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Characteristics and changes of glacial lakes and outburst floods

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Abstract:

Global glacier mass loss has accelerated, producing more and larger glacial lakes. Many of these glacial lakes are a source of glacial lake outburst floods (GLOFs), which pose threats to people and infrastructure. In this Review, we synthesize global changes in glacial lakes and GLOFs. More than 110,000 glacial lakes currently exist, covering a total area of ~15,000 km^2. These lakes are transient features, increasing in area by ~22% dec^{-1} from 1990-2020. GLOFs from these lakes are commonly initiated by dam failure or wave overtopping associated with mass movements, with >ten million people globally exposed to their impacts. Although data limitations are substantial, >3000 GLOFs have been recorded from 850-2022, particularly in Alaska (24%), High Mountain Asia (HMA; 18%) and Iceland (19%). GLOFs from ice-dammed lakes account for 64.8% of the global total, while moraine-dammed and bedrock-dammed GLOFs account for only 12.6% and 1.0%, respectively. GLOFs have increased in most glaciated mountain regions of the world. Ongoing deglaciation and lake expansion is expected to increase GLOF frequency further, particularly in HMA where GLOF-related hazards are projected to triple by 2100. However, changes in other regions will likely be lower given topographic constraints on lake evolution. Future research should prioritize acquiring field data on lake and dam properties and producing globally-coordinated multi-temporal lake mapping, and robust and efficient modelling of GLOFs for comprehensive hazard assessment and response planning.

[H1] Introduction

Glaciers have been losing mass since the end of the Little Ice Age[1-3], and at high—and accelerating—rates since the 1960s (ref [4,5]). Indeed, overall mass loss from glaciers and ice caps (excluding the Greenland and Antarctic ice sheets) totalled 267 ± 16 Gt yr^{-1} from 2000-2019 (ref [4]), much of which can be attributed to anthropogenic warming [6-8]. When the resultant meltwater is naturally dammed (by ice, a moraine or bedrock), glacial lakes can form on (supraglacial), within (englacial), under (subglacial), at the edge of (ice-marginal), or beyond the front of (proglacial) glaciers. There are an estimated 14,394 (>0.05 km^2) of these lakes globally[9], the majority of which are in Greenland, the southern Andes, Antarctica and the Subantarctic, Alaska, Canada and High Mountain Asia (HMA) (**Fig. 1a**). The number and size of glacial lakes is generally increasing, especially for proglacial lakes, which is due to them being closely connected to contemporary glacier retreat and meltwater production at local[10,11], regional[12-15] and global[9] scales. However, there is considerable regional variability[9,16-19], including notable expansion in Alaska, Greenland periphery, Patagonia, and HMA. Nevertheless, the overall growth pattern is expected to continue[20-24], in line with a projected 26-41% decrease in glacial mass by 2100 under 1.5-4℃ temperature increases[25].

The stability and longevity of glacial lakes are highly variable. Glacial lakes can drain suddenly and very quickly (hours to days), releasing a glacial lake outburst flood (GLOF). More than 3,000 GLOFs have been reported worldwide from 850-2022 (**Fig. 1b**)[26], each with characteristic rapid rise to peak discharge and often very large flood volumes. For example, the 1996 volcanic eruption beneath the Vatnajökull ice cap, Iceland, produced an outburst flood with an estimated peak discharge ~55,000 m^3 s^{-1}, thereby temporarily becoming the second largest river in the world after the Amazon[27,28]. Indeed, ice-dammed lakes have produced some of the largest peak discharges recorded in human history[29-31], including peak discharges of >10^5 m^3 s^{-1} in High Mountain Asia[32], and 10^9 m^3 in the Andes and Alaska[30,33,34]

Accordingly, GLOFs rank among the most prominent glacier hazards, killing thousands of people over the past century[35] and causing extensive damage tens to hundreds of kilometers downstream. For instance, the 1941 GLOF in Huaraz, Peru, destroyed a third of the city and killed about 5,000 people[36], and the 2013 GLOF in Kedarnath, India, killed more than 6,000 people[37]. Given that millions of people are potentially at risk from GLOFs worldwide[38], especially in a warming, understanding the location, timing of formation, evolution and physical characteristics of glacial lakes is critical to mitigating the downstream impacts to communities and infrastructure.

In this Review, we synthesize glacial lake and GLOF hazard datasets from most glaciated regions of the world to assess their ongoing and projected changes. We begin by documenting the global and regional distribution of glacial lakes. We follow by assessing the characteristics and historical trends of GLOFs. We subsequently discuss future projections in glacial lakes and the corresponding GLOF hazard and risk, before ending with research priorities. Throughout, focus is on the physical aspects of glacial lakes and GLOFs in a warming world.

[H1] Global and regional changes of lake size and abundance

Understanding glacial lakes is the first step in estimating GLOF hazard and risk (**Fig. 2**). Methods used to map glacial lakes are now discussed, followed by quantification of their historical changes at global and regional scales.

[H2] Mapping glacial lakes

A growing archive of satellite products and enhanced computing power[39] have improved mapping of glacial lakes (**Fig. 2**). In most cases, mapping relies on the use of the normalized difference water index (NDWI[40]); a satellite image-derived calculation combining green and near-infrared (NIR) wavelength bands to differentiate water bodies from all other landcover. Automated and semi-automated methods are used for lake mapping from a NDWI classification, although lake outlines have also been delineated manually with enhanced accuracy[12,41]. Landsat satellite imagery is often used as the basis for glacial lake mapping by NDWI owing to its temporal coverage and a medium-resolution sensor[9,17,42]. Nevertheless, Landsat imagery has limitations for NDWI-based lake mapping, including poor image contrast due to seasonal snow and ice cover on lakes, as well as confusion introduced by mountain shadows and cloud cover[43]. Cloud-free Synthetic Aperture Radar (SAR) can overcome this limitation, but are of limited length and hence generally only suitable for validation of mapping algorithms or case studies[44,45]. Cloud computing, artificial intelligence and machine learning are rapidly improving the ability to efficiently manage and automatically analyze remote sensing data[46,47]. However, interactive visual inspection and manual editing combined with original imagery is still essential to ensure a consistent data quality with time.

In addition to mapping lake outlines, knowledge of glacial lake volume is important for quantifying hazard and for estimating downstream impacts of GLOFs[48,49] (**Fig. 2**). Empirical volume-area relationships for glacial lakes have been established in many instances (**Supplementary Table 1**). Global compilations of lake depths, areas and volumes suggest that lake area and depths are moderately-correlated, and lake area and volumes are well-correlated[50]. These correlations allow for the estimation of lake depths and volumes from area, especially in regions where direct measurements are rare and difficult (**Supplementary Table 1**). Bathymetric measurements of ice-marginal lakes have also been carried out in some locations, including the Southern Alps of New Zealand[51,52] and on the Tibetan Plateau[53,54].

[H2] Global glacial lake characteristics

After mapping the outline of glacial lakes, it is possible to determine their overarching characteristics, including size, area and volume. Various such inventories exist (**Supplementary Table 2**), each compiled from satellite imagery but differing in maximum distance between glaciers and lakes (buffers of 1, 3, 5 or km) and the smallest lake size included (0.0002, 0.005 or 0.05 km^2), introducing slight discrepancies at the regional and global scale. Here, several regional inventories[9,12,18,19] (**Supplementary Table 2**) are merged to produce a global contemporary glacial lake compilation; a size threshold of 0.05 km^2 is set for all RGI regions[55] except Svalbard and Jan Mayen, Southern Andes and New Zealand (**Supplementary Table 2**).

This global compilation provides much insight into glacial lake characteristics. 22,133 glacial lakes are revealed in 2015-2019, collectively covering ~14,438 km^2 (**Supplementary Tables 2**). These totals are more than other reports of 14,394 lakes >0.05 km^2 situated within 1 km of glacier margins, covering a total area of ~8,950 km^2 in the time period between 2015 and 2018 (ref [9]). Regional differences in the number, area, and volume of global glacial lakes are evident (**Fig. 2**). Glacial lakes are predominantly distributed in Greenland and the eastern Canadian Arctic, the southern Andes, Alaska and western Canada, and HMA. Glacial lakes in HMA are widespread, but with a smaller signal size and volume.

[H2] Glacial lake changes

Glacial lakes are naturally transient features. Each tends to follow a common trajectory, as documented in many mountainous regions around the world[16,56-59]. Specifically, glacial lakes show an extensive and robust expansion after 2000. Various processes can lead to such changes in glacial lake evolution, including shifts in inflow or outflow; gradual infilling by sediment particularly in deglaciating environments[23,60,61]; abrupt infilling following mass movements[62,63]; coalescence of several lakes; detachment of an ice-marginal lake from the parent glacier as it retreats; or partial or complete dam failure resulting in a GLOF[23]. Although global statistics are unavailable, evidence from the tropical Andes suggests that, on average, only one in ten GLOFs has resulted in complete lake drainage[62]. Indeed, most moraine- and bedrock-dammed glacial lakes persist after a GLOF has occurred[62]. Accordingly, lakes can exist for vastly different timeframes: ice-dammed lakes can form and fail repeatedly as long as the ice dam is thick enough to impound a lake[33,64]; bedrock-dammed lakes within overdeepenings can persist for tens of thousands of years[65-67]; moraine-dammed lakes can survive over centennial or millennial timescales[68]

The abovementioned inventories provide an opportunity to track these glacial lakes over time (**Fig. 3a; Supplementary Fig. 1**). The number and area of glacial lakes has increased by ~53% and ~51%, respectively, between 1990 and 2018 (ref [9]). This global increase is subject to uncertainties due to missing lakes when compared to regional multi-temporal lake inventories (**Supplementary Table 2**). Overall, the evolution of

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glacial lakes within most regions showed a steady expansion between 1990 and 2020. Some sub-regions of the Himalaya, Andes, and Alps showed faster trends in lake expansion than the global pattern **(Supplementary Fig. 1)**. However, there are regional differences within sub-regions, which might be due to different types of glacial lakes.

Regional datasets, which undergo extensive quality control during compilation, also indicate a general increase in glacial lake area. Between ~1990 and 2020, glacial lake area increased by an average of ~22% dec^{-1} (**Fig. 3a**), higher than 17% dec^{-1} suggested by the global dataset[9]. Of course, there is much regional and temporal variability embedded. For instance, overarching changes in the Southern Andes and Greenland periphery are smaller than several other locations at <10% dec^{-1} (**Fig. 3a**) and potentially highlight the importance of short-term temporal variability; lake area temporarily decreased at the edge of the Northern Patagonian Icefield from 1945-1976 (ref [69]) and in Greenland from 1987 to 1992 and from 2005 to 2010 (ref [16]), perhaps contributing to the smaller, yet still positive, long-term trends[69,16] observed there. In contrast, overall changes were much larger in Iceland, Scandinavia, and Russian Arctic at >40% dec^{-1}

Local variability is also observed, as evidenced in HMA, particularly the Himalaya which has some of the longest records of glacial lake growth. In the greater Himalaya, glacial lake area increased by ~3.7 km^2 yr^{-1} (0.6% yr^{-1}) from 1990-2020. Yet, changes in the Chinese Himalaya and Nepal Himalaya were ~1.28 km^2 yr^{-1} (0.8% yr^{-1}) between the 1970 and the 2008 (ref [70]) and 0.6 km^2 yr^{-1} (1.1% yr^{-1}) from 1977-2017 (ref [71]), respectively.

In addition to such substantial local and regional changes, there is also evidence of changes by glacial lake type. The imbalance between ice-marginal and glacier-detached proglacial lakes has been recorded worldwide (Figs. 3b–e), whereby the former are lakes in direct contact with their parent glaciers and have strong interactions between them. For example, in Southern Pamir, the number of proglacial lakes remained largely constant from 1968 to 1993 (the lower number in 1977 might be related to uncertainties due to poor image quality), increased to a peak of 44 in 2008, and then decreased to 26 by 2015 (ref [72]) (Fig. 3b).

In the Andes, the number and area of glacial lakes has progressively increased. From 1948-2017, three to four new lakes formed each year, with an average expansion rate of ~0.1 km^2 yr^{-1} [73]. Of these total lakes, the number of proglacial lakes was stable from 1948-1990 (71 to 74, with some fluctuations in between) and then decreased to 35 by 2018 (ref [73]). For the Peruvian Andes, an almost constant gain of detached proglacial lake area was observed throughout the study period (Fig. 3c). This phenomenon, together with the increasing average elevation of proglacial lakes, is a strong indication that large lakes dammed by Little Ice Age terminal moraines have lost contact with their parent glaciers, while bedrock-dammed lakes are forming at higher elevations[73].

In the Southern Alps of New Zealand, an almost linear trend in lake area change has also been reported, with an average of ~0.5 $km^2 yr^{-1}$ in four time steps from 1990-2020 (ref [74]). Tasman Glacier, New Zealand's largest glacier, is retreating rapidly, and a proglacial lake formed in 1990 (ref [52]). The number of ice-marginal proglacial lakes in New Zealand was greatest in 2011 and thereafter has decreased slightly as lakes coalesced and as some became disconnected from the glaciers[74] (Fig. 3d).

