# The rise of GLOF danger: trends, drivers and hotspots between 2000 and 2020

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## Abstract

Between 2000 and 2020, the potential for glacial lake outburst floods (GLOFs) and the exposure and vulnerability of downstream populations to them, have changed across the globe. The impact of these changes on the danger posed by GLOFs, as well as the relative importance of each factor, remains contentious, making the implementation of appropriate management and risk reduction strategies challenging. Here we show that globally, since 2000, the number of people exposed to GLOF impacts has increased by 3.2 million (27% increase), to a total of 15 million people as of 2020. The largest increase in GLOF danger occurred across the Andes, while only nine countries experienced a decrease in GLOF danger, most notably in Nepal and Kyrgyzstan. Importantly, contrary to the notion presented in current research, we find the changes in the threat from GLOFs have not been universally driven by either lake change, exposed population, or vulnerability; instead, the primary driver varies both at regional- and national-scales. Further, we show that vulnerability to GLOF impacts has declined almost everywhere, but this decline has been insufficient to offset the combined growth in the number and area of glacial lakes and downstream exposure. We highlight the Andes as a global hotspot for high, and rapidly increasing, contemporary GLOF danger, and suggest the region be targeted for further research. Critically, we show that mitigating GLOF impacts will require bespoke solutions depending on the relative impact of lake conditions, exposure and vulnerability on changing GLOF danger.

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# The rise of GLOF danger: trends, drivers and hotspots between 2000 and 2020.

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**Key Points:**

1. Drivers of outburst danger vary globally, with population exposure being a key driver of danger in High Mountain Asia.
2. Increasing GLOF hazard does not equate to increasing danger and decreases in vulnerability have dampened rising exposure and hazard.
3. Danger in the Andes has increased rapidly, making this a particular area of global concern.

## Abstract

Between 2000 and 2020, the potential for glacial lake outburst floods (GLOFs) and the exposure and vulnerability of downstream populations to them, have changed across the globe. The impact of these changes on the danger posed by GLOFs, as well as the relative importance of each factor, remains contentious, making the implementation of appropriate management and risk reduction strategies challenging. Here we show that globally, since 2000, the number of people exposed to GLOF impacts has increased by 3.2 million (27% increase), to a total of 15 million people as of 2020. The largest increase in GLOF danger occurred across the Andes, while only nine countries experienced a decrease in GLOF danger, most notably in Nepal and Kyrgyzstan. Importantly, contrary to the notion presented in current research, we find the changes in the threat from GLOFs have not been universally driven by either lake change, exposed population, or vulnerability; instead, the primary driver varies both at regional- and national-scales. Further, we show that vulnerability to GLOF impacts has declined almost everywhere, but this decline has been insufficient to offset the combined growth in the number and area of glacial lakes and downstream exposure. We highlight the Andes as a global hotspot for high, and rapidly increasing, contemporary GLOF danger, and suggest the region be targeted for further research. Critically, we show that mitigating GLOF impacts will require bespoke solutions depending on the relative impact of lake conditions, exposure and vulnerability on changing GLOF danger.

## Plain Language Summary

Glacial lake outburst floods (GLOF) are  a major contemporary hazard faced by millions of people worldwide. As glacial lakes and populations downstream change and grow, hazard, exposure and vulnerability to GLOFs will all change, ultimately impacting overall danger from GLOFs. Despite their potential social and economic impacts, it remains unclear how

GLOF danger has changed over recent decades, and more importantly, what is responsible for driving these changes. This study quantifies GLOF danger over the last two decades globally and then identifies key drivers of changes in this danger at global to local scales. We find that the number and area of glacial lakes and the downstream population have increased globally, but vulnerability to GLOFs has declined almost everywhere. However, this decrease in vulnerability has not been enough to offset growth of lakes and population, meaning GLOF danger has got worse. While all of the main mountain ranges have seen an increase in GLOF danger, the Andes have experienced the largest increase. Nevertheless, the factors driving these increases vary across the globe, meaning there is no single approach to reduce danger, which instead requires more bespoke approaches at the regional, national, and local scale.

## 1 Introduction

Glacial lakes are rapidly increasing in both size and number, due to climate driven ice loss and represent both an important resource in mountain regions and a major natural hazard (Dubey & Goyal, 2020; Shugar et al., 2020). Specifically, glacial lakes can fail and generate glacial lake outburst floods (GLOFs), where water and sediment are suddenly released downstream (Begam & Sen, 2019). GLOFs can be highly destructive and arrive with little prior warning, causing significant damage to residential and commercial infrastructure and agricultural land as well as resulting in extensive loss of life and livestock (Emmer et al., 2020; Zheng et al., 2021). In the last 70 years, the largest estimates suggest as many as 30,000 people have been killed by GLOFs in the Cordillera Blanca alone (Carey, 2008; Emmer et al., 2020).

The risk posed by GLOFs to downstream communities depends on a complex interplay between hazard (the probability and intensity of a GLOF based on characteristics of both the glacial lake and surrounding environment), exposure (the proximity of people to potential outburst inundation limits) and vulnerability (the exposed populations likelihood to be impacted) (IPCC, 2019; Wisner et al., 2004). Since 1990, the number, area and volume of glacial lakes globally has increased rapidly (Shugar et al., 2020) and, at the same time, many glacial catchments have experienced rapid population growth, infrastructural development and implementation of hydroelectric schemes, as well as an increasing intensification of agriculture (Allen et al., 2019; Immerzeel et al., 2020; Wester et al., 2019). Concurrent with these changes, socio-economic vulnerability to climate-related hazards is thought to have decreased (Formetta & Feyen, 2019) due in part to the success of the Millennium Development Goals (MDGs; 2000-2015) and the succeeding Sustainable Development Goals (SDGs; 2015-2030) (Vorisek & Yu, 2020). A recent study (Taylor et al., 2023) highlighted the importance of including exposure and vulnerability alongside hazard in GLOF assessments. However, the relative impact of changes to these factors on the total global threat from GLOFs remains unclear. If current and future GLOF danger is to be effectively managed we urgently need a better understanding of the past and present trajectory of global GLOF danger (Zheng et al., 2021). Furthermore, there is a critical need to establish which factor(s) is responsible for driving changes in GLOF danger at regional, national and local scales, in order to better direct mitigation efforts and ultimately save lives and reduce impacts. This becomes particularly important for transboundary GLOF hazard management, where the same hazard from a single lake can cross borders that separate populations with very different vulnerabilities.

Here, we assess how glacial lake conditions, population exposure and vulnerability have changed at a global, regional, and local scale over the past 20 years (2000-2020). We combine this information to quantify the change in GLOF danger over the same period. The rates of change in each factor (glacial lake conditions, exposure, vulnerability and danger) are then compared to establish the primary driver(s) of changing GLOF danger thus identifying targeted options for future mitigation of GLOFs impacts on a location-specific basis. Finally, we highlight regions of current high GLOF danger and areas with a past trajectory of rapidly increasing GLOF danger, to objectively identify priority locations for future research.

## 2 Methods

We apply and adapt the approach of Taylor et al (2023) to quantify and rank the glacial lake conditions, population exposure, vulnerability, and resulting danger from GLOFs globally. We repeat these analyses at 5 yearly timesteps: 2000, 2005, 2010, 2015, 2020, allowing us to calculate both contemporary values and trends since 2000. We evaluate our results at both the national-scale and mountain range scale, considering the four main mountain ranges (European Alps, Andes, High Mountains Asia (HMA) and Pacific Northwest (PNW)), with lakes outside these ranges being combined into a single region we term High Arctic and Outlying Countries.

We calculate GLOF danger as opposed to GLOF risk because estimating the probability of GLOF occurrence from glacial lakes at a global scale is fraught. Previous approaches have sought to infer the likelihood of failure using metrics based on surrounding topography, assuming landslides and ice avalanches are the most likely GLOF trigger (Furian et al 2021, Zheng et al 2021). However, GLOF triggers are multiple and complex (Dubey and Goyal 2020, Allen et al 2017), and the quality of global DEMs in the regions where glacial lakes are present is highly variable (Bolch and Loibl 2017). Consequently, we choose to instead focus on the changing glacial lake conditions, i.e. the number and area of glacial lakes present, as a proxy for potential GLOF intensity, with more and larger lakes representing a larger potential intensity. The lack of probability in our calculations means we prefer the terminology 'lake conditions' instead of 'hazard' and 'GLOF danger' instead of 'GLOF risk'. Nevertheless, our approach is intended to be adaptable to facilitate future inclusion of probability into the lake conditions calculation allowing GLOF hazard and thus GLOF risk to be calculated.

