 0.5, 0.75 and 1 (Table 2), respectively. Finally, we obtained the GLOFs susceptibility (P) for each glacial lake by Equation (5).

$$P = \sum_{i=1}^{n} W_i SV_i \quad (5)$$

where SV_i is the danger value in Table 2. The calculated GLOFs susceptibility of glacial lakes was classified as low ($P < 0.5$), medium ($P = 0.5$~0.65), high ($P = 0.65$~0.75), and very high ($P > 0.75$) to characterize the danger of the glacial lakes.

Table 2. Interval division of indicators and the calculated susceptibility value for each interval.

Indicators	I	II	III	IV
Susceptibility value (SV)	0.25	0.5	0.75	1
Area of the glacial lake/km^2	<0.27	0.27~0.37	0.37~0.65	>0.65
Width of the moraine dam/m	>115	115~56	56~33	<33
Mean slope of the moraine dam/°	<8	8~15	15~25	>25
Area of the mother glacier/km^2	<0.5	0.5~1.3	1.3~7.5	>7.5
Slope of the ice tongue/°	<10	10~12.5	12.5~19	>19
Distance between the lake and glacier terminus/km	>800	800~370	370~30	<30

4. Results

4.1. Distribution of Glacial Lakes

In 2020, there were 2420 glacial lakes with an area of ≥0.0001 km^2 in Nepal, having a total area of 87.21 km^2 and an average area of 0.036 km^2. The water storage of glacial lakes was 2082.06 × 10^6 m^3. Only six glacial lakes were larger than 1 km^2, of which the largest glacial lake was the Phoksundo Tal lake (29°11′47″ N, 82°56′52″ E), with an area of 4.79 km^2 and a water storage of 258.48 × 10^6 m^3. According to the administrative division, the glacial lakes in Nepal were distributed in 11 prefecture-level administrative regions, and were concentrated in the Karnali region where a total of 1042 glacial lakes had developed, with an area of 34.78 km^2 and a water storage of 782.95 × 10^6 m^3, accounting for 43.06%, 39.88% and 37.60% of the corresponding total of the glacial lakes in Nepal, respectively. Followed by Sagarmatha and Meggie regions, there were 392 and 305 glacial lakes in 2020, having areas of 18.46 km^2 and 8.76 km^2, and water storages of 468.29 × 10^6 m^3 and 155.85 × 10^6 m^3, respectively. The number and area of glacial lakes in other regions were relatively small.

The number of glacial lakes with an area of smaller than 0.01 km^2 was highest (1208) in Nepal in 2020 (Figure 2a), accounting for 49.9% of the total number of glacial lakes. However, the area distribution of glacial lakes did not have obvious regularity, mainly concentrated in 0.02~0.05 km^2 (13.76 km^2), 0.1~0.2 km^2 (15.13 km^2), 0.2~0.5 km^2 (14.07 km^2) and >1 km^2 (15.17 km^2), accounting for 66.66% of the total area of glacial lakes in Nepal in 2020. Glacial lakes were distributed between 2300 and 5900 m (Figure 2b), and the number of glacial lakes increased with increasing altitude up to 5100 m. Glacial lakes were concentrated in the altitude range of 4500~5500 m, in which, the number and area of glacial lakes were 1840 and 62.04 km^2, respectively, accounting for 76% and 71.14% of the total of glacial lakes in Nepal. The snow line in the middle Himalayas ranges from 5800 to 6000 m [63] where glaciers and snow melt violently, which promotes the expansion and generation of glacial lakes within the altitude range of 4500~5500 m.

