Science Bulletin 64 (2019) 435–445

Contents lists available at ScienceDirect

Science Bulletin

journal homepage: www.elsevier.com/locate/scib

Science Bulletin
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Potentially dangerous glacial lakes across the Tibetan Plateau revealed using a large-scale automated assessment approach

Simon Keith Allen [a,*], Guoqing Zhang [b,c], Weicai Wang [b,c], Tandong Yao [b,c], Tobias Bolch [a,d]

[a] Department of Geography, University of Zurich, Zurich 8057, Switzerland
[b] Key Laboratory of Tibetan Environmental Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China
[c] Center for Excellence in Tibetan Plateau Earth Sciences, Chinese Academy of Sciences, Beijing 100101, China
[d] School of Geography and Sustainable Development, University of St Andrews, St Andrews KY16 9AL, Scotland, UK

ARTICLE INFO

Article history:
Received 28 December 2018
Received in revised form 7 March 2019
Accepted 8 March 2019
Available online 18 March 2019

Keywords:
GLOF
Hazard
Exposure
Danger
Tibetan Plateau
Himalaya

ABSTRACT

Glacial lake outburst floods (GLOFs) are a major concern in the Himalaya and on the Tibetan Plateau (TP), where several disasters occurring over the past century have caused significant loss of life and damage to infrastructure. This study responds directly to the needs of local authorities to provide guidance on the most dangerous glacial lakes across TP where local monitoring and other risk reduction strategies can subsequently be targeted. Specifically, the study aims to establish a first comprehensive prioritisation ranking of lake danger for TP, considering both the likelihood and possible magnitude of any outburst event (hazard), and the exposure of downstream communities. A composite inventory of 1,291 glacial lakes (>0.1 km^2) was derived from recent remote sensing studies, and a fully automated and object assessment scheme was implemented using customised GIS tools. Based on four core determinates of GLOF hazard (lake size, watershed area, topographic potential for ice/rock avalanching, and dam steepness), the scheme accurately distinguishes the high to very high hazard level of 19 out of 20 lakes that have previously generated GLOFs. Notably, 16% of all glacial lakes threaten human settlements, with a hotspot of GLOF danger identified in the central Himalayan counties of Jilong, Nyalam, and Dingri, where the potential trans-boundary threat to communities located downstream in Nepal is also recognised. The results provide an important and object scientific basis for decision-making, and the methodological approach is ideally suited for replication across other mountainous regions where such first-order studies are lacking.

1. Introduction

Glacial lake outburst floods (GLOFs) refer to the sudden discharge of a water reservoir that has formed either underneath, at the side, in front, within, or on the surface of a glacier, and related dam structures can be composed of ice, moraine or bedrock. Across high mountain Asia, and elsewhere in the world, considerable focus has been on flood hazard associated with the catastrophic failure of moraine dammed lakes [1–4]. In particular, lakes trapped behind proglacial moraines can be large, with volumes of up to 100 million m^3, and depths exceeding 200 m [5]. Failure of moraine dammed lakes occurs when the material strength of the dam structure is exceeded by driving forces, including the weight of the impounded water mass, shear stresses from seepage, and overtopping or additional momentum from displacement waves [6]. In the Himalaya, displacement waves from large impacts of ice or rock have contributed to over 50% of catastrophic moraine dam failures [2,7]. GLOFs characteristically transform into hyperconcentrated or debris flows following the entrainment of loose, unconsolidated para-glacial debris [8], and some of the most devastating and far reaching (>100 km) impacts have involved subsequent flow transformations or chain reactions, such as damming of valleys, secondary outbursts and debris flows [9,10]. As such, approaches to GLOF hazard assessment must consider large spatial scales, not restricted by administrative or political boundaries.

Because of the large spatial scales potentially involved, and the fact that GLOFs originate often in high elevation, poorly inaccessible terrain, various first-order schemes have been proposed for assessing the susceptibility of glacial lakes, drawing primarily upon remotely sensed information for studies undertaken in the Southern Alps of New Zealand [11], the Andes [12–14], North America [15], European Alps [16], and high mountain Asia [17–21]. These studies have typically taken advantage of reflectance properties of water in the visible and near infrared wavelengths of sensors

SPECIAL TOPIC: The Second Tibetan Plateau Scientific and Research (I).

* Corresponding author.
E-mail address: simon.allen@geo.uzh.ch (S.K. Allen).

https://doi.org/10.1016/j.scib.2019.03.011
2095-9273/

such as Landsat to undertake large-scale mapping of glacial lakes. An attempt is then made to semi-quantitatively characterize (often requiring higher resolution data or imagery) the cryospheric environment, lake and dam area, and other geotechnical and geomorphic characteristics of the upstream catchment area that make a lake susceptible to outburst [22]. While these approaches are often described as automated, and suitable for large-scale applications, a high degree of subjectivity and expert judgement is involved. For example, the choice of susceptibility factors varies between studies, and some characteristics can only be measured with expert judgment (e.g. dam composition and ice-content). As a consequence of differences in methodological approaches, results between different studies can vary considerably, and the same lake may have several different hazard levels assigned depending on the approach taken [23]. From a practical or applied perspective this is a major limitation, because it is impossible or difficult to reasonably compare assessment results from different studies and/or different regions, and thereby make decisions on resource allocation for potential hazard or risk reduction measures. Recognising these challenges, some studies have developed more objective classification schemes using clear criteria and decision trees [13,17,20,24]. However, these approaches have not been designed for the scale of implementation required on the Tibetan Plateau (TP), where the number of glacial lakes is in the thousands [25] (by comparison, approaches developed for Nepal have been applied to 131 lakes [26]), and/or have not considered the exposure of communities living downstream of the lakes.

GLOFs have proven particularly common on the TP, with reports indicating at least 40 GLOF disasters (causing loss of life or infrastructure) have occurred since 1935, mostly in the central-eastern section of the Chinese Himalaya [27]. However, despite rapidly increasing population and infrastructural development on the TP, risk reduction strategies for GLOFs remain limited. Hence, there has been recent calls for authorities to take action and implement measures at all potentially dangerous lakes [28]. But with many thousands of lakes across TP, recommendations based on a sound and transparent methodology are needed in order to obtain information that can guide authorities about where to focus further local hazard and risk investigations, and eventually mitigation efforts. While studies aiming to identify potentially dangerous lakes have been undertaken along the entire main Himalayan Range [24,29,30], or at a regional scale in the Poiqu Basin, central Himalayas [27,31], and the Boshula range in southeastern TP [19], underlying assessment methodologies are not comparable. Hence, an objective, large-scale assessment is clearly lacking.

This study aims to fill this important gap, and responds directly to the needs of local authorities by providing guidance on the most dangerous lakes, where monitoring and other risk reduction strategies can subsequently be targeted. Specifically, the study aims to establish a comprehensive inventory and prioritisation ranking of potentially dangerous lakes across the TP, considering both the likelihood and possible magnitude of any outburst event, and consequences for downstream communities. Secondarily, the developed methodological approach should be objective and replicable, allowing local authorities to periodically update the assessment, and in view of potential upscaling to other areas of high mountain Asia where such first-order studies are lacking.

