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Potential threats of glacial lake changes to the Sichuan-Tibet Railway

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Abstract

The Sichuan-Tibet Railway, China's second inland railway to Tibet, is currently being constructed and will run between Chengdu and Lhasa. It will cross the southeastern Tibetan Plateau and be surrounded by glacial lakes, some of which may pose a threat of glacial lake outburst flood (GLOF) events. Both the specific location and the outburst susceptibility of these glacial lakes are largely unknown. In this study, we mapped the glacial lakes using declassified Corona KH-4 and Hexagon KH-9 from the 1960s and Sentinel-2 imagery from 2020 and assessed their spatio-temporal changes. GLOF-susceptibility criteria were established based on historical GLOF events. The results show that the total area (number) of glacial lakes has increased by 22% (20%) from $126.1 \pm 2.4\ km^2$ (1662 lakes) in the 1960s to $153.6 \pm 11.1\ km^2$ (1994 lakes) in 2020. Of these lakes, this study identified 38 very high and 85 high GLOF-susceptibility lakes; mainly distributed along the Bomi-Nyingchi railway section in the Parlung Zangbo River basin. Four of the very high GLOF-susceptibility glacial lakes may pose a threat to the railway and will require monitoring. The insights from this study can be used to mitigate the risk of GLOFs during the construction and maintenance of the Sichuan-Tibet Railway.

1. Introduction

The construction of the Sichuan-Tibet Railway is of great significance for the transport and economic development of western China, especially the region of Tibet (Lu and Cai, 2019). However, the geomorphological conditions along the Sichuan-Tibet Railway are complex and diverse, as it must cross a network of high mountains, valleys and numerous rivers on the southeastern Tibetan Plateau, where the railway is still under construction. Earthquakes, landslides, glacier collapse and glacial lake outburst floods (GLOFs) are common in this region, making it a sensitive area for geological and glacial hazards (Cui and others, 2022; Zhao and others, 2022*a*; Kääb and Girod, 2023; Nie and others, 2023).

Some previous studies have been conducted on geological hazards and emergency prevention along the railway (Cui and others, 2021; Kang and others, 2021; Zhang and others, 2022*a*), mainly focusing on landslides (Guo and others, 2021; Zhao and others, 2023), debris flows (Hu and others, 2019; Sun and others, 2023) and in situ geostress (Ren and others, 2021). However, few studies have been reported on GLOF assessment along the Sichuan-Tibet Railway, which has caused significant destruction and may continue to be one of the major natural hazards in the southeastern Tibetan Plateau (Furian and others, 2021).

Glaciers on the southeastern Tibetan Plateau are losing mass at a higher rate compared to other regions of High Mountain Asia (Brun and others, 2017; Hugonnet and others, 2021; Zhao and others, 2022*b*), contributing to faster glacial lake expansion (Zhang and others, 2015; Wang and others, 2020*b*). In this context, the hazard magnitude of GLOFs would increase if glacial lake dams fail due to external or internal triggers (Worni and others, 2014; Harrison and others, 2018). Once a GLOF occurs, it will severely destroy artificial infrastructure such as the Sichuan-Tibet Railway, and the natural ecosystem downstream in a very short time.

More than 151 GLOF events have occurred in the Tibet Autonomous Region since the 1960s (Nie and others, 2018; Liu and others, 2019; Zheng and others, 2021*b*; Shrestha and others, 2023). The 2020 outburst of Jiweng Co in Lhari County is the most recent GLOF event, destroying most of the downstream electrical facilities, roads and bridges (Yang and others, 2022; Peng and others, 2023). The planned Sichuan-Tibet Railway will pass the downstream of Jiweng Co, albeit at a hydrological distance of ~150 km. This suggests that identifying GLOF susceptible lakes is important to improve the understanding of the GLOF hazard on the Sichuan-Tibet Railway, which will provide insights for future GLOF risk reduction along it. Several previous studies have conducted GLOF susceptibility assessments, but most focused on individual lakes (Liu and others, 2014; Duan and others, 2023), small basins (Wang and others, 2012; Duan and others, 2020; Zhang and others, 2023*a*) or much larger geographical regions of the entire Tibetan Plateau (Allen and others, 2019; Wang and others, 2020*a*; Zheng and others, 2021*a*). However, none of these studies have considered the practical impact of future GLOF events on the important infrastructure, such as the Sichuan-Tibet Railway.

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To this end, this study examined the spatio-temporal changes of glacial lakes along the Sichuan-Tibet Railway using high-resolution remote-sensing data including Corona KH-4, Hexagon KH-9 (declassified spy satellite imagery) in the 1960s and Sentinel-2 data in 2020. Using these glacial lake datasets, combined with detailed field investigations of selected glacial lakes, supplemented by open access secondary products such as glacier velocity data, a comprehensive GLOF susceptibility assessment was conducted.

2. Study area, data and methods

2.1 Study area

The Sichuan-Tibet Railway starts from Chengdu in Sichuan Province to Lhasa in the Tibet Autonomous Region, located between longitudes 91°E and 104°E and latitudes 29°N and 31°N. It stretches over a total length of ∼1543 km (Fig. 1). The cities of Ya'an and Nyingchi divide the railway into three sections, two of which have been completed, while the Ya'an-Nyingchi section is still under construction. When completed, the Sichuan-Tibet Railway will cross the southeastern Tibetan Plateau, specifically the Hengduan and Nyainqêntanglha mountains. The topography along the route is complex and varied, with a maximum altitude gradient of ∼5000 m. The construction of the railway faces significant difficulties as it passes through plate collision zones and seismic zones with intense tectonic activity (Xue and others, 2021; Cui and others, 2022).

The study area was delineated based on the mountain ridges and river basins surrounding the Sichuan-Tibet Railway. Fifteen basins across the railway were marked out by the hydrology toolset in ArcGIS. The study focused on 12 glaciated basins to map glacial lakes and investigate GLOF susceptibility of these lakes. The 12 basins are the Brahmaputra, Lhasa River, Nyang Qu, Yi'ong Zangbo, Nu River, Parlung Zangbo tributary, Parlung Zangbo, Lancang, Jinsha River, Litang River, Yalong River and Dadu River basins (Fig. 1). The southern boundary of the study area completely overlaps with the basin boundaries. The historical occurrence of GLOF events and the presence of glaciers were considered to define the outer extent of the northern study area. This was because the boundaries of the northern basin are well beyond the distance that a GLOF could reach the Sichuan-Tibet Railway. In addition, the northern boundary was verified by tracing the mountain ridges on Google Earth to ensure that the area encompassed the watershed directing water flow towards the railway.

2.2 Mapping and classification of glacial lakes

In this study, glacial lakes were defined as those located within a 10 km buffer distance from the glacier RGI v6.0 terminus (Zhang and others, 2015; RGI Consortium, 2017). Glacial lakes in the 1960s were mapped from the panchromatic declassified Corona KH-4 and Hexagon KH-9 imagery. Glacial lakes in 2020 were delineated from Sentinel-2 imagery using a Normalized Difference Water Index threshold determined by the Otsu method (Otsu, 1979). The outlines of the glacial lakes were then carefully inspected and manually corrected by combining the original satellite data. The area uncertainty of the extracted glacial lakes was estimated based on the vectorized lake perimeter and image pixel size (Zhang and others, 2015; Wang and others, 2020*b*), considering that pixels along the lake boundary are on average a mixture of 50% water pixels and 50% non-water pixels.

Glacial lakes were further classified into three types: proglacial lakes, supraglacial lakes and detached glacial lakes, based on the

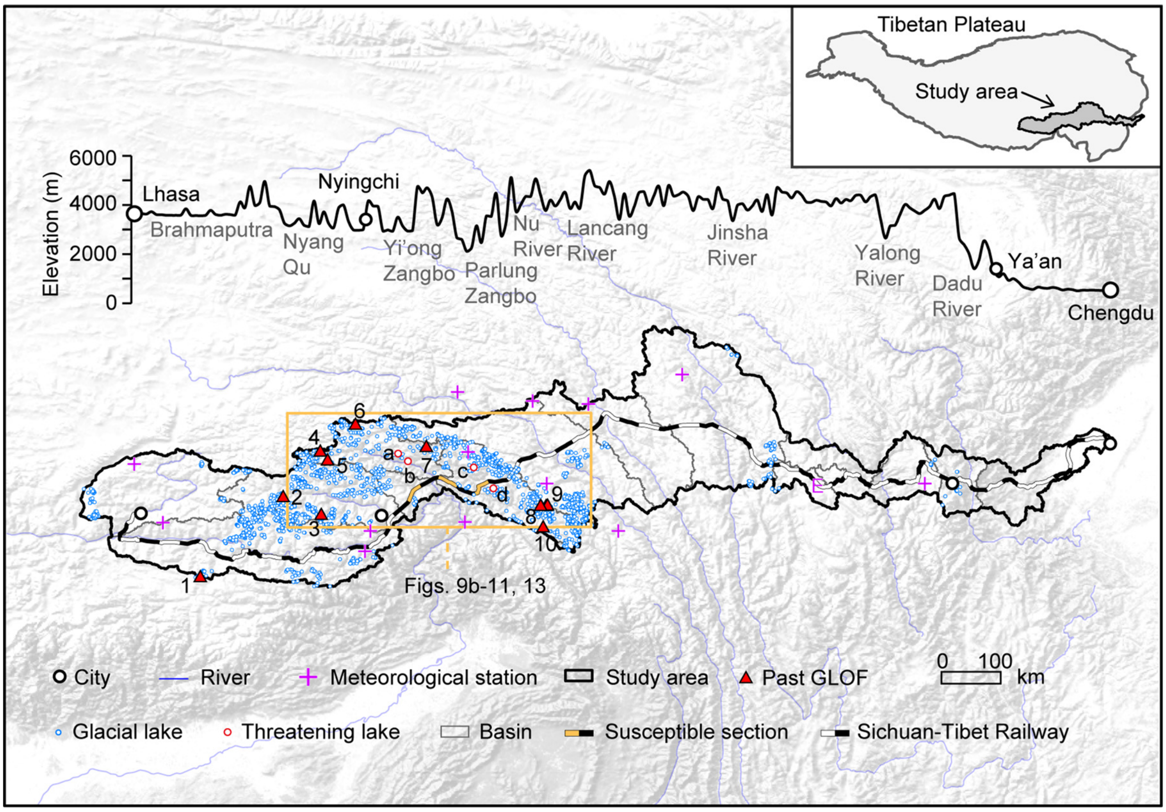

Figure 1. Overview of the study area. The inset shows the elevation profile along the Sichuan-Tibet Railway and the location of the study area on the Tibetan Plateau. The digitization of the railway line was based on Cui and others (2022), with reference to Xue and others (2021) and Zhao and others (2023). The boundary of study area was defined along the mountain ridge and river basins to ensure the watershed flow towards the Sichuan-Tibet Railway. The orange line marks the most GLOF susceptible section of the railway. Letters are the threatening lakes: (a) Dongguanla Co, (b) Gong Co, (c) Cuomaoqie, (d) Lake No.17. Numbers are the historical outburst lakes: (1) Xiaga, (2) Damenlake Co, (3) Upstream lake of Ouguchongguo Co, (4) Ranzeria Co, (5) Jiweng Co, (6) Cuoga, (7) Tributary lake of Narlung Zangbo, (8) Dagonglongba, (9) Gebuma Co and its upstream lake, (10) Guangxie Co.

hydrological relationship with their parent glaciers following the approach of Zhang and others (2015). Only glacial lakes with an area >0.0036 km^2 were mapped in this study (Zhang and others, 2023*b*). Lake attributes, including lake ID, source image, type, latitude, longitude, elevation, area, perimeter and RGI ID of the parent glacier, were annotated. The parent glacier was defined as the largest glacier that directly contacts to or feeds the glacial lake (Wang and others, 2016).