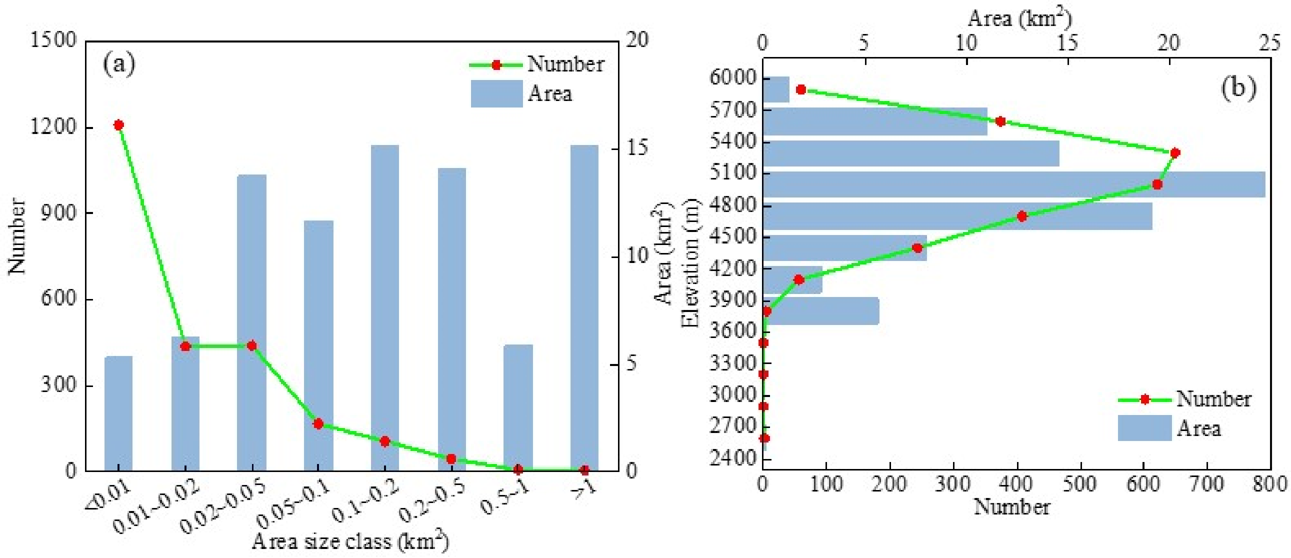

Figure 2. Statistics of glacial lakes in Nepal in 2020 (**a**) the number and area of glacial lakes in different areas, (**b**) the number and area of glacial lakes in different altitude ranges.

4.2. Glacial Lake Change

From 2000 to 2020, glacial lakes in Nepal experienced an overall increasing trend. The number of glacial lakes with an area greater than 0.01 km^2 increased from 850 to 1210, with a change rate of 42.3%, including 499 newly formed glacial lakes and 139 disappeared glacial lakes. Additionally, the total area of glacial lakes increased from 62.29 km^2 to 81.75 km^2, with the area increased by 19.41 km^2 (31.2%). From 2000 to 2010, the number of glacial lakes increased from 850 to 984 (15.76%), including 191 newly formed glacial lakes and 57 disappeared ones. The total area expanded from 62.29 km^2 to 71.39 km^2 (14.6%), corresponding to a water storage increase of 199.6 $\times 10^6$ m^3. From 2010 to 2020, the number of glacial lakes increased even more than that in the previous 10 years, from 984 to 1210 (22.97%), of which 308 glacial lakes were newly born and 82 glacial lakes disappeared. However, the area expansion rate was slightly slower than that in the previous 10 years, from 71.39 km^2 to 81.75 km^2 (14.51%). Water storage increased by 203.46 $\times 10^6$ m^3. The reason for the rapid growth of number but the slow growth of area is that the differential ablation of the glacier surface results in the accumulation of water in the depressions. These lakes are numerous in number but small in size, which is consistent with the findings of Rounce et al. [15].

4.2.1. Changes of Glacial Lakes of Different Scales

Although the glacial lakes in the whole study area showed an overall increasing and expanding trend, the variation difference of different sized glacial lakes was still obvious (Figure 3). Among them, the number of glacial lakes with an area of <0.05 km^2 showed the most obvious change, increasing by 283 in the past two decades, corresponding to an area increase of 6.64 km^2. In 2000, the number of glacial lakes was 594 and the area was 13.33 km^2. By 2010, the number and area increased to 698 and 16.09 km^2, respectively. Then, by 2020 the number and area increased to 877 and 19.97 km^2, respectively. This was followed by glacial lakes with areas between 0.05 km^2 and 0.1 km^2. The number of glacial lakes in this range showed a trend of decreasing and then increasing, while the area kept increasing. In 2000, the number of glacial lakes was 128 with an area of 8.84 km^2; in 2010, the number of glacial lakes was 113, while the area expanded to 9.38 km^2. In 2020, the number of glacial lakes increased to 168 with an area of 11.66 km^2, and the number and area increased by 40 and 2.82 km^2, respectively. The number and area of glacial lakes in a 0.1~0.3 km^2 area range showed an increasing trend. In 2000, there were 96 glacial lakes with an area of 15.29 km^2. In 2020, there were 131 glacial lakes with an area of 21.23 km^2. The number of glacial lakes with areas ranging from 0.3 km^2 to 0.5 km^2 and larger than 0.5 km^2 was basically stable, and the area increased slightly. This shows that the number and area of small glacial lakes in Nepal have experienced large fluctuations.