2. Methodology

A composite glacier lake inventory covering the TP was compiled from several previous studies [19,25,31], augmented with mapping from latest Google Earth and Landsat 8 imagery to fill any gaps in these earlier efforts. The areal extent of the TP is in accordance with previous work [32]. While definitions vary, we considered glacial lakes as either being dammed by glacial processes or fed directly by glacial melt (within 1 km of a parent glacier), and we included only those lakes with an area >0.1 km^2. In total, 1,291 glacial lakes were included in the final composite inventory, with a mean and maximum area of 0.42 and 13 km^2 respectively.

Potentially dangerous lakes are defined in this study as a function of the hazard (likelihood and potential magnitude of a flood), and exposure (potential for people to be affected). Details on how these specific components were analysed and combined are provided below. All analyses were conducted using the CGIAR-CSI void-filled version of the SRTM 90 m Digital Elevation Model (DEM). This resolution enabled computational efficiency while still proving sufficient for first-order modelling of topographically driven processes [33].

2.1. GLOF hazard

While there are numerous characteristics of a lake, its dam, parent glacier, and topographic surroundings that are relevant for the susceptibility of a glacial lake and subsequent magnitude of any outburst event [12], few of these factors can be reasonably parameterised using automated approaches at large-scales. Our approach therefore considers four primary determinants of GLOF hazard outlined below that can be calculated using readily and freely available geospatial datasets (Fig. 1).

(1) Lake area, which provides an often used proxy for lake depth (and volume) and thereby potential flood magnitude [16]. Lake area is directly calculated from the digitised lake polygons.
(2) Potential for ice and rock avalanches to strike a lake, thereby capturing the main process responsible for pervious GLOF triggering in the TP [19]. The assessment procedure is based on the concept of topographic potential [35] which encompasses (a) the potential for rock or ice to detach (parameterised by slope angle) and (b) the potential for the resulting rock and/or ice avalanche to reach a glacial lake (parameterised by the overall trajectory slope or angle of reach). This concept has been integrated within a comprehensive GLOF risk assessment for the Swiss Alps [36], and for Northwest India [37]. At this large scale, we do not distinguish between whether the slope is bedrock, ice-covered, or debris, and assume an impact into a lake is possible from any slope >30° [38,39], where the overall slope trajectory is >14° ($\tan\alpha = 0.25$) [35,40]. These conservative values are based on ice and/or rock avalanches reported within an extensive global catalogue of events contained in the cited literature, although mass movements from more gentle slopes and obtaining larger run-out distances are possible in exceptional cases. Within each lake watershed, the $\tan\alpha$ values for all grid cells fulfilling these two criteria were summed, to give a quantitative measure of the potential for avalanches to trigger an outburst from that lake. In this way, steep slopes located closer to a lake (i.e., from which an avalanche is more likely to reach the lake), automatically contribute more to the overall hazard estimate.
(3) Total watershed area upstream of the lake, recognising the potential for runoff from heavy rainfall or glacier/snow melt to drain into and overwhelm a glacial lake [4,41]. A larger upstream watershed is considered to increase the potential for runoff.
(4) Downstream slope of the dam, as a crucial control on stability of the dam and potential for self-destruction [17,29]. For this analysis, the downstream dam area was automatically extracted as the area downslope of the lake, within a

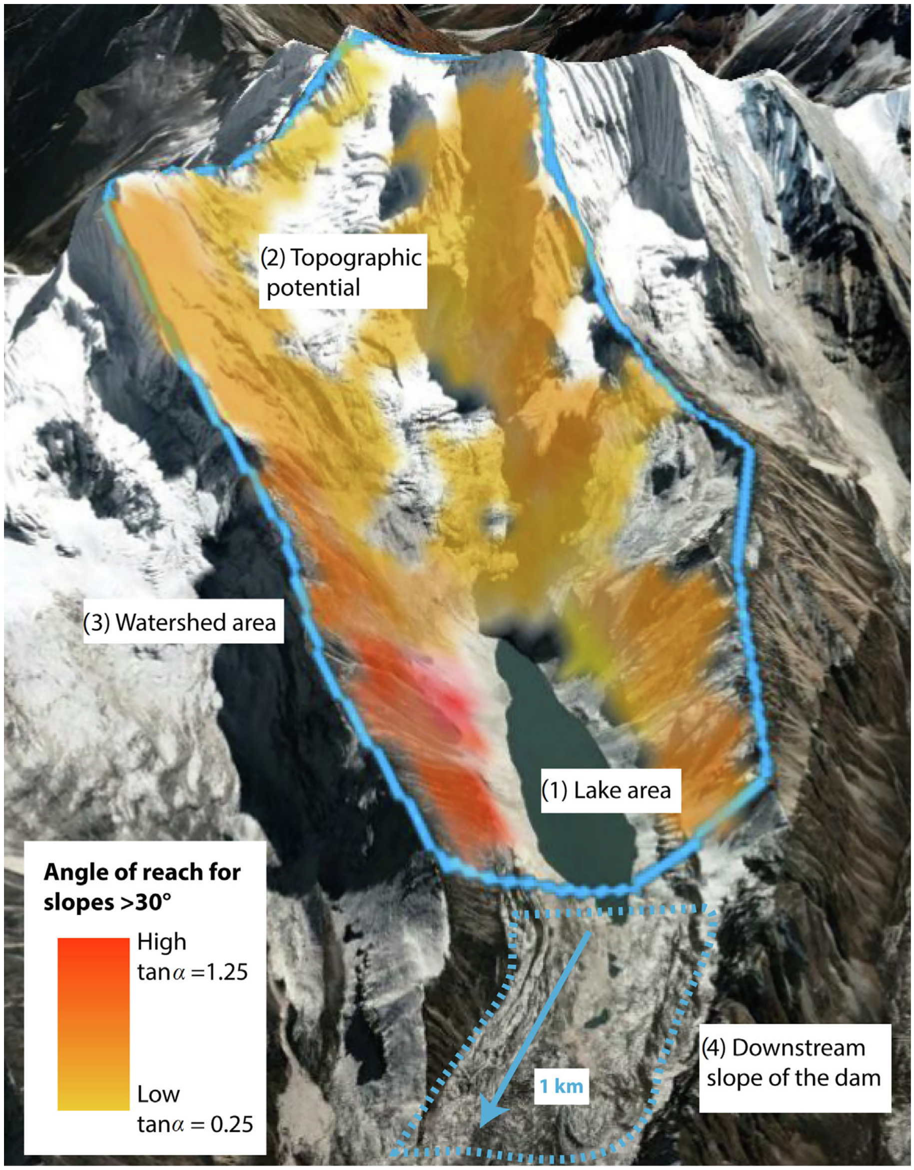

Fig. 1. (Color online) The glacial lake Cirenmaco, in Nyalam county, showing the four components of the GLOF hazard assessment. This lake features a wide, flat outwash area, followed by a steep frontal section of the moraine dam (4). At least three outbursts (1964, 1981 and 1983) have previously occurred from this lake, triggered by mass movements of ice and/or rock, and possible thawing of ground ice in the dam area [34].

horizontal buffer distance of 1 km. Where more than 50% of the slope pixels in the dam area exceeded the 35° typical angle of repose [42], the dam was considered to be formed in bedrock and hence stable. For all other dams, the mean slope value was used as a quantitative measure of the dam stability. The 1 km distance in many cases encompasses more than the lake foreshore and dam area. However, this is considered beneficial given that steeper slopes downstream are relevant also for the erosional capacity of any outburst event, and hence, important for the hazard potential.