2.3 GLOF susceptibility assessment

The attributes, including glacial lake area/volume, parent glacier characteristics, moraine dam geometry and composition and above-lake slope stability, are commonly used for GLOF susceptibility assessment in the Tibetan Plateau (Allen and others, 2019; Wang and others, 2020*a*; Zheng and others, 2021*b*) and surrounding regions (Bolch and others, 2011; Rounce and others, 2016; Dubey and Goyal, 2020; Rinzin and others, 2021). These attributes were identified and quantified based on the historical GLOF events. However, the causes of most of the events are unknown, which makes challenging to generalize the indicator for the GLOF susceptibility assessment (Lützow and others, 2023; Shrestha and others, 2023). Additionally, the previous GLOF events vary and are not identical across the various geographical regions. In order to identify the appropriate GLOF susceptibility indicator in this study area, the causes of 12 historical GLOF events reported by Liu and others (2019) and Yao and others (2014) were thoroughly verified by the Landsat imagery. These investigations revealed that ice avalanches are the main trigger of proglacial lake dam failure, accounting for six of these historical GLOF events, one caused by upstream GLOF, and another by melting of dead ice in the moraine. At least two events occurred from the glacial lakes that were disconnected from the glaciers (Table 1). To further consolidate the GLOF susceptibility indicator, three lakes with outburst flood records (Jiweng Co, Ranzeria Co and Guangxie Co) were investigated during the 2020–2022 field survey, including lake boundaries by differential global positioning system, bathymetry by uncrewed surface vessel and aerial photogrammetry measurements by uncrewed aerial vehicle (Fig. S1). The survey suggests that the topography of glaciers and lateral landforms, sufficient lake volume and glacier movement are important factors influencing the GLOF susceptibility of glacial lakes.

Eventually, the GLOF susceptibility factors relevant to this study area were identified, including lake volume, dam geometry, stability of the parent glacier and the impact from upstream mass movement or rapid flow. In order to better focus on the susceptible glacial lakes and to avoid the influence from redundant data, the GLOF susceptibility assessment has been done for the supraglacial/proglacial lakes larger than 0.01 km^2 and detached lakes (>0.01 km^2) located within 500 m of their parent glaciers. Based on the remote-sensing analysis, field surveys and previous studies, six indicators (lake volume, downstream slope of the dam, parent glacier velocity, topographic potential for ice and rockfall into the lake, volume ratio of an upstream unstable lake) were then determined to assess the GLOF susceptibility of the selected glacial lakes after examining their differentiation from historical outburst lakes and other glacial lakes (Fig. 2).

Lake volume, which is the total amount of water stored in the lake, is the primary determinant of lake status and flood magnitude in the event of a GLOF. Large volume means higher potential flood volume and higher hydrostatic pressure exerting on the moraine-dammed lakes (Huggel and others, 2004; Fujita and others, 2013). Lake volume has been used as one of the essential GLOF susceptibility indicators in previous studies (Aggarwal and others, 2017; Falatkova and others, 2019). In this study, the volume of glacial lakes was estimated using an empirical area–volume relationship developed by Zhang and others (2023*b*) ($V = 42.95 \times A^{1.408}$, where V is the lake volume in 10^6 m^3 and A is the area in km^2). This equation has been calibrated using 59 bathymetric measurements from 47 proglacial lakes in the greater Himalaya, and, therefore, has a relatively smaller uncertainty compared to other area–volume scaling relationships (Huggel and others, 2002; Fujita and others, 2013; Cook and Quincey, 2015), rendering it highly suitable for estimating volume in this study.

The investigation of historical events in the study area revealed that at least one past event in our study area was caused by an unstable moraine dam. While stability of the moraine dam can be constrained by considering factors such as ratio of moraine width to height and the presence of dead ice or permafrost (Wang and others, 2018, 2023), it is highly challenging to obtain these attributes using remote-sensing data. In this study, the concept of steep lakefront area (SLA) proposed by Fujita and others (2013) was used. The SLA is the region within 1 km of the lake where the pixel's depression angle between the flat lake surface and the surrounding terrain is over 10°. The SLA was determined in this study based on ASTER GDEM v3 by using the program provided by Fujita and others (2013). The average angle of the total SLA was then calculated to provide a proxy for the stability of the moraine dam, which is mainly limited by the vertical accuracy of the DEM (±16 m). Besides, as the SLA is not relevant for bedrock-dammed lakes, a value of zero was assigned irrespective of calculated values for lakes with this dam type.

The activity of the parent glacier, which can be reflected in glacier calving, glacier velocity and glacier thinning, may also be a factor in a lake's susceptibility to outburst flooding. In this study, flow velocity was used as a proxy for glacier activity. The glacial lakes could accelerate the velocity of their parent glaciers by increasing flotation and thermal conversion (Carrivick and others, 2020; Main and others, 2022; Zhou and others, 2022). The stability of the glacier would decrease with a high glacier

Table 1. The list of verified historical outburst glacial lakes

Lake name	Outburst date	Key trigger	Lake type	Dam type
Damenlake Co	26 September 1964	Ice avalanche/slide	Proglacial	Moraine
Guangxie Co	15 July 1988	Ice avalanche	Proglacial	Moraine
Gebuma Co	12 June 1991	Upstream outburst flood	Detached	Bedrock
Upstream lake of Gebuma Co	12 June 1991	Retreat of ice dam	Proglacial	Ice
Xiaga Lake	26 May 1995	Ice avalanche	Proglacial	Bedrock
Upstream lake of Ouguchongguo Co	2004	Ice avalanche	Proglacial	Moraine
Dagonglongba	Between 12 July 2007 and 18 October 2008	Retreat of ice dam	Proglacial	Ice
Cuoga	29 July 2009	Ice avalanche	Proglacial	Moraine
Ranzeria Co	5 July 2013	Ice avalanche	Proglacial	Moraine
Narlung Zangbo tributary lake	June 2014	Upstream debris flow	Supraglacial	Moraine
Tulagou glacial lake	3 July 2015	Melting of dead ice in the dam	Detached	Moraine
Jiweng Co	26 June 2020	Landslide	Proglacial	Moraine

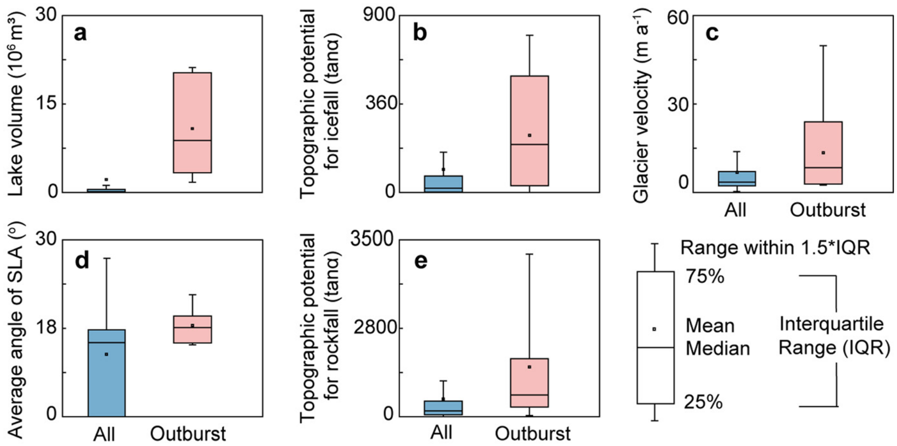

Figure 2. Comparison of factor values between outburst lakes and other glacial lakes. (a) Lake volume. (b) Topographic potential for icefall into the lake. (c) Velocity of parent glacier. (d) Average angle of steep lakefront area (SLA). (e) Topographic potential for rockfall into the lake.

flow rate, making the adjacent lakes susceptible to GLOF triggers like glacier calving (Zhang and others, 2019). Besides, the rapid flow of glacier trunks can form temporary and highly unstable ice-dammed lakes which often rupture leading to the frequent GLOF event (Bazai and others, 2021). The Sentinel-1 based glacier flow velocity data (Friedl and others, 2021) were used to parameterize the glacier activity for GLOF susceptibility assessment.

Mass movement such as ice/snow avalanche and landslide/rockfall into the lake are the most known cause of historical GLOF events in the Tibetan Plateau and the surrounding regions. Within the study area, six of the 12 reported past events were caused by ice-avalanches into the lake. Here, glacial lake's disposal to mass movement from the above slope was estimated by calculating topographic potential for ice and rock falls into the lake. Accordingly, any terrain with a slope steeper than 30° and a trajectory leading towards the lake at an angle of >14° was identified as prone to causing material to slide into the lake, potentially triggering a GLOF (Allen and others, 2019). To further differentiate ice-avalanche and rockfall, the topographic potential area pixels located within the glacier polygon were identified as ice avalanche area.