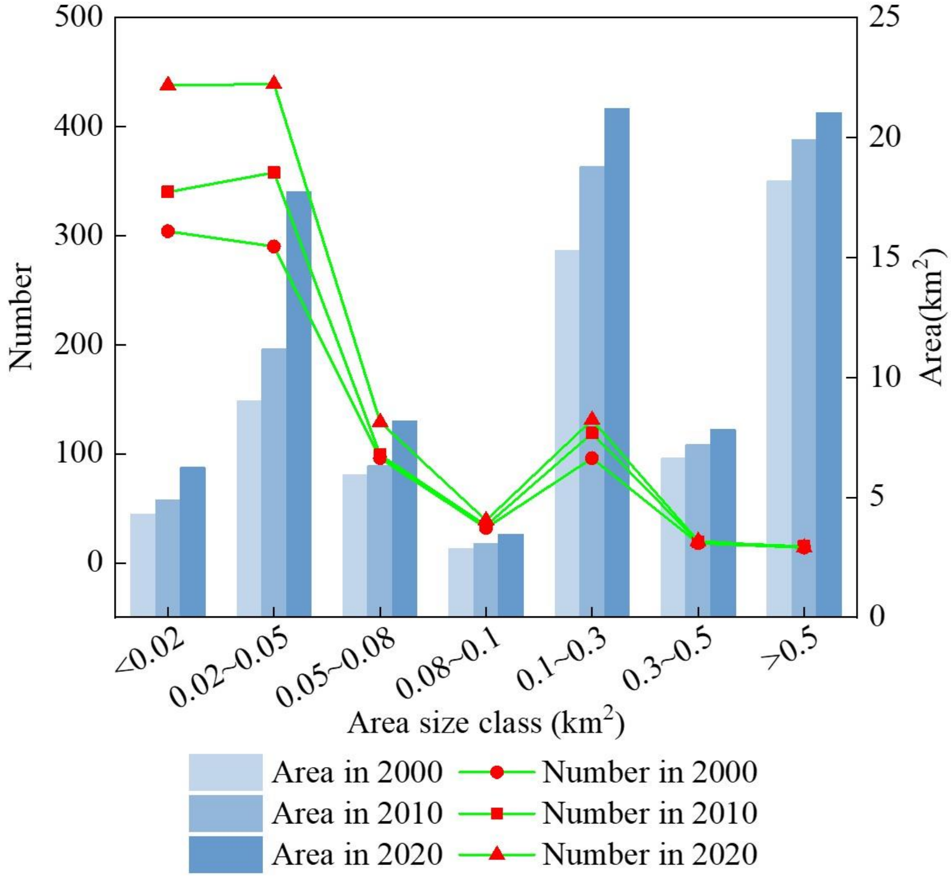

Figure 3. Changes in the number and area of glacial lakes of different scales and grades in Nepal from 2000 to 2020.

4.2.2. Altitude Variation of Glacial Lakes

There are significant altitudinal differences in the change trends of the number and area of glacial lakes in Nepal. The number and area of glacial lakes below 4000 m had small changes (Figure 4). In 2000, there were 17 glacial lakes with a total area of 6.93 km^2; in 2010, there were 25 glacial lakes with an expanded area of 7.47 km^2 and an area growth rate of 7.79%; the number of glacial lakes in 2020 was 24, and although the number of glacial lakes decreased by one, the area expanded to 7.49 km^2. It should be noted that the highest altitude of the distribution of glacial lakes has basically remained unchanged in the past 20 years, but the minimum altitude has continued to decline. That is because increased glacial meltwater collects in depressions at lower altitudes in the context of a warming climate. The number and area of glacial lakes in the altitude range of 4000~4500 m showed a steady increasing trend. In 2000, the number of glacial lakes was 175, with an area of 11.41 km^2, and in 2020 they were 220 and 13.73 km^2. The number and area of glacial lakes in the altitude range of 4500~5500 m increased rapidly. Among them, there were

335 glacial lakes located in the altitude range of 4500~5000 m in 2000, with a total area of 27.01 km^2, and by 2020, the number and area increased by 133 and 9.3 km^2, with the growth rate of 39.7% and 34.43%, respectively. The number and area of glacial lakes at an altitude of 5000~5500 m changed dramatically. In 2000, the number of glacial lakes was 278, with an area of 15.08 km^2. In 2010, the number of glacial lakes increased by 44, and the area expanded to 17.69 km^2. From 2010 to 2020, the number of glacial lakes increased explosively, from 322 to 426, and the area expanded to 21.44 km^2 with a growth rate of 21.2%. Glacial lakes with altitudes over 5500 m were less variable.