Quantified values for each determinant were normalised to percentile rankings (from 0 to 1), ensuring all components contributed fairly to the final hazard index, and ensuring results are not influenced by the skewed distribution of some determinants (such as lake area). We gave equal weighting to all determinants, such that the final hazard index (H) for each lake was simply calculated as the average across all normalised scores. The sum of all lake hazard scores provides an aggregated level of GLOF hazard at the administration level of a county.

A major challenge in automated approaches to GLOF hazard assessment is that the basis for validating any methodology is extremely limited, because GLOFs are typically high magnitude yet very low frequency events. Taking advantage of the large spatial scale of our study, we were able to compile a comparatively large inventory of previous GLOF events occurring across the TP since 1935 [19,43,44], against which we could assess the validity of our lake hazard classification. In other words, we establish how well the automated approach to hazard classification has identified those lakes that have generated outburst events in the past. We focus on hazard (rather than danger), because information on societal losses and damages from these past GLOFs is not given in all cases, and is not consistently reported. Following careful evaluation of the outburst events and lakes described in these studies using various archival satellite imagery, a total of 31 GLOFs were confirmed for which exact geocoordinates for the source lake are known. However, for some of these cases, the lake has completely drained and the previous areal extent of the lake cannot be reliably estimated, or the dam geometry is considerably modified post-event and eroded over time. In these situations the current hazard index cannot be expected to provide a reasonable proxy for the hazard situation pre-event, and hence, these lakes were excluded from the analyses. In total, 20 lakes were considered for the validation exercise (Table 1).

2.2. GLOF exposure

Exposure marks the presence of people, livelihoods, environmental services, infrastructure and other resources that could be adversely affected by a potential hazard [45]. In this study we characterised exposure by identifying buildings located within the potential flood path of a glacial lake. Buildings were downloaded as polygon features from Open Street Map (OSM, www.openstreetmap.org, accessed 2018), and a check of completeness was undertaken at various random locations across the TP using imagery available in Google Earth.

The downstream flood path for each lake was simulated using the modified single-flow model (MSF)—a simple GIS-based hydrological flow routing algorithm that calculates the flow direction from one DEM pixel to another according to the steepest downward gradient between each pixel and its eight neighbours [46], modified to allow flow spreading of up to 45° from the main flow direction [47]. The maximum downstream travel distance for each GLOF path was determined using an empirically derived worst-case scenario defined by the angle of reach from the source lake, with tanα values as low as 0.05 (3° angle of reach) considered appropriate for highly mobile sediment-laden events [16]. Beyond these worst-case run-out distances, severe damages are not expected.

Each building polygon was represented by a single point, aligned to the same 90 m raster grid used for the flood path modelling (Fig. 2). In this way, the built environment (i.e., characterising the likely presence of people) located within each flood path was coarsely generalised. Recognising that communities and infrastructure located closer to the lake source are more likely to be affected than areas further downstream, the overall angle of reach (H/L) for each exposed grid cell was used as the quantified measure of exposure. All exposed grid cell values were then summed within each GLOF path, and the overall exposure value assigned to that lake.

This approach represents a significant advance in the usefulness of the MSF model for large-scale studies, as the model was previously only able to produce a single raster output of all combined flood paths, and hence, was of little use in establishing exposure and risk associated for any individual lake. This advanced version of the MSF now is computationally more complex, looping to model the GLOF path and establish the exposure level for each lake systematically in turn. The entire procedure is run as an ArcGIS tool, and for the 1,291 lakes required around 12 h to complete on a standard personal computer, at 90 m spatial resolution. Localised testing with higher resolution 30 m DEMs (SRTM and ASTER GDEM) resulted in an exponential increase in processing time, with little influence on the resulting exposure estimate.

2.3. GLOF danger

The final exposure values were normalised to the common range of 0–1 (again using percentile rankings), and then multiplied with the normalised hazard scores (for the subset of lakes having an exposure value >0) to give a final danger level for each lake. For lakes that threaten no buildings (exposure = 0) no danger level is given. The sum of all lake danger levels provides an aggregated level of GLOF danger at the administration level of a county.

3. Results

For display purposes, all results from the lake hazard and danger assessment are categorised into 5 levels using the natural Jenks classification method of ArcGIS that identifies natural groupings inherent in the data. Class breaks are identified that best group similar values and that maximize the differences between classes. This is illustrative only to inform the prioritization of GLOF hazard and danger across the TP, and specific classes cannot be directly compared with categories used in other studies or regions.

Table 1
Twenty lakes that have previously generated outburst floods on the TP [19,43,44].[a)]

ID	Lake name	GLOF date	Latitude (°N)	Longitude (°E)	Hazard (0–1)	Class
1214	Taraco	August 28, 1935	28.29	86.13	0.68	High
1247	Lure Co	1950 s	28.27	90.59	0.82	Very high
1207	Swangwang Co	July 16, 1954	28.24	90.1	0.76	Very high
810	Cirenma Co	1964 July 11, 1981 1983	28.07	86.06	0.79	Very high
455	Gelhaipu Co	September 21, 1964	27.96	87.81	0.84	Very high
1267	Aya Co	August 15, 1968	28.35	86.49	0.64	High
3884	Poge Co	July 23, 1972	31.73	94.73	0.77	Very high
3907	Boge Lake	July 6, 1975	31.86	94.76	0.71	Very high
1271	Zhari Co	June 24, 1981	28.3	90.61	0.61	High
422	Yindapu Co	August 27, 1982	27.95	87.91	0.81	Very high
1036	Jin Co	August 27, 1982	28.2	87.64	0.73	Very high
6723	Guangxie Co	July 15, 1988	29.46	96.5	0.71	Very high
1371	Unknown	1995–1996	28.66	85.48	0.65	High
1105	Longjiu Co	August 6, 2000	28.21	89.74	0.80	Very high
3597	Unknown	2002–2003	30.69	94.32	0.78	Very high
1065	Jialong Co	May 23, 2002	28.21	85.85	0.84	Very high
1296	Dega Co	September 18, 2002	28.33	90.67	0.66	High
1242	Unknown	2007–2008	28.28	90.23	0.54	Medium
3630	Cuoga Lake	July 29, 2009	30.83	94	0.82	Very high
6750	Ranzeria Co	July 5, 2013	30.47	93.53	0.76	Very high

[a)] The ID is unique to this study and is cited in the text. Hazard index values and classification established in the current study are given.