The rapid flow of water into a lake caused by the breaching of an upstream lake can generate a large wave enough to break the

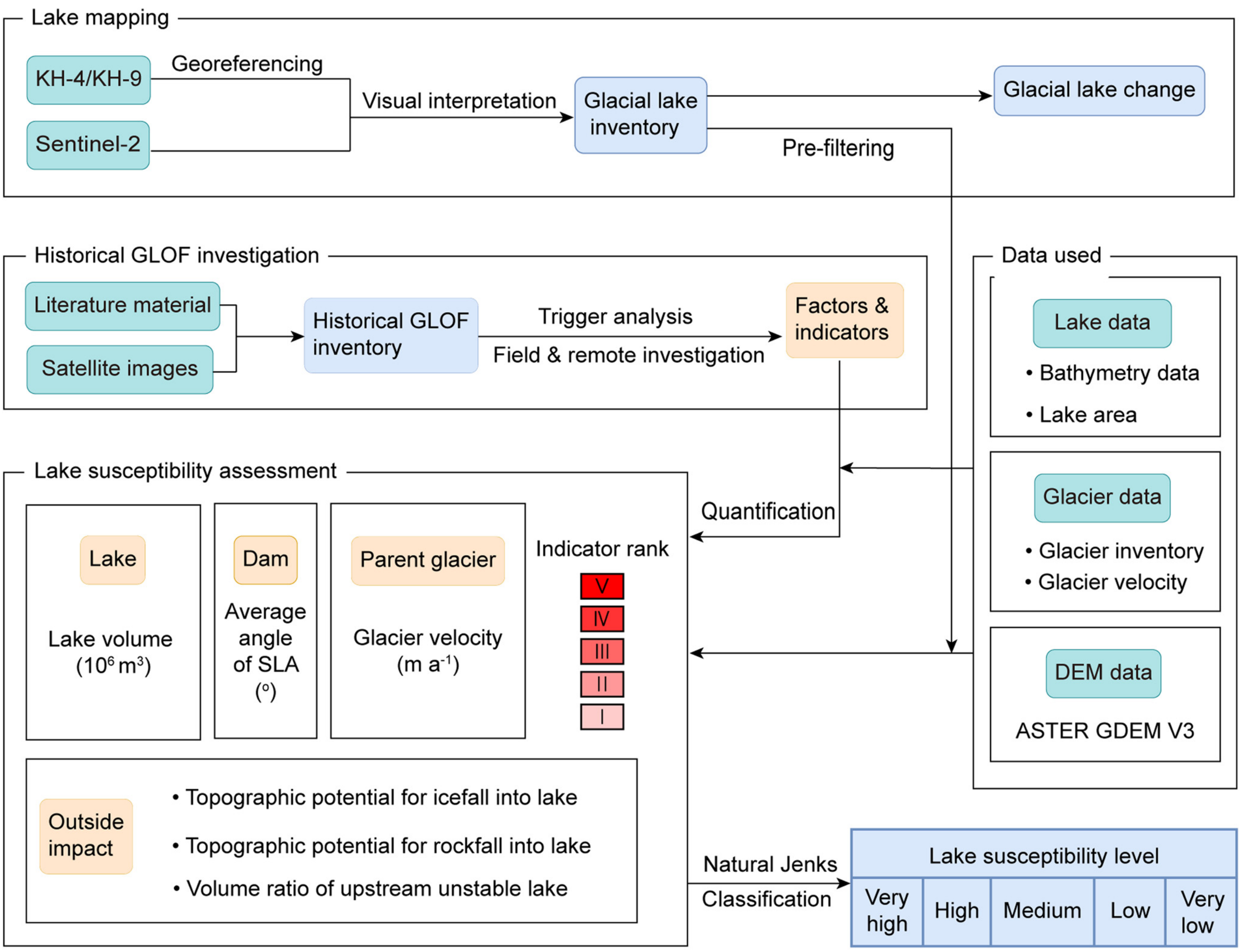

Figure 3. The flowchart of glacial lake susceptibility assessment, which includes lake mapping, historical GLOF investigation and lake susceptibility assessment.

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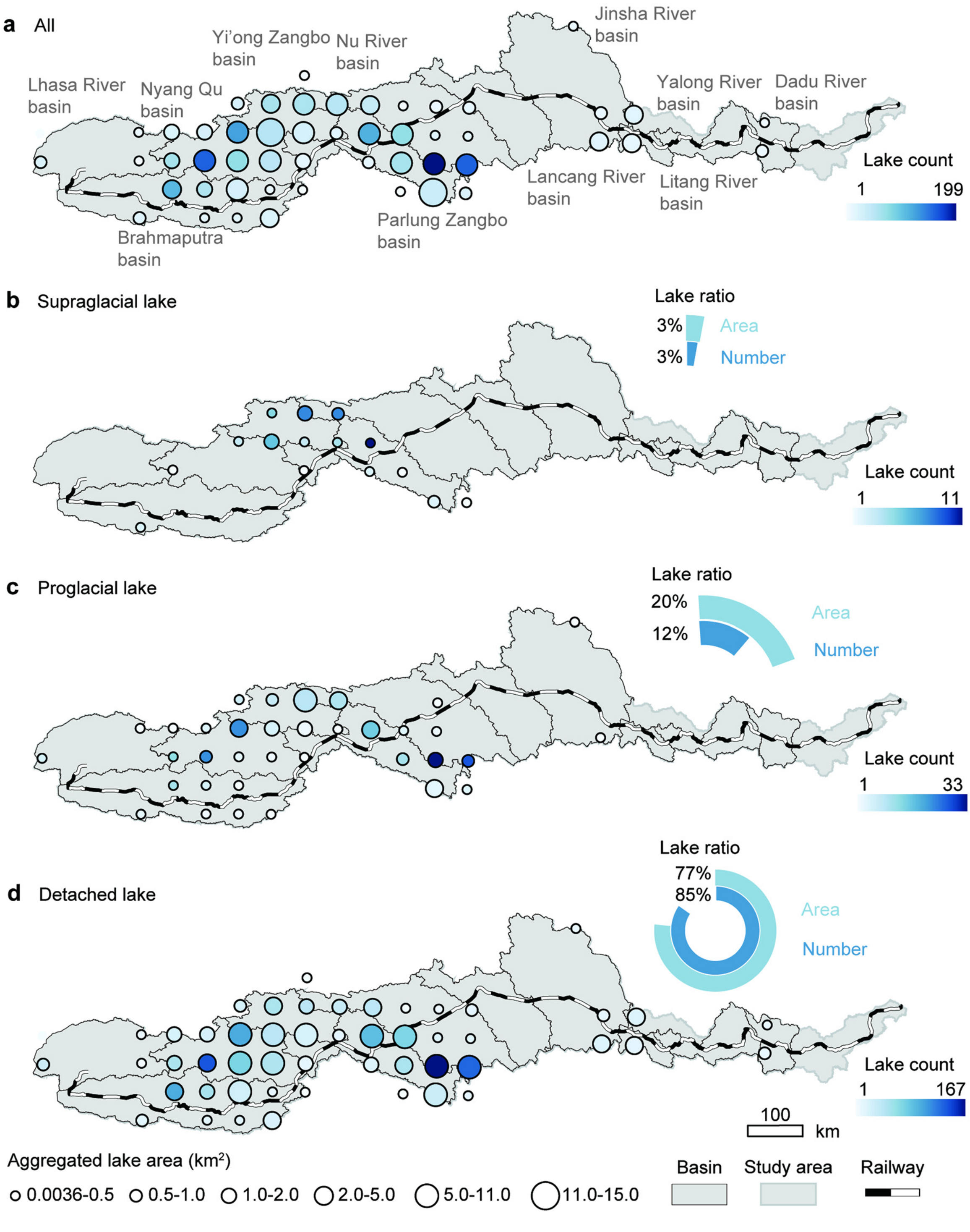

Figure 4. Spatial distribution of glacial lakes by types in 2020 along the Sichuan-Tibet Railway (50 km grid). The insets show the area and number percentage of each type of glacial lake. (a) All glacial lakes. (b) Supraglacial lakes. (c) Proglacial lakes. (d) Detached glacial lakes.

moraine damming the lake. Within the study area at least two GLOF events (Gebuma Co and Quguchongguo Co) are associated with the outburst event of the upstream lakes. It was hypothesized that the upstream volume ratio of the former event could cause the similar cascading GLOF, while the latter would exactly not.

Each indicator was classified into five ranks, 0.2, 0.4, 0.6, 0.8 and 1, based on the minimum, 25%, 50% and 75% quantile values of the historical GLOF events (Fig. 3). As for the upstream unsteady lake volume ratio, the indicator score of it was set to 0, 1 and 0.2, when the ratio is less than Ouguchongguo Co upstream lake/Ouguchongguo Co, larger than Gebuma Co upstream lake/ Gebuma Co, or in between, respectively. Finally, to obtain the GLOF susceptibility score for each lake, the total parameter value for each lake is normalized to a percentile ranking between 0 and 1. Using this normalized susceptibility score, the sampled glacial lakes were classified into five susceptibility levels: very high, high, medium, low and very low using Natural Jenks classification (Allen and others, 2019; Zheng and others, 2021*a*).

3. Changes in glacial lakes along the Sichuan-Tibet Railway

3.1 Spatial distribution of glacial lakes

There are 1994 glacial lakes along the Sichuan-Tibet Railway, covering an area of $153.6 \pm 11.1\ \text{km}^2$ in 2020. They are mainly distributed in the western part of the Sichuan-Tibet Railway, especially in the Basu-Gyaca section (Fig. 4a). Of these lakes, 57 are supraglacial lakes covering an area of 4.7 ± 0.01 km^2, distributed mainly in the Yi'ong Zangbo River basin, accounting for ∼3% of the total number and area of lakes (Fig. 4b). There are 241 proglacial lakes covering 31.4 ± 1.8 km^2, which are predominant in the Parlung Zangbo River basin. The proglacial lakes account for 12% and 20% of the total number and area of lakes, respectively (Fig. 4c). Most of the mapped lakes are detached glacial lakes, accounting for 85% of the total number and 77% of the total area (Fig. 4d).

3.2 Size and elevation variations of glacial lakes

Glacial lakes range in size from 0.0036 to 5.31 km^2 and are located in elevation between 2698 and 5642 m a.s.l. in 2020 (Figs 5a–d). In the 1960s, most lakes were between 0.0036 and 0.05 km^2 in size, but by 2020, 191 new small lakes (0.0036–0.01 km^2) had formed and were the dominant size (Fig. 5a). The glacial lake area and number maintain the similar increases rate between 1960s and 2020, except for the eight large lakes (>2 km^2), which means the expansion of lake area would accelerate when it becomes larger (Fig. 5b). Lakes with a size between 0.2 and 2 km^2 account for the largest proportion of the area and have increased the most. Most of the glacial lakes (1025) are located between 5000 and 5500 m, but lakes between 4000 and 5000 m have a larger total area (97.2 ± 6.4 km^2, 63%, Figs 5c, d).