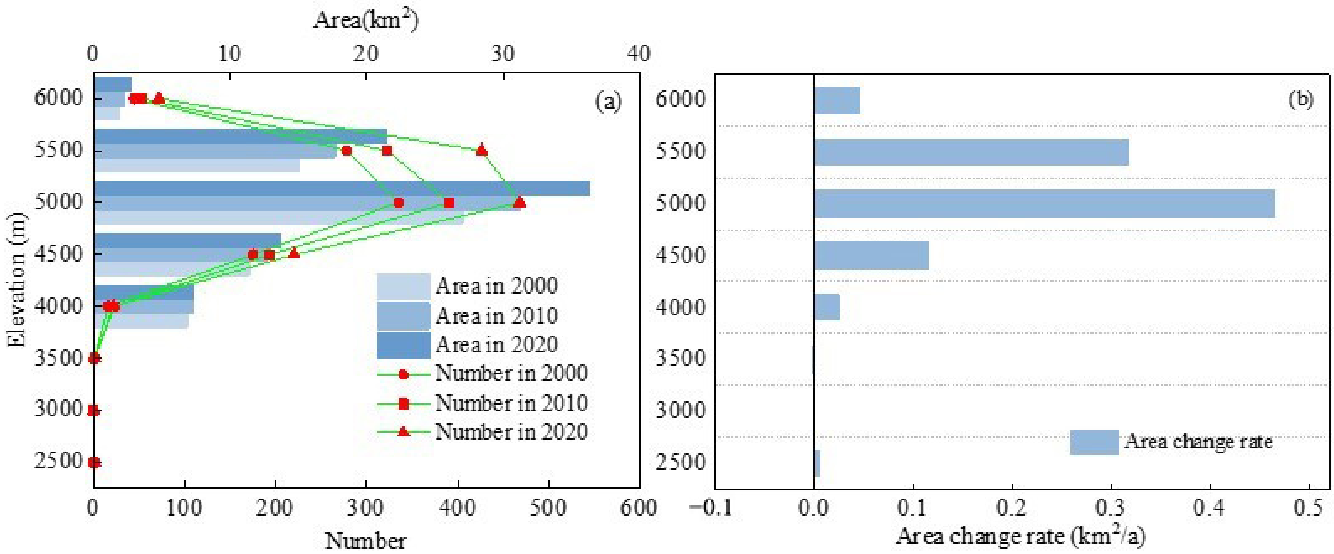

Figure 4. Number and area of glacial lakes at different altitudes in Nepal from 2000 to 2020. (**a**) Changes in the number and area from 2000 to 2020, (**b**) area variation from 2000 to 2020 at different altitude ranges.

4.2.3. Regional Changes of Glacial Lakes

Although the overall area and number of glacial lakes in Nepal are increasing, there are significant regional differences. Glacial lakes in the Mahakali, Rapti, Dhawalagiri, Gandaki, Bagmati, Janakpur, and Koshi regions were all less than 100 in 2000 (Table 3), and the number and area have shown a slight increase over the past 20 years. The number and area of glacial lakes in the Seti region showed a trend of first increasing and then decreasing. The number increased by 16 from 2000 to 2010, and the area and water storage increased by 1.02 km^2 and 21.73 × 10^6 m^3, respectively. From 2010 to 2020, the number of glacial lakes decreased to 50, with the area and water storage decreasing to 2.63 km^2 and 45.77 × 10^6 m^3, respectively. The Karnali region is located at the north of Nepal where the altitude is high and numerous glaciers have developed, and the number of glacial lakes has increased significantly. From 2000 to 2010, the number and area of glacial lakes increased by 44 and 2.75 km^2, with a growth rate of 11.73% and 10.55%, respectively. The number of glacial lakes in 2020 was 520, corresponding to the total area of 714.20 km^2. In addition, the water storage in this region has increased by 90.05 × 10^6 m^3 by 2020. There are 129 settlements in Karnali region, all of which are close to glacial lakes. Therefore, glacial lakes in this region should be observed as a priority in the coming years. The number and area of glacial lakes in Sagarmatha in 2000 were 135 and 12.92 km^2, respectively. From 2000 to 2010, the number and area of glacial lakes increased by 22 (16.29%) and 1.59 km^2 (12.31%). In 2020, the number of glacial lakes increased to 206, and the area expanded to 17.59 km^2, an increase of 71 in number, 4.67 km^2 in area and 115.08 × 10^6 m^3 in water storage compared to 2000. Although there were more than 100 glacial lakes in the Meggie region in 2000, and the number and area of glacial lakes has changed little. From 2000 to

2020, the number increased by 49, the area expanded by 2.06 km^2, and the water volume increased by 37.33×10^6 m^3.

Table 3. Changes of glacial lakes in various regions of Nepal.