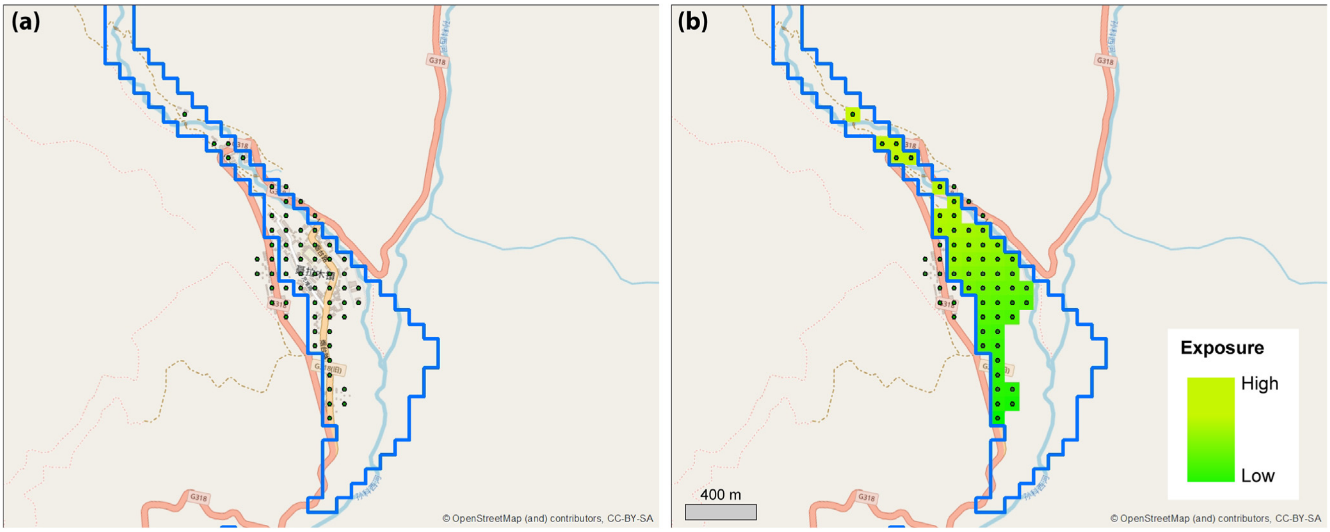

Fig. 2. (Color online) Example of GLOF exposure, focussing on a GLOF path (blue outline) affecting the village of Nyalam (Nyalam county, 28.16°N, 85.98°E, central Himalaya). Building polygons from OSM are converted to centroid points at 90 m grid spacing (a), and intersected with the modelled flood path raster giving the overall angle of reach for that exposed cell back to the source lake (b).

3.1. GLOF hazard and assessment validation

Glacial lakes are distributed widely across the TP, but are clustered more densely along the main Himalayan range. It is also in this region, along the main Himalayan range, and in southeast TP, where the greatest concentration of lakes with high to very high hazard levels are located (Fig. 3a). Further north, glacial lakes are more sparsely distributed, and are typically having very low to low levels of assessed hazard. The main determinants driving the higher hazard potential is the greater likelihood for ice and rock avalanches to enter a lake and steeper dam geometries. Considering the 187 lakes located in the two counties with the highest aggregated hazard levels along the Himalayan range (Chayu and Dingri counties) standardised values for topographic potential (mean = 0.60) and dam steepness (mean = 0.73), are significantly higher than respective mean values of 0.48 and 0.49 recorded for all lakes across the TP. Conversely, there is no significant difference in mean values for lake area or watershed area.

Hazard index values for the 20 lakes that have previously generated outburst floods (Table 1) are compared against the general distribution of values for all 1,291 lakes (Fig. 4). From these 20 lakes, 19 are classed as having high (5 lakes) to very high (14 lakes) hazard levels under the current assessment scheme with one lake falling towards the upper limit of the moderate range. The median hazard index value for lakes across the TP is 0.48, and hence, all lakes from which GLOFs have occurred have hazard index values that are above the median value. As a first-order automated tool for prioritizing further efforts towards potentially problematic lakes, these results lead to a high overall level of confidence.

3.2. GLOF danger and the transboundary threat

Once human exposure it taken into account, the extent of the GLOF danger across the TP becomes far more constrained, and in fact, only 210 lakes (16% of all lakes) potentially threaten human settlements (Fig. 3b). It must be highlighted that this does not imply that other lakes can simply be ignored, as infrastructure, assets, and livelihoods may still be threatened, but, in terms of prioritising further attention towards areas where humans are most likely to be impacted by an outburst event, these results prove enlightening. What emerges are three counties along the central Himalayan range (Nyalam, Dingri, and Jilong), with distinctively higher levels of potential GLOF danger. Notably, these three counties all share international boarders, such that GLOFs originating in this region of Tibet also threaten infrastructure located downstream in Nepal. It is the trans-boundary nature of the GLOF threat in this central Himalayan region that leads to high levels of exposure and overall danger levels, as villages located both in Tibet and Nepal are located in harm's way (Fig. 5). This is particularly evident in Nyalam, where the Sun-Koshi (Friendship) highway has historically linked China with Nepal, and as a consequence, considerable built infrastructure and large communities are located along this important transportation corridor, particularly on the Nepalese side of the boarder, leading to very high levels of danger associated with GLOFs originating in this county. In fact, 7 out of the 10 lakes with the highest levels of potential danger across the TP are located in Nyalam, and more specifically, within the upper reaches of the transboundary Poiqu/Sun Koshi River Basin (Table 2).

Cirenmaco (Lake 810) located above the Sun-Koshi highway in Nyalam emerges as the most dangerous lake (Table 2, Fig. 5). This result further enhances confidence in the assessment methodology, given that this lake has been the source already of 3 major GLOF events (Table 1), including the devastating event of July 1981 in which 200 people were killed [34]. Both Cirenmaco, and Galongco (Lake 1257 – rank 2) represent potentially high probability – high impact outburst events, characterised by both high hazard and exposure levels. From Galongco (Fig. 6a) the overall angle of reach from the lake down to the major village of Nyalam is close to the minimum $\tan\alpha$ value of 0.05, suggesting an outburst event at this point may not be significantly laden with debris (requiring a steeper flow path to sustain entrainment), although given the large size of the lake, a devastating flood or hypercontracted flow is likely. The river gorge downstream of Nyalam then steepens significantly, such that entrainment and mobilisation of debris along this reach would likely produce an even greater threat to downstream villages in Nepal (overall $\tan\alpha$ values increase to 0.07 beyond the boarder). Some other lakes included in the listing (Table 2) represent low probability – very high impact scenarios, where hazard levels are low but exposure values high. Lake 3595 (rank 17) is a clear example, where a possible chain-reaction type event