3.3 Newly formed lakes and type transformations

There are 340 new lakes formed between the 1960s and 2020, with a total area of 19.5 ± 1.9 km^2. The emergence of new glacial lakes occurred mainly in the Yi'ong River basins (Figs 6a, b). While seven glacial lakes with a total area of 0.32 ± 0.01 km^2 drained

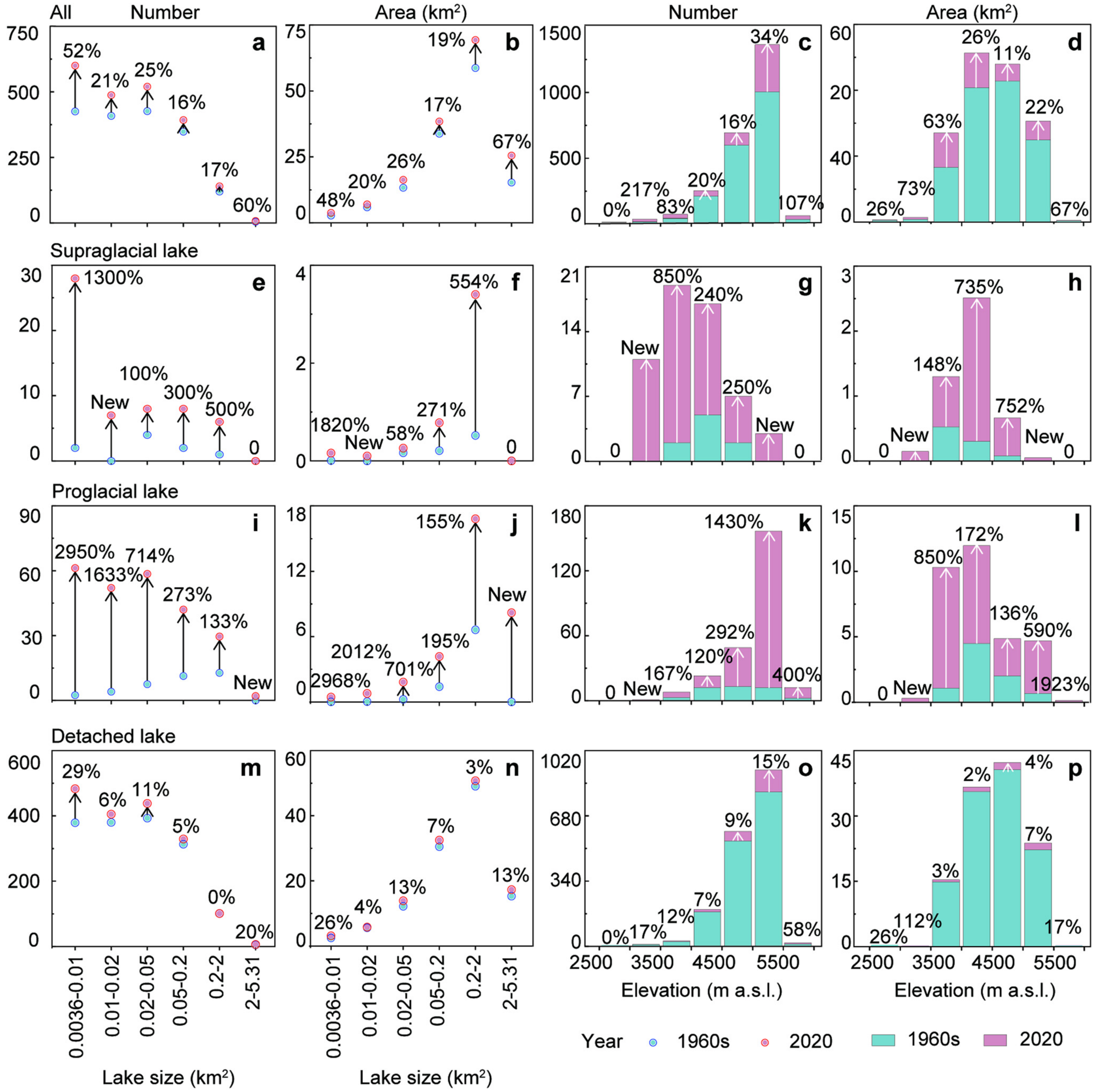

Figure 5. Changes in glacial lakes of different sizes and elevations. (a–d) All glacial lakes. (e–h) Supraglacial lakes. (i–l) Proglacial lakes. (m–p) Detached glacial lakes.

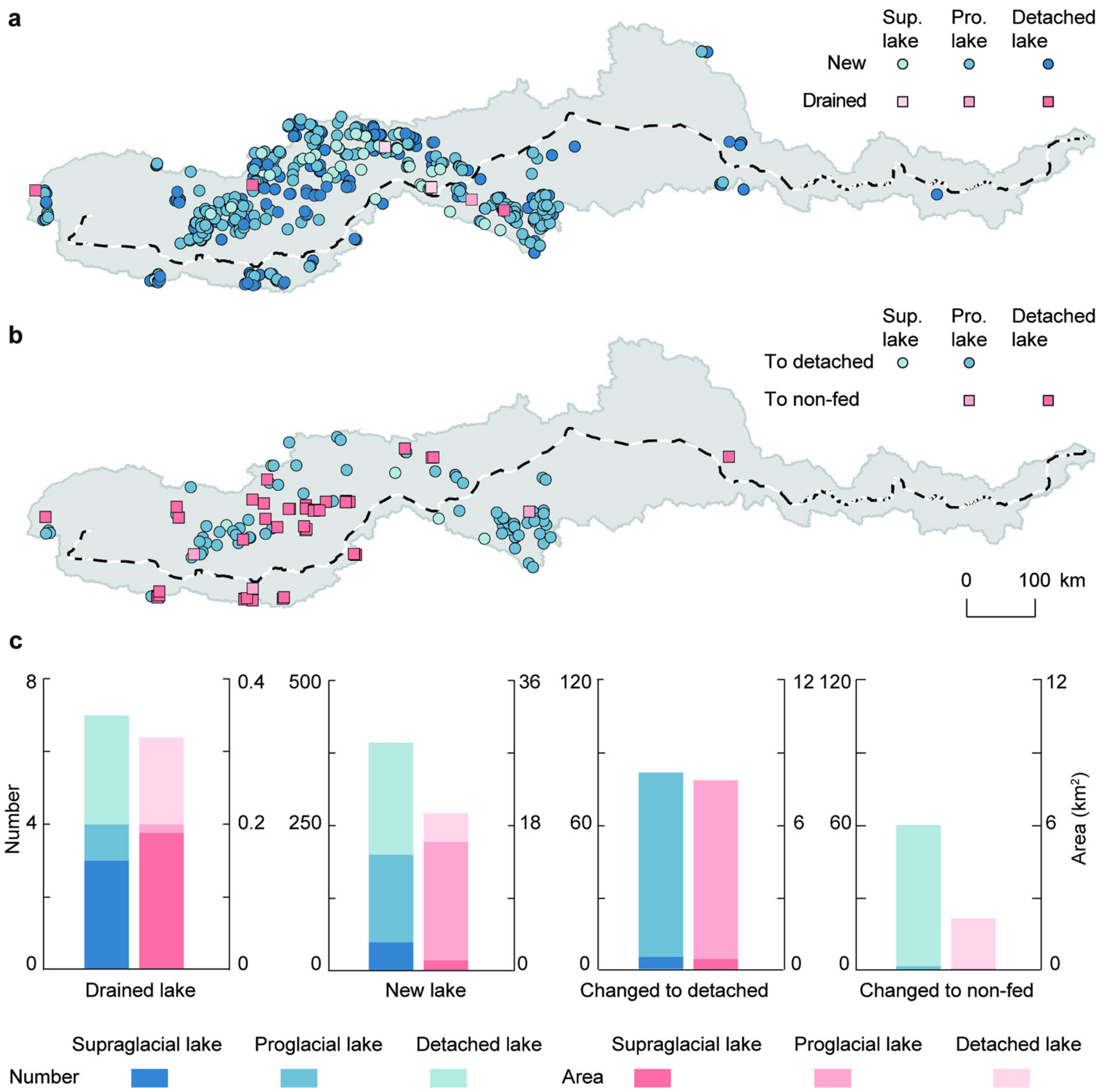

Figure 6. Type transformation of glacial lakes. (a) Newly formed and drained lakes in 2020. (b) Lakes that have transformed into detached glacial lakes and those that have transformed into non-glacier-fed glacial lakes. (c) Number and area of lake-type transformations.

and disappeared from the 1960s to 2020. The number and area of new supraglacial, proglacial and detached glacial lakes are 48 (1.2 ± 0.2 km^2), 204 (14.5 ± 1.2 km^2) and 88 (3.8 ± 0.6 km^2), respectively.

Over the past six decades, 77 proglacial lakes and 5 supraglacial lakes have transformed into detached glacial lakes due to the retreat of their parent glaciers (Fig. 6c). The parent glacier of one proglacial lake disappeared, resulting in its transformation into non-glacier-fed lake (Fig. S2). There were also 56 parent glaciers that disappeared, making the detached glacial lakes no longer glacier-fed.

The glacial lakes experienced a relative real expansion of ~22% between the 1960s and 2020. Lakes in the Yi'ong Zangbo River basin have a relative expansion of ~171%, which is the basin with the largest area increase, followed by the Parlung Zangbo River basin with ~36.7% (Fig. 7). The area increases of proglacial lakes account for ~74% of the total area expansion, followed by detached glacial lakes with 14% and supraglacial lakes with 12%.

4. Potential threat of glacial lakes to Sichuan-Tibet Railway

4.1 Spatial distribution of GLOF susceptible lakes

Of the 651 glacial lakes considered for GLOF susceptibility assessment (Figs 8a, b), 38, 85 and 174 are classified as very high, high and medium level GLOF susceptibility lakes, respectively (Fig. 8c). Most of these high to very high GLOF susceptibility lakes (11 very high and 35 high GLOF susceptibility lakes) are located in the Parlung Zangbo River basin with a total area of ~21.8 km^2. The Yi'ong Zangbo River basin has 16 very high susceptibility glacial lakes with a total area of ~10.1 km^2 (Figs 8a, b). Eight very high susceptibility lakes are in the Nyang Qu River basin and two in the Nu River basin.