In the European Alps, particularly the Austrian Alps, the number and area of lakes increased from 1850-2015, with the mean change in lake area doubling from ~0.038 $km^2 yr^{-1}$ during 1998 to 2006, to ~0.079 $km^2 yr^{-1}$ during 2006 to 2015 (ref [75]). Similar changes have occurred in Switzerland. There, the number of proglacial lakes increased from 21 in 1900 to 47 in 2006, and from 47 in 2006 to 82 in 2016 (ref [59]) (Fig. 3e). The increase in total lake area in the Swiss Alps has accelerated from ~0.01 $km^2 yr^{-1}$ in 1850-1900 up to ~0.15 $km^2 yr^{-1}$ in 2006-2016 (ref [59]). However, part of this variability is due to the artificial impoundment of some lakes, mainly for hydropower generation purposes.

[H1] Historical glacial lake outburst floods

With the presence of glacial lakes comes the risk of a GLOF. GLOFs arise when the lake dam is breached (by various triggers depending on the dam type) and meltwater is suddenly and rapidly released from the lake, subsequently flowing downstream where it can cause substantial societal and environmental impacts (**Fig. 4**). Together, data from river gauges, satellite images, sediment stratigraphy, and eyewitness and media reports suggest that at least 3,151 GLOFs have occurred globally since 850 (**Fig. 1b**)[26], with most recorded in Alaska (24%, *n*=768), HMA (18%, *n*=569) and Iceland (19%, *n*=590).

However, understanding of GLOFs is severely limited by inadequate data. Triggers are often unknown or speculated owing to absent field data, necessitating reliance on climatic or geological-geomorphological evidence[35,76-78]. Numerical modelling is similarly challenged by absent knowledge of parameter values such as lake water temperature or time-varying lake level, limiting insight[58,79,80]. Moreover, GLOF frequency calculations suffer from selective reporting and changes in instrumentation and satellite coverage[33,81,82]. Nevertheless, it is possible to glean evidence of GLOF characteristics, as now discussed for ice-dammed, moraine-dammed and bedrock-dammed GLOFs. Resulting hazards and changes are also assessed.

[H2] Ice-dammed GLOFs

GLOFs from ice-dammed lakes are the most common type. Their activity is largely controlled by the damming glaciers activity and resulting fracture or flexure of the ice dam (**Fig. 4a)**. Flotation of the ice dam once a critical lake level is reached also acts as a potential breach mechanism[33,83,84]. When lake water suddenly drains through an ice dam, thermal and mechanical erosion (usually progressively enlarging a subglacial tunnel) leads to an exponentially-rising discharge[54,85,86] .

GLOFs from ice-dammed lakes constitute roughly two-thirds (2039 of 3151) of all reported GLOFs worldwide[26,81]. Their frequent occurrence is linked to the fact that they can drain repeatedly as an ice dam will 're-heal' temporarily once energetic egress of lake water has subsided. At the regional scale, Alaska is a hotspot of GLOFs from ice-dammed lakes (*n*=764, 99% within Alaska, 37% of the global total in this category[19,26,33] (**Fig. 1a**). Indeed, 750 ice-dammed lakes have formed in Alaska over the 20th century[87,88], with some lakes having a volume >10^9 m^3 when impounded by thick outlet glaciers[87]. Yet, their GLOFs rarely cause damage owing to low exposure of assets along river channels. Ice-dammed lakes are also the dominant source of reported GLOFs in Greenland Periphery (*n*=153; 100% of all GLOFs within Greenland Periphery, 7.5% of global ice-dammed GLOFs)[89,90], the Karakoram (*n*=190; 33.4% within HMA, 9.3% of global)[29,91], Scandinavia (*n*=183; 96.8% within Scandinavia, 9.0% of global)[92], Central Europe (*n*=258; 58.2% within Central Europe, 12.7% of global), and Iceland (*n*=237; 40.2% within Iceland, 11.6% of global)[86] (**Fig. 1b**). In Central Europe, fatalities and damage from these occasional ice-dam failures were particularly high before the 20th century, possibly related to limited warning and flood control measures[93]. In Scandinavia and particularly in Norway, whilst the percentage of ice-dammed GLOFs was high in the mid-20th century, the total number and size of outbursts is small compared to other regions[26]

[H2] Moraine-dammed GLOFs

GLOFs from moraine-dammed lakes are the second-most common type globally after ice-dammed lakes (**Fig. 1b**). In these situations, dam breaching can be caused by seepage of lake water through unconsolidated material, degradation of an ice core, or overtopping due to calving, avalanches or landslides into the lake[76,83] (**Fig. 4**). Moraine-dammed lakes in the ice-marginal phase of evolution are the most likely to produce GLOFs due to calving processes and proximity to ice avalanche release zones. In contrast, glacial lakes detached from glaciers become disconnected from the most frequent GLOF-triggering processes with increasing distance from glaciers[56]. The almost instantaneous and sometimes complete failure of a moraine dam produces a linearly-rising discharge[94]. Furthermore, complete failure of the (moraine) dam restricts any future ability to impound meltwater[95,96]. Hence, moraine-dammed lakes usually fail only once.

GLOFs from moraine-dammed lakes make up at least ~13% (398 of 3151) of the global total number of recorded GLOFs from 850-2022 (**Fig. 1a**). However, their occurrence is highly regionally-variable. The majority of those reported are found in the low latitude Andes (*n*=100; 61.3% of GLOFs within the low latitude Andes, 25.1% of global moraine-dammed GLOFs), Central Asia (*n*=110; 46.2% within Central Asia, 27.6% of global) and the Himalaya (*n*=71; 77.2% within the Himalaya, 17.8% of global (**Fig. 1b**). Indeed, 52% and 32% of glacial lakes in the central Andes and Himalaya are moraine-dammed, respectively[17,97], and many others have associated geomorphological features suggesting possible past dam failures[62,98,99]. The exact timing of these dam failures has yet to be determined, as the geomorphological evidence is largely limited to that visible in satellite images that were first available in the 1960s.

[H2] Bedrock-dammed and subglacial GLOFs

Bedrock dams are usually stable and so these glacial lakes produce fewer GLOFs compared to ice- and moraine-dammed lakes. GLOFs from bedrock-dammed lakes make up only ~1% (30 of 3151) of the total number of GLOFs from 850-2022 (**Fig. 1a**). Indeed, overtopping of bedrock barriers have only rarely been reported[81], in contrast with the with the high regional abundance of bedrock-dammed lakes[62], especially in the Himalaya and Andes[17,97]. Their limited occurrence might arise from the fact that unfractured bedrock dams can withstand increases in hydrostatic pressure, and hence are only overtopped by displacement waves from a mass movement entering the lake[62]. GLOFs from bedrock-dammed lakes are only reported after the 1960s and those occurred mainly in the low latitude Andes (*n*=27; 16.6% within the low latitude Andes, 90% of global bedrock-dammed GLOFs). While evidence is limited, GLOF counts from bedrock-dammed lakes might be underestimated given the short preservation time of any geomorphic evidence, especially compared to moraine dam failures[100].

Similarly, there are relatively few GLOFs attributed to englacial or subglacial lakes induced by geothermal or volcanic activity compared to other GLOF triggers and mechanisms[101]. GLOFs from englacial lakes produce poorly-preserved geomorphological evidence and are difficult to detect with optical remote sensing. They are mainly reported in Central Europe (*n*=112, 25.3% within Central Europe, 69.1% of global englacial-GLOFs). The majority of GLOFs from subglacial lakes are found in Central Europe (*n*=5; 1.13% within Central Europe, 71.4% of global subglacial-GLOFs), Southeast Asia (*n*=1; 1.18% within Iceland, 14.3% of global) and the low latitude Andes (*n*=1; 0.61% within the low latitude Andes, 14.3% of global) (**Fig. 1b**). In Iceland, for example, at least 264 outbursts from a small number of subglacial lakes[31], which repeatedly form and drain due to geothermal activity beneath the ice caps, have been observed, with further evidence of glacier-volcano interactions both in historical and prehistoric times[102,103]. Floods caused by rapidly-draining englacial lakes have also occasionally been reported in New Zealand, central Europe, western Canada and the USA[104-106] (**Fig. 1b**).

[H2] GLOF hazard assessment

Understanding the characteristics of glacial lakes, changes to them, and GLOF triggers and mechanisms is the basis for GLOF hazard assessment, which is critical for disaster prevention and damage mitigation. Globally, more than ten million people are potentially exposed to the impacts of GLOFs, mainly in HMA[38,107]. Potentially dangerous glacial lakes have been identified using a range of assessment approaches, ranging from large-scale automated methods considering key determinants such as lake size, catchment area, ice/rock avalanche potential, and dam steepness[108,109], through to detailed catchment or lake-specific assessments including field investigations[110-112]. Identifying the type of glacial lake dam is a critical first step in GLOF hazard assessments, as it determines the stability of the lake, triggering processes, the potential magnitude of the GLOF, and the mechanisms of drainage[113].

For GLOF hazard assessment a distinction is typically made between those factors that are critical to the inherent stability of the lake dam (geometry and structure of the dam) and those that influence the potential for an external triggering event (a rock or ice avalanche)[114]. Additionally, the hydro-geomorphic characteristics of the lake catchment area, which can influence the susceptibility to precipitation or melt-triggered outburst events have also been highlighted[37,115]. With high resolution optical imagery (such as available from google earth) and corresponding high quality digital terrain models, it has become possible to quantify various physical characteristics of the dam and catchment area remotely over large spatial scales[109,116]. However, precise geometric measurements (such as dam freeboard or dam height) and in situ characteristics (such as ice-core, lithology) are lacking, and can only be confirmed through local site investigations.

Typically, large glacial lakes are emphasized owing to the potential high-magnitude GLOFS that could originate from them, yet outbursts from small or even seasonal lakes have proven capable of eroding huge volumes of sediment and producing catastrophic downstream process chains[117]. GLOFs can be both the trigger of a process chain, or they can be initiated as part of a larger process chain, as in the case of a mass movement causing a displacement wave, overtopping and downstream flood[118]. Several hydrodynamic numerical models[80,119-122] have been used to numerically propagate flood waves downstream, modelling not only a GLOF but also entire process chains (Supplementary Table 3). However, in the absence of robust field data from past events, modelling is often undertaken with poorly-constrained conditions and parameters. Some morphodynamic models that include sediment transport and bed elevation changes during a simulation have also been applied where independent pre- and post-GLOF topographic data are available[123,124]. These models can estimate sediment entrainment and transport rates[125], and more generally this numerical modelling has potential to interpolate between observations along a river reach, or to extend beyond them downstream.

[H2] Trends in GLOF frequency and magnitude

Although suffering from known biases and limitations[62,100], remote sensing observations and geomorphological evidence offers an opportunity to roughly estimate whether GLOFs have changed in frequency. The number of reported GLOFs increased from 1 in 850 to 3151 in 2022, peaking from 2000-2020 (refs [26,35]). However, poor instrumentation and limited available satellite imagery might be responsible for fewer records of historical GLOF events before ~1980, suggesting a bias in the estimation of the historical GLOF trend[26,81,126]. At the regional scale, this bias has been confirmed. For instance, GLOFs from ice-dammed lakes in Alaska revealed an unchanged frequency and decreasing magnitude from 1985-2020 (ref [82]). Furthermore, time-series analysis of satellite images in the Himalaya suggest an unchanged frequency of moraine-dammed GLOFs from 1980s to 2017 (ref [127]). Therefore, the increasing number of moraine- and bedrock-dammed lakes in mountainous regions worldwide does not necessarily imply more GLOFs[9,12].

Little is also known about how average or extreme GLOF flood discharges and volumes have changed, but some general themes have emerged. For instance, flood volumes of the largest reported GLOFs from ice-dammed lakes worldwide have decreased by an order of magnitude since 1900 [33]. In contrast, the average peak discharge and volume of ice-dammed GLOFs remain unchanged[33]. These changes align with the thinning of ice dams with atmospheric warming and glacier ablation, such that maximum lake levels gradually fall and drainage of ice-dammed lakes occurs earlier in the melt season[33,83]. Moreover, as glaciers retreat, many glacier dams can no longer impound lakes at their termini at lower elevations, or the glaciers are lost altogether[82]. Where ice-dammed lakes can form at higher elevations they tend to be smaller because the topography is steeper and thus the water storage capacity is limited.

[H1] Future glacial lakes and outburst floods

Whether the increasing number and size of glacial lakes will lead to higher-magnitude GLOF discharges and greater GLOF volumes in the future remains a controversial hypothesis. With such apparent historical changes in glacial lake number and corresponding GLOFs, predicting their changes in a warming climate is important for understanding future natural hazards[128,129]. The future of glacial lakes and potential hazard hotspots are now discussed.

[H2] Future glacial lake evolution

The life cycle of glacial lakes is known to shift in a warming climate (**Fig. 5**). Supraglacial lakes can grow, coalesce, and eventually form proglacial lakes. Simultaneously, existing proglacial lakes can expand in area and in volume (Fig. 5). Formation of new lakes and the growth of existing lakes can accelerate glacier terminus retreat, via increased frontal ablation[130,131]. Future increases in the volume of proglacial lakes will generally increase the downstream damage of any GLOFs[38]. In addition, some ice-dammed lakes might form following glacier surges, and episodic failures of ice-dammed lakes are highly destructive[132,133]. Ice-dammed lakes will continue to breach in the near future, even as glaciers thin and retreat[33,64].

Beyond these conceptual change, estimating subglacial topography and identifying potential overdeepenings are critical to project the location and size of future glacial lakes. As glaciers retreat, depressions can be exposed that have the potential to fill partly or fully with meltwater to develop into glacial lakes[128]. Identification of these overdeepenings requires knowledge (or an estimate) of subglacial bedrock morphology, which can be modelled by subtracting ice thickness[20,134] from a digital elevation model[135], and a hydrological filling algorithm applied to fill the overdeepenings[136]. The difference between the filled and the original subglacial bed topography provides a bathymetric grid suggesting the extent and volume of the overdeepenings and, hence, of potential future glacial lakes[24,135]. Glacier evolution models[20,137] can also predict future rates of glacier retreat so as to estimate when glacial lakes might begin to form[21,24,135]. However, these studies cannot currently determine the dam type nor even can they confidently suggest the height of the future lake outlet [24].