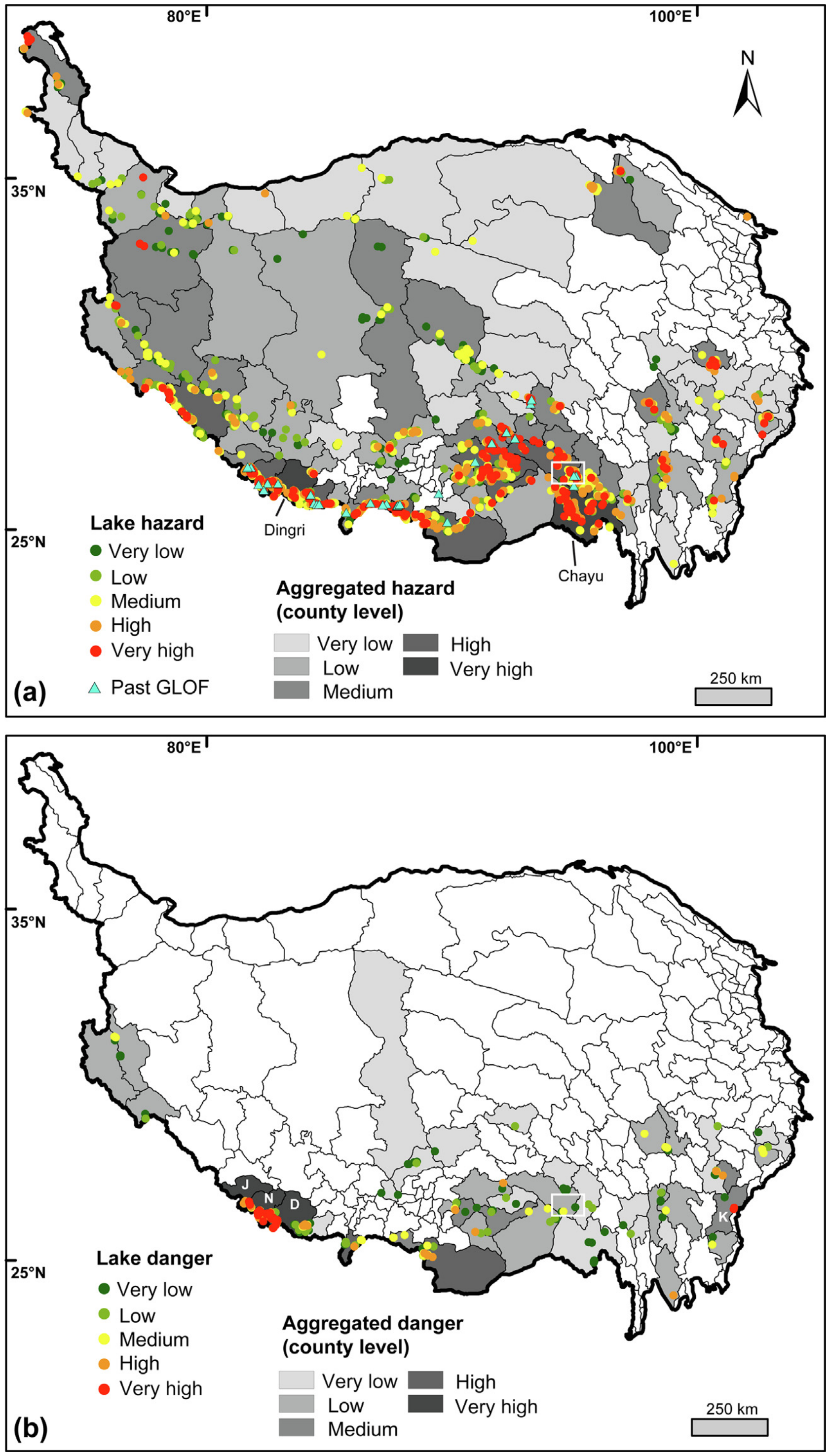

Fig. 3. (Color online) GLOF hazard (a) and danger (b) across the TP, with results aggregated to the county level. Counties of Jilong (J), Nyalam (N), Dingri (D), and Kangding (K) are indicated. The Boshula mountain region (white square) is affected by artefacts in the topographic data.

initiating from the bedrock dammed lake above could threaten the heavily populated town of Garze below where 17,000 inhabitants reside (Fig. 6b).

Regrettably, although several different DEMs were examined, including latest high resolution products, all suffered from significant data gaps in some localised areas within the Boshula mountains, southeast Tibet (see white square in Fig. 3), likely due to the steepness of the topography, and effects of snow and cloud cover in this monsoon-dominated sector of the TP. Caution is therefore needed in interpreting results over this region, particularly in terms of GLOF danger (Fig. 3b), as some modelled GLOF paths did not correctly propagate downstream due to spurious topographic artefacts.

3.3. Transient influences

Thirteen of the 30 most dangerous lakes have potential to continue expanding in lake area, and hence, volume (Table 2). For

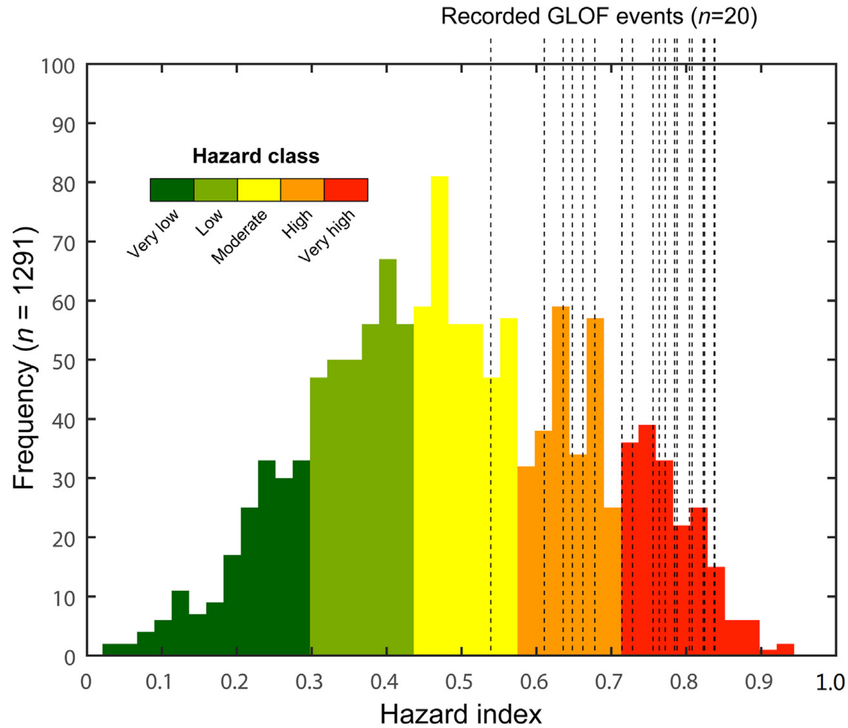

Fig. 4. (Color online) GLOF hazard index values for all 1,291 lakes across the TP, compared to values from lakes that have produced recent outburst events (Table 1).