The size of 26 very high susceptibility glacial lakes ranges from 0.2 to 5.31 km^2, six from 0.05 to 0.2 km^2 and six from 0.01 to 0.05 km^2 (Fig. 8d). In terms of lake type, 24 very high susceptibility glacial lakes are proglacial lakes. Supraglacial lakes and detached glacial lakes both account for seven each.

4.2 Spatio-temporal variation of the most GLOF susceptible lakes

After comparing the expansion rate of the lakes, 18 very high susceptibility lakes with higher expansion rate were selected for further analysis. Investigation by satellite scenes from Landsat, Copernicus and Maxar between 2018 and 2020 on Google Earth and Tianditu Map showed that all these lakes are connected to glaciers. The flow paths originating from all these lakes converge into the Bomi-Nyingchi section of the Sichuan-Tibet Railway (Figs 8, 9). Nine of these lakes are expanding

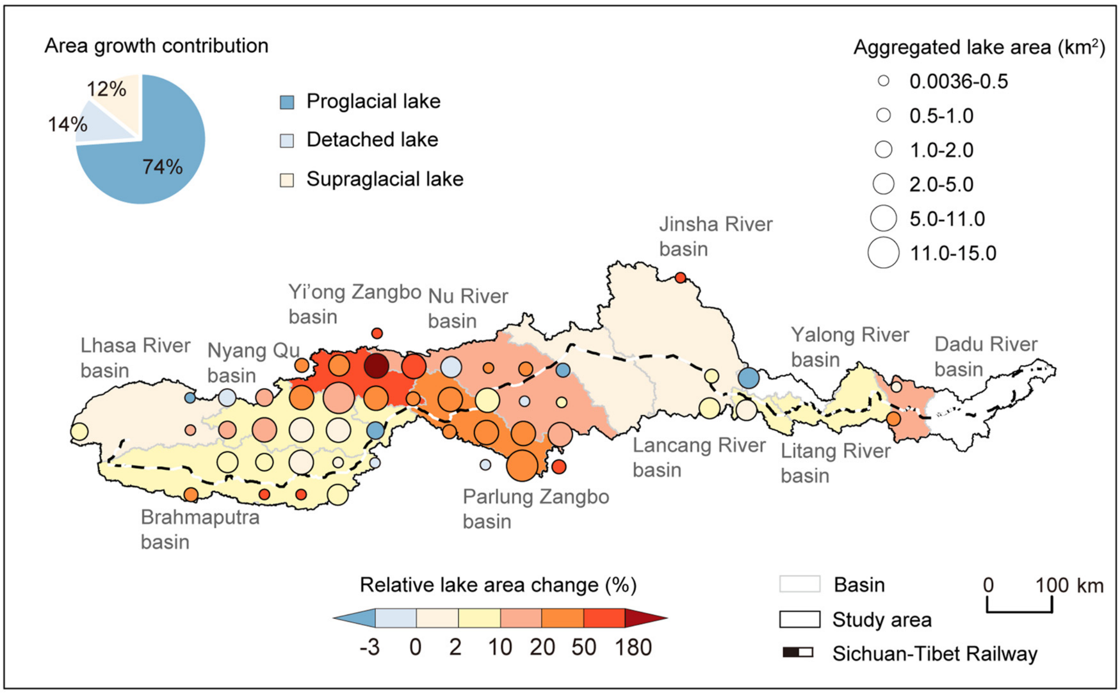

Figure 7. Changes in the relative area of glacial lakes in different river basins and grids (50 km) from the 1960s to 2020. The inset shows the proportion of area increase of three different lake types in the total area.

exponentially. Lake No.6 (Jiongpu Co) showed the fastest expansion at a rate of ~0.11 $km^2\ a^{-1}$, with the largest absolute area increase of ~3.58 km^2. Lakes No.11 and No.14 were formed in the 21st century and increased to ~0.11 and ~0.22 km^2, respectively. Lakes No.9, No.10, No.16 and No.17 have the shortest flow distance (75 km) to the Sichuan-Tibet Railway. Nevertheless, the flow paths of six of these lakes do not pass through the Sichuan-Tibet Railway (Fig. 9).

Lake No.1 was a small pond in 1960 but has grown by 637% to an area of ~0.92 km^2 in 2020. In addition, this lake has floating ice, indicating the glacier is calving (Fig. 10). Most of these lakes are expanding steadily, except for Lakes No.2, No.8 and No.10, which showed moderate expansion before the 21st century, but experienced rapid growth around 2000. The area of Lake No.3 (Cuoga) showed a sudden area decrease due to its outburst in 2013, but it is still a proglacial lake and continues to expand after its dam failure.

4.3 Detailed analysis of GLOF susceptible lakes near the Sichuan-Tibet Railway

There are seven susceptible lakes that are likely to affect the Sichuan-Tibet Railway, including three high susceptibility level lakes and four very high susceptibility level lakes. The three high susceptibility glacial lakes are within 15 km of the Sichuan-Tibet Railway (Fig. S3), and may threaten the operation of it, including the one whose susceptibility would increase in the future (Fig. 13d). The four lakes with very high GLOF susceptibility closest to the Sichuan-Tibet Railway were selected to further explore the environmental conditions around these lakes and to provide an overview of trajectory of their potential flows (Fig. 11). This extent was considered referencing to the furthest distance, ~70 km, that the historical outburst flood ever reached (Ranzeria Co).

The flow distance of Lake No.9 travels to Sichuan-Tibet Railway is ~63 km, passing through Lake No.10 and Yi'ong Village. Its elevation ranges from 4001 to 2044 m a.s.l. with an average gradient of 5.8% (Fig. 10a). The tongue of the parent glacier of Lake No.9 has two obvious crevasse zones, indicating that it is being squeezed by the upper part (Fig. 11b). The floating ice on the lake and the ice cliff on the glacier front suggest that ice calving is taking place here. In addition, there is another supply discharge from the lateral side. These conditions make this lake highly susceptible to outburst flooding in the future.

The average gradient of the flow from Lake No.10 is 4% with a smaller difference in elevation of ~681 m (Fig. 11c). Its outlet is close to the river channel and could flow directly over the Sichuan-Tibet Railway. The terminus of this lake's parent glacier is covered by a moraine and the lake is directly connected with the glacier (Fig. 11d). Remote-sensing imagery analysis shows the active sliding from the lateral moraine dam.

Lake No.16 is located ~74 km away in flow distance from the Sichuan-Tibet Railway. However, in the event of future GLOF from this lake, there is a high likelihood of a cascade of outbursts from other two glacial lakes located along this flow path. The flow path also has a high elevation gradient from lakes to the downstream villages (Fig. 11f).

Lake No.17 is located within ~15 km in flow distance from Sichuan-Tibet Railway. It also has the steepest flow path with an average gradient of ~12.1% (Fig. 11g). The gradient is particularly steep where it enters the river channel, which may increase the velocity and thus the risk of GLOF as observed during the flood event of Ranzeria Co outburst (Peng and others, 2023). There is also indication that moraine-dammed Lake No.17 has an unstable apparent SLA (Fig. 11h). There are also clear traces of ice cliffs and ice calving at the terminus of the parent glacier.

5. Discussion

5.1 Possible causes of changes in glacial lakes

Climate change is a background factor affecting the changes of glaciers and glacial lakes in the Tibetan Plateau and surrounding region (Song and Sheng, 2015; Wang and others, 2017). According to the data from the China Meteorological Administration between 1955 and 2018, the temperature of the study area showed a significant warming trend of ~0.4°C per decade, while precipitation showed a slight decreasing tendency, but

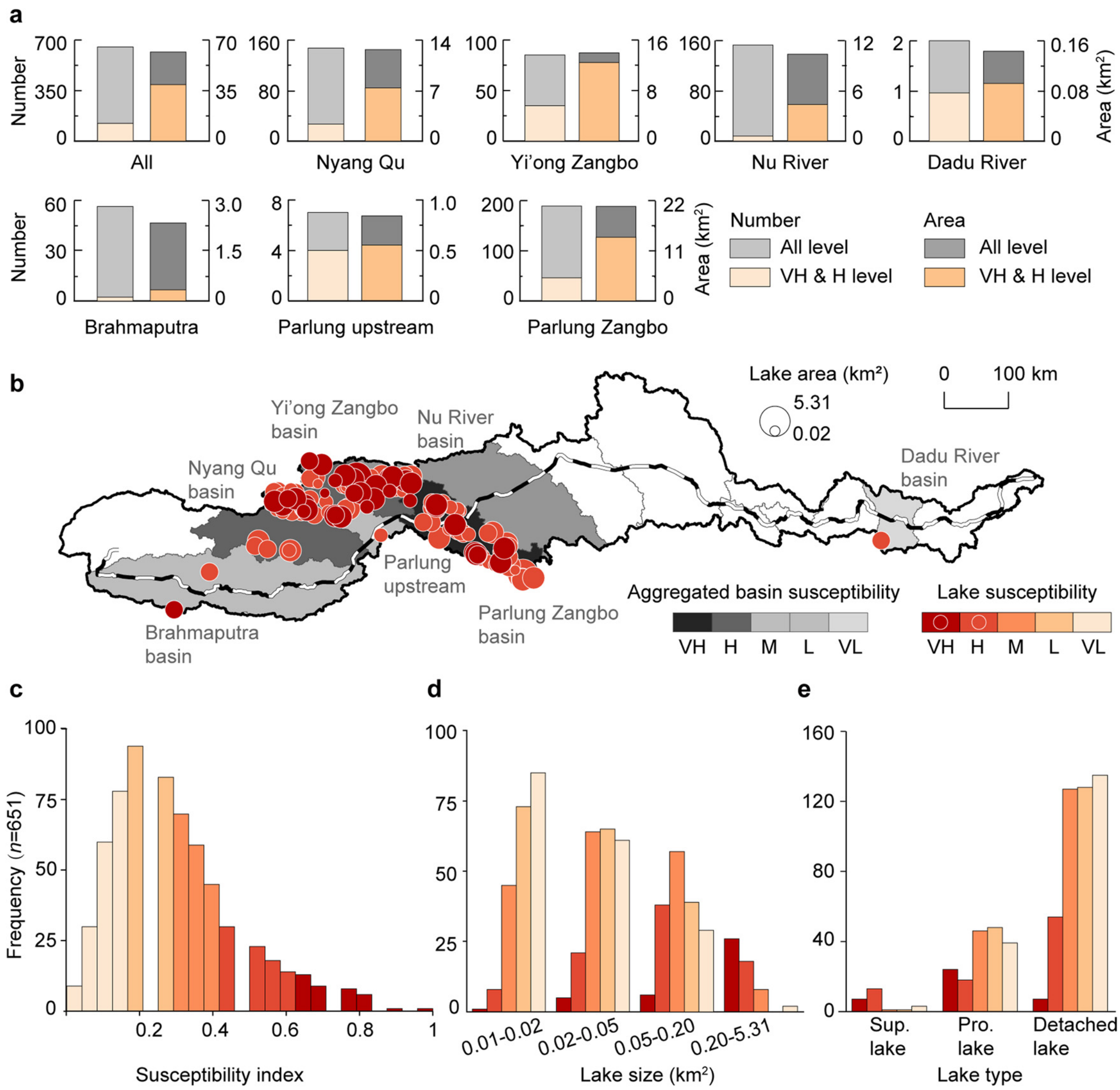

Figure 8. GLOF susceptible lakes. (a) Number and area of GLOF susceptible lakes in each river basin. (b) Spatial distribution of GLOF susceptible lakes and susceptible level at basin-scale. (c) Distribution of glacial lake susceptibility index. (d) Distribution of susceptibility levels of glacial lakes of different sizes. (e) Distribution of susceptibility levels of glacial lakes of different types.