Nonetheless, despite the high and yet unassessed uncertainty, these ice thickness – overdeepening approaches have been used to project regional changes in glacial lakes, including HMA[21,24] (**Fig. 6; Supplementary Table 4**).

In HMA, glacial lake area and volume is generally expected to increase. These changes arise due to high projected glacier volume losses (60-75% by 2100 under unabated CO_2 emissions[25,138]), exposing subglacial overdeepenings and, thus, expanding existing lakes and developing new glacial lakes[21,24]. For example, with complete glacier disappearance in HMA, ~13,000 new glacial lakes (each larger than 0.01 km^2) could potentially form, with a total area of ~1,510 km^2 and volume of ~52.3 km^3 (ref [24]). Similar estimates of a maximum number of 10,068 [6981, 13538] new ice-dammed lakes are projected by 2100 under SSP585, with an area of 290 [204, 639] km^2, and a volume of 2.9 [1.9, 4.9] km^3 (ref [64]). However, these quantifications are uncertain. Indeed, a different ice thickness model and hence subglacial bed topography suggests ~25,285 lakes (larger than 0.01 km^2) could form by complete deglaciation, having an area of 2,683 ± 773.8 km^2 and volume of 99.1 ± 28.6 km^3 [135].

The magnitude of the projected glacial lake changes in HMA is regionally variable as well as strongly dependent on the emission scenario (hence, temperature rise). Generally, greater changes are expected in western regions (**Figs. 6a-c**). Glacial lake area, for example, is expected to increase by 26.8×10^2 km^2 in south-western Asia compared to 15.1×10^2 km^2 in south-eastern and 8.3×10^2 km^2 in central Asia (**Fig. 6a, c**). Glacial lake volume also reflects similar shifts (**Fig. 6b, c**). Future lake area and volume in most subregions under all emission scenarios show a continuous increase until about 2090 and then decrease (**Fig. 6e, f**). However, there are sub-regional differences, with larger increases in the Karakoram and Himalaya under all emission scenarios (**Fig. 6e, f**).

Glacial lakes area and volume is also expected to increase somewhat in the European Alps. At the bigger regional scale, lake area and volume are expected to increase by 477.0 km^2 and 1.7 km^3, respectively by deglaciation (**Fig. 6a, b**). However, at a national level, different climate scenarios and glacier evolution models are often used that make comparisons difficult. In the Swiss Alps, the number and area of lakes are 987 and 6.22 ± 0.25 km^2 in 2016, respectively (ref [59]). If all glaciers were to disappear, ~500 new glacial lakes (of at least 0.01 km^2) could form, with a total area of about 50 km^2 and volume of 1.6 km^3 (ref [128]). These estimates are broadly in keeping with ice free scenarios based on current ice thickness measurements; they suggest 683 glacial lakes (larger than 0.005 km^2) with a total area and volume of 45.2 ± 9.3 km^2 and 1.16 [1.05, 1.32] km^3, respectively, could develop[23]. Looking at specific emissions scenarios rather than total ice elimination, glacial lake volumes of 0.35 [0.12, 0.49] km^3 and 0.94 [0.51, 1.04] km^3 could be realized by 2100 for SSP1-2.6 and SSP5-8.5, respectively[23]. In the upper Rhône catchment, southwestern Swiss Alps, alone, 100 sites are predicted to have a high potential for future glacial lake formation[139].

Smaller changes are anticipated in other regions of the European Alps. In Austria, 42 potential new glacial lakes with a total area of about 2 km^2 could form by deglaciation [140], an increase from the current 1410 lakes with a total area of 17.1 km^2 in 2015 (ref [75]). A similar number of new lakes are expected under complete ice loss in the Aosta Valley region, Italy; 46 potential new lakes larger than 0.01 km^2 might develop, with a total area of 3.1 ± 0.9 km^2 and a volume of 0.06 ± 0.02 km^3 (ref [141]), expanding the current 186 lakes with a total area of 1.4 km^2 (ref [142]). Likewise, 80 (48 with a high level of confidence) potential new lakes could form under full deglaciation in the Mont Blanc massif of the French Alps[143]

Smaller changes are generally expected in glacial regions of the Southern Hemisphere, including the New Zealand Alps. Here, lake area is expected to increase by 42.3 km^2 by 2100 under RCP4.5 (**Fig. 6a, b)**. More specifically, ice-marginal lakes across the Southern Alps could expand from 20.9 km^2 in 2020 to 40.4 km^2 in 2050 (ref [74]). However, from 2050 onwards, the rate of increase in total area is projected to decrease from 0.65 km^2 yr^{-1} in 2020-2050 to 0.04 km^2 yr^{-1} in 2050-2100 as lakes detach from glaciers and/or fill with sediment[74].

In the Peruvian Andes, glacial lake area is projected to increase by 65.5 km^2 and volume by 0.7 km^3 by 2100 under RCP8.5[73,144] (**Fig. 6a, b)**. In the still glaciated Cordillera Blanca, 38 or 50 new lakes could emerge by 2100 under RCP2.6 or RCP8.5, respectively[73], increasing from the current 870 lakesaccordingly, glacial lake area is expected to increase by ~10% compared to 2018 values, from 35.2 to 37.0 km^2. In the deglaciating Vilcanota-Urubamba basin, lake area in 2100 is projected to be 3.2% higher than 2016 values under RCP2.6 (from 26.9 to 27.8 km^2 and 6.0% higher under RCP8.5 (from 26.9 to 28.5 km^2)[144]. The topographic setting means that the rate of increase is higher for 2016-2050 compared to 2050-2100 as glaciers are already retreating to very steep slopes by 2050 (ref [144]). In deglaciated areas of the Peruvian Andes, 201 sites (of at least 0.01 km^2) with a total volume of 0.26 km^3 have been compiled for a future glacial lake inventory[145].

Often not included in these assessments is sediment deposition within newly exposed overdeepenings, infilling potential future lakes and complicating specific projections. Such infilling is particularly likely in tectonically active, high-relief regions with abundant sediment supply such as HMA and the Southern Alps[61,146]. Where lakes receive meltwater from GLOFs as well as from ablation-fed meltwater flows, and where GLOF-induced bank erosion widens river channels hundreds of kilometers downstream[23,78], then sedimentation rates within future lakes will also be very high. Indeed, erosion rates and sediment transport in glacierized basins are generally expected to increase due to cryosphere degradation[61,146] , but there has been almost no quantitative analysis of this process. One exception is in the Swiss Alps, where approximately half of newly-formed glacial lakes and 11-25 % of the total overdeepening volume are expected to disappear by 2100 due to sediment infilling[23]. If sediment delivery is not considered, the potential future glacial lakes are likely to be over-estimated in number and size.

[H2] Future GLOF hazard and risk

With projected changes in glacial lakes come potential changes in GLOFs. Based on physical understanding and supported by models, increasing GLOFs are assumed for the future[24,64,135], albeit with much regional variability. The higher potential for GLOF impacts in HMA compared to other regions is due to the large (and exposed) population and to low economic development[38]. In HMA, future GLOF hazards are expected to triple from current conditions due to lake development (**Fig. 6d)**. Even greater increases (>fivefold) are projected in the Karakoram and Pamir regions[24], which are expected to become a hotspot of potential GLOF hazard[135], although the timing of lake formation is uncertain[147]. The characteristics of GLOFs in HMA are also expected to shift. Scenario modelling in the Poiqu River basin of China and Nepal, for example, suggests that permafrost degradation will enhance large mass movements (of tens of millions of m^3) into glacial lakes, resulting in larger flood magnitudes and thereby longer distances downstream of flood impact than historically observed[148].

Future GLOF hazards in other regions of the world are unlikely to increase as in HMA. For example, there is relatively low potential future for GLOFs in the Mont Blanc massif (Western European Alps) owing to the flat glacier bed topography [143]. In the Cordillera Blanca (Peru), glacier retreat and lake formation are already at an advanced stage, and new lakes still to form will be predominantly dammed by stable bedrock[73]. However, in Iceland mega GLOFs induced by volcanic activity can occur in the future, irrespective and independent of climate change[89].

Of course, while GLOF hazard might increase, overall risk also necessitates consideration of exposure and vulnerability. To date, comprehensive risk assessments considering the changing flood hazard and societal vulnerability and exposure have been lacking. However, the expansion of communities and infrastructure, including hydropower facilities, has been and will continue to be a major driver of GLOF risk [149-151]. Thus, infrastructure expansion in glacial valleys, coupled with expanded glacial likes, will likely result in enhanced GLOF risk, threatening downstream populations and infrastructure[129,152-154]. Accordingly, there are new challenges for warning systems or other disaster risk reduction measures[155].

[H1] Summary and future perspectives

Global glacier melt has accelerated due to atmospheric warming, feeding rapid growth of glacial lakes in most world regions from the 1960s onwards. Although uncertain, it is estimated that glacial lake number and area have increased ~50% from 1990-2018 (ref [9]), such that more than 110,000 glacial lakes with a total area of ~15,000 km^2 in 2015-2019 have been identified. This trend in glacial lakes is associated with a potential increase in GLOF hazards and risks. More than 3,000 GLOFs have occurred worldwide from 850-2022, with ~88% recorded since 1900. Indeed, GLOFs have increased in frequency and magnitude in most glaciated mountain regions, especially after 2000 (ref [26,35]), a trend that is likely to continue with ongoing deglaciation, increasing

GLOF risk and hazard when coupled with enhanced development in downstream river valleys. In HMA, in particular, GLOF risk is projected to increase threefold by deglaciation [24,126].

While GLOF knowledge has advanced considerably, key challenges remain, particularly surrounding data. As a starting point, homogeneous and standardized multi-temporal glacial lake inventories are needed, so far limited by mapping efficiency. Visual inspection and manual editing of lake outlines have been the main methods used to date, time-consuming approaches that rely heavily on individual expertise. The use of cloud computing, machine learning and artificial intelligence technologies should overcome manual limitations. However, access to regional high-quality lake inventories to train machine learning classifiers is vitally important. With any such inventories, consistent thresholds for minimum lake area and distance from glaciers are needed, as well as consistent classifications. An updated multi-period inventory of global glacial lakes with a single criterion is expected to fill the gaps of missing lakes and regional deficiencies

Hydrodynamic modelling and reconstruction of GLOFs is also hindered by absent data. Field data of lake properties (including bathymetry, temperature and lake outflow peak discharge) and GLOF mechanisms is desperately needed in different glaciated environments and for different lake types to refine and test model parameters, as well as parametrize dam breach models. Yet, such data is extremely difficult to acquire given accessibility and safety that makes successful recovery of instrumentation and sensors challenging, especially in ice-proximal locations. Accordingly, local, regional and even global understanding of GLOF flow dynamics is limited, feeding into hazard assessment, early warning systems, infrastructure design, and emergency response. In addition to the use of modern field observation instruments and data transmission, broader international cooperation and the establishment of data opening and sharing are important ways forward. Future research should focus on comparing model results with field observations, historical flood records, and other independent data sets to improve model credibility.

Assessments of future glacier lakes under-report the common problem of uncertainty about the location, size and timing of potential future lakes. The average error in measured ice thickness of 10 ± 24%[156] masks considerably higher uncertainties for specific glaciers, including an uncertainty range of ±30% suggested by the validation of ground-penetrating radar measurements in the Swiss Alps[128]. Thus, while common ice thickness models can estimate the total ice volume of all glaciers globally[20,134] or regionally[157,158], differences between ice thickness models can lead to substantial local differences. Crucially, the potential future lake area is highly sensitive to small errors in, for example, the height of a subglacial rock barrier or the depth of an overdeepening[23]. Obtaining accurate glacier bed topography by ice thickness modelling remains a challenge, but it can be improved by increasing the accuracy of the underlying input data, adding measured thickness data, and multi-model synthesis[20,156,159,160]. In the future, with the launch of P-band and L-band radar satellites, obtaining ice thickness using tomographic SAR technology will provide new opportunities and possibilities to improve the accuracy of future glacial lake prediction[161,162].

These improved data and models are vital to enhance GLOF hazard assessment, particularly in a warming world associated with enhanced GLOF risk. However, GLOF hazard assessments suffer from inconsistent approaches (indicators and their thresholds) and a lack of a common assessment framework (filed survey, hazard and risk assessment and management action)[108,116]. Technical guidelines have been established at the international level, but have yet to be adapted or widely consolidated into regional or national approaches, as the level and development of guidelines varies widely across regions[113]. Where existing assessments provide conflicting results, efforts should be undertaken to consolidate findings to determine which lakes should be prioritized for monitoring and other response actions. In particular, the need to consider small lakes is emphasized, as such lakes have often been overlooked but can have devastating downstream impacts[77,117]. Importantly, this knowledge needs to be used to anticipate the hazards of future GLOF events, including worst-case scenarios. Given the tendency for GLOFs to be triggered by or associated with other mass movements and cascading processes, multi-hazard perspectives are encouraged.