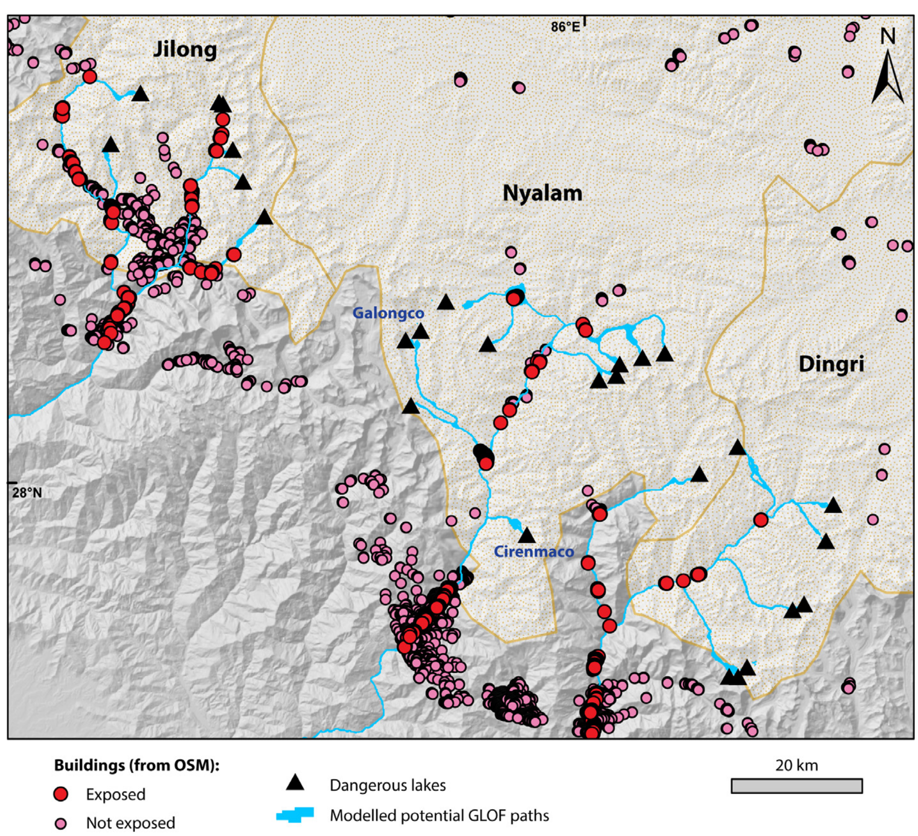

Fig. 5. (Color online) Transboundary GLOF threats originating from dangerous lakes (from Table 2) in the Central Himalayan region of Tibet, showing modelled GLOF paths and exposed buildings located in both Tibet and Nepal.

these lakes, a clear expansion has been observed over the past decade, both by existing studies [25,31] and/or from multi-temporal imagery in Google Earth, and the tongues of the glaciers are sufficiently flat that further calving and expansion of at least 500 m can be anticipated (in some cases in the order of kilometres). This has implications not only for the magnitude of any

Table 2
Ranking of 30 most dangerous lakes across TP, based on assessed danger score (function of hazard and exposure).[a)]

Rank	ID	County	Latitude (°N)	Longitude (°E)	Elevation (m a.s.l)	Lake area (km^2)	Hazard (H) (0–1)	Exposure (E) (0–1)	Danger ($H \cdot E$)	Permafrost
1	810	Nyalam	28.067	86.066	4660	0.37	0.96	0.99^	0.95	Evident
2	1257	Nyalam	28.321	85.839	5090	5.06+	0.98	0.96^	0.94	Not evident
3	1065	Nyalam	28.211	85.848	4370	0.60	0.97	0.90^	0.87	Not evident
4	1288	Nyalam	28.360	85.871	5230	4.74	0.92	0.87^	0.80	Not evident
5	403	Dingri	27.945	86.445	5060	1.44+	0.92	0.86^	0.79	Not evident
6	1225	Nyalam	28.305	86.157	5320	0.67	0.89	0.89^	0.79	Not evident
7	940	Dingri	28.135	86.530	5000	0.96+	0.97	0.79^	0.77	Not evident
8	3582	Kangding	29.968	102.007	4140	0.11+	0.78	0.98	0.76	Not evident
9	1259	Nyalam	28.336	86.192	5440	0.61	0.87	0.84^	0.73	Evident
10	1214	Nyalam	28.294	86.131	5250	0.28	0.82	0.88^	0.72	Not evident
11	1331	Jilong	28.508	85.494	4740	0.22+	0.95	0.76^	0.72	Not evident
12	1023	Dingri	28.186	86.531	5040	0.69+	0.90	0.80^	0.71	Evident
13	1323	Jilong	28.468	85.519	4460	0.45+	0.96	0.73^	0.70	Not evident
14	1241	Nyalam	28.314	85.948	5250	0.34	0.77	0.90^	0.70	Not evident
15	1034	Nyalam	28.194	86.314	5260	0.29	0.76	0.91^	0.69	Evident
16	341	Dingri	27.929	86.434	5040	0.34	0.80	0.86^	0.68	Not evident
17	3595	Kangding	30.008	102.009	4210	0.10	0.68	1.00	0.68	Not evident
18	1108	Nyalam	28.240	86.366	5330	0.29+	0.81	0.82^	0.66	Evident
19	1273	Nyalam	28.348	86.225	5360	0.53+	0.86	0.76^	0.66	Not evident
20	1245	Nyalam	28.321	86.159	5560	0.25	0.71	0.92^	0.65	Not evident
21	710	Dingri	28.034	86.499	5070	0.49+	0.76	0.84^	0.64	Not evident
22	1218	Nyalam	28.298	85.820	5090	0.30	0.66	0.96^	0.63	Evident
23	1348	Jilong	28.566	85.464	4440	0.18	0.87	0.70^	0.61	Not evident
24	334	Dingri	27.928	86.420	5010	0.11+	0.68	0.85^	0.58	Not evident
25	116	Yadong	27.809	89.231	5150	0.57	0.99	0.58	0.57	Evident
26	759	Dingri	28.045	86.514	5250	0.59	0.67	0.85^	0.56	Not evident
27	1349	Jilong	28.568	85.457	4500	0.25+	0.79	0.72^	0.56	Not evident
28	1329	Jilong	28.483	85.302	4420	0.10	0.76	0.72^	0.55	Not evident
29	1345	Jilong	28.559	85.333	4980	0.20	0.79	0.68^	0.54	Not evident
30	1317	Nyalam	28.427	85.563	4870	0.21+	0.72	0.74^	0.54	Evident

a) Permafrost indicates that there is evidence of ground ice in and around the moraine dam, based on visual analyses of geomorphological features using Google Earth.
+ Lake is actively calving, and further expansion of the lake is possible.
^ Transboundary exposure: includes buildings/communities located downstream in Nepal.