Region	2000			2010			2020		
	Area /km^2	Number /n	Volume /$\times 10^6$ m^3	Area /km^2	Number /n	Volume /$\times 10^6$ m^3	Area /km^2	Number /n	Volume /$\times 10^6$ m^3
Mahakali	0.17	7	1.57	0.26	10	2.46	0.27	11	2.37
Seti	2.09	42	29.72	3.07	58	51.45	2.63	50	45.77
Karnali	26.07	375	624.15	28.82	419	668.16	32.63	520	714.20
Rapti	0.25	12	2.71	0.28	15	2.59	0.46	17	4.89
Dhawalagiri	1.87	31	36.44	2.34	37	48.24	2.73	51	50.14
Gandaki	6.04	26	239.44	6.41	26	250.89	6.87	43	258.67
Bagmati	1.49	31	20.02	2.14	48	29.89	2.33	50	31.23
Janakpur	2.38	25	68.28	2.95	31	83.64	3.27	38	91.89
Sagarmatha	12.92	135	328.88	14.51	157	366.34	17.59	206	443.96
Koshi	2.99	50	66.29	3.78	53	96.35	4.89	59	140.13
Meggie	6.01	116	101.13	6.83	130	118.26	8.07	165	138.46

4.3. GLOF Susceptibility Analysis of Glacial Lakes

In 2020, there were 59 glacial lakes in Nepal with an area larger than 0.2 km^2, of which 40 were moraine-dammed glacial lakes. The GLOFs susceptibility assessment of these moraine-dammed glacial lakes was carried out. Among them, there were six lakes with very high, 14 with high, 12 with medium, and eight with low GLOFs susceptibility (Figure 5), accounting for 15%, 35%, 30% and 20% of the total dangerous glacial lakes, respectively. These glacial lakes are not evenly distributed in Nepal and have significant spatial differences. From the perspective of administrative divisions, the Karnali and Sagarmatha regions have more dangerous glacial lakes, with the numbers of 14 (35%) and 13 (32.5%), respectively. In the Karnali region, there was one glacial lake with a very high GLOF susceptibility, four glacial lakes with high susceptibility, five with medium susceptibility, and four with low susceptibility. The Sagarmatha region contained two glacial lakes with very high, five with high, five with medium and one with low GLOF susceptibility. The Dhawalagiri, Gandaki and Meggie regions all had three dangerous glacial lakes, with one high, medium and low of GLOF susceptibility each in the Dhawalagiri region; one very high, two high of GLOF susceptibility in the Gandaki region, and two high and one low of GLOF susceptibility in the Meggie region. One dangerous glacial lake was distributed in each of the Seti, Bagmati, Janakpur, and Koshi regions, with a GLOF susceptibility of low, medium, very high, and very high, respectively. The 40 dangerous glacial lakes were distributed in the altitude range of 3500~5600 m, of which, 12 of which with medium GLOF susceptibility had the highest average altitude of 4925.1 m, and those of low GLOF susceptibility had the lowest average altitude of 4639.1 m. Area is one of the indicators used to assess the GLOF susceptibility of glacial lakes, and the average area of glacial lakes gradually increases with the increasing GLOF susceptibility level, the average areas of the low, medium, high and very high GLOF susceptibility glacial lakes were 0.33 km^2, 0.43 km^2, 0.71 km^2 and 1.15 km^2 in 2020, respectively.