Future efforts to move beyond hazard to comprehensive GLOF risk assessment must also involve a wider network of local experts and broader disciplines. Failure to adequately consider local vulnerabilities, needs and perceptions can ultimately limit the success of disaster risk reduction measures, such as early warning systems[163]. As a transboundary phenomenon, GLOFs pose particular challenges for disaster risk reduction where cooperation and sharing across political boundaries are required, and where societal and institutional capacities to manage GLOF risks can vary widely between upstream and downstream regions. Scientists, policymakers and stakeholders should work together towards broader international and regional across transboundary cooperation to reduce the risk of GLOFs.

References

1 Marta, S. *et al.* The Retreat of Mountain Glaciers since the Little Ice Age: A Spatially Explicit Database. *Data* **6**, 107, doi:10.3390/data6100107 (2021).

2 Lee, E. *et al.* Accelerated mass loss of Himalayan glaciers since the Little Ice Age. *Scientific Reports* **11**, 24284, doi:10.1038/s41598-021-03805-8 (2021).

3 Carrivick, J. L. *et al.* Mass Loss of Glaciers and Ice Caps Across Greenland Since the Little Ice Age. *Geophys Res Lett* **50**, e2023GL103950, doi:10.1029/2023GL103950 (2023).

4 Hugonnet, R. *et al.* Accelerated global glacier mass loss in the early twenty-first century. *Nature* **592**, 726–731, doi:10.1038/s41586-021-03436-z (2021).

5 Zemp, M. *et al.* Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. *Nature* **568**, 382-386, doi:10.1038/s41586-019-1071-0 (2019).

6 Roe, Gerard H., Baker, Marcia B. & Herla, F. Centennial glacier retreat as categorical evidence of regional climate change. *Nature Geoscience* **10**, 95-99, doi:10.1038/ngeo2863 (2017).

7 Roe, G. H., Christian, J. E. & Marzeion, B. On the attribution of industrial-era glacier mass loss to anthropogenic climate change. *The Cryosphere* **15**, 1889-1905, doi:10.5194/tc-15-1889-2021 (2021).

8 Vargo, L. J. *et al.* Anthropogenic warming forces extreme annual glacier mass loss. *Nature Climate Change*, doi:10.1038/s41558-020-0849-2 (2020).

9 Shugar, D. H. *et al.* Rapid worldwide growth of glacial lakes since 1990. *Nature Climate Change* **10**, 939–945, doi:10.1038/s41558-020-0855-4 (2020).

10 Andreassen, L. M., Nagy, T., Kjøllmoen, B. & Leigh, J. R. An inventory of Norway's glaciers and ice-marginal lakes from 2018–19 Sentinel-2 data. *J Glaciol* **68**, 1085-1106, doi:10.1017/jog.2022.20 (2022).

11 Zhang, G. *et al.* Glacial lake evolution and glacier-lake interactions in the Poiqu River basin, central Himalaya, 1964–2017. *J Glaciol* **65**, 347–365, doi:10.1017/jog.2019.13 (2019).

12 Wang, X. *et al.* Glacial lake inventory of high-mountain Asia in 1990 and 2018 derived from Landsat images. *Earth Syst. Sci. Data* **12**, 2169–2182, doi:10.5194/essd-12-2169-2020 (2020).

13 Chen, F. *et al.* Annual 30 m dataset for glacial lakes in High Mountain Asia from 2008 to 2017. *Earth System Science Data* **13**, 741–766, doi:10.5194/essd-13-741-2021 (2021).

14 Corr, D., Leeson, A., McMillan, M., Zhang, C. & Barnes, T. An inventory of supraglacial lakes and channels across the West Antarctic Ice Sheet. *Earth Syst. Sci. Data* **14**, 209-228, doi:10.5194/essd-14-209-2022 (2022).

15 Wood, J. L. *et al.* Contemporary glacial lakes in the Peruvian Andes. *Global Planet Change*, 103574, doi:10.1016/j.gloplacha.2021.103574 (2021).

16 Carrivick, J. L. & Quincey, D. J. Progressive increase in number and volume of ice-marginal lakes on the western margin of the Greenland Ice Sheet. *Global Planet Change* **116**, 156-163, doi:10.1016/j.gloplacha.2014.02.009 (2014).

17 Wilson, R. *et al.* Glacial lakes of the Central and Patagonian Andes. *Global Planet Change* **162**, 275-291, doi:10.1016/j.gloplacha.2018.01.004 (2018).

18 How, P. *et al.* Greenland-wide inventory of ice marginal lakes using a multi-method approach. *Scientific Reports* **11**, 4481, doi:10.1038/s41598-021-83509-1 (2021).

19 Rick, B., McGrath, D., Armstrong, W. & McCoy, S. W. Dam type and lake location characterize ice-marginal lake area change in Alaska and NW Canada between 1984 and 2019. *The Cryosphere* **16**, 297-314, doi:10.5194/tc-16-297-2022 (2022).

20 Farinotti, D. *et al.* A consensus estimate for the ice thickness distribution of all glaciers on Earth. *Nature Geoscience* **12**, 168-173, doi:10.1038/s41561-019-0300-3 (2019).

21 Furian, W., Maussion, F. & Schneider, C. Projected 21st-Century Glacial Lake Evolution in High Mountain Asia. *Frontiers in Earth Science* **10**, 821798, doi:10.3389/feart.2022.821798 (2022).

22 Linsbauer, A. *et al.* Modelling glacier-bed overdeepenings and possible future lakes for the glaciers in the Himalaya—Karakoram region. *Ann Glaciol* **57**, 119–130, doi:10.3189/2016AoG71A627 (2016).

23 Steffen, T., Huss, M., Estermann, R., Hodel, E. & Farinotti, D. Volume, evolution, and sedimentation of future glacier lakes in Switzerland over the 21st century. *Earth Surf. Dynam.* **10**, 723-741, doi:10.5194/esurf-10-723-2022 (2022).

24 Zheng, G. *et al.* Increasing risk of glacial lake outburst floods from future Third Pole deglaciation. *Nature Climate Change* **11**, 411–417, doi:10.1038/s41558-021-01028-3 (2021).

25 Rounce, D. R. *et al.* Global glacier change in the 21st century: Every increase in temperature matters. *Science* **379**, 78-83, doi:10.1126/science.abo1324 (2023).

26 Lützow, N., Veh, G. & Korup, O. A global database of historic glacier lake outburst floods. *Earth Syst. Sci. Data* **2023**, 2983–3000, doi:10.5194/essd-15-2983-2023 (2023).

27 Gudmundsson, M. T., Sigmundsson, F. & Björnsson, H. Ice–volcano interaction of the 1996 Gjálp subglacial eruption, Vatnajökull, Iceland. *Nature* **389**, 954-957, doi:10.1038/40122 (1997).

28 Stefánsdóttir, M. B. & Gíslason, S. R. The erosion and suspended matter/seawater interaction during and after the 1996 outburst flood from the Vatnajökull Glacier, Iceland. *Earth Planet Sc Lett* **237**, 433-452, doi:10.1016/j.epsl.2005.07.002 (2005).

29 Hewitt, K. Natural dams and outburst floods of the Karakoram Himalaya. *Hydrolog Sci J* **27**, 266-267 (1982).
30 Mayo, L. R. Advance of Hubbard Glacier and 1986 Outburst of Russell Fiord, Alaska, U.S.A. *Ann Glaciol* **13**, 189-194, doi:10.3189/S0260305500007874 (1989).
31 Björnsson, H. Subglacial lakes and jökulhlaups in Iceland. *Global Planet Change* **35**, 255-271, doi:10.1016/S0921-8181(02)00130-3 (2003).
32 Hewitt, K. in *Glaciers of the Karakoram Himalaya: Glacial Environments, Processes, Hazards and Resources* (ed Kenneth Hewitt) 245-265 (Springer Netherlands, 2014).
33 Veh, G. *et al.* Less extreme and earlier outbursts of ice-dammed lakes since 1900. *Nature* **614**, 701–707, doi:10.1038/s41586-022-05642-9 (2023).
34 Motyka, R. J. & Truffer, M. Hubbard Glacier, Alaska: 2002 closure and outburst of Russell Fjord and postflood conditions at Gilbert Point. *Journal of Geophysical Research: Earth Surface* **112**, doi:10.1029/2006JF000475 (2007).
35 Carrivick, J. L. & Tweed, F. S. A global assessment of the societal impacts of glacier outburst floods. *Global Planet Change* **144**, 1-16, doi:10.1016/j.gloplacha.2016.07.001 (2016).
36 Carey, M. Living and dying with glaciers: people's historical vulnerability to avalanches and outburst floods in Peru. *Global Planet Change* **47**, 122-134, doi:10.1016/j.gloplacha.2004.10.007 (2005).
37 Allen, S. K., Rastner, P., Arora, M., Huggel, C. & Stoffel, M. Lake outburst and debris flow disaster at Kedarnath, June 2013: hydrometeorological triggering and topographic predisposition. *Landslides* **13**, 1479-1491, doi:10.1007/s10346-015-0584-3 (2016).
38 Taylor, C., Robinson, T. R., Dunning, S., Rachel Carr, J. & Westoby, M. Glacial lake outburst floods threaten millions globally. *Nature Communications* **14**, doi:10.1038/s41467-023-36033-x (2023).
39 Gorelick, N. *et al.* Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sens Environ* **202**, 18-27, doi:10.1016/j.rse.2017.06.031 (2017).
40 McFeeters, S. K. The use of the normalized difference water index (NDWI) in the delineation of open water features. *Int J Remote Sens* **17**, 1425−1432, doi:10.1080/01431169608948714 (1996).
41 Zhang, G., Yao, T., Xie, H., Wang, W. & Yang, W. An inventory of glacial lakes in the Third Pole region and their changes in response to global warming. *Global Planet Change* **131**, 148-157, doi:10.1016/j.gloplacha.2015.05.013 (2015).
42 Wulder, M. A. *et al.* Fifty years of Landsat science and impacts. *Remote Sens Environ* **280**, doi:10.1016/j.rse.2022.113195 (2022).
43 Wulder, M. A. *et al.* Current status of Landsat program, science, and applications. *Remote Sens Environ* **225**, 127-147, doi:10.1016/j.rse.2019.02.015 (2019).
44 Shugar, D. H. *et al.* A massive rock and ice avalanche caused the 2021 disaster at Chamoli, Indian Himalaya. *Science* **373**, 300-306, doi:10.1126/science.abh4455 (2021).
45 Wangchuk, S., Bolch, T. & Zawadzki, J. Towards automated mapping and monitoring of potentially dangerous glacial lakes in Bhutan Himalaya using Sentinel-1 Synthetic Aperture Radar data *Int J Remote Sens* **40**, 4642-4667, doi:10.1080/01431161.2019.1569789 (2019).
46 Taylor, L. S. *et al.* Remote sensing of the mountain cryosphere: Current capabilities and future opportunities for research. *Progress in Physical Geography: Earth and Environment* **45**, 931-964, doi:10.1177/03091333211023690 (2021).
47 Kaushik, S., Singh, T., Joshi, P. K. & Dietz, A. J. Automated mapping of glacial lakes using multisource remote sensing data and deep convolutional neural network. *International Journal of Applied Earth Observation and Geoinformation* **115**, 103085, doi:10.1016/j.jag.2022.103085 (2022).
48 Clague, J. J. & Mathews, W. H. The Magnitude of Jökulhlaups. *J Glaciol* **12**, 501-504, doi:10.3189/S0022143000031907 (1973).
49 Walder, J. S. & Costa, J. E. Outburst floods from glacier-dammed lakes: The effect of mode of lake drainage on flood magnitude. *Earth Surf Proc Land* **21**, 701-723, doi:10.1002/(SICI)1096-9837(199608)21:8<701::AID-ESP615>3.0.CO;2-2 (1996).
50 Cook, S. J. & Quincey, D. J. Estimating the volume of Alpine glacial lakes. *Earth Surface Dynamics* **3**, 559–575, doi:10.5194/esurf-3-559-2015 (2015).
51 Dykes, R. C., Brook, M. S., Robertson, C. M. & Fuller, I. C. Twenty-First Century Calving Retreat of Tasman Glacier, Southern Alps, New Zealand. *Arctic, Antarctic, and Alpine Research* **43**, 1-10, doi:10.1657/1938-4246-43.1.1 (2011).
52 Purdie, H., Bealing, P., Tidey, E., Gomez, C. & Harrison, J. Bathymetric evolution of Tasman Glacier terminal lake, New Zealand, as determined by remote surveying techniques. *Global Planet Change* **147**, 1-11, doi:10.1016/j.gloplacha.2016.10.010 (2016).
53 Zhang, G. *et al.* Underestimated mass loss from lake-terminating glaciers in the greater Himalaya. *Nature Geoscience* **16**, 333–338, doi:10.1038/s41561-023-01150-1 (2023).
54 Carrivick, J. L. *et al.* Ice-Dammed Lake Drainage Evolution at Russell Glacier, West Greenland. *Frontiers in Earth Science* **5**, doi:10.3389/feart.2017.00100 (2017).
55 RGI-Consortium. Randolph Glacier Inventory — a dataset of global glacier outlines: Version 6.0. Technical report: Global Land Ice Measurements from Space, Colorado, USA. doi:10.7265/N5-RGI-60 (2017).

56 Emmer, A., Merkl, S. & Mergili, M. Spatiotemporal patterns of high-mountain lakes and related hazards in western Austria. *Geomorphology* **246**, 602-616, doi:10.1016/j.geomorph.2015.06.032 (2015).

57 Nie, Y. *et al.* A regional-scale assessment of Himalayan glacial lake changes using satellite observations from 1990 to 2015. *Remote Sens Environ* **189**, 1–13, doi:10.1016/j.rse.2016.11.008 (2017).