potential outburst event, but also can increase the likelihood of a GLOF as the lake expands towards steeper topography of the glaciated valley headwall, increasing the potential for ice and/or rock avalanches to enter a lake [36]. This process is illustrated here for lakes 710 and 759 (ranked 21 and 26 respectively – Table 2, Fig. 6c). Lake 710 has expanded 400 m upglacier between 2009 and 2017, and continued expansion is likely (supraglacial ponds are already evident). Lake 759 on the other hand cannot further expand, as the lake has already reached an abrupt steepening in topography. However, as a consequence of the expansion of Lake 710 and associated retreat and lowering of the glacier surface, the lateral moraine wall that dams Lake 759 could obtain a less stable geometry (steeper and higher dam), and the buttressing effect provided by the glacier would be removed. This could lead to a catastrophic outburst scenario involving a chain reaction and drainage of both lakes. The presence of permafrost is an additional transient factor that could influence the stability of a lake dam, due to degradation and thawing of ice in the moraine. Based on geomorphological features at the surface (hummocky surface, lobe-like creeping formations, slumping etc.), permafrost and the presence of ground ice in the dam structure is considered potentially relevant for 8 of the 30 most dangerous lakes (e.g. lake 1218, Fig. 6a).

4. Discussion

The clear recognition of a hot-spot of GLOF danger within the central Himalayan region of China, is a robust finding that agrees well with previous regional-scale assessment studies [30,48]. In particular, Nyalam country, and Poiqu basin therein, has been the focus of several studies that focus on monitoring of lake expansion and the related GLOF threat [27,31,49]. These studies have all highlighted the danger of Cirenmaco (Lake 810), Galongco (Lake 1257), Jialongco (Lake 1065) and Gangxico (Lake 1288), the same lakes that emerge out of the current assessment as the four most dangerous lakes, considering potential impacts not only in Nyalam county, but also further downstream in Nepal. While the transboundary threat associated with GLOFs originating in the Poiqu Basin has been well described [50–52], our large-scale assessment, considering maximum distance worst-case runout modelling of GLOF paths, highlights that transboundary threats originate also from dangerous lakes located in neighbouring counties of Jilong and Dingri (Fig. 5). The fact that GLOFs originating in the central Himalayan region can impact communities in both Tibet and Nepal largely explains the higher danger levels associated with lakes in the region, compared to areas further north and east. In the Boshula mountains, southeast TP, artefacts in the topographic data affected the modelling of GLOF paths in some localised areas, meaning GLOF danger may have been underestimated in this region where at least 3 historical outburst events have been recorded [19], and several lakes with very high hazard levels are located (Fig. 3b).

The remarkably robust performance of the methodological approach in successfully characterising the high to very high hazard level associated with known dangerous lakes suggests the four core factors (lake size, watershed area, topographic potential for ice/rock avalanches, dam steepness) capture well the main predisposing and triggering processes of GLOFs across the TP (Fig. 4). One key area of improvement in the assessment could be the integration of information on ground temperature and permafrost distribution, given that degradation of ice in the moraine dam structure is considered to have played a role in some past GLOFs occurring in the region [19]. In the current study, the presence of ground ice is inferred based on surface geomorphology only for

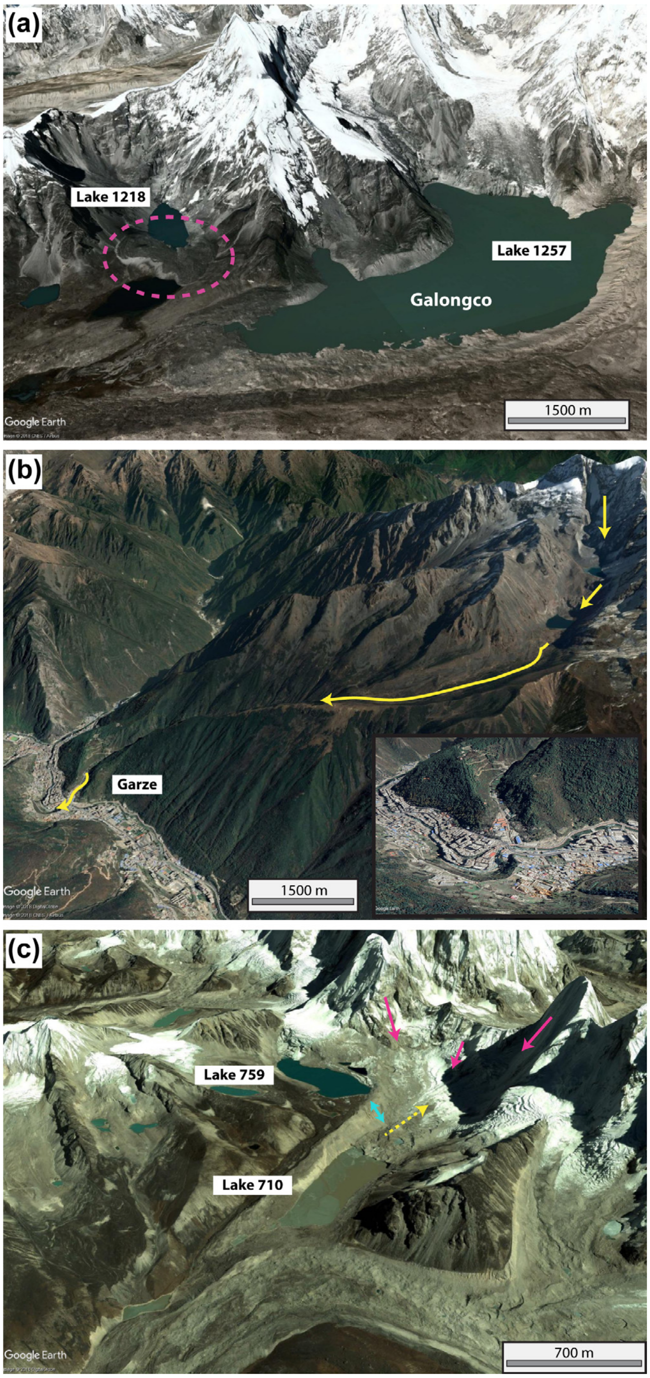

Fig. 6. (Color online) Google Earth view of identified potentially dangerous lakes (a) above the town of Nyalam in central Himalaya (Nyalam county). The lobe-like creeping debris landform (dashed) damming Lake 1218 is indicative of permafrost and the presence of ground ice in the moraine dam structure. (b) Above the heavily populated town of Garze in Southeast TP (Kangding county). The hazard (likelihood and magnitude) of an outburst event from the moraine dammed lower lake (Lake 3595) is relatively low (Table 2), but an outburst could be triggered by a mass movement into and overtopping wave from the bedrock dammed lake above (arrows). (c) In the central Himalaya (Dingri county), where further retreat of the glacier and expansion of Lake 710 (dashed) will increase the likelihood of ice and/or rock avalanches to enter the lake from the surrounding steep slopes (arrows), and will undermine the lateral moraine that dams Lake 759 (double-headed arrow).

the final listing of most dangerous lakes, and not in an automated manner for all 1291 lakes. GLOF studies that have considered permafrost as part of the assessment criteria typically use simple empirically-derived models to estimate likely permafrost distribution [20,53], and while providing a useful regional overview, such approaches cannot account for important site-specific characteristics (e.g., surface structure, snow cover, micro-topography) that influence ground temperature. Similarly, latest permafrost maps available for Tibet [54] remain too coarse for GLOF hazard assessment, and promising high resolution modelling approaches that could provide site-specific relevant information [55] are yet to be upscaled across high mountain Asia.