it is not statistically significant (Fig. 12). Changes in glaciers could dominantly affect the development of glacial lakes, especially proglacial lakes, as the thinning and retreat of glaciers provide water supply and space for glacial lake development (Sakai and Fujita, 2017; Otto, 2019). A comparison of the average thinning rates of the individual parent glaciers between 2000 and 2019 shows that the parent glaciers of newly formed proglacial lakes (formed between 1960 and 2020) had a thinning rate of 0.97 ± 0.19 m a^{-1} (Hugonnet and others, 2021), which is slightly higher than the 0.86 ± 0.19 m a^{-1} of parent glaciers of proglacial lakes that became detached glacial lakes. Parent glaciers of newly detached glacial lakes experienced the lowest thinning rate of 0.70 ± 0.21 m a^{-1} (Hugonnet and others, 2021). The total area of this type of glacial lake is also the smallest, which may be the reason why they detached from the glaciers within the two study periods. It is suggested that the melting of the parent glacier is the main driver leading to the growth of proglacial lakes.

5.2 Validation and uncertainties of glacial lake susceptibility assessment

Validation of glacial lake susceptibility assessment is difficult because the cause of GLOFs is complex and relatively random. Some previous studies (Rinzin and others, 2021; Zhang and others, 2023*a*) illustrated the assessment accuracy by showing that the historical outburst glacial lakes were classified as high or very high susceptibility levels. However, such a similar validation was deemed not necessary for this study since the collection of GLOF susceptibility assessment indicators and subsequent parameterization of the indicators were done based on the historical GLOF events. The assessment indicators and methods remain heterogeneous in different studies due to the different regions and spatial scales. However, the previous studies (e.g. Allen and others, 2019; Zheng and others, 2021*a*) were considered reasonable and the comparison with them can provide a comprehensive understanding.

There are several previous studies overlapping the region of this study (Shijin and others, 2017; Fan and others, 2019; Wang and others, 2020*a*; Zhang and others, 2022*b*), with three covering the entire area of this study and having shared the data (Allen and others, 2019; Zheng and others, 2021*a*; Zhang and others, 2023*c*). Comparing the susceptibility levels of glacial lakes individually with Zheng and others (2021*a*) and Zhang and others (2023*c*), there are 234 and 254 glacial lakes identified as medium or higher GLOF-susceptible lakes in both respective studies at the same time, representing 79% and 86% of the total

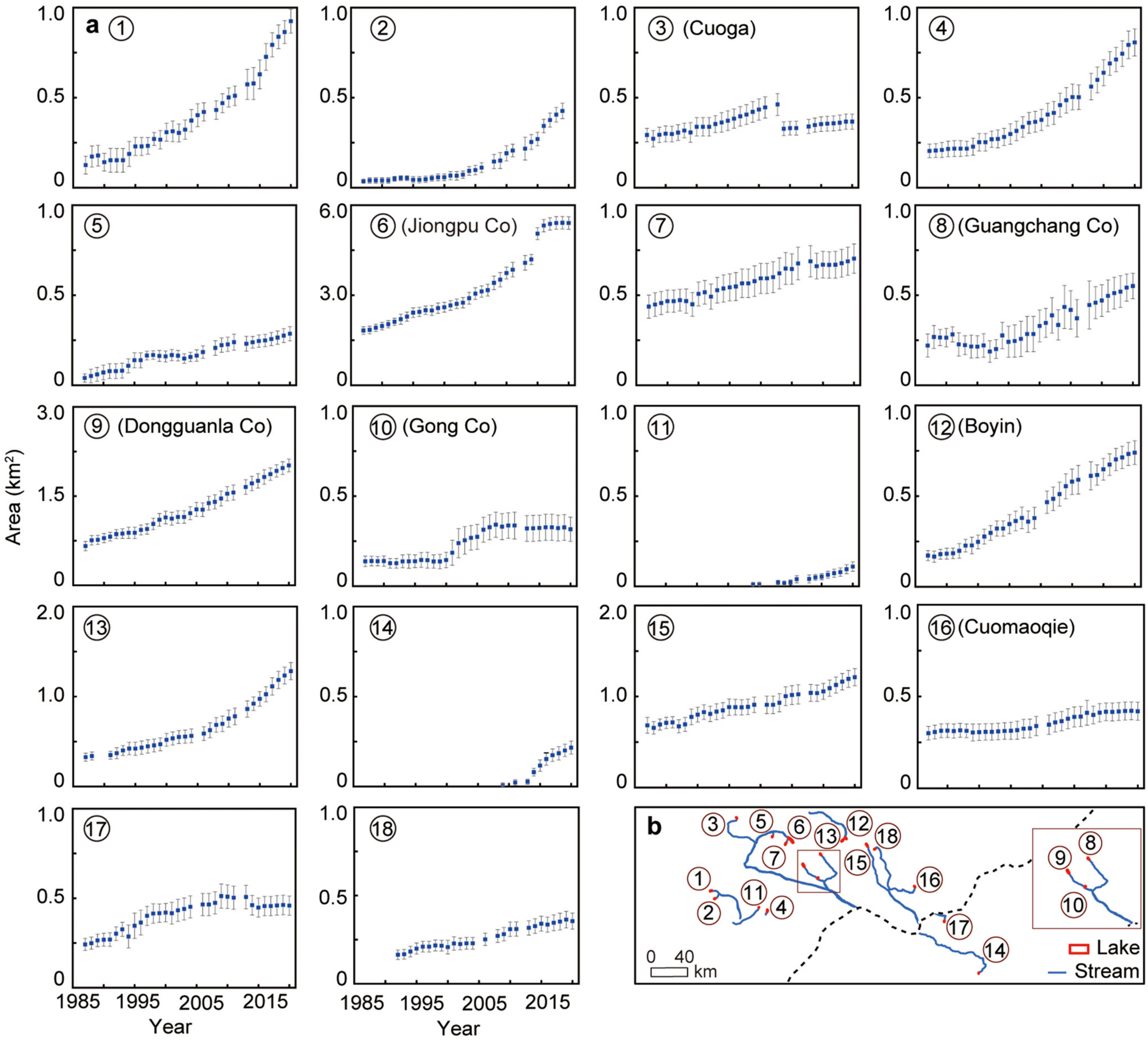

Figure 9. Time series of the most GLOF susceptible lakes (No.1 to No.18) from 1987 to 2020) (panel a). The inset shows the location and flow path of these lakes (panel b), and their locaitons in the study are indicated in Fig. 1.

number of medium or higher level in this study (Table S3). Of the 38 very high susceptibility glacial lakes found in this study, 28 (~74%) and 26 (~68%) glacial lakes are in the very high susceptibility level in both respective studies. Three and six glacial lakes are classified as very high susceptible in this study, while as high susceptible in Zheng and others (2021*a*) and Zhang and others (2023*c*). There are a further seven new glacial lakes with very high susceptibility that were not included in the inventory of glacial lakes they used, which means that these lakes may have been overlooked by Zheng and others (2021*a*). When compared with Allen and others (2019), it was found that the susceptible lakes within this study area did not match well. Only eight glacial lakes with very high susceptibility are being identified as susceptible lakes in both studies. However, considering that the method of Zheng and others (2021*a*) was generally consistent with Allen and others (2019), it is likely that the difference could be induced by the glacial lake inventories used. It implies the advantage of the glacial lake inventory in this study. For example, Shugar and others (2020), Zhang and others (2023*c*) and Zhang and others (2023*b*) identified 268, 315 and 478 glacial lakes (>0.05 km^2), respectively, in this study area in about 2020, which is less than the 512 glacial lakes mapped in our study.