58 Carrivick, J. L., Tweed, F. S., Sutherland, J. L. & Mallalieu, J. Toward Numerical Modeling of Interactions Between Ice-Marginal Proglacial Lakes and Glaciers. *Frontiers in Earth Science* **8**, 577068, doi:10.3389/feart.2020.577068 (2020).

59 Mölg, N. *et al.* Inventory and evolution of glacial lakes since the Little Ice Age: lessons from the case of Switzerland. *Earth Surf Proc Land* **46**, 2551–2564, doi:10.1002/esp.5193 (2021).

60 Otto, J.-C. in *Geomorphology of Proglacial Systems: Landform and Sediment Dynamics in Recently Deglaciated Alpine Landscapes* (eds Tobias Heckmann & David Morche) 231-247 (Springer International Publishing, 2019).

61 Carrivick, J. L. & Tweed, F. S. Deglaciation controls on sediment yield: Towards capturing spatio-temporal variability. *Earth-sci Rev* **221**, 103809, doi:10.1016/j.earscirev.2021.103809 (2021).

62 Emmer, A. *et al.* 160 glacial lake outburst floods (GLOFs) across the Tropical Andes since the Little Ice Age. *Global Planet Change* **208**, doi:10.1016/j.gloplacha.2021.103722 (2022).

63 Vilca, O., Mergili, M., Emmer, A., Frey, H. & Huggel, C. The 2020 glacial lake outburst flood process chain at Lake Salkantaycocha (Cordillera Vilcabamba, Peru). *Landslides* **18**, 2211-2223, doi:10.1007/s10346-021-01670-0 (2021).

64 Compagno, L., Huss, M., Zekollari, H., Miles, E. S. & Farinotti, D. Future growth and decline of high mountain Asia's ice-dammed lakes and associated risk. *Communications Earth & Environment* **3**, doi:10.1038/s43247-022-00520-8 (2022).

65 Glasser, N. F., Jansson, K. N., Harrison, S. & Kleman, J. The glacial geomorphology and Pleistocene history of South America between 38°S and 56°S. *Quaternary Sci Rev* **27**, 365-390, doi:10.1016/j.quascirev.2007.11.011 (2008).

66 Lister, G. S. A 15,000-year isotopic record from Lake Zürich of deglaciation and climatic change in Switzerland. *Quaternary Res* **29**, 129-141, doi:10.1016/0033-5894(88)90056-7 (1988).

67 Sutherland, J. L., Carrivick, J. L., Shulmeister, J., Quincey, D. J. & James, W. H. M. Ice-contact proglacial lakes associated with the Last Glacial Maximum across the Southern Alps, New Zealand. *Quaternary Sci Rev* **213**, 67-92, doi:10.1016/j.quascirev.2019.03.035 (2019).

68 Carrivick, J. L. & Tweed, F. S. Proglacial lakes: character, behaviour and geological importance. *Quaternary Sci Rev* **78**, 34–52, doi:10.1016/j.quascirev.2013.07.028 (2013).

69 Loriaux, T. & Casassa, G. Evolution of glacial lakes from the Northern Patagonia Icefield and terrestrial water storage in a sea-level rise context. *Global Planet Change* **102**, 33-40, doi:10.1016/j.gloplacha.2012.12.012 (2013).

70 Wang, X. *et al.* Using Remote Sensing Data to Quantify Changes in Glacial Lakes in the Chinese Himalaya. *Mt Res Dev* **32**, 203-212, doi:10.1659/MRD-JOURNAL-D-11-00044.1 (2012).

71 Khadka, N., Zhang, G. & Thakuri, S. Glacial Lakes in the Nepal Himalaya: Inventory and Decadal Dynamics (1977–2017). *Remote Sensing* **10**, 1913, doi:10.3390/rs10121913 (2018).

72 Mergili, M., Müller, J. P. & Schneider, J. F. Spatio-temporal development of high-mountain lakes in the headwaters of the Amu Darya River (Central Asia). *Global Planet Change* **107**, 13-24, doi:10.1016/j.gloplacha.2013.04.001 (2013).

73 Emmer, A. *et al.* 70 years of lake evolution and glacial lake outburst floods in the Cordillera Blanca (Peru) and implications for the future. *Geomorphology* **365**, 107178, doi:10.1016/j.geomorph.2020.107178 (2020).

74 Carrivick, J. L. *et al.* Coincident evolution of glaciers and ice-marginal proglacial lakes across the Southern Alps, New Zealand: Past, present and future. *Global Planet Change* **211**, 103792, doi:10.1016/j.gloplacha.2022.103792 (2022).

75 Buckel, J., Otto, J. C., Prasicek, G. & Keuschnig, M. Glacial lakes in Austria - Distribution and formation since the Little Ice Age. *Global Planet Change* **164**, 39-51, doi:10.1016/j.gloplacha.2018.03.003 (2018).

76 Westoby, M. J. *et al.* Modelling outburst floods from moraine-dammed glacial lakes. *Earth-sci Rev* **134**, 137-159, doi:10.1016/j.earscirev.2014.03.009 (2014).

77 Cook, K. L., Andermann, C., Gimbert, F., Adhikari, B. R. & Hovius, N. Glacial lake outburst floods as drivers of fluvial erosion in the Himalaya. *Science* **362**, 53-57, doi:10.1126/science.aat4981 (2018).

78 Kargel, J. S. *et al.* Geomorphic and geologic controls of geohazards induced by Nepal's 2015 Gorkha earthquake. *Science* **351**, aac8353, doi:10.1126/science.aac8353 (2015).

79 Lala, J. M., Rounce, D. R. & McKinney, D. C. Modeling the glacial lake outburst flood process chain in the Nepal Himalaya: reassessing Imja Tsho's hazard. *Hydrol Earth Syst Sc* **22**, 3721–3737, doi:10.5194/hess-22-3721-2018 (2018).

80 Westoby, M. J. *et al.* Numerical modelling of glacial lake outburst floods using physically based dam-breach models. *Earth Surface Dynamics* **3**, 171-199, doi:10.5194/esurf-3-171-2015 (2015).

81 Veh, G. *et al.* Trends, Breaks, and Biases in the Frequency of Reported Glacier Lake Outburst Floods. *Earth's Future* **10**, doi:10.1029/2021ef002426 (2022).

82 Rick, B., McGrath, D., McCoy, S. W. & Armstrong, W. H. Unchanged frequency and decreasing magnitude of outbursts from ice-dammed lakes in Alaska. *Nature Communications* **14**, 6138, doi:10.1038/s41467-023-41794-6 (2023).

83 Tweed, F. S. & Russell, A. J. Controls on the formation and sudden drainage of glacier-impounded lakes: implications for jökulhlaup characteristics. *Progress in Physical Geography: Earth and Environment* **23**, 79-110, doi:10.1177/030913339902300104 (1999).

84 Richardson, S. D. & Reynolds, J. M. An overview of glacial hazards in the Himalayas. *Quatern Int* **65-66**, 31-47, doi:10.1016/S1040-6182(99)00035-X (2000).
85 Björnsson, H. Understanding jökulhlaups: From tale to theory. *J Glaciol* **56**, 1002-1010, doi:10.3189/002214311796406086 (2010).
86 Roberts, M. J., Pálsson, F., Gudmundsson, M. T., Björnsson, H. & Tweed, F. S. Ice–water interactions during floods from Grænalón glacier-dammed lake, Iceland. *Ann Glaciol* **40**, 133-138, doi:10.3189/172756405781813771 (2005).
87 Post, A. & Mayo, L. R. Glacier dammed lakes and outburst floods in Alaska. Report No. 455, (1971).
88 Stone, K. H. Alaskan ice-dammed lakes. *Annals of the Association of American Geographers* **53**, 332-349, doi:10.1111/j.1467-8306.1963.tb00453.x (1963).
89 Carrivick, J. L. & Tweed, F. S. A review of glacier outburst floods in Iceland and Greenland with a megafloods perspective. *Earth-sci Rev* **196**, 102876, doi:10.1016/j.earscirev.2019.102876 (2019).
90 Russell, A. J., Carrivick, J. L., Ingeman-Nielsen, T., Yde, J. C. & Williams, M. A new cycle of jökulhlaups at Russell Glacier, Kangerlussuaq, West Greenland. *J Glaciol* **57**, 238-246, doi:10.3189/002214311796405997 (2011).
91 Iturrizaga, L. Historical glacier-dammed lakes and outburst floods in the Karambar valley (Hindukush-Karakoram). *GeoJournal* **62/63**, 1-47 (2005).
92 Liestøl, O. Glacier Dammed Lakes in Norway. *Norsk Geografisk Tidsskrift - Norwegian Journal of Geography* **15**, 122-149, doi:10.1080/00291955608542772 (1956).
93 Ancey, C. *et al.* Hydraulic reconstruction of the 1818 Gitro glacial lake outburst flood. *Water Resour Res* **55**, 8840-8863, doi:10.1029/2019wr025274 (2019).
94 Awal, R. *et al.* Experimental study on glacial lake outburst floods due to waves overtopping and erosion of moraine dam. *Annuals of Disaster Prevention Research Institute, Kyoto University* **53**, 583-594 (2010).
95 Clague, J. J. & Evans, S. G. J. Q. S. R. A review of catastrophic drainage of moraine-dammed lakes in British Columbia. *Quaternary Sci Rev* **19**, 1763-1783, doi:10.1016/S0277-3791(00)00090-1 (2000).
96 Evans, S. G. & Clague, J. J. Recent climatic change and catastrophic geomorphic processes in mountain environments. *Geomorphology* **10**, 107-128, doi:10.1016/0169-555X(94)90011-6 (1994).
97 Maharjan, S. B. *et al. The Status of Glacial Lakes in the Hindu Kush Himalaya - ICIMOD Research Report 2018/1*. (International Centre for Integrated Mountain Development (ICIMOD), 2018).
98 Komori, J., Koike, T., Yamanokuchi, T. & Tshering, P. Glacial lake outburst events in the Bhutan Himalayas. *Global Environmental Research* **16**, 59-70 (2012).
99 Zheng, G. *et al.* Numerous unreported glacial lake outburst floods in the Third Pole revealed by high-resolution satellite data and geomorphological evidence. *Science Bulletin* **66**, 1270-1273, doi:10.1016/j.scib.2021.01.014 (2021).
100 Emmer, A. Vanishing evidence? On the longevity of geomorphic GLOF diagnostic features in the Tropical Andes. *Geomorphology* **422**, 108552, doi:10.1016/j.geomorph.2022.108552 (2023).
101 Emmer, A. *et al.* Progress and challenges in glacial lake outburst flood research (2017–2021): a research community perspective. *Natural Hazards and Earth System Sciences* **22**, 3041-3061, doi:10.5194/nhess-22-3041-2022 (2022).
102 Smellie, J. L. & Edwards, B. R. *Glaciovolcanism on Earth and Mars: Products, Processes and Palaeoenvironmental Significance*. (Cambridge University Press, 2016).
103 Björnsson, H. *et al.* Glacier–volcano interactions deduced by SAR interferometry. *J Glaciol* **47**, 58-70, doi:10.3189/172756501781832520 (2001).
104 Bigelow, D. G. *et al.* The Role of Englacial Hydrology in the Filling and Drainage of an Ice-Dammed Lake, Kaskawulsh Glacier, Yukon, Canada. *Journal of Geophysical Research: Earth Surface* **125**, e2019JF005110, doi:10.1029/2019JF005110 (2020).
105 Huss, M., Bauder, A., Werder, M., Funk, M. & Hock, R. Glacier-dammed lake outburst events of Gornersee, Switzerland. *J Glaciol* **53**, 189-200, doi:10.3189/172756507782202784 (2007).
106 Goodsell, B., Anderson, B., Lawson, W. J. & Owens, I. F. Outburst flooding at Franz Josef Glacier, South Westland, New Zealand. *New Zeal J Geol Geop* **48**, 95-104, doi:10.1080/00288306.2005.9515101 (2005).
107 Wang, S., Qin, D. & Xiao, C. Moraine-dammed lake distribution and outburst flood risk in the Chinese Himalaya. *J Glaciol* **61**, 115-126, doi:10.3189/2015JoG14J097 (2015).
108 Allen, S. K., Zhang, G., Wang, W., Yao, T. & Bolch, T. Potentially dangerous glacial lakes across the Tibetan Plateau revealed using a large-scale automated assessment approach. *Science Bulletin* **64**, 435-445, doi:10.1016/j.scib.2019.03.011 (2019).
109 Dubey, S. & Goyal, M. K. Glacial Lake Outburst Flood Hazard, Downstream Impact, and Risk over the Indian Himalayas. *Water Resour Res* **56**, e2019WR026533, doi:10.1029/2019wr026533 (2020).
110 Rinzin, S. *et al.* GLOF hazard, exposure, vulnerability, and risk assessment of potentially dangerous glacial lakes in the Bhutan Himalaya. *J Hydrol* **619**, 129311, doi:10.1016/j.jhydrol.2023.129311 (2023).
111 Sattar, A. *et al.* Modeling Lake Outburst and Downstream Hazard Assessment of the Lower Barun Glacial Lake, Nepal Himalaya. *J Hydrol* **598**, doi:10.1016/j.jhydrol.2021.126208 (2021).
112 Klimeš, J., Benešová, M., Vilímek, V., Bouška, P. & Cochachin Rapre, A. The reconstruction of a glacial lake outburst flood using HEC-RAS and its significance for future hazard assessments: an example from Lake 513 in the Cordillera Blanca, Peru. *Nat Hazards* **71**, 1617-1638, doi:10.1007/s11069-013-0968-4 (2013).
113 Allen, S. *et al.* (xford Research Encyclopedias: Natural Hazard Science, 2022).