Previous studies have demonstrated that the addition of further parameters into a GLOF hazard assessment scheme does not necessarily improve the reliability of the results, and in fact, can introduce redundancies and biases into the assessment [12]. Also, in large-scale applications, not all parameters assessed may be equally relevant across vastly different geomorphological and climatic zones, and typically empirical evidence and region-specific process-understanding is too incomplete to support the use of weightings to emphasize some key parameters over others [22]. In relation to the current study, it may be reasonable to assign a relative weighting to the hazard and exposure components of the danger assessment, depending on how end-users want to apply the results. For example, if an emphasis is to be given to those lakes that are considered to have the greatest likelihood of producing an outburst, a higher weighting could be given to the hazard component, or the exposure and final danger assessment could be applied only to a subset of lakes that have a hazard value above a certain threshold (e.g., 75th percentile). Such decisions should ultimately be linked to the motivation and agenda of local authorities and other stakeholders, to ensure the information provided best meets their needs and expectations. Related to this, if authorities want to better focus on those communities with least capacity to prepare, respond, and recover from a GLOF disaster, then information on local social, economic, and institutional drivers of societal vulnerability could be included within a comprehensive risk assessment [56].

It is important to reiterate that high danger levels assigned in this study do not necessarily suggest an imminent danger to the population, particularly for those cases where hazard levels are relatively low (e.g., Lake 3595 – Fig. 6b). In such cases, further studies to substantiate the actual risk associated with these lakes could be justified, considering also the broader geotechnical situation and possibility for seismic triggered ice and/or rock avalanches that could trigger an otherwise unlikely outburst event and/or cascading process chain. For those lakes characterised by both high levels of hazard and exposure, local field studies (supported with very high resolution remote sensing) would be essential to quantify the threat. For example, where permafrost is expected to play a role in the stability of the dam (Table 2), in-situ geophysical measurements could confirm the presence and likely thermal conditions of any ice within the moraine structure [57], and multi-temporal DEM differencing could detect deformation linked to thawing of this ice over time [58,59]. Lake bathymetries are crucial as input for the dynamical simulation of outburst scenarios, establishing downstream flow heights, inundations depths, velocities and other parameters needed for local hazard and risk mapping [60]. Such local investigations can most appropriately inform the design of risk reduction strategies that span a full range of possible hard (e.g., lake lowering, dam stabilisation) and soft (e.g., monitoring and early warning systems, community response strategies etc.) options that reduce the likelihood, potential magnitude, and societal impact of any GLOF event.

Several recent studies have emphasised the importance of forward-looking, anticipatory approaches to GLOF hazard and risk assessment, recognising that atmospheric warming is leading to rapidly evolving glacial and periglacial landscapes [37,61,62]. In the current study, we have rather focussed on establishing current baseline conditions of GLOF hazard and danger to society across TP, while recognising that many of the most dangerous lakes are continuing to expand in area, and/or in other cases, could be influenced by further warming and thawing of ice in the dam area (Table 2). Some lakes that have recently emerged over the past decade may have been under the 0.1 km^2 area threshold considered in this study, and new lakes will almost certainly develop in the future [63], necessitating that the large-scale assessment as presented here be updated at regular intervals using latest lake inventories. In addition to climate driven changes, urbanisation and economic development programmes across TP are leading to new infrastructural developments [64], changing the distribution of exposed people and their assets. The use of OSM in large-scale hazard and eventually risk assessment is a promising avenue in this regard, as crowdsourced datasets can better keep pace with changes on the ground, in comparison with official cadastres that may be updated only once every few years to decade.

5. Conclusion

This study has provided a first objective assessment of GLOF hazard and danger to communities across the TP using a fully automated procedure, providing a robust basis for the prioritisation of further studies, monitoring efforts, and local field investigations that will ultimately guide on-ground risk management and climate adaptation strategies. Using four core determinates of GLOF hazard (lake size, watershed area, topographic potential for ice/rock avalanching, and dam steepness), the assessment scheme accurately distinguishes the high to very high hazard level of 19 out of 20 lakes that have previously generated GLOFs, located primarily along the main Himalayan range and in south-east TP. Only around 16% of all glacial lakes threaten human settlements, and a notable hotspot of GLOF danger is identified in the central Himalayan counties of Jilong, Nyalam, and Dingri. Here glacial lakes are a significant trans-boundary threat to communities located in both Tibet and also downstream in Nepal. The most dangerous lake of Cirenmaco has caused repeated devastating outburst events over the past century.

Overall, the significant advantage of the methodology presented here is the ease and speed with which objective assessments can be undertaken and updated by local authorities using latest datasets, with the entire automated workflow packaged within a user-friendly ArcGIS toolbox. This is particularly important in view of rapid environmental and societal changes that will alter GLOF danger and risk. With a focus on prioritising efforts towards those lakes that most directly threaten human lives, this study has considered only the presence of buildings as a proxy for the possible exposure of communities to the modelled GLOF events. However, the workflow could be expanded in the future to include impacts to major roads, industry (hydropower), and livelihoods (e.g., agricultural land), depending on the needs and priorities of local stakeholders. Furthermore, the methodology is well suited for replicating across other regions of high-mountain Asia and elsewhere where objective, large-scale GLOF assessment studies are currently lacking. This would be important, for instance in countries such as India, Pakistan, and Afghanistan, to ensure that nationally and internationally funded GLOF risk reduction strategies are most appropriately targeting those areas where the threat is greatest.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

This work was supported by the Swiss National Science Foundation (IZLCZ2_169979/1) and counterpart grant of the National Natural Science Foundation of China (21661132003). The work further benefited from support of the Strategic Priority Research Program (A) of the Chinese Academy of Sciences (XDA20060201) and collaboration within the Dragon 4 project funded by the European Space Agency (4000121469/17/I-NB).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scib.2019.03.011.

Author contributions

Allen designed the study and led all development and implementation of the methodology, and led the drafting of the manuscript. Zhang and Wang developed and updated glacial lake inventories that were used in the study. Dr. Bolch and Prof. Yao contributed to the methodological development and overall framing of the study. All authors contributed to the interpretation and discussion of results.

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Simon Allen obtained his Ph.D. in 2009 from the University of Canterbury, New Zealand. His research addresses climate change impacts, hazards and risks in mountain environments, with a particular focus on High Mountain Asia.