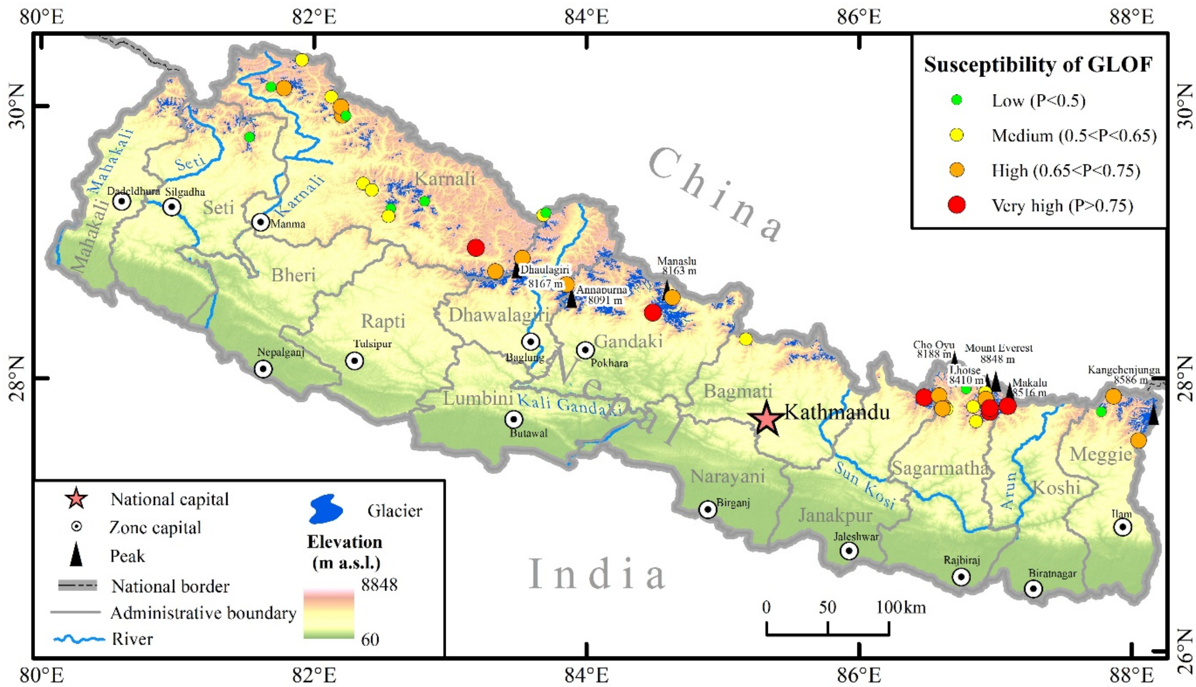

Figure 5. Distribution map of glacial lakes with different GLOFs susceptibility in Nepal.

5. Discussion

5.1. Causes of Glacial Lake Change in Nepal

As a sensitive indicator of climate change, the area change of glacial lakes is closely related to climate change. Increased precipitation, decreased evaporation, warming and humidification of a climate can all lead to an expansion of glacial lakes. Studies have found that both the average annual temperature (0.36 °C/10 a) and annual precipitation (10.4 mm/10 a) on the Qinghai-Tibet Plateau experienced an increasing trend from 1961 to 2020, which is similar on the southern part of Mount Everest in Nepal (0.25 °C/10 a for temperature and 4.27 mm/10 a for precipitation, 1971~2009) [5,64]. A 1 °C increase in the average summer temperature leads to an increase of 100~160 m of the mass balance line of glaciers, and the resulting mass balance needs to be offset by a 40~50% increase in precipitation [65,66]. Obviously, increased precipitation cannot compensate for glacial mass loss due to rising temperatures in Nepal. From 2000 to 2019, the average mass balance of mountain glaciers in the world was negative, and the glaciers in Nepal were also in a state of strong retreat (−0.8%/a, 1980–2010) [67]. This directly leads to an increase of lake recharge water sources, which is basically consistent with the conclusion in this study that the area of glacial lakes in Nepal is increasing. In addition, the long periods of strong insolation and high temperatures may cause melting of buried ice inside the moraines and a subsequent tunneling effect [68–71], which increases the risk of glacial lake outbursts.

The causes of glacial lake changes also vary within different administrative regions. For example, the number and area of glacial lakes in the Seti region showed a trend of first increasing and then decreasing. This is because the glaciers in this region are low in altitude and small in scale. In 2000–2010, glaciers retreated rapidly due to global warming, the increased replenishment resulted in an increase in the number and area of glacial lakes. However, in 2010–2020, glaciers retreated to a certain size, resulting in a decrease in the replenishment, and the supply of some downstream glacial lakes was reduced [72]. The increase in the area of glacial lakes in this region is mainly due to the large number of new glacial lakes and the existence of two glacial lakes larger than 1 km^2 (Imja lake and Limding Tsho lake), and glacial lakes in this region are basically stable if the area changes of these two glacial lakes and the newly born glacial lakes are not considered.

5.2. The Effect of Different Spatial Resolution Images on Extracting Glacial Lakes Area

Two factors may lead to errors in glacial lake extraction, one is the single pixel extraction error caused by manual visual interpretation, and the other is caused by an image with different spatial resolutions. In this study, multi-source remote sensing data were used to extract glacial lakes in three phases through artificial visual interpretation. The spatial resolution of Landsat TM, Landsat ETM+/OLI, Sentinel-2A/2B MSI and Gaofen-1/6 PMS images are 30 m, 15 m,10 m and 2 m, respectively. To explore the impact of spatial resolution on glacial lake extraction, four glacial lakes with different sizes (A) larger than 0.5 km^2, (B) in 0.3–0.5 km^2, (C) in 0.1–0.3 km^2 (D) less than 0.1 km^2 in Nepal in 2020 were selected for study (Figure 6). In this study, the Landsat OLI unfused multispectral composite image (spatial resolution of 30 m) was used as a representative of Landsat TM images, while the multispectral composite image fused with panchromatic band (spatial resolution of 15 m) was used as a representative of Landsat ETM+ images. Additionally, areas of glacial lakes extracted from Gaofen-1/6 PMS images with a resolution of 2 m were used as the true areas.

As shown in Table 4, for glacial lake A, the lower the resolution, the larger the error. The true value of the glacial lake's area obtained from the Gaofen-1/6 PMS image was 1.6514 km^2, and the area obtained from the 10 m-resolution image was 1.6513 km^2 with an error of 0.06%; the area obtained from the 15 m-resolution image was 1.6029 km^2 (2.93%); the area obtained from the 30 m-resolution image was 1.5902 km^2 (3.71%). The error pattern of glacial lake B and C from different spatial resolution images was similar to that of glacial lake A. The extracted areas of glacial lake D from the three resolutions images were all larger than the accurate area, which are 0.0772 km^2, 0.0761 km^2, and 0.0756 km^2 of 10 m, 15 m and 30 m-resolution images with the errors of 2.79%, 1.33%, and 0.67%, respectively.

In summary, the area errors of the four glacial lakes selected in this paper were all less than 3.5% in the experiment, which were all within the allowable error range. Therefore, it is completely feasible to extract the glacial lakes from multi-source remote sensing images with resolution differences.

5.3. Validation of GLOF Susceptibility Assessment

In this paper, six extremely dangerous glacial lakes, i.e., with very high GLOF susceptibility were identified in Nepal, which are basically consistent with the dangerous glacial lakes identified by Rounce et al. [15] using the hierarchical matrix graphic model in 2017. Of the six glacial lakes, Tsho Rolpa lake, Chamlang North lake and Lumding lake were all assessed to be of high or very high danger by Rounce et al. The danger level of the Lower Barun lake obtained in this paper is consistent with the results of Sattar et al. [73] and Haritashya et al. [21], which are very dangerous. The danger assessment of the Imja Tsho lake disagrees with the current studies. For example, Kattelmann et al. believed that it was of high danger [74], Rounce et al. thought that it was currently of medium danger and will be highly dangerous in the future [15]; however, Fujita et al. considered that its GLOFs susceptibility was very low [75]. In this study, it was identified as a medium-danger glacial lake. To sum up, the results of this study are similar to those of most scholars, with high accuracy.

Among the six glacial lakes with very high GLOF susceptibility, the glacial lake coded GL87091E27797N is the closest to the surrounding residential region, with a distance of 11 km. Once it bursts, the damage may be greater than other potentially dangerous glacial lakes. There were two glacial lakes greater than 1 km^2, the Tsho Rolpa lake and the Lower Barun lake, with an area of 1.65 km^2 and 2.19 km^2 in 2020, respectively, and 17 km and 23 km from the nearest settlement, respectively. Both of which are directly connected to the mother glacier. The area of the Tsho Rolpa lake and the Lower Barun lake have increased by 0.24 km^2 and 1.18 km^2, respectively, in the past 20 years. The above three glacial lakes are more dangerous than other glacial lakes, and should be intensely monitored.