114 Emmer, A. 1-36 (Oxford University Press., 2017).

115 Worni, R. *et al.* Analysis and dynamic modeling of a moraine failure and glacier lake outburst flood at Ventisquero Negro, Patagonian Andes (Argentina). *J Hydrol* **444**, 134-145, doi:10.1016/j.jhydrol.2012.04.013 (2012).

116 Rounce, D. R., McKinney, D. C., Lala, J. M., Byers, A. C. & Watson, C. S. A new remote hazard and risk assessment framework for glacial lakes in the Nepal Himalaya. *Hydrol. Earth Syst. Sci.* **20**, 3455–3475, doi:10.5194/hess-20-3455-2016 (2016).

117 Chen, N. *et al.* Small outbursts into big disasters: Earthquakes exacerbate climate-driven cascade processes of the glacial lakes failure in the Himalayas. *Geomorphology* **422**, 108539, doi:10.1016/j.geomorph.2022.108539 (2023).

118 Mani, P. *et al.* Geomorphic process chains in high-mountain regions – A review and classification approach for natural hazards assessment. *Rev Geophys* **61**, e2022RG000791, doi:10.1029/2022RG000791 (2023).

119 Bajracharya, B., Shrestha, A. B. & Rajbhandari, L. Glacial Lake Outburst Floods in the Sagarmatha Region. *Mt Res Dev* **27**, 336-344, doi:10.1659/mrd.0783 (2007).

120 Schneider, D., Huggel, C., Cochachin, A., Guillén, S. & García, J. Mapping hazards from glacier lake outburst floods based on modelling of process cascades at Lake 513, Carhuaz, Peru. *Adv. Geosci.* **35**, 145-155, doi:10.5194/adgeo-35-145-2014 (2014).

121 Nie, Y., Liu, W., Liu, Q., Hu, X. & Westoby, M. J. Reconstructing the Chongbaxia Tsho glacial lake outburst flood in the Eastern Himalaya: Evolution, process and impacts. *Geomorphology* **370**, 107393, doi:10.1016/j.geomorph.2020.107393 (2020).

122 Mergili, M., Fischer, J.-T., Krenn, J. & Pudasaini, S. P. r.avaflow v1, an advanced open-source computational framework for the propagation and interaction of two-phase mass flows. *Geoscientific Model Development* **10**, 553-569, doi:10.5194/gmd-10-553-2017 (2017).

123 Carrivick, J. L., Manville, V., Graettinger, A. & Cronin, S. J. Coupled fluid dynamics-sediment transport modelling of a Crater Lake break-out lahar: Mt. Ruapehu, New Zealand. *J Hydrol* **388**, 399-413, doi:10.1016/j.jhydrol.2010.05.023 (2010).

124 Staines, K. E. H. & Carrivick, J. L. Geomorphological impact and morphodynamic effects on flow conveyance of the 1999 jökulhlaup at sólheimajökull, Iceland. *Earth Surf Proc Land* **40**, 1401-1416, doi:10.1002/esp.3750 (2015).

125 Worni, R., Huggel, C., Clague, J. J., Schaub, Y. & Stoffel, M. Coupling glacial lake impact, dam breach, and flood processes: A modeling perspective. *Geomorphology* **224**, 161-176, doi:10.1016/j.geomorph.2014.06.031 (2014).

126 Harrison, S. *et al.* Climate change and the global pattern of moraine-dammed glacial lake outburst floods. *The Cryosphere* **12**, 1195–1209, doi:10.5194/tc-12-1195-2018 (2018).

127 Veh, G., Korup, O., von Specht, S., Roessner, S. & Walz, A. Unchanged frequency of moraine-dammed glacial lake outburst floods in the Himalaya. *Nature Climate Change*, doi:10.1038/s41558-019-0437-5 (2019).

128 Linsbauer, A., Paul, F. & Haeberli, W. Modeling glacier thickness distribution and bed topography over entire mountain ranges with GlabTop: Application of a fast and robust approach. *J Geophys Res* **117**, F03007, doi:10.1029/2011JF002313 (2012).

129 Haeberli, W. *et al.* New lakes in deglaciating high-mountain regions – opportunities and risks. *Climatic Change* **139**, 201-214, doi:10.1007/s10584-016-1771-5 (2016).

130 King, O., Bhattacharya, A., Bhambri, R. & Bolch, T. Glacial lakes exacerbate Himalayan glacier mass loss. *Sci Rep* **9**, 18145, doi:10.1038/s41598-019-53733-x (2019).

131 Sutherland, J. L. *et al.* Proglacial lakes control glacier geometry and behavior during recession. *Geophys Res Lett* **47**, e2020GL088865, doi:10.1029/2020gl088865 (2020).

132 Khan, G. *et al.* Expansion of Shishper Glacier lake and recent glacier lake outburst flood (GLOF), Gilgit-Baltistan, Pakistan. *Environ Sci Pollut R* **28**, 20290-20298, doi:10.1007/s11356-020-11929-z (2021).

133 Hewitt, K. & Liu, J. Ice-Dammed Lakes and Outburst Floods, Karakoram Himalaya: Historical Perspectives on Emerging Threats. *Phys Geogr* **31**, 528-551, doi:10.2747/0272-3646.31.6.528 (2010).

134 Millan, R., Mouginot, J., Rabatel, A. & Morlighem, M. Ice velocity and thickness of the world's glaciers. *Nature Geoscience*, doi:10.1038/s41561-021-00885-z (2022).

135 Furian, W., Loibl, D. & Schneider, C. Future glacial lakes in High Mountain Asia: an inventory and assessment of hazard potential from surrounding slopes. *J Glaciol* **67**, 653–670, doi:10.1017/jog.2021.18 (2021).

136 Frey, H., Haeberli, W., Linsbauer, A., Huggel, C. & Paul, F. A multi-level strategy for anticipating future glacier lake formation and associated hazard potentials. *Nat. Hazards Earth Syst. Sci.* **10**, 339-352, doi:10.5194/nhess-10-339-2010 (2010).

137 Maussion, F. *et al.* The Open Global Glacier Model (OGGM) v1.1. *Geosci. Model Dev.* **12**, 909-931, doi:10.5194/gmd-12-909-2019 (2019).

138 Kraaijenbrink, P. D. A., Bierkens, M. F. P., Lutz, A. F. & Immerzeel, W. W. Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers. *Nature* **549**, 257–260, doi:10.1038/nature23878 (2017).

139 Gharehchahi, S. *et al.* Glacier Ice Thickness Estimation and Future Lake Formation in Swiss Southwestern Alps—The Upper Rhône Catchment: A VOLTA Application. *Remote Sensing* **12**, 3443, doi:10.3390/rs12203443 (2020).

140 Otto, J. C., Helfricht, K., Prasicek, G., Binder, D. & Keuschnig, M. Testing the performance of ice thickness models to estimate the formation of potential future glacial lakes in Austria. *Earth Surf Proc Land*, doi:10.1002/esp.5266 (2021).

141 Viani, C. *et al.* Potential future lakes from continued glacier shrinkage in the Aosta Valley Region (Western Alps, Italy). *Geomorphology* **355**, 107068, doi:10.1016/j.geomorph.2020.107068 (2020).

142 Viani, C., Giardino, M., HuGgel, C., Perotti, L. & Mortara, G. An overview of glacier lakes in the Western Italian Alps from 1927 to 2014 based on multiple data sources (historical maps, orthophotos and reports of the glaciological surveys). *Geografia Fisica e Dinamica Quaternaria* **39**, 203-214, doi:10.4461/GFDQ.2016.39.19 (2016).

143 Magnin, F., Haeberli, W., Linsbauer, A., Deline, P. & Ravanel, L. Estimating glacier-bed overdeepenings as possible sites of future lakes in the de-glaciating Mont Blanc massif (Western European Alps). *Geomorphology* **350**, 106913, doi:10.1016/j.geomorph.2019.106913 (2020).

144 Drenkhan, F., Guardamino, L., Huggel, C. & Frey, H. Current and future glacier and lake assessment in the deglaciating Vilcanota-Urubamba basin, Peruvian Andes. *Global Planet Change* **169**, 105-118, doi:10.1016/j.gloplacha.2018.07.005 (2018).

145 Colonia, D. *et al.* Compiling an Inventory of Glacier-Bed Overdeepenings and Potential New Lakes in De-Glaciating Areas of the Peruvian Andes: Approach, First Results, and Perspectives for Adaptation to Climate Change. *Water* **9**, 336, doi:10.3390/w9050336 (2017).

146 Zhang, T. *et al.* Warming-driven erosion and sediment transport in cold regions. *Nature Reviews Earth & Environment* **3**, 832–851, doi:10.1038/s43017-022-00362-0 (2022).

147 Azam, M. F. *et al.* Review of the status and mass changes of Himalayan-Karakoram glaciers. *J Glaciol* **64**, 61-74, doi:10.1017/jog.2017.86 (2018).

148 Haeberli, W., Schaub, Y. & Huggel, C. Increasing risks related to landslides from degrading permafrost into new lakes in de-glaciating mountain ranges. *Geomorphology* **293**, 405-417, doi:10.1016/j.geomorph.2016.02.009 (2017).

149 Schwanghart, W., Worni, R., Huggel, C., Stoffel, M. & Korup, O. Uncertainty in the Himalayan energy–water nexus: estimating regional exposure to glacial lake outburst floods. *Environmental Research Letters* **11**, doi:10.1088/1748-9326/11/7/074005 (2016).

150 Mal, S., Allen, S. K., Frey, H., Huggel, C. & Dimri, A. P. Sectorwise Assessment of Glacial Lake Outburst Flood Danger in the Indian Himalayan Region. *Mt Res Dev* **41**, doi:10.1659/mrd-journal-d-20-00043.1 (2021).

151 Allen, S. K. *et al.* Glacial lake outburst flood hazard under current and future conditions: worst-case scenarios in a transboundary Himalayan basin. *Nat. Hazards Earth Syst. Sci.* **22**, 3765-3785, doi:10.5194/nhess-22-3765-2022 (2022).

152 Nie, Y. *et al.* Glacial change and hydrological implications in the Himalaya and Karakoram. *Nature Reviews Earth & Environment* **2**, 91-106, doi:10.1038/s43017-020-00124-w (2021).

153 Li, D. *et al.* High Mountain Asia hydropower systems threatened by climate-driven landscape instability. *Nature Geoscience*, doi:10.1038/s41561-022-00953-y (2022).

154 Tiberti, R. *et al.* Food Web Complexity of High Mountain Lakes is Largely Affected by Glacial Retreat. *Ecosystems* **23**, 1093-1106, doi:10.1007/s10021-019-00457-8 (2020).

155 Allen, S. K. *et al.* Glacial lake outburst flood risk in Himachal Pradesh, India: an integrative and anticipatory approach considering current and future threats. *Nat Hazards* **84**, 1741-1763, doi:10.1007/s11069-016-2511-x (2016).

156 Farinotti, D. *et al.* How accurate are estimates of glacier ice thickness? Results from ITMIX, the Ice Thickness Models Intercomparison eXperiment. *The Cryosphere* **11**, 949-970, doi:10.5194/tc-11-949-2017 (2017).

157 Carrivick, J. L., Davies, B. J., James, W. H. M., Quincey, D. J. & Glasser, N. F. Distributed ice thickness and glacier volume in southern South America. *Global Planet Change* **146**, 122-132, doi:10.1016/j.gloplacha.2016.09.010 (2016).

158 Carrivick, J. L., Davies, B. J., James, W. H. M., McMillan, M. & Glasser, N. F. A comparison of modelled ice thickness and volume across the entire Antarctic Peninsula region. *Geografiska Annaler: Series A, Physical Geography* **101**, 45-67, doi:10.1080/04353676.2018.1539830 (2019).

159 Li, F. *et al.* Influence of glacier inventories on ice thickness estimates and future glacier change projections in the Tian Shan range, Central Asia. *J Glaciol* **69**, 266-280, doi:10.1017/jog.2022.60 (2023).

160 Chen, W. *et al.* Towards ice-thickness inversion: an evaluation of global digital elevation models (DEMs) in the glacierized Tibetan Plateau. *The Cryosphere* **16**, 197-218, doi:10.5194/tc-16-197-2022 (2022).

161 Moreira, A. *et al.* Tandem-L: A Highly Innovative Bistatic SAR Mission for Global Observation of Dynamic Processes on the Earth's Surface. *IEEE Geoscience and Remote Sensing Magazine* **3**, 8-23, doi:10.1109/MGRS.2015.2437353 (2015).

162 Banda, F., Dall, J. & Tebaldini, S. Single and Multipolarimetric P-Band SAR Tomography of Subsurface Ice Structure. *Ieee T Geosci Remote* **54**, 2832-2845, doi:10.1109/TGRS.2015.2506399 (2016).

163 Huggel, C. *et al.* Glacier Lake 513, Peru: Lessons for early warning service development. *WMO BULLETIN* **69**, 45-52 (2020).

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Author contributions

G.Z. and J.C. conceptualized the Review and coordinated inputs. D.S. and C.L. contributed the Introduction. A.E., M.M. and N.M. contributed the section on global and regional glacial lake changes. G.V., J.C., S.S. and N.L. contributed the section on global and regional historical GLOF events. G.Z., M.H. and S.A. contributed the section on future glacial lakes and impacts. G.Z., S.A., and J.C. contributed the section on summary and perspectives. X.W. contributed to some of the figures. G.Z. and J.C. led the writing, and all authors reviewed and edited the manuscript before submission.