### 2.1 Glacial lake conditions

Following the approach of Taylor et al (2023), we use measurable changes in the number and area of glacial lakes from the Cooperative Institute for Research and Environmental Sciences (CIRES) National Snow and Ice Data Centre to provide a proxy for GLOF intensity between 2000 and 2020, given at 5 yearly static intervals. Scores attributed to each static period are given as the average scores of the preceding five years, e.g. 2005 is the average of scores in 2001, 2002, 2003, 2004, and 2005. We use a linear transformation function to produce a normalised value for both lake number and area **(Equation 1)**;

$$y_{N/A} = \frac{(\mathrm{X-Min})}{(\mathrm{Max-Min})} \tag{1}$$

where *x* is the absolute number/area of glacial lakes per catchment, *Min* is the minimum non-zero number/area of glacial lakes globally, *Max* is the maximum number/area of glacial lakes globally, and *y* is the normalised value of glacial lake number/area. Individual normalized values of glacial lake number ($y_N$) and area ($y_A$) are then multiplied to produce a singular score between 0 and 1, with 1 relating to the glacial lake conditions likely to produce the highest intensity GLOFs. No scores of absolute 0 were recorded in any location during any epoch.

### 2.2 Exposure

Runout distances of GLOFs primarily vary as a function of outburst volume and stream gradient, as well as other factors such as bed roughness, sediment concentration etc. (Westoby et al., 2015). Thus, defining a universal runout distance or reach angle to assess population exposure at a global scale is difficult. Previous research (Dubey & Goyal, 2020;

Taylor et al., 2023) set a runout cut-off distance of 50 km, to facilitate a standardized comparison between glacial lakes. A 50 km threshold is consistent with a number of observed runout distances of past GLOFs, such as at Dig Tsho in 1985 (Watson et al., 2015), Chilleon Valley in 2015 (Wilson et al., 2019) and Chorabari in 2014 (Rafiq et al., 2019). Comparisons of likely GLOF discharges with that of meteorological floods (Cook et al., 2018) suggest the majority (50%) of likely GLOFs that exceed the 100-year meteorological flood discharge do so to only ~20 km downstream, with 1% theoretically reaching >85 km (Schwanghart et al., 2016). Consequently, although we recognise runout distances vary considerably, with some GLOF events showing runout length >200 km (Richardson & Reynolds, 2000), considering such distances at a global scale could lead to the overestimations of downstream exposure (Dubey & Goyal, 2020). Following the approach of Dubey and Goyal (2020) and Taylor et al (2023), we consider a maximum runout distance of 50 km, which should encapsulate the majority of runouts globally, whilst avoiding overestimations by excluding major outliers.

Given GLOF runout pathways tend to follow river channels (Carrivick & Tweed, 2016; Veh et al., 2019) exposure increases with proximity to the channel (Takenaka et al., 2012). Following previous approaches (Veh, 2019), we further constrain our exposed populations by applying a 1 km buffer either side of any main river channel (level 1 channel (Yan et al., 2019)) with a glacial lake in its upper reaches up to a distance of 50 km, and used the 2000-2020 Gridded Population of the World version 4 (GPWv4) (CIESIN, 2018) at 5 yearly static intervals to sum the population count per 1 $km^2$ cell within this buffer to obtain exposed population **(Fig. S1).** We recognise that a 1 km buffer is a crude estimate for identifying potential GLOF impact zones; exposed population is likely overestimated in the upper reaches where steeper elevations and narrow river valleys likely mean populations within even 100 m of a river channel may in fact be far above the inundated zone on terraces and hillslopes, whilst in the lower reaches where valleys are flatter and wider, the population is likely underestimated. However, as the overall impact of a GLOF wanes with distance from the river channel (Takenaka et al., 2012; Veh, 2019), and given the 1 $km^2$ resolution of the population data used (CIESIN, 2018), we suggest at a global scale a 1 km buffer will provide a conservative but consistent estimate of the potentially exposed population. Our results therefore provide a global scale indictor of areas of high and/or increasing GLOF danger, which can then be targeted for further, more detailed analysis using more complex GLOF runout modelling and higher resolution population data (often only available on a patchy regional or catchment scale) to refine our initial estimates.

Once the total exposed population has been calculated for each region and country, we use the same linear transformation function as **Equation 1,** using $y_E$ (where $E$ is exposed population) to produce a normalised exposure score for each region/country.

### 2.3 Vulnerability

Many factors influence human vulnerability to natural hazards (**Table S1**) and yet, due in part to the absence of sufficient data, few studies have considered the temporal trend in vulnerability (Huggel et al., 2015). Since the implementation of the MDGs and succeeding SDGs, there has been a vast improvement in the amount, and quality, of vulnerability data available. Here, following the approach of Taylor et al (2023), we combine qualitative information obtained from the Corruption Perception Index (CPI) and Human Development Index (HDI) with a Social Vulnerability Index (SVI) to provide a proxy for GLOF vulnerability. At a global scale, corruption and human development are indicative of population fragility (Ambraseys & Bilham, 2011; Lewis, 2017) with higher levels of corruption and lower levels of development individually associated with larger impacts.

The CPI scores and ranks countries/territories based on how corrupt a country's public sector is perceived to be by experts and business executives. It is a composite index comprised through 13 data sources and is the most widely used indicator of corruption worldwide. Launched two years after Transparency International was first established, CPI data is available annually since 1995.

The HDI is available at sub-national (first administrative unit, e.g. State) level and is a summary measure of three key dimensions of human development: health, education, and standard of living (UNDP, 2020), comprised of normalised indices of: life expectancy, expected years of schooling, mean years of school and Gross National Income (GNI) per capita. The HDI has been successfully used in previous GLOF risk assessments in the Andes (Drenkhan et al., 2019). HDI data can be obtained annually from 1990.

While both the CPI and HDI provide a useful metric for assessing development of a country/territory they do not reflect on many factors that influence social vulnerability (Cutter et al., 2003). Thus, to assess the coping capacity of downstream communities, an SVI was also calculated. Drawing upon an existing flood vulnerability assessment (Tascón-González et al., 2020) the SVI used in this study follows that of Taylor et al (2023) and integrates 5 indicators **(Table S1)** that either reduce or enhance a populations capacity to cope with GLOF disaster that are neither included in, or correlated with variables included in, the CPI and HDI calculations **(Equation 2).**

$$\mathrm{SVI} = \frac{\left(\frac{\text{reducing indicators}}{\text{enhancing indicators}}\right)}{5} \qquad \textbf{(2)}$$

Data for each of the indicators was averaged across 5-yearly intervals from 2000 to 2020 from their respective sources, with the resulting value assigned to the final year in the interval, i.e. values in 2005 represent the annual average value from the period 2001-2005. Again, all three indicators (HDI, CPI and SVI) at each time-step are normalised and combined with equal weighting **(Equation 1)** to produce a single proxy for vulnerability **(Equation 3)**. We acknowledge the relative importance of each indicator on social vulnerability will change with location, with studies often assigning various weightings (e.g. Tascón-González et al., 2020). Final values range between 0 and 1, where 1 equates to the highest vulnerability. No scores of absolute 0 were recorded in any location during any epoch.

$$\text{Vulnerability} = 1 - \left[\text{HDI x } \left(\frac{CPI}{100}\right) \text{ x SVI}\right] \quad \textbf{(3)}$$

### 2.4 GLOF Danger

The normalised results of all three parameters (glacial lake conditions, exposure and vulnerability) at each time-interval were then combined with equal weighting to produce a semi-quantitative metric for GLOF danger **(Equation 4):**

$$\text{GLOF danger} = [\text{Lake conditions x Exposure x Vulnerability}] \quad \textbf{(4)}$$

We note that the relative importance of each indicator on GLOF danger will change with location, with studies often assigning weights using an analytic hierarchy process or expert knowledge to fit the specific context of the study. Given the global scale of this study, an ‘equal weighting’ approach was selected with the understanding that the outputs should be taken as a baseline value, and exact values per country/region may vary.