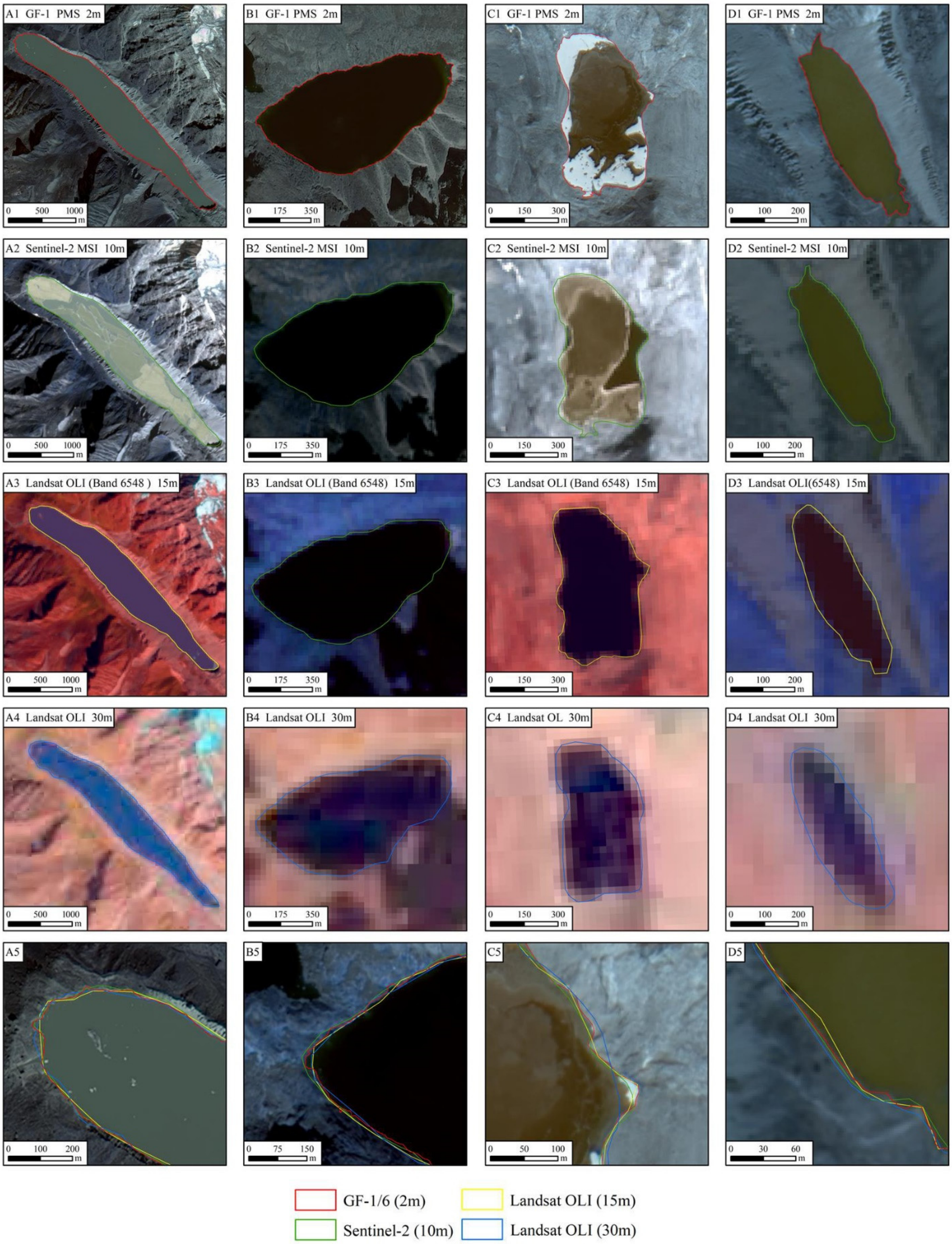

Figure 6. Glacial lake boundaries at different spatial resolutions. (A1 acquired on 15 November 2020, A2 acquired on 28 December 2020, A3 and A4 acquired on 29 October 2020; B1 acquired on 29 September, B2 acquired on 10 October 2020, B3 and B4 acquired on 18 October 2020; C1 acquired on 30 November 2020, C2 acquired on 28 December 2020, C3 and C4 acquired on 29 October 2020; D1 acquired on 26 October 2020, D2 acquired on 10 October 2020, D3 and D4 acquired on 18 October 2020).

Table 4. Areas and errors of different glacial lakes extracted from images of different spatial resolutions.

Glacial Lake	Gaofen-1/6 PMS 2 m		Sentinel-2 MSI 10 m		Landsat OLI 15 m		Landsat OLI 30 m	
	Area/km^2	Error/%	Area/km^2	Error/%	Area/km^2	Error/%	Area/km^2	Error/%
A	1.6514	0	1.6513	0.06	1.6029	2.93	1.5902	3.71
B	0.4681	0	0.4653	0.59	0.4551	2.78	0.4496	3.95
C	0.2246	0	0.2203	1.91	0.2193	2.36	0.2173	3.25
D	0.0751	0	0.0772	2.79	0.0761	1.33	0.0756	0.67

6. Conclusions

(1) In 2020, there were 2420 glacial lakes with an area of $\geq$0.0001 km^2 in Nepal, having a total area of 87.21 km^2, an average area of 0.036 km^2, and a total water storage of about 2082.06 $\times$ 10^6 km^3. The number is dominated by glacial lakes each with an area of <0.02 km^2 (1646, 68.02); while the area is dominated by glacial lakes with an area of >0.1 km^2 (50.23 km^2, 57.59%). The glacial lakes in Nepal are concentrated in the Karnali region with the number, area and water storage of 1038 (42.89%), 34.96 km^2 (40.09%), and 714.20 $\times$ 10^6 m^3 (37.16%), respectively. The altitude range of 4500–5500 m is the concentrated development area of glacial lakes, with 1840 glacial lakes (76.03%) and an area of 62.04 km^2 (71.14%).

(2) From 2000 to 2020, the number, area, and water storage of glacial lakes with an area of >0.01 km^2 in Nepal showed an overall increasing trend. The number of glacial lakes increased from 850 to 1210, with a change rate of 42.35%, including 499 newly formed, and 139 disappeared glacial lakes at the same time. The total area of glacial lakes expanded from 62.29 km^2 to 81.75 km^2, with a growth rate of 31.2%. The retreat of glaciers caused by climate warming provides development space for the formation and expansion of glacial lakes, which is the main reason for the changes of glacial lakes in Nepal.

(3) The assessment results of GLOF susceptibility revealed that there are 6, 14, 12 and 8 glacial lakes with very high, high, medium and low GLOF susceptibility, respectively. Forty glacial lakes are mainly distributed in the Karnali and Sagarmatha regions. Of these, potential outburst flooding of glacial lakes, including the Tsho Rolpa lake (GLIMS code: GL86477E27861N), Lower Barun lake (GLIMS code: GL87091E27798E), and the lake with GLIMS code of GL87091E27797N will likely pose the greatest dangerous to the downstream areas. Therefore, remote sensing monitoring and basin investigation should be continuously strengthened, and corresponding disaster prevention and reduction plans should be formulated.

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