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The authors declare no competing interests.

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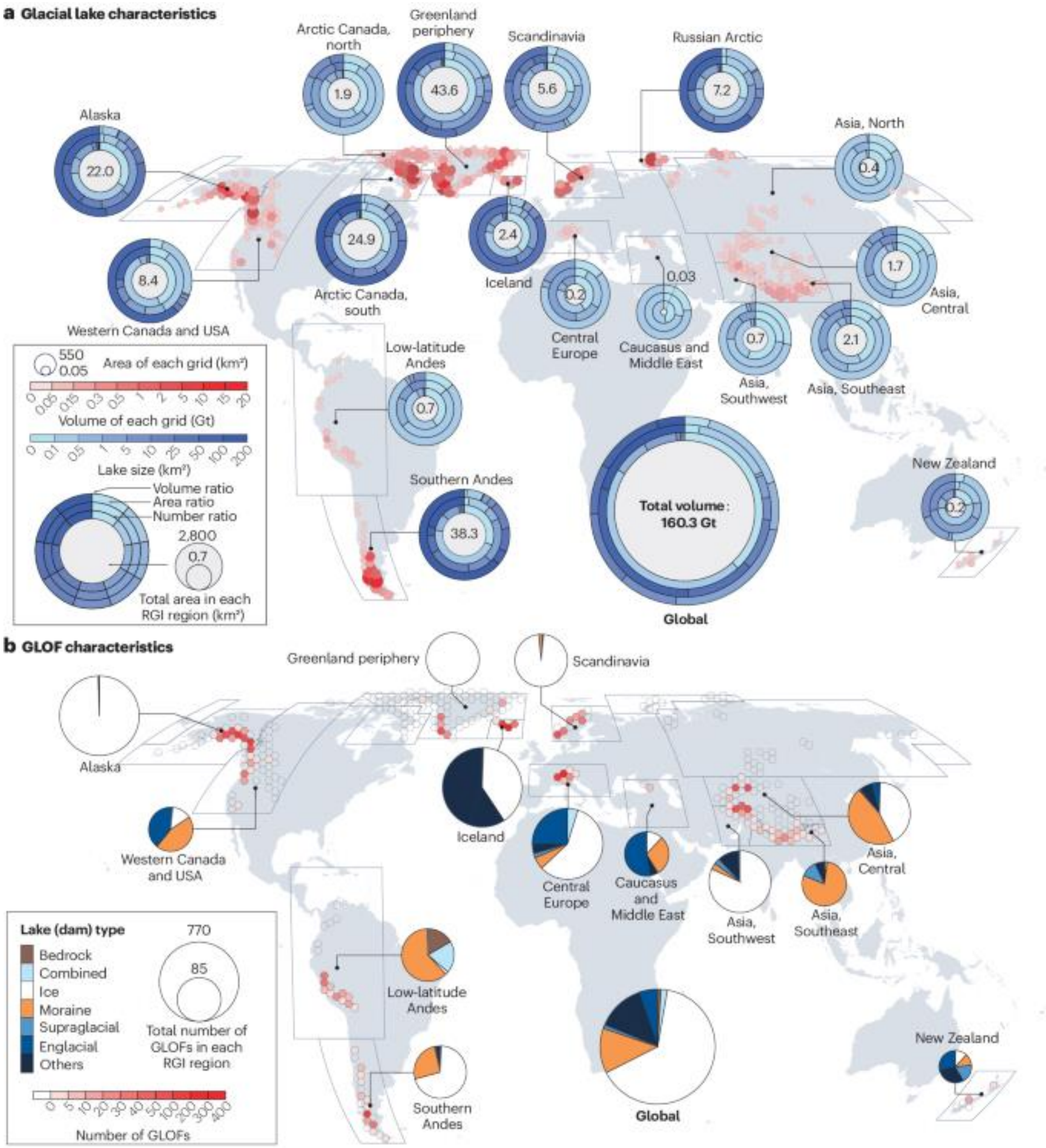

Fig. 1 | Global distribution of glacial lakes and historical GLOFs. a, Area and volume of present-day (~2018) glacial lakes within 1 km of glaciers, aggregated over 220 km hexagon grid cells[9] (red shades), and regional statistics of lake volume, area and number according to GTN-G glacier regions of the Randolph Glacier Inventory (RGI) [55] (donut plots); outer, middle and inner circles indicate the total volume, area and number percentage of glacial lakes in a given size interval, respectively, with the total lake area in each region in the center of the circle. Two RGI subregions (Svalbard and Jan Mayen, Antarctic and Subantarctic) are not included as they are not part of the underlying global glacial lake dataset [9]. **b**, The global distribution of historical GLOFs aggregated over 220 km hexagon grid cells (red shading), and regional break down of GLOF number by glacial lake (dam) types [26] (pie charts). Some RGI subregions are not presented as they are not covered by the global

GLOF inventory [26]. The global distribution of glacial lakes and historical GLOFs would help to understand the regional differences in the number, area and volume, and types of GLOFs

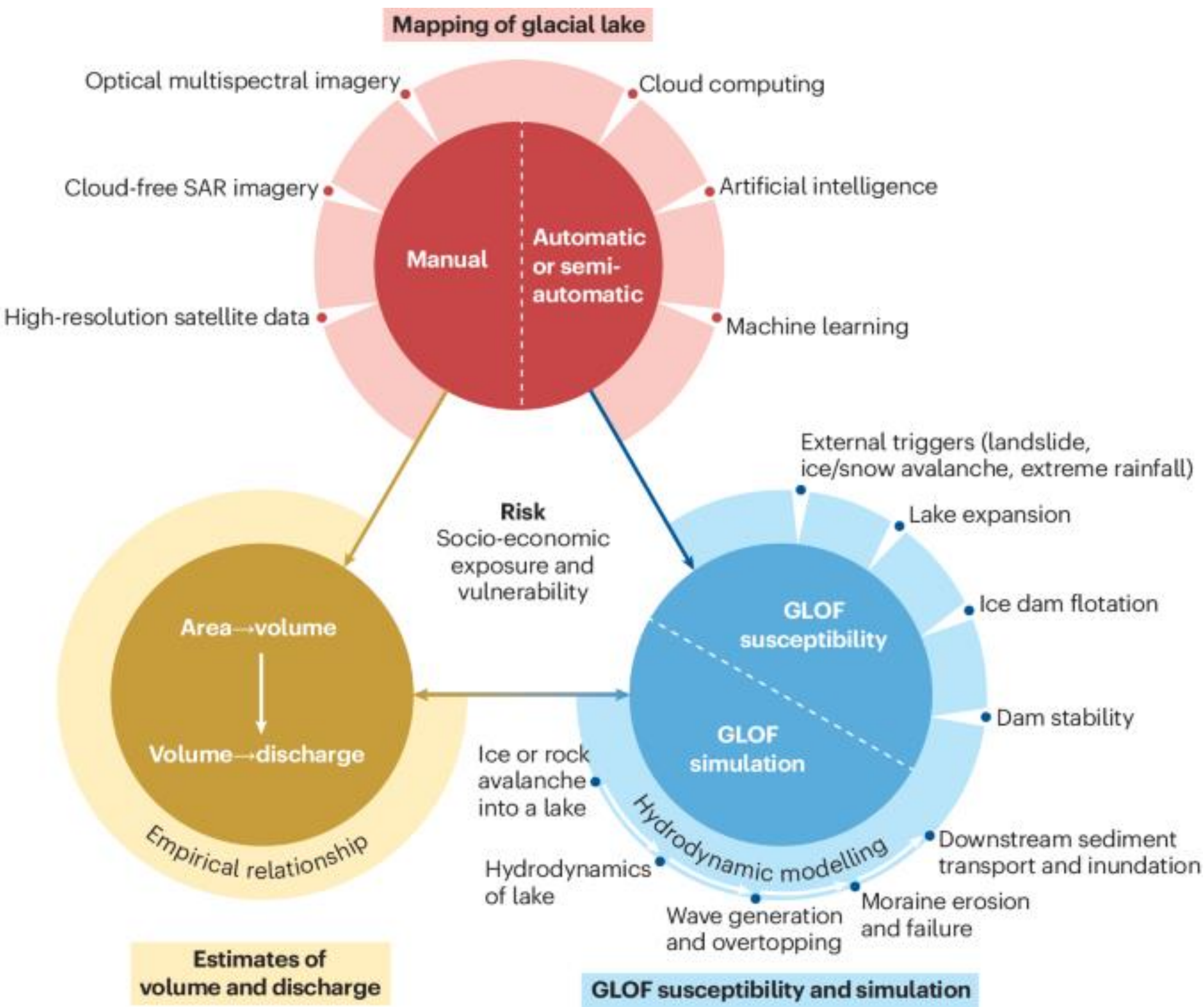

Fig. 2 | Methodology for quantifying glacial lake changes and impacts. Methods to map glacial lakes (red), estimate lake volume and peak (yellow) and assess GLOF susceptibility and simulation (blue). Glacial lake mapping, estimates of GLOF susceptibility, volume and peak discharge, and hydrodynamic simulations provide important baseline integrated data for GLOF hazard assessment.

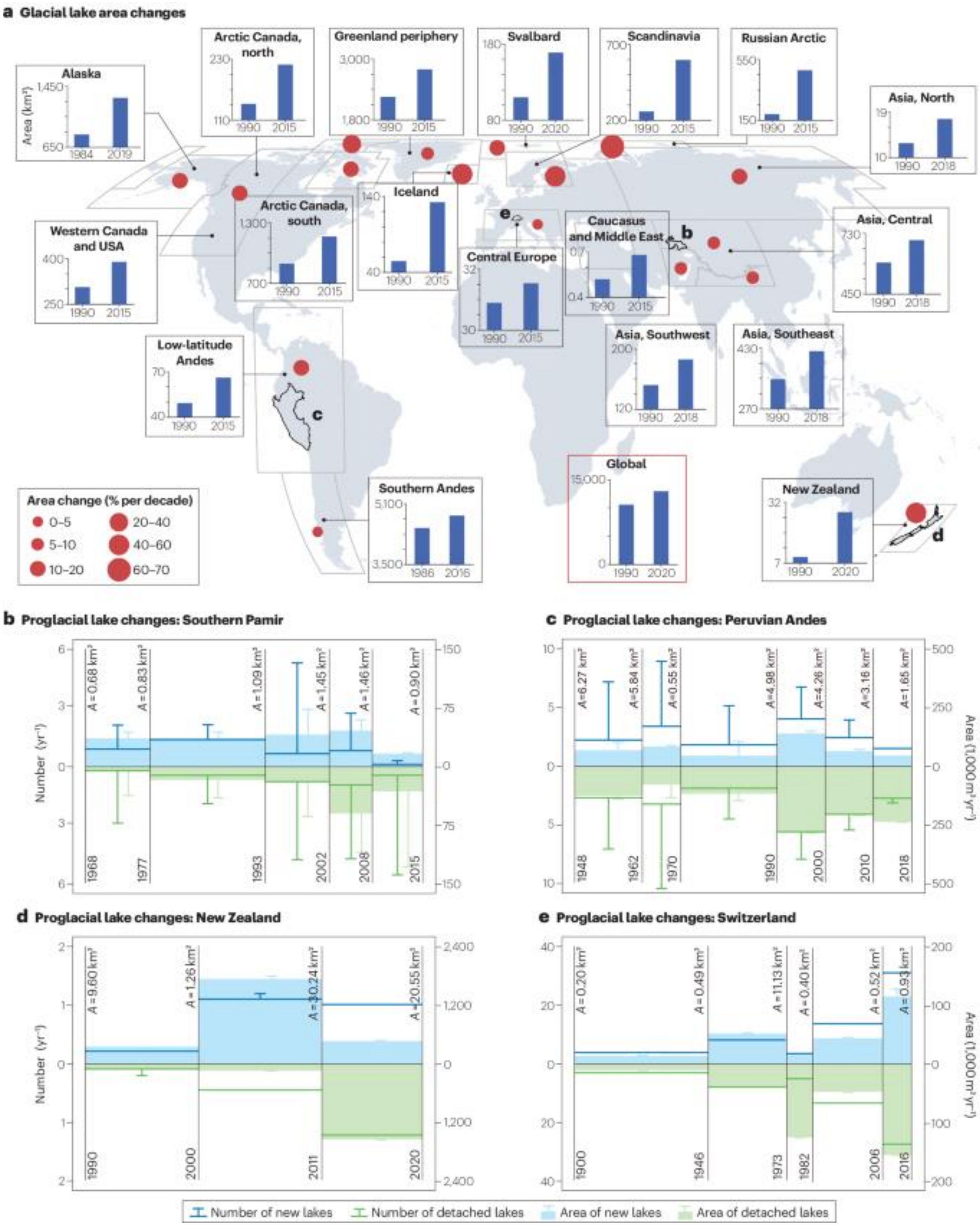

Fig. 3 | **Global and regional changes in glacial lake area**. **a**, Absolute regional lake area in ~1990 and ~2020 (bars) and the percentage changes from 1990-2020 (red circles) (Supplementary Table 2). The data available in the start year close to 1990 and the end year close to 2020 were selected with several year spans as the limited data available. **b,** changes in the number (dark blue line) and area (light blue bar) of new lakes, and the

number (dark green line) and area (light green bar) of detached proglacial lakes in Southern Pamir[72] (see panel a for location). The spans in the different time blocks are shown as the limited data available. Error bars indicate uncertainties and inaccuracies owing to low image resolution or quality, or the use of images from different years for the same time step. **c,** As in b, but for the Peruvian Andes [73]. **d**, As in b, but for New Zealand [74]. **e**, As in b, but for Switzerland [59]. Global patterns of glacial lake change show that glacial lakes have expanded worldwide, especially for proglacial lakes

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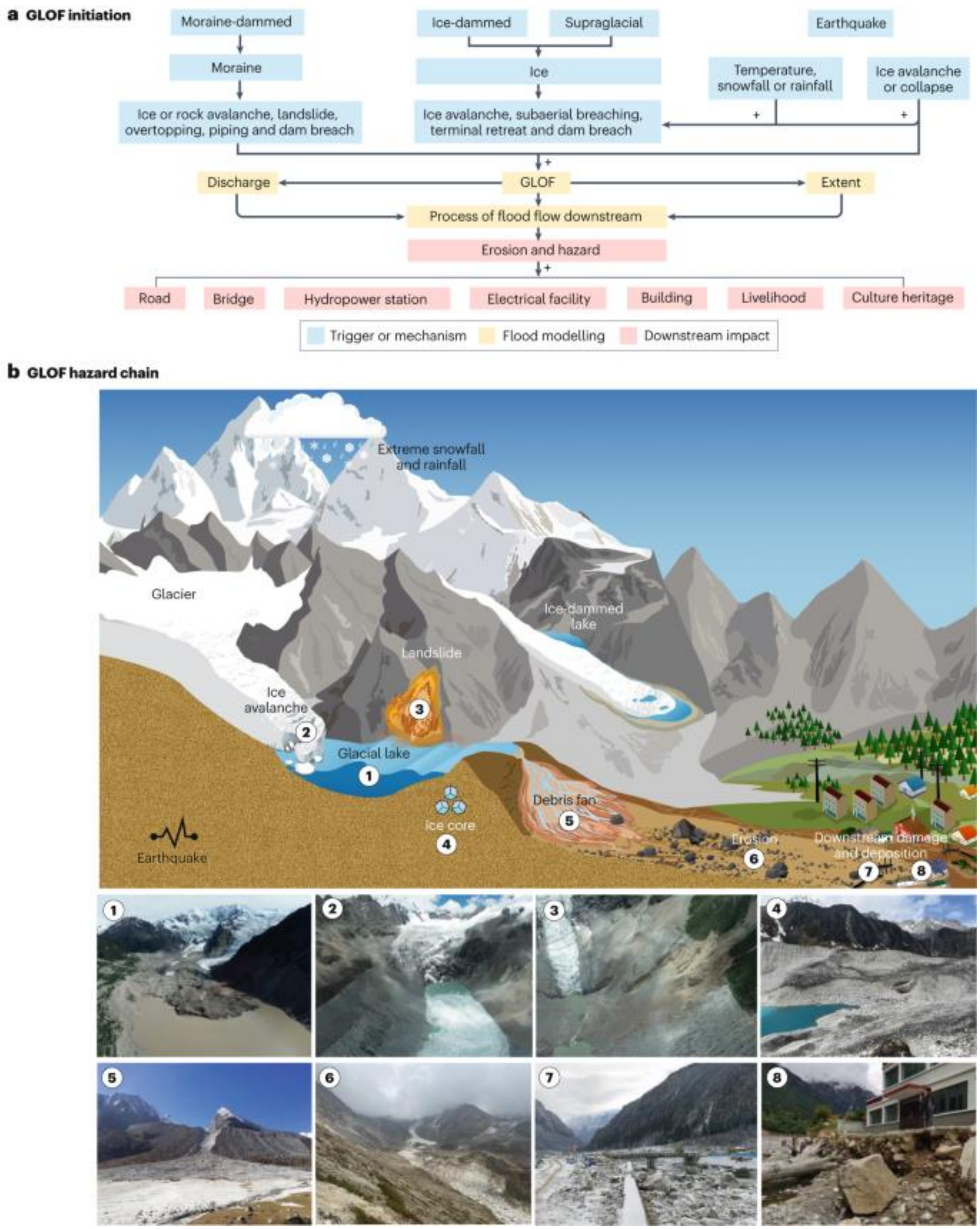

Fig. 4 | The triggers and mechanisms of GLOFs. a, Flowchart indicating the process of a GLOF, from trigger of mechanisms (blue), flood modelling (yellow), to downstream impact (red). **b**, Schematic diagram and corresponding photos (1-8) of the hazard chain, from triggering factors to glacial lake outburst, downstream impacts and damage). Understanding the triggers and mechanisms of GLOFs and flood modelling practices can improve hazard mitigation.

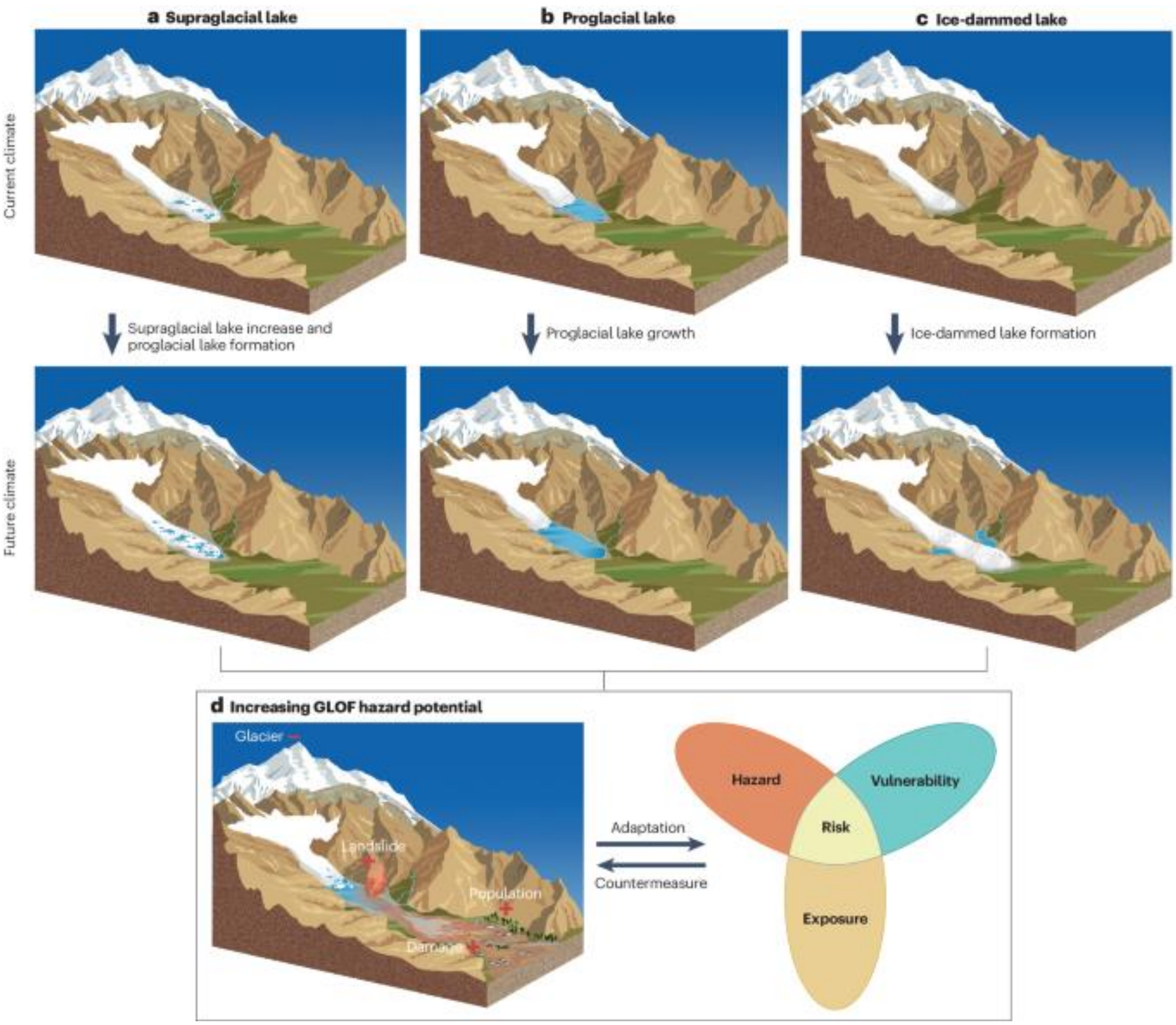

Fig. 5 Future formation and growth of glacial lakes and GLOF hazard. Future development of supraglacial, proglacial and ice-dammed lakes (top 2 rows), their corresponding impact on GLOF occurrence (bottom left) and potential change in GLOF hazard (bottom right). The life cycle of different types of glacial lakes shifts in a warming climate

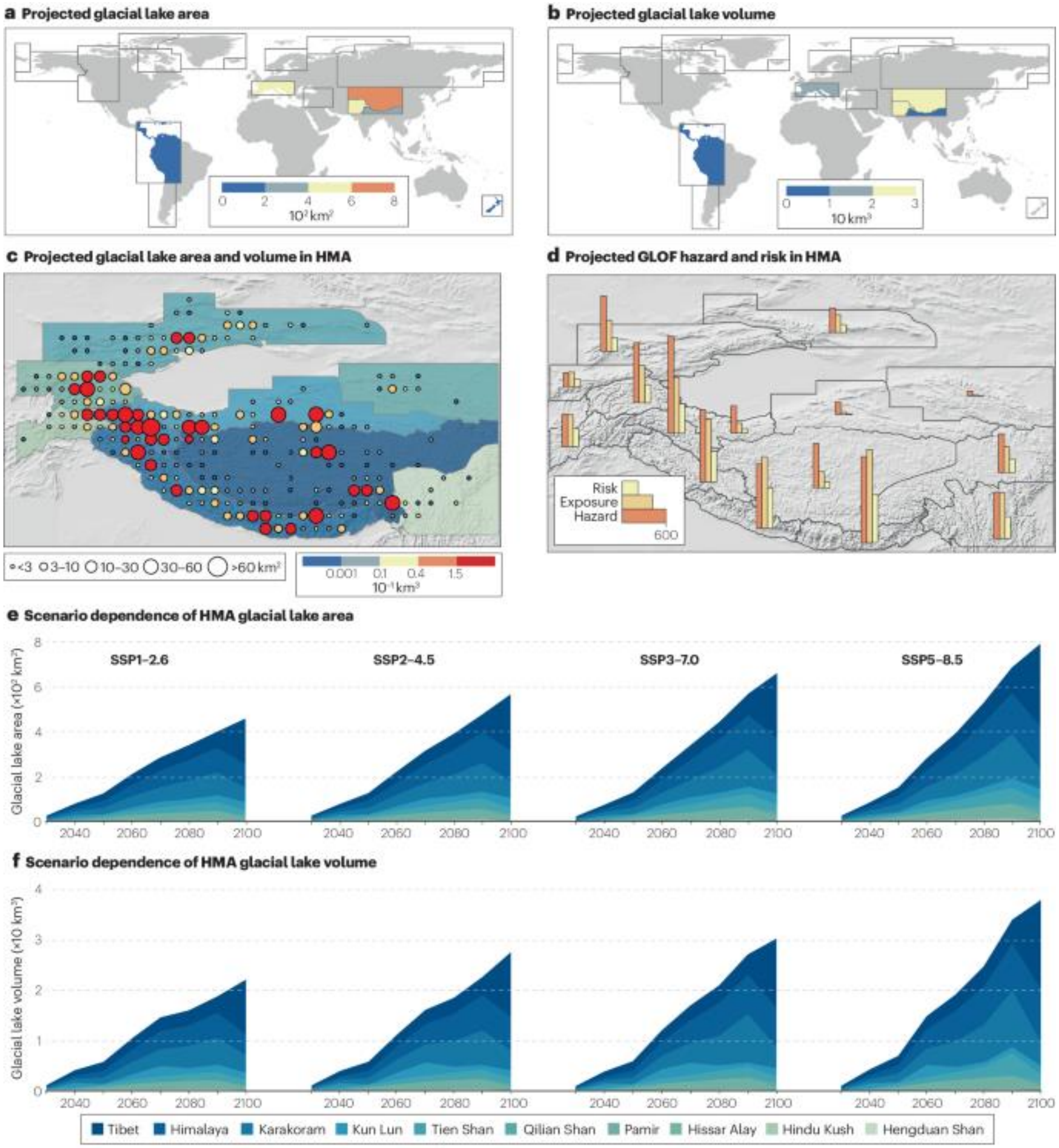

Fig. 6 | Global potential future glacial lakes and GLOF hazard. **a** | Published estimates of potential future glacial lake area by deglaciation (Supplementary Table 4). **b**, As in a, but for potential future glacial lake volume by deglaciation. **c** | Potential future glacial lake area (circles) and volume (shading) in HMA by 2100 under RCP 8.5 (ref [24]). Background shading depicts drainage basins using the colours in panels e and f. **d**, Future GLOF risk (light shading), exposure (medium shading) and hazard (dark shading) in HMA by 2100 under RCP 8.5 (ref [24]). Physical or social vulnerability is not considered. **e**, Time series of potential future glacial lake area in HMA under different SSPs, with shading representing different subregions[21]. **f**, As in e, but for lake volume. Projected global glacial lakes will increase globally by 2100 under different emission scenarios, posing a potential hazard threat to downstream communities