Field surveys of three glacial lakes (Bencoguo Co, Rewu Co and Talong Co) in the Nidu Zangbo River basin where two historical GLOF events occurred during the past decade were conducted in 2021 and 2022 for further validation (Fig. S4). The Bencoguo Co is likely to outburst because of the lateral landslide or sudden increasing water from melting buried ice, which action would also weaken the dam in a long-term (Wang and others, 2018, 2023). Its lateral side is steep (>30°), and it has a loose and steep-downstream moraine dam with a narrow outlet (Fig. S4d–h). The parent glacier of Rewu Co is steep and hanging over the summit, making it possible to be impacted by the glacier collapse (Fig. S4m). However, it has two wide outlets, reducing the susceptible level due to the shallow downstream (Fig. S4l–n). The average slope of Talong Co's parent glacier tongue is 22.3°, and the slope of its lateral dam is over 30° with a maximum slope up to 87.6°. However, there are abundant shrubs and grasses over the dam of Talong Co without obviously dead ice observed during the field survey or in the uncrewed aerial vehicle photography, satellite imagery and Google Earth imagery. This means the lake is

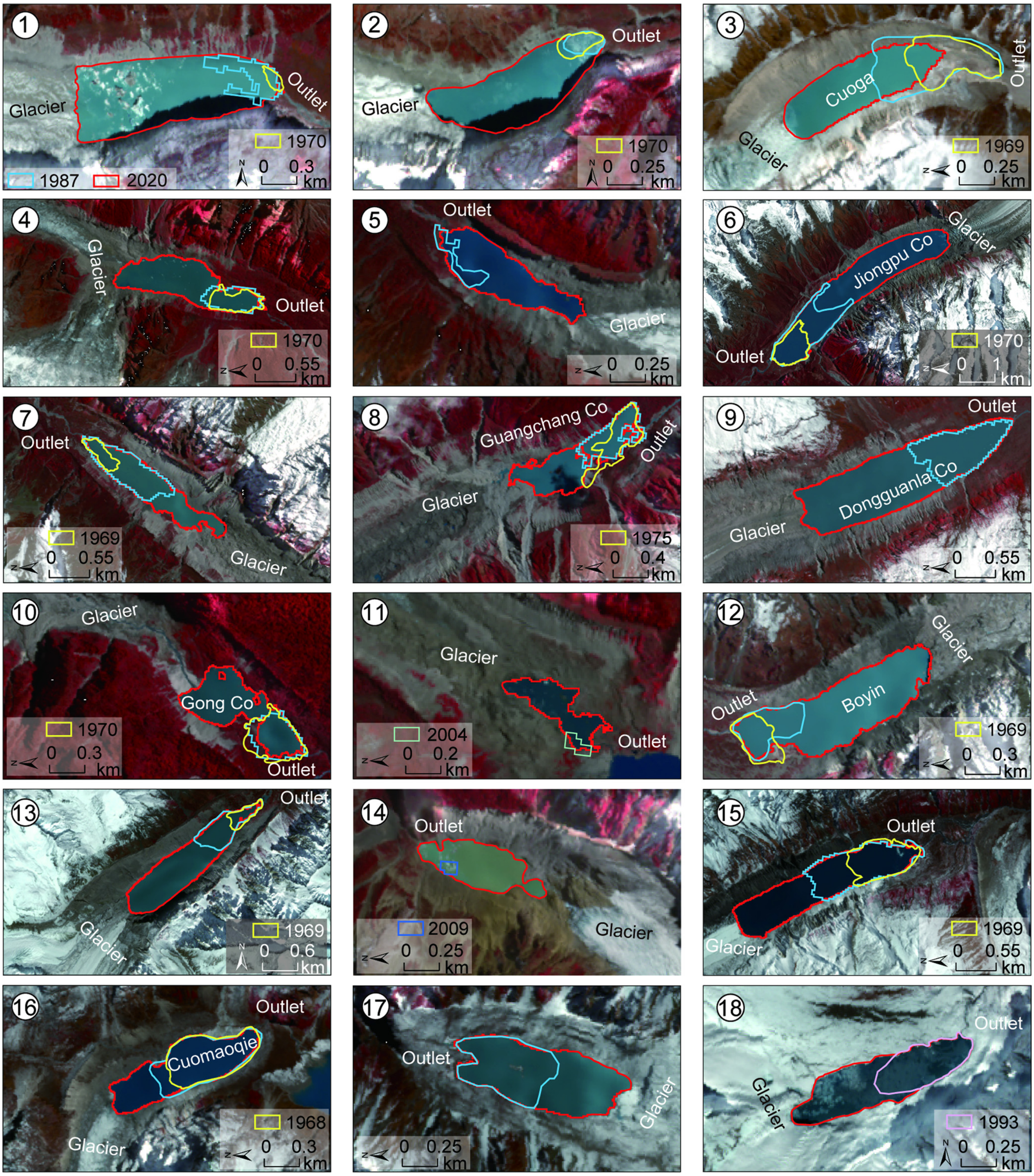

Figure 10. Spatial changes in the boundaries derived from KH, Landsat and Sentinel-2 imagery for the most GLOF susceptible lakes (No.1 to No.18) in three time periods. The locations of these lakes are indicated in Fig. 1.

susceptible to landslides and glacier avalanches, but the vegetation would help maintain the stability of the moraine dam. Combining these investigations, the in situ measurements support the assessments of this study, i.e., Bencoguo Co is very highly susceptible, and the others are highly susceptible.

Uncertainties in the susceptibility assessments could arise from the data and methods used. The glacial lake inventory was established using 10 m (pixel size) Sentinel-2 satellite images, reducing the assessment uncertainty by improving spatial resolution. The Root Mean Squared Error (RMSE) was calculated to be 2.8×10^6 m^3 between the bathymetry-based volume and the volume from empirical relationship (Table S3). The terrains of historical GLOFs were obtained from ASTER GDEM gathered between 2000 and 2009. The outburst dates of some lakes were earlier, so the pre-outburst terrains are not available and are replaced by post-outburst terrains. The factors determining the very high susceptibility status of supraglacial and detached glacial lakes are ice avalanche and the landslide topographic potential. The quality of used DEM would mainly affect the calculated slope of the dam, as the glacier and lateral rock terrains are

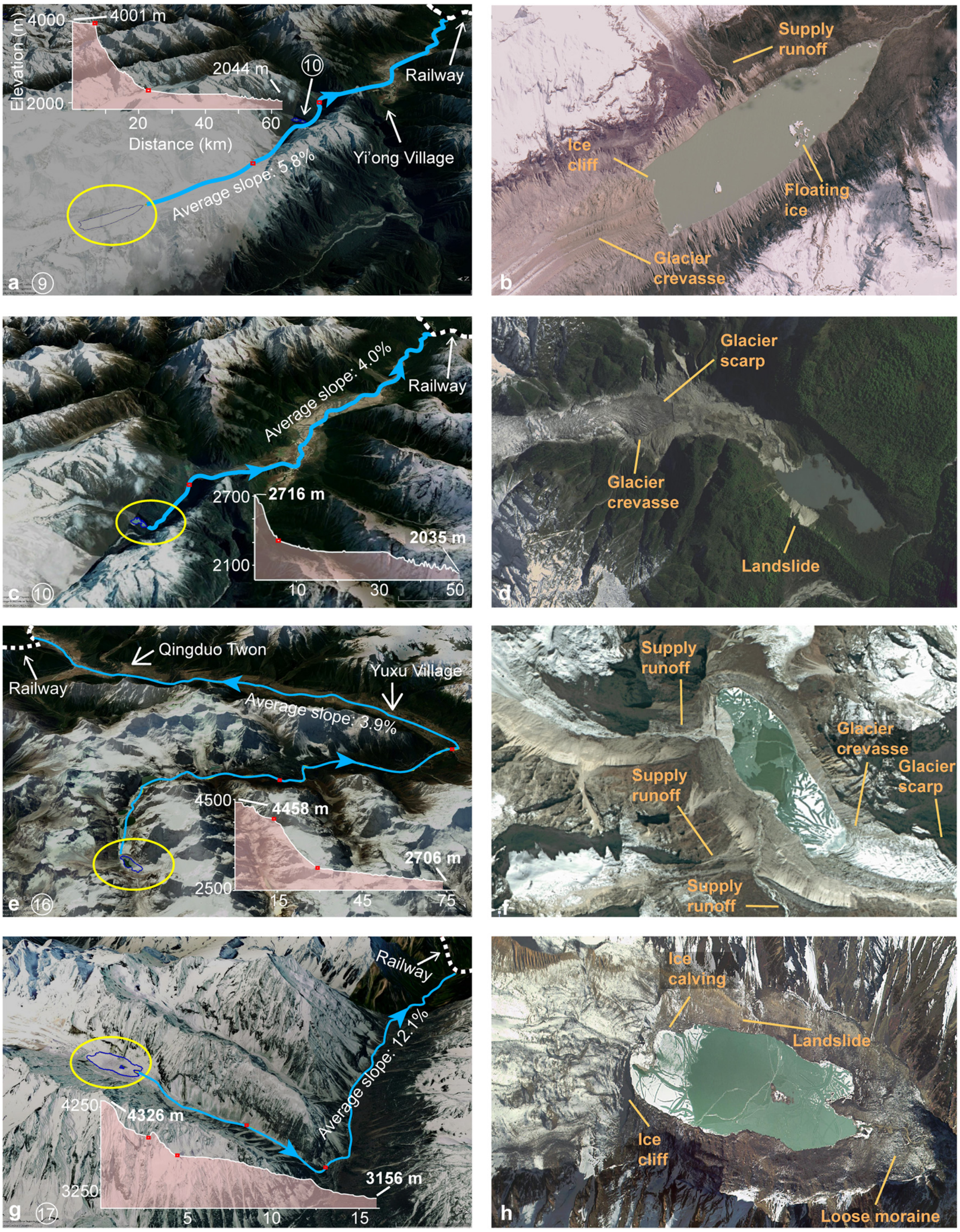

Figure 11. The flow path and surrounding environment of the glacial lakes may threaten the Sichuan-Tibet Railway. The insets in the left columns show the elevation change in the flow path from the lake to the Sichuan-Tibet Railway, and the red dots mark the steepest sections. The locations of these lakes are indicated in Fig. 1.

relatively stable. In addition, the distance between glaciers and glacial lakes was calculated using the glacier boundaries from RGI v6.0 (RGI Consortium, 2017), adding extra lakes that may be outside the 500 m distance from their parent glaciers when conducted prefiltering of susceptible lakes.

5.3 Future GLOF susceptible lakes threatening to the Sichuan-Tibet Railway

According to the future overdeepening data (Furian and others, 2021; Zheng and others, 2021*a*), there are two lakes whose susceptibility may increase in the future, and two new threatened lakes will emerge (Figs 1, 13). Lake No.9 (Dongguanla Co) will expand by ~0.2 km^2 in 2050 with a mean depth of ~37 m, and by ~0.75 km^2 in the ice-free scenario with a mean depth of ~113 m (Fig. 13a). If the lake would expand to the glacier margin, the likelihood of ice avalanches would increase. Similarly, the mean depth of Lake No.10 will triple to ~113 m with an expansion of only ~0.1 km^2 (Fig. 13b). The outburst of Lake No.9 will most likely trigger the outburst of Lake No.10, as the flow path will pass Lake No.10, whose distance from the river channel is less than 500 m (Fig. 11a).