## 3 Results

### 3.1. Changing Lake Conditions, Exposure and Vulnerability

#### 3.1.1. Lake Conditions

Over our 20-year study period, both the number and area of glacial lakes showed marked variation globally. Since 2000, glacial lake area increased the most in the PNW (924 km$^2$) whilst the number of glacial lakes increased the most in the High Arctic and Outlying Countries, with an increase of 1221 lakes. The European Alps saw the lowest increase in both area (92 km$^2$) and number (9) of lakes over the study period **(Fig. 1).** The rate of change in both lake number and area varies globally, with some areas witnessing large increases in lake area despite limited changes in lake number and vice versa (**Fig. 2).**

Within these broader mountain range trends, the areas of glacial lakes decreased in six of the 31 study countries: Austria, France, Columbia, Mongolia, Myanmar, and Uzbekistan, and the number of lakes decreased in just two (Uzbekistan and Mongolia) **(Fig. 2)**. Overall, the area of glacial lakes increased the most in Sweden, from 5.52 $km^2$ to 20.25 $km^2$ (267%) and the number of lakes increased the most in Bhutan, from 29 to 161 (455%) **(Fig. 1 and 2)**. Consequently, the score for GLOF lake conditions increased most across the High Arctic and Outlying Countries region (0.027) and the least across the Alps (0.002) **(Fig. 3)**. Within this are substantial national variations **(Fig. 3)**, e.g. increases in Sweden and Norway accounted for the majority of increase in the High Arctic and Outlying Countries region. The glacial lake score (**Equation 1)** reduced in 13 countries, remained unchanged in Greenland, and increased in the remaining 14 countries **(Fig. 3)**. The largest increase in glacial lake conditions score occurred in Norway (0.077) and China (0.075) and the largest decrease was in Canada (0.012) **(Fig. 3)**. The glacial lake condition score remained the highest in Greenland and Canada for the duration of the study period such that by 2020 they had the highest scores globally (1.000 and 0.865 respectively) **(Fig. 3)**.

| ID | Number of glacial lakes | | | | |
|---|---|---|---|---|---|
| | 2000 | 2005 | 2010 | 2015 | 2020 |
| AFG | 119 | 124 | 113 | 128 | 129 |
| ARG | 94 | 130 | 102 | 123 | 156 |
| AUT | 18 | 20 | 19 | 19 | 18 |
| BOL | 35 | 51 | 56 | 60 | 62 |
| BTN | 29 | 158 | 162 | 154 | 161 |
| CAN | 2322 | 2655 | 2673 | 2865 | 3034 |
| CHE | 36 | 40 | 37 | 38 | 38 |
| CHL | 583 | 794 | 806 | 815 | 1200 |
| CHN | 833 | 947 | 1061 | 1018 | 1109 |
| COL | 4 | 5 | 6 | 4 | 5 |
| ECU | 1 | 2 | 1 | 1 | 3 |
| FRA | 10 | 12 | 13 | 14 | 11 |
| GEO | 6 | 7 | 4 | 6 | 6 |
| GRL | 3009 | 3454 | 3880 | 4461 | 4489 |
| IND | 123 | 187 | 184 | 184 | 214 |
| ISL | 32 | 83 | 131 | 79 | 106 |
| ITA | 18 | 20 | 17 | 22 | 20 |
| KAZ | 58 | 73 | 67 | 63 | 67 |
| KGZ | 94 | 107 | 109 | 116 | 119 |
| MNG | 24 | 16 | 28 | 15 | 14 |
| NOR | 172 | 933 | 887 | 915 | 939 |
| NPL | 103 | 123 | 128 | 127 | 153 |
| NZL | 41 | 41 | 45 | 43 | 46 |
| PAK | 166 | 190 | 180 | 172 | 175 |
| PER | 146 | 199 | 204 | 203 | 236 |
| RUS | 360 | 583 | 409 | 590 | 708 |
| SWE | 30 | 69 | 58 | 59 | 57 |
| TJK | 69 | 79 | 70 | 73 | 70 |
| USA | 679 | 867 | 779 | 928 | 1049 |
| UZB | 1 | 2 | 3 | 3 | 0 |

| ID | Area of glaial lakes | | | | |
|---|---|---|---|---|---|
| | 2000 | 2005 | 2010 | 2015 | 2020 |
| AFG | 14.85 | 15.74 | 14.37 | 16.03 | 16.04 |
| ARG | 290.73 | 314.13 | 304.40 | 304.59 | 337.59 |
| AUT | 5.88 | 6.12 | 6.35 | 6.38 | 5.67 |
| BOL | 15.17 | 41.52 | 42.54 | 42.60 | 44.46 |
| BTN | 9.28 | 11.13 | 11.84 | 12.59 | 13.06 |
| CAN | 1399.95 | 1608.79 | 1684.21 | 1727.91 | 1941.05 |
| CHE | 5.52 | 21.45 | 12.64 | 12.39 | 20.25 |
| CHL | 18.78 | 20.98 | 19.78 | 19.52 | 19.66 |
| CHN | 475.30 | 684.86 | 774.87 | 821.19 | 1094.44 |
| COL | 168.78 | 217.23 | 236.00 | 234.37 | 257.97 |
| ECU | 1.57 | 1.76 | 1.84 | 1.41 | 1.38 |
| FRA | 1.11 | 1.14 | 0.38 | 0.38 | 1.17 |
| GEO | 1.23 | 1.47 | 1.41 | 1.37 | 1.09 |
| GRL | 2253.69 | 2420.14 | 2573.99 | 2852.97 | 2798.72 |
| IND | 29.61 | 42.38 | 42.80 | 43.62 | 48.38 |
| ISL | 0.74 | 0.87 | 0.72 | 0.65 | 0.79 |
| ITA | 54.83 | 62.49 | 86.37 | 75.26 | 132.42 |
| KAZ | 4.99 | 5.06 | 4.93 | 5.44 | 5.10 |
| KGZ | 6.40 | 7.78 | 7.32 | 6.78 | 7.48 |
| MNG | 20.15 | 20.05 | 20.32 | 21.86 | 22.61 |
| NOR | 25.77 | 30.19 | 31.12 | 32.09 | 34.89 |
| NPL | 2.73 | 1.75 | 2.89 | 1.24 | 1.51 |
| NZL | 252.64 | 531.43 | 570.03 | 476.82 | 576.69 |
| PAK | 18.37 | 20.97 | 23.69 | 25.63 | 27.53 |
| PER | 24.30 | 28.35 | 26.48 | 26.29 | 25.80 |
| RUS | 37.37 | 45.52 | 47.61 | 45.66 | 50.52 |
| SWE | 210.62 | 380.31 | 246.36 | 420.63 | 502.10 |
| TJK | 19.65 | 20.32 | 19.68 | 20.18 | 19.93 |
| USA | 560.43 | 701.64 | 677.09 | 810.64 | 943.00 |
| UZB | 0.05 | 0.13 | 0.19 | 0.51 | 0.00 |

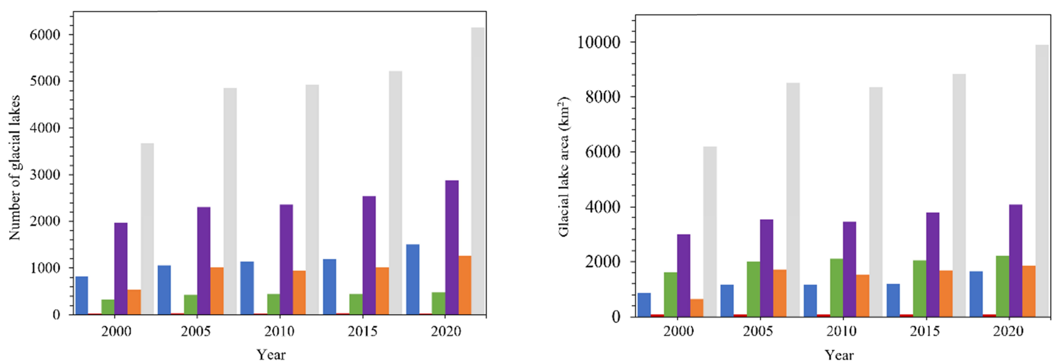


**Figure 1. Global change in GLOF Lake Conditions. Change in the number and area of glacial lakes for the period 2000-2020, grouped by mountain range at 5-yearly interval, where each interval represents the average of the 5-year period. Greenland was not included in the bar charts as its large number and area of glacial lakes skewed results.**

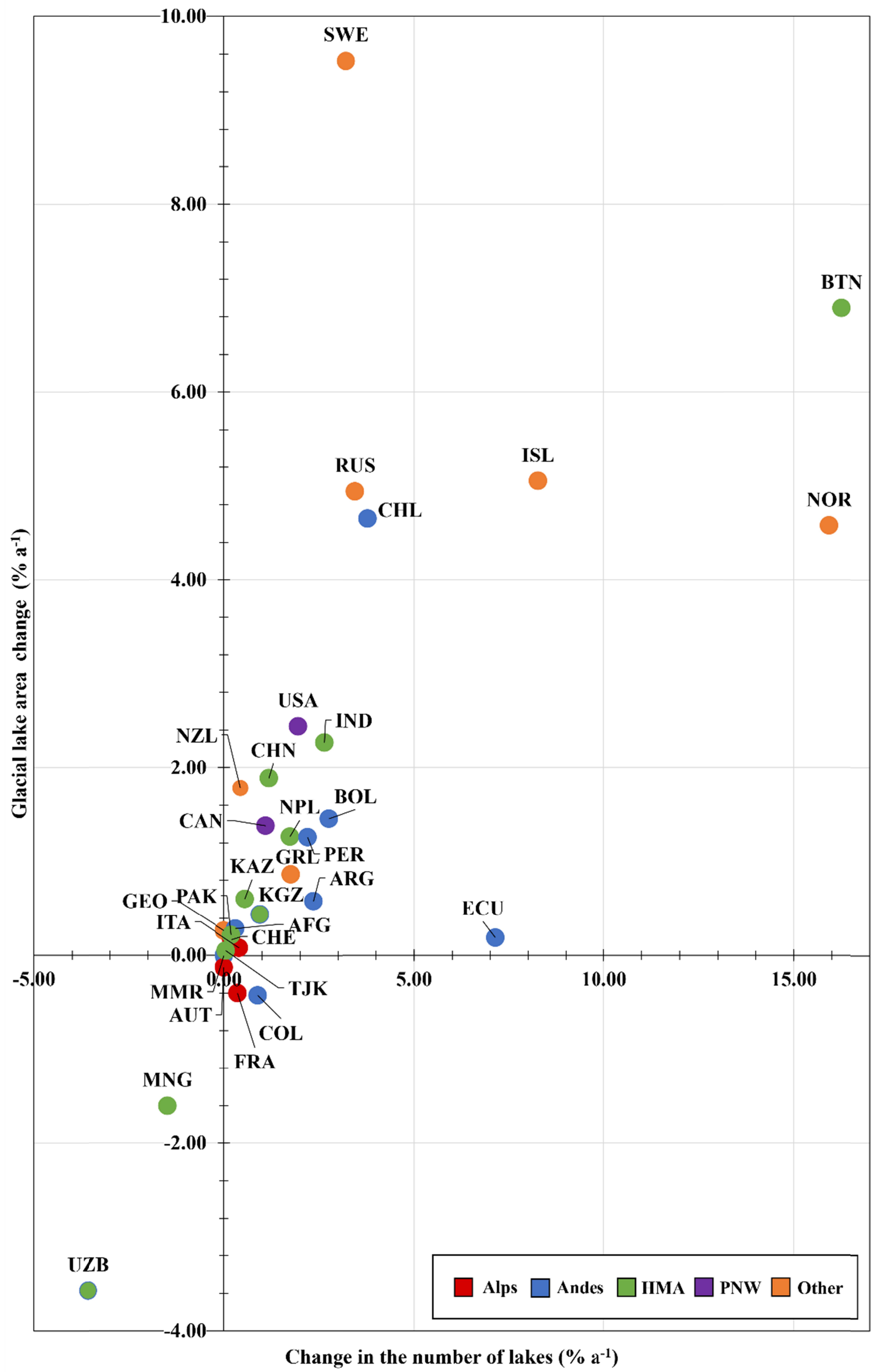


**Figure 2. Lake conditions rate of change. Rate of change in the number and area of glacial lakes for the period 2000-2018. Countries are colour coded according to mountain range.**

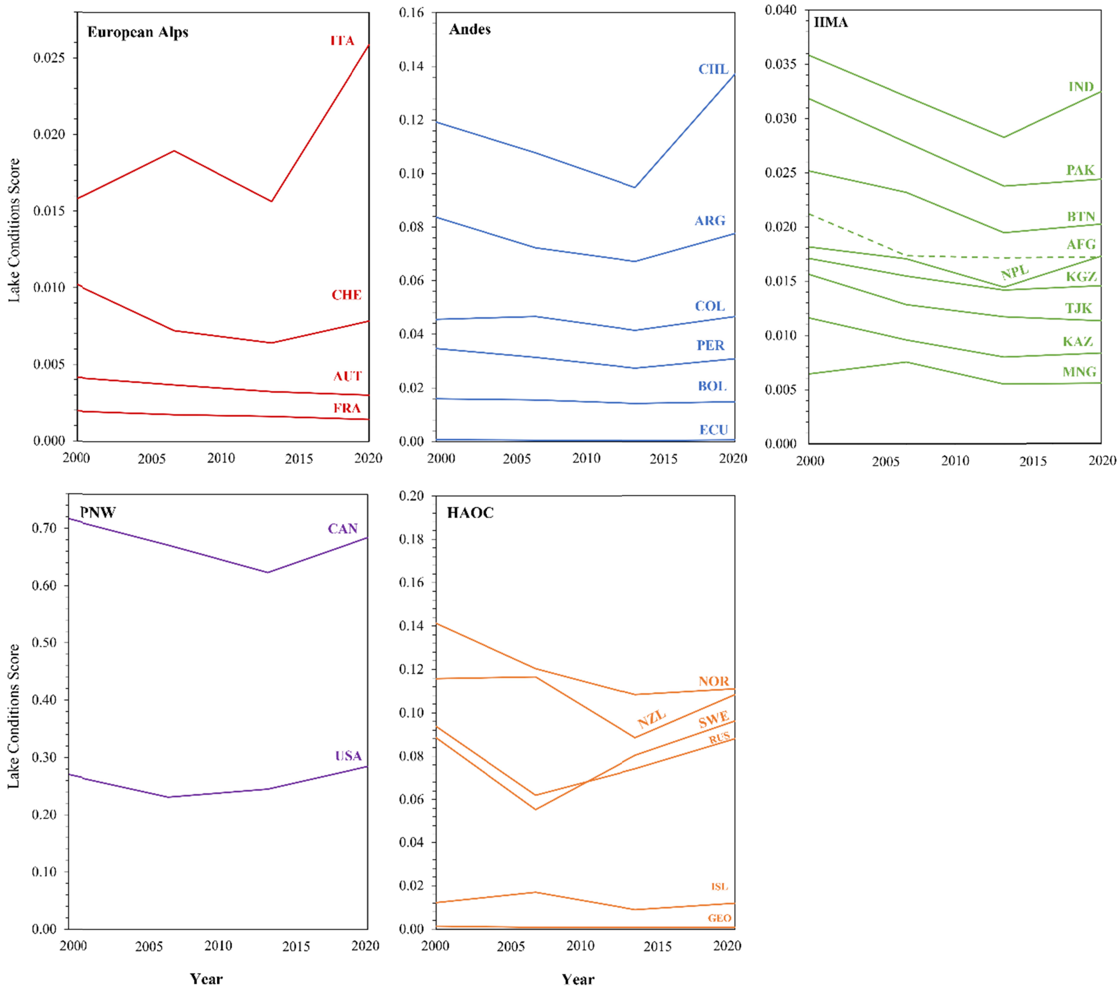


**Figure 3. Global change in GLOF lake conditions from 2000-2020. Values are given as the normalization of combined glacial lake number and area per country. Colour coded according to mountain range. ID of each nation is given above the lines. Note that y-axis values are different for each mountain range to aid visualisation.**

### 3.1.2. Exposure

The number of people residing along potential GLOF runout tracks and within 50 km of a glacial lake increased by 3.2 million (27%) over the last 20 years: increasing from ~11.8 million in 2000 to ~15 million in 2020 **(Fig. 4, Table 1)**. The greatest change in exposed population occurred across HMA (2.2 million; >68% of total change) followed by the Andes (0.5 million; >15% of total change) **(Fig. 4b, Table 1)**, while populations exposed to GLOFs in the High Arctic and Outlying Countries region decreased by ~30,000 **(Fig. 2b).** On the country level, India and Pakistan had the largest absolute increase in exposed population, by ~1 million each (equating to a score increase of 0.312 (45%) and 0.358 (67%) respectively), while Pakistan and Argentina saw the largest percentage increases (67% and 63% respectively) **(Fig. 4a).** Mongolia, Georgia, Nepal and Sweden were the only countries where exposed population decreased, with the largest absolute decrease of ~400,000 (32%) in Nepal **(Fig. 4a)**.

Outside of HMA, the majority of the change in exposed population occurred at distances of >30 km from glacial lakes (**Fig. 4c**). This is particularly notable in the PNW, where little change occurred until 40 km downstream **(Fig. 4c)**. In HMA, however, the number of people living close to glacial lakes increased markedly; of the total 2.2 million increase over the 20-year period, ~46% occurred between 10 km and 25 km, and 13% within the first 10 km **(Fig. 4c).** As a result, overall GLOF exposure increased the most across HMA and the Andes (0.071 and 0.036 respectively), while countries in the High Arctic and Outlying Countries region declined the most **(**0.001, **Fig. S2, Table 1).** In total, 23 countries (76%) increased in overall population exposure (**Fig. S2).**

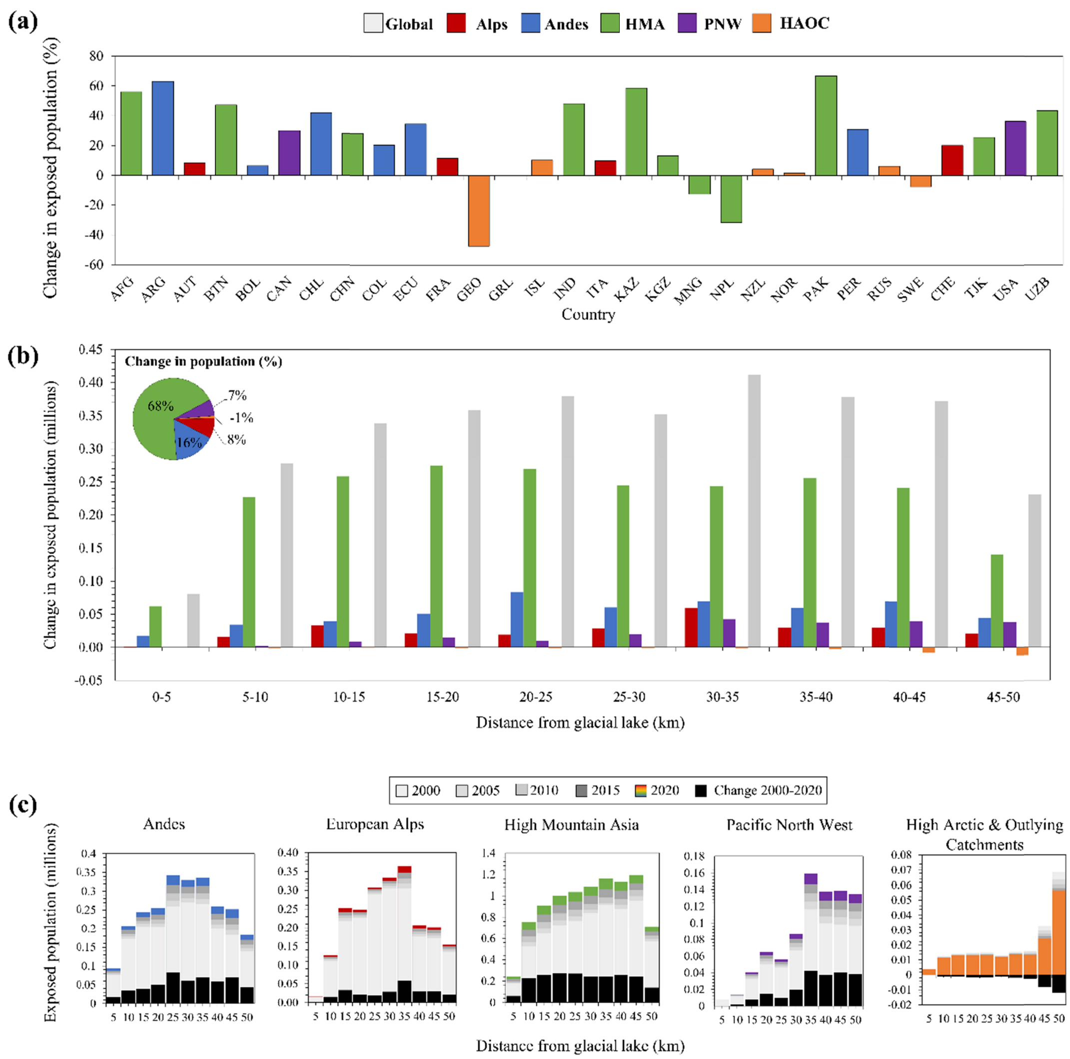


**Figure 4. Global change in static GLOF exposure. (a) Change in population per country living within the 1 km river buffer between 2000 and 2020. (b) Overall change in population within the first 50 km from a glacial lake, given at 5 km intervals per mountain range (coloured bars) and as a global total (grey bars) for the 20-year period. (c) Change in population living along likely GLOF runout tracks within 50 km from a glacial lake for the period 2000 to 2020 for each mountain range at 5-yearly intervals. Progressive time periods shown in light grey to dark grey, with 2020 values coloured according to mountain range. Total change over the 20-year period is shown in black.**

**Table 1. Static population exposed to GLOFs between 2000 and 2020. Here population is taken as the number of people living within 1km of a likely GLOF runout track up to a distance of 50km from a glacial lake.**

| Exposed population | | | | | | |
|---|---|---|---|---|---|---|
| **ID** | **2000** | **2005** | **2010** | **2015** | **2020** | **Change** |
| AFG | 236281 | 262973 | 293485 | 328455 | 368636 | 132355 |
| ARG | 38486 | 43034 | 48381 | 54807 | 62751 | 24265 |
| AUT | 214268 | 218281 | 222601 | 227242 | 232217 | 17949 |
| BTN | 71066 | 78265 | 86210 | 94980 | 104661 | 33595 |
| BOL | 377629 | 380904 | 385831 | 392694 | 401850 | 24221 |
| CAN | 226675 | 241651 | 257879 | 275465 | 294527 | 67852 |
| CHL | 160359 | 174297 | 189987 | 207706 | 227787 | 67428 |
| CHN | 872608 | 925584 | 983824 | 1047994 | 1118861 | 246253 |
| COL | 276988 | 287707 | 300613 | 315819 | 333500 | 56512 |
| ECU | 139391 | 150097 | 161646 | 174107 | 187555 | 48164 |
| FRA | 356150 | 364719 | 374304 | 385040 | 397084 | 40934 |
| GEO | 82362 | 69673 | 59199 | 50557 | 43428 | -38934 |
| GRL | 0 | 0 | 0 | 0 | 0 | 0 |
| ISL | 236 | 240 | 246 | 252 | 260 | 24 |
| IND | 2003345 | 2206185 | 2432727 | 2686020 | 2969534 | 966190 |
| ITA | 777813 | 794332 | 812409 | 832152 | 853682 | 75869 |
| KAZ | 354405 | 394866 | 442142 | 497452 | 562271 | 207865 |
| KGZ | 795368 | 820098 | 845872 | 872738 | 900743 | 105375 |
| MNG | 6750 | 6530 | 6317 | 6112 | 5912 | -837 |
| NPL | 1215583 | 1000850 | 899152 | 851937 | 831954 | -383629 |
| NZL | 7599 | 7591 | 7640 | 7748 | 7922 | 323 |
| NOR | 4248 | 4260 | 4276 | 4296 | 4321 | 74 |
| PAK | 1247028 | 1416300 | 1609311 | 1829462 | 2080650 | 833622 |
| PER | 986005 | 1039078 | 1105210 | 1187853 | 1292086 | 306081 |
| RUS | 110061 | 111496 | 113110 | 114910 | 116903 | 6842 |
| SWE | 289 | 283 | 278 | 272 | 267 | -22 |
| CHE | 604912 | 632085 | 661434 | 693144 | 727422 | 122509 |
| TJK | 105725 | 111190 | 117447 | 124608 | 132800 | 27075 |
| USA | 400449 | 431095 | 465170 | 503150 | 545592 | 145143 |
| UZB | 107545 | 117667 | 128785 | 141001 | 154427 | 46882 |
| | | | | | | |
| Alps | 1953144 | 2009417 | 2070749 | 2137578 | 2210405 | 257261 |
| Andes | 1978858 | 2075117 | 2191667 | 2332986 | 2505529 | 526671 |
| HMA | 7015704 | 7340507 | 7845274 | 8480758 | 9230450 | 2214746 |
| PNW | 627124 | 672746 | 723049 | 778615 | 840120 | 212995 |
| Other | 204794 | 193543 | 184748 | 178037 | 173101 | -31693 |
| **Global** | **11779624** | **12291330** | **13015487** | **13907974** | **14959605** | **3179981** |

#### 3.1.3. Vulnerability

Over the 20-year period all three indicators of GLOF vulnerability (CPI, HDI, and SVI), showed marked variability **(Fig. 5).** All regions have experienced improvement in levels of development since 2000 (indicating an increase in life expectancy, education, and annual income), with HMA in particular improving the most (**Fig. 5**). Countries in the PNW have the highest average development score as of 2020 **(Fig. 5b)**. Changes in perceived corruption are more static, with small decreases in the European Alps and HMA, but minor increases in the PNW and High Arctic and Outlying Countries **(Fig. 5a)**. SVI scores have decreased everywhere at the mountain range scale but are dominated by large improvements across HMA in particular, with notable, but less dramatic, improvements in the Andes **(Fig. 5c, Table S2 and S3, Fig. S3).** Despite clear improvements, particularly in development and social vulnerability such that vulnerability across the region reduced the most over the study period (0.092), HMA remains the most vulnerable region to GLOF impacts globally, averaging a score of 0.767 in 2020, down from a peak score of 0.859 in 2000. Conversely, the PNW was the least vulnerable region on average across all time intervals, at 0.336 in 2020, despite an increase in vulnerability since 2015 due to an increase in perceived corruption, making the PNW the only region to see an increase in vulnerability since 2000 **(Fig. 5d)**. Within this, vulnerability to GLOF impacts reduced in 25 countries, with the largest reduction taking place in Austria (35%) **(Table S4)**. Four countries, Chile, USA, France, and Iceland increased in overall vulnerability by a minimum of 2% to a maximum of 13%. Over the last 5 years of the study (2015-2020) 11 countries saw a notable increase in vulnerability. Afghanistan remains the most vulnerable country over the 20-year period, only reducing from 0.99 to 0.92 (7%), with the 2020 score representing conditions prior to its fall to the Taliban.

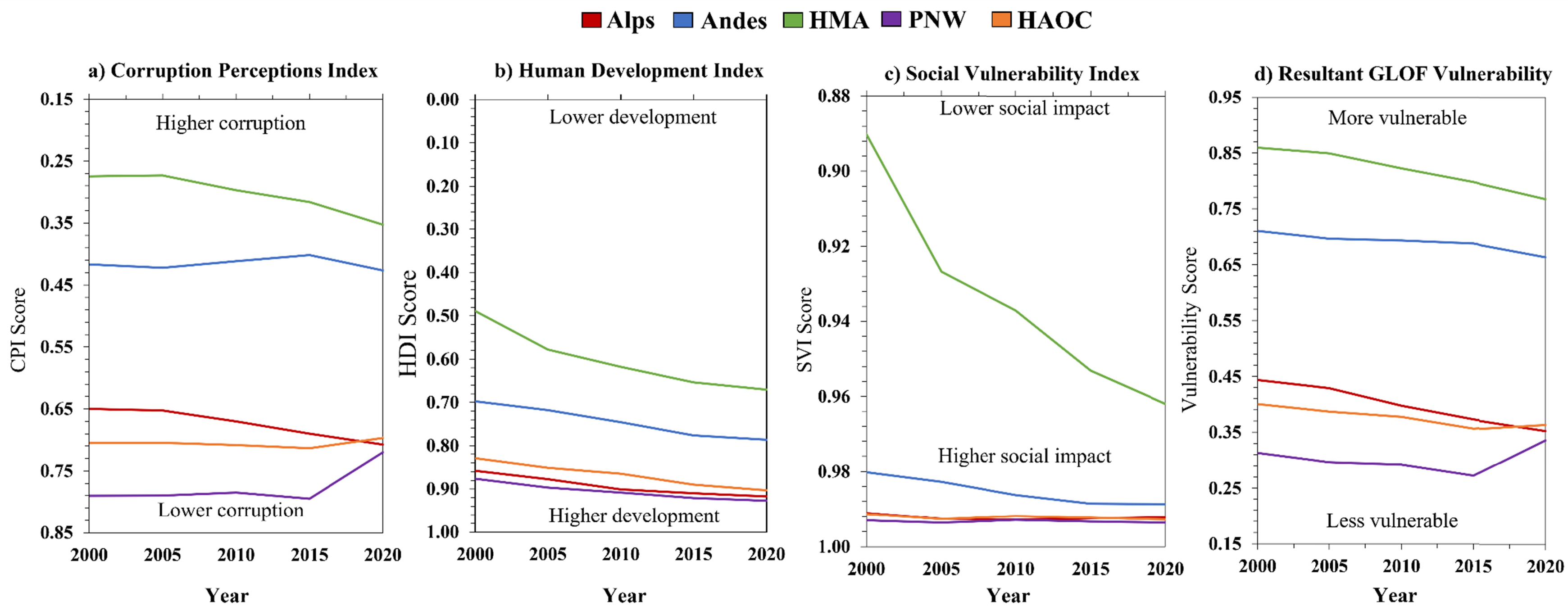


**Figure 5. Global change in GLOF vulnerability. (a) corruption perception index, (b) human development index, (c) social vulnerability index and (d) GLOF vulnerability per mountain range for the period 2000-2020. Note that with the exception of panel (d), the y-axis values do not start at 0, and value decrease upwards**

### 3.2. Change in GLOF Danger

As of 2020, HMA had the highest GLOF danger globally **(0.**133 average) and the Alps the lowest (0.007)**.** The biggest actual change in GLOF danger occurred in HMA (0.040) and the smallest in the Alps (0.002). However, between 2000 and 2020, the PNW and the Andes had the largest overall percentage increase in GLOF danger (52% and 49% respectively) (**Table S5**). In the European Alps and PNW, GLOF danger increased the most between 2015 and 2020 **(Fig. 6).** In the Andes and HMA, the most rapid increased in GLOF danger occurred between 2000-2005 and again between 2015-2020. Within this regional picture, GLOF danger increased in 22 countries and declined in 9 (**Fig. S4**). The largest absolute increase in danger was observed in India and Pakistan (0.186 and 0.177 respectively), however Bhutan saw the largest percentage increase (421%). The largest increase in normalised danger was observed in China (0.283), however, again, Bhutan saw the largest percentage increase (256%). China and India remained the country's most in danger throughout the study period (**Table S4).**

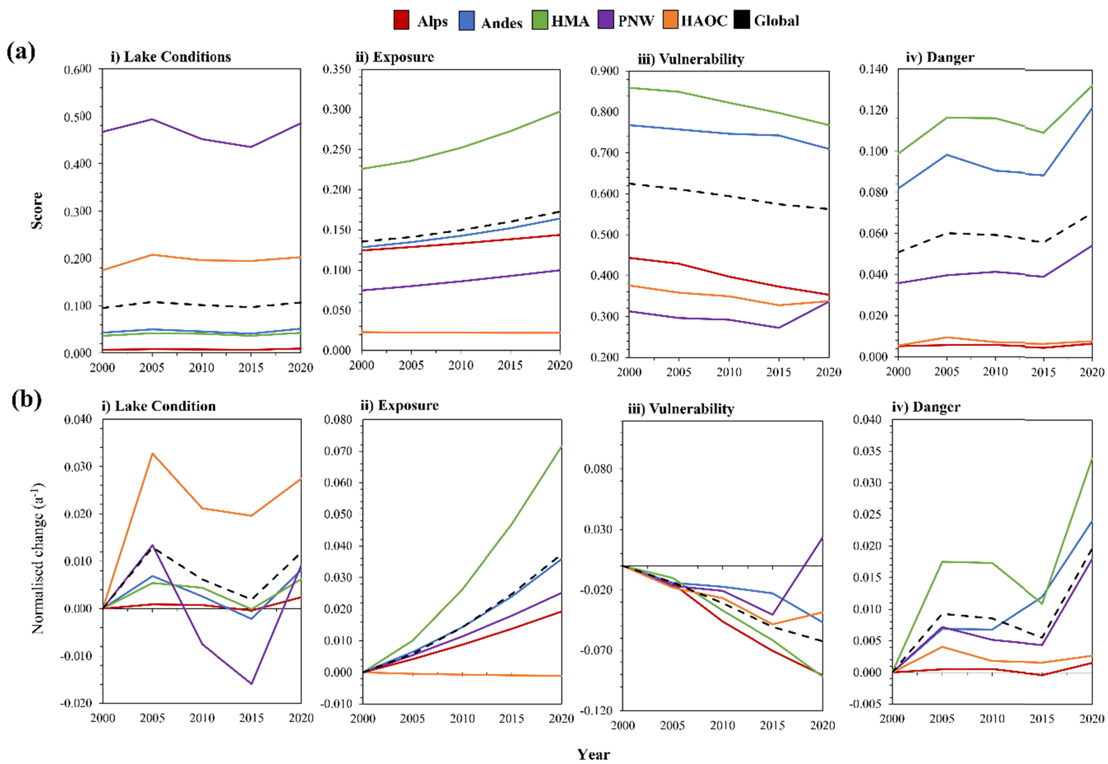


**Figure 6. Change in GLOF danger metrics. (a) Normalised scores 2000-2020 and (b) Normalised scores against the 2000 values, 2000-2020 for i) Lake conditions, ii) Exposure, iii) Vulnerability and iv) Danger, summarised by mountain range. The global average (black dashed) is given for comparison.**

### 3.3. Change in danger drivers

The rate of change in GLOF lake conditions, exposure and vulnerability varied markedly between and within regions over the 20-year period. Whilst glacial lake condition scores increased everywhere over the 20-year period, in the PNW scores decreased between 2005 and 2015 (**Fig. 6b i**), such that the overall increasing trend is the result of increases over the last 5 years. In the European Alps, lake conditions have remained comparatively static since 2000, however saw a notable increase between 2015 and 2020, although remained the lowest globally (**Fig. 6b i**). The rate at which exposure to GLOF increased over the 20-year period grew in all regions except High Arctic and Outlying Countries **(Fig. 6b ii),** with the most rapid change occurring across HMA, almost double that of the next fastest (the Andes) **(Fig. 6b ii).** Vulnerability decreased everywhere globally, except since 2015 in the PNW and High Arctic and Outlying Countries regions, where vulnerability increased, albeit from a very low absolute score **(Fig. 6b iii).** In the PNW, the increase in vulnerability in 2015 was sufficient to undo and exceed the reductions over the preceding 15 yrs.

Taken together, GLOF danger globally has increased since 2000 **(Fig. 6b iv)**, most rapidly in HMA followed by the Andes. Although danger in the European Alps and the High Arctic and Outlying Countries is currently higher than it was in 2000, it has remained largely unchanged since 2005 **(Fig. 6b iv).** Danger in the PNW is interesting, with danger decreasing between 2005 and 2015 before increasing markedly since 2015 (**Fig. 6b iv**). Lake conditions, exposure and vulnerability have all increased here since 2015.

## 4 Discussion

### 4.1. Mitigating GLOF danger

Many recent studies have focused on the growth in glacial lakes and other lake parameters as an indication of potentially dangerous lakes (Aggarwal et al., 2017; Prakash & Nagarajan, 2017), with a long running narrative that relates increasing glacial hazard to rising GLOF danger globally (Bolch et al., 2011; Prakash & Nagarajan, 2017; Rounce et al., 2016; Shugar et al., 2020). Few studies consider the influence of changing exposure, in terms of infrastructure and human population, as a driver of changing danger, particularly in global scale analyses. However, our results clearly show GLOF danger does not universally mirror glacial lake conditions. Instead, comparisons of danger with changes in glacial lake conditions, exposure, and vulnerability over the past 20 years show the primary driver of GLOF danger varies between and within regions **(Fig. 7; Fig. S4)**. As a result, the most effective mechanisms for mitigating GLOF danger will also vary between and within region. Without knowing the key driver of GLOF danger it is difficult to accurately direct funding and implement policy to mitigate increases. By highlighting the key driver of GLOF danger our results provide the first global scale indication of the most appropriate mitigation pathways at the regional and basin scale, and could be used to inform future policies, strategies, and funding.

Broadly, where lake conditions are the key driver of increasing danger, such as across the European Alps and in some nations in High Arctic and Outlying Countries (**Fig. 7, Fig. S4**), implementing hard engineering solutions would be most appropriate, to lower hazard scores and thus mitigate danger. However, where increasing exposure is the main driver, such as across the Andes and HMA (**Fig. 7**), hard engineering solutions would be neither effective nor economically sensible for danger reduction. Our results clearly highlight the significant role of exposure in driving GLOF danger; the High Arctic and Outlying Countries is the only region that does not see an increase in exposure over the 20-year period and is the only region where danger does not see a marked increase (**Fig. 7**). Thus, a focus on land use planning, or the potential relocations of communities would be more suitable for nations across the Andes and HMA. Comparative to hazard, mitigating exposure is more difficult, given the range of political and social factors that must be considered. However, knowing which factor to focus mitigation efforts on would help reduce GLOF danger moving forward and should be a consideration of all future strategies.

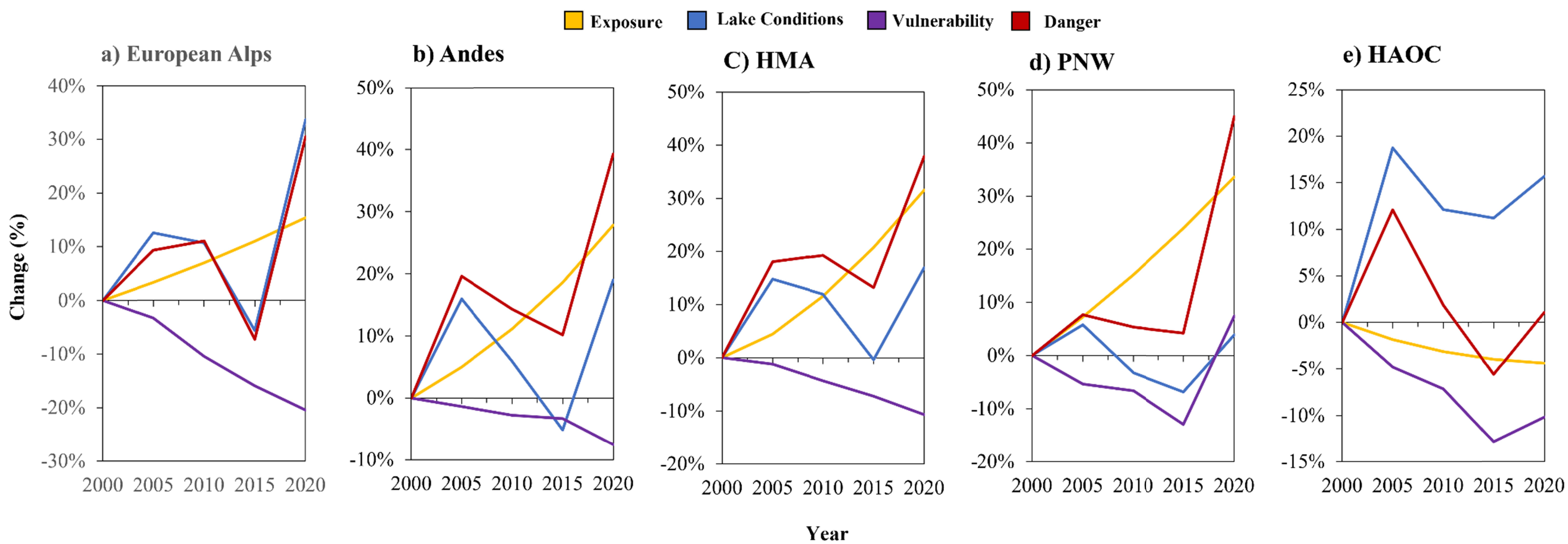


**Figure 7. Percentage change in the three drivers of GLOF danger (Lake Conditions, Exposure, and Vulnerability) as well as GLOF danger itself for each mountain range over the period 2000 to 2020. Values are normalised against the 2000 value. Note the y-axis varies between panels.**

### 4.1.1. High Mountains Asia

Across HMA, we show increasing exposure plays a significantly larger role in driving higher GLOF danger than changes in lake condition **(Fig. 7c, Table S5)**; although danger does appear to mirror the trend of lake conditions, danger scores are exacerbated by rapidly growing exposure. As the region develops, populations are moving into higher elevations for tourism, agriculture and as settlements around new HEP (Allen et al., 2019; Schwanghart et al., 2016; Zheng et al., 2021), and over the last 20 years alone, the population exposed to GLOFs in HMA has increased by 2.2 million **(Fig. S3, Table 1).** Despite HMA having the highest danger of GLOF globally as of 2020, if we exclude the changes in population exposure, HMA would have the second lowest danger globally as of 2020, given the comparatively slower rate of change in lake conditions and rapid decrease in vulnerability **(Fig. S7c)**. These findings are reflected in the unchanged frequency of GLOF disasters observed across the region over the past few decades (Veh et al., 2019). Thus, although monitoring and quantifying changes in the number and area of glacial lakes is important, particularly for identifying new exposure corridors, across HMA a greater focus on forecasting, managing, and mitigating the increasing exposure to existing lakes may prove more effective for GLOF risk management over the coming decades.

Despite finding exposure to be a vital driver of GLOF danger, many reduction strategies continue to ignore exposure; recently, the Green Climate Fund announced a £30+ million adaptation programme to reduce GLOF risk in Northern Pakistan, which seeks to build 250 engineering structures (e.g. damns, spill ways, tree plantation), introduce monitoring stations (weather, flood gauges), undertake hydrological modelling, and install early warning systems (UNDP, 2021). Whilst all these methods may reduce GLOF hazard, our results indicate that for Pakistan, like much of HMA, hazard is not the primary driver of increasing danger, exposure is (**Fig. S4**). Over our 20-year study period national population in Pakistan increased by 57%, however the number of people living within GLOF exposed areas (within 50 km of a glacial lake and within 1 km of likely runout tracks) increased by 67%. In short, Pakistan's population in GLOF exposed areas is rising faster than elsewhere within the country. Thus, our results suggest a focus on managing exposure in glacial basins across Pakistan may be more valuable than hazard management. Whilst unpopular and more difficult to implement, directing more funding to the likes of land-use zoning or relocation costs could be more effective than hard engineering approaches here. In some cases, where populations are unwilling or unable to relocate, funds might be better suited to remediation post event, increasing response and recovery within communities.

We acknowledge that exposure mitigation may be more challenging to implement than hazard mitigation, and that focusing on hazards may therefore be more favourable socially and politically. But given we identify exposure as the key driver of GLOF danger we suggest research, funding, and policy across the region to be directed towards managing exposure changes and not just engineering strategies, which may have little impact on overall danger. We also acknowledge this will need to be balanced against the day-to-day challenges faced by many communities across HMA, where the prioritisation of achieving the sustainable development goals, such as access to clean drinking water and adequate sanitation (**Table S2**), is a pressing issue that may outweigh the risk from GLOF. Nevertheless, future GLOF events will almost certainly exacerbate both issues.

#### 4.1.2 European Alps

In contrast, it is difficult to separate the role of GLOF lake conditions on the observed increase in GLOF danger across the European Alps during the study period **(Fig. 7a),** with the danger trend closely mirroring the hazard trend**.** Whilst GLOFs in the region are generally low volume, discharge, and frequency, GLOFs are having wider reaching impacts on communities (Carrivick & Tweed, 2016) due to the large number of high-value structures at higher elevation for tourism purposes. Whist exposure did increase 15% between 2000 and 2020 (**Fig. S2**), vulnerability decreased by 20%, which we suggest may have offset the exposure increase and thus made lake conditions the primary driver of danger (with lake conditions increasing by 34%).

As such, in order to manage future changes in GLOF danger across the Alps we recommend a focus on hard engineering to mitigate GLOF hazard. Given the higher economic development and political stability in the region, the construction of spill ways, artificial lake lowering, levee strengthening etc. would be highly achievable and effective in managing further increases in GLOF danger here. It has been suggested that the European Alps have not yet experienced the same major glacial lake growth observed in other glaciated regions (Magnin et al., 2020). Modelled likely glacial bed overdeepenings for the Mount Blanc Massif alone indicates a further 80 glacial lakes could form here in the future (Magnin et al., 2020). Thus, the spatial distribution and size of lakes, and exposure, in the European Alps is likely to change substantially in the coming decades, making it crucial to continue monitoring of both glacial lake conditions and exposure in this region. Implementing engineering solutions now to mitigate danger may allow for long-term management as the number and size of lakes changes over the coming years.

#### 4.1.3 Pacific Northwest and High Arctic and Outlying Countries

In the PNW and High Arctic and Outlying Countries, relatively static danger between 2000 and 2015 was driven by a combination of increasing GLOF lake conditions and/or exposure, with a counter effect from declining vulnerability **(Fig. 7d, e).** Thus, locations here may require a combined approach to GLOF danger management, including both engineering solutions and exposure management. However, between 2015 and 2020, danger increased rapidly in both regions, although more notable in PNW, due to sharp increases in vulnerability and lake conditions **(Fig. 7d, e).** Whilst changes in vulnerability are not foreseeable, countries in both regions typically have well-developed natural risk management plans, with state support implemented in several areas, including in preparedness (warning systems, evacuations), response (rescue and aid) and recovery (social benefits and compensation for damage) (Holand et al., 2011). As such, resilience to GLOF events is considered high, reflected in the few recorded GLOF related deaths in these regions; there are no records of loss of life from GLOF in the PNW while out of the seven countries in the High Arctic and Outlying Countries region, only seven deaths have been recorded, all in Iceland (Carrivick & Tweed, 2016). For comparison, 200 people were killed by a single GLOF from Cirenmaco on the Tibetan Plateau in 1981 (Wang et al., 2018). Thus, although overall GLOF danger in the PNW was the third highest globally in 2020, this was primarily due to the vulnerability increase 2015-2020. We therefore suggest that glacial lake expansion, both lake area and number, should continue to be monitored, but our data indicate that GLOF danger in these regions is less of a concern than elsewhere globally. Ensuring vulnerability scores return to the decreasing trend witnessed between 2000 and 2015 is also key.

#### 4.1.4 The Andes as a region of concern.

HMA is often cited as having one of the highest GLOF risks globally (Carrivick & Tweed, 2016; Zheng et al., 2021) and over the past 20-years we show the region did have the highest, and most rapidly increasing GLOF danger. However, we also show the Andes experienced the second most rapid increase in GLOF danger globally as well as a percentage increase in danger nearly 1.5 times that of HMA **(Fig. 7, Table S4, S5).** Until 2005, this increase can be attributed almost solely to increasing GLOF lake conditions, reflecting the rapid and accelerated deglaciation observed across the Andes over the past two decades (Masiokas et al., 2020; Ryan Wilson et al., 2018). During this period, the increase in exposure was offset by reductions in vulnerability **(Fig. 7b)**. In response to the growth in glacial lakes, numerous engineered safety features have been installed across the region over the past few decades; in the Cordillera Blanca alone, 35 of the most dangerous lakes now have engineered interventions (Motschmann et al., 2020). Despite these interventions, GLOF danger continued to increase during our study period, although such interventions have not been accounted for **(Fig. 3)**. Since 2005, GLOF danger in the Andes continues to increase despite a decline in lake conditions (**Fig. 7b**). This suggests that rising exposure is driving GLOF danger whilst vulnerability changes may be offsetting. This highlights the value of decreasing vulnerability, particularly in areas where exposure is increasing rapidly. As such, here, mitigating the changing exposure could be beneficial for managing future GLOF danger, and will likely require significant financial investment over the coming years, particularly given the