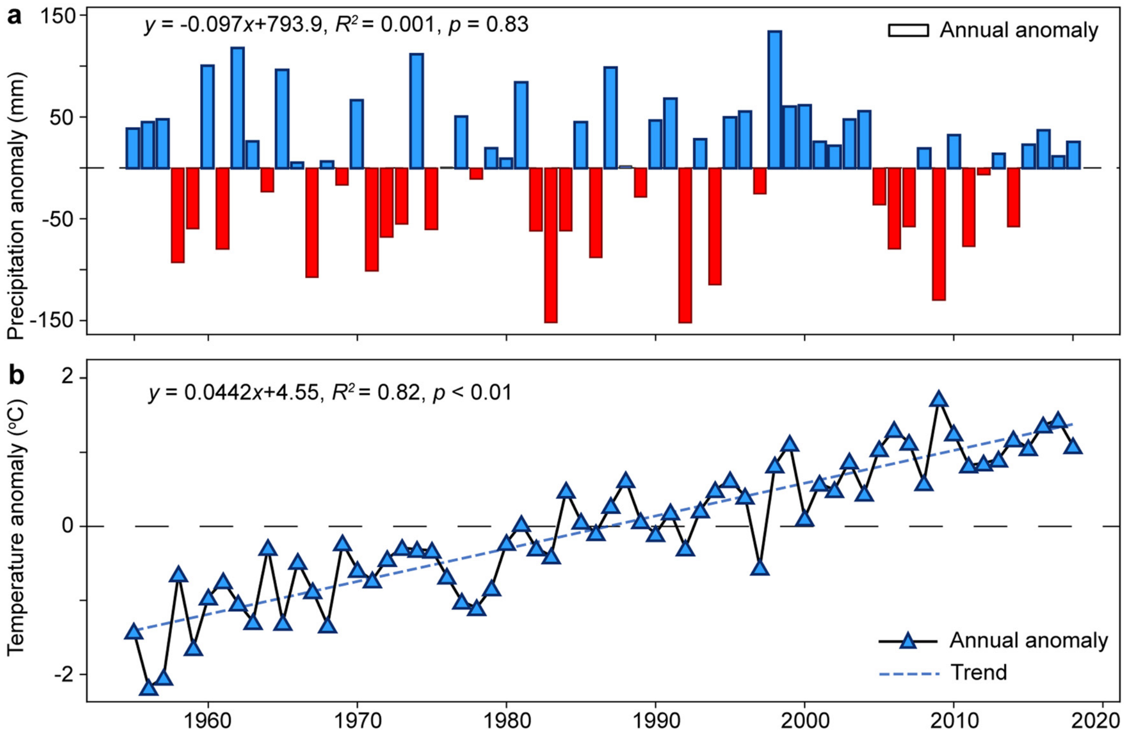

Figure 12. The time series of precipitation (panel a) and temperature (panel b) between 1955 and 2018. The statistical precipitation and temperature data are aggregated from meteorological stations, the locations of which are shown in Figure 1.

Two new lakes will form with a linear distance of ~9 and ~12 km away from the Sichuan-Tibet Railway (Figs 13c, d). Lake in Figure 13c would be one of the closest to the Sichuan-Tibet Railway and the GLOF would cause considerable damage to the exposed section of the Sichuan-Tibet Railway. The supraglacial lake upon Zhuxi Glacier has an unstable geomorphological environment, with landslides and ice calving occurring frequently observed during the field survey. The downstream survey showed that there is a lot of sediment along the channel, suggesting that the outburst flood would become a debris flow. The flood from this supraglacial lake has a small direct impact on the Sichuan-Tibet Railway. However, it may also affect the Sichuan-Tibet Railway indirectly by blocking the river or destroying the national road G318.

This study has identified glacial lakes that have the potential to burst and affect the Sichuan-Tibet Railway now and in the future. As the dam failure of glacial lake is complex and its occurrence is random, it is difficult to predict when a GLOF will happen. To further clarify and quantify the susceptibility and damage of these glacial lakes, the hydrological modelling combined with detailed field surveys and high-resolution observations should be used to simulate and predict the flow peak discharge and downstream impacts on the Sichuan-Tibet Railway. For the four most threatening glacial lakes identified (Dongguanla Co, Gong Co, Cuomaoqie, Lake No.17), it implies that particular attention should be paid to the potential for landslides and ice avalanches. The lateral slope of the dam, the composition of the dam, the topography of the glacier tongue, and the bathymetry of the lakes, are essential to be measured. It is suggested that the GLOF mitigation should be built on the Bomi–Nyingchi section of the Sichuan-Tibet Railway, particularly two terminals (Fig. 13).

6. Conclusions

The glacial lakes within 120 km line distance and hydrological towards the Sichuan-Tibet Railway were mapped using high-resolution KH-4/-9 and Sentinel-2 satellite imagery from the 1960s and 2020, and show an increase of 22% and 20% in area and number, respectively. The susceptibility of glacial lakes was assessed based on the analysis of the historical GLOF events and field surveys, identifying 38 very high, 85 high and 174 medium susceptibility glacial lakes, ~80% of which had been identified in previous larger scale studies. Proglacial lakes contributed most to the increase in area of all glacial lakes. Glacial lakes of 0.2–2 km^2 expanded the most, while lakes of 0.0036–0.01 km^2 increased the most in number. The number of glacial lakes increased mainly at altitudes between 5000 and 5500 m, while the increase in area occurred mainly at altitudes between 3500 and 4500 m.

The glacial lakes with area expansion and GLOF high susceptibility are mainly distributed in the Yi'ong Zangbo River and Parlung Zangbo River basins, corresponding to the Bomi–Nyingchi section of the Sichuan-Tibet Railway. More attention and hazard mitigation measures should be paid and implemented in this region to reduce the damage caused by GLOFs. Outburst floods from four of the most susceptible glacial lakes are likely to affect the Sichuan-Tibet Railway. These glacial lakes are mainly threatened by glacier avalanches and landslides, especially Lake No.16 (Cuomaoqie). We predict that four potentially susceptible lakes will affect the Sichuan-Tibet Railway in the future, including Lake No.9 (Dongguanla Co), Lake No.10 and two new high susceptibility glacial lakes.

This study provides primary investigations of the glacial lake change and GLOF susceptibility level along the Sichuan-Tibet Railway and identifies the most vulnerable sections and river basins threatened by GLOFs. Further detailed field surveys should be conducted to confirm the susceptibility of the most susceptible glacial lakes, and hydrological modelling combined with high-resolution observations should be conducted to simulate the magnitude of the GLOFs.

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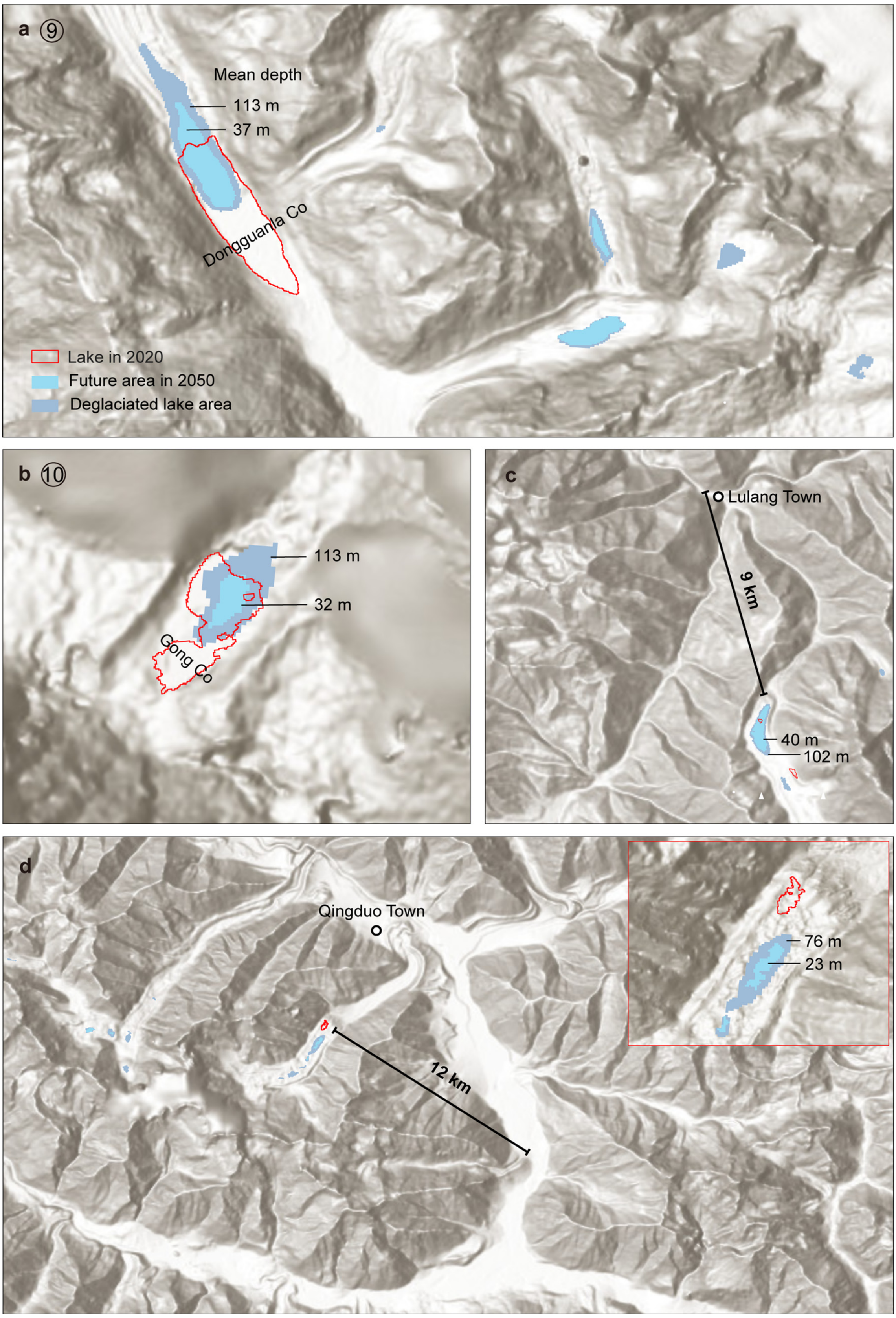

Figure 13. GLOF susceptible lakes that may affect the Sichuan-Tibet Railway in the future. (a–b) Glacial lakes that are with very high susceptibility now and will continue to expand in the future. (c–d) Glacial lakes that may become more susceptible in the future, located near the GLOF susceptible railway section shown in Fig. 1.

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Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/jog.2024.40.

Data. The KH-4 and KH-9 images were downloaded from https://earthexplorer.usgs.gov. Sentinel-2 imagery is available from https://apps.sentinel-hub.com. Glacier surface velocity data used in this study were downloaded from https://retreat.geographie.uni-erlangen.de/search. The glacial lake inventory and the GLOF susceptibility generated in this study are available at https://zenodo.org/records/10314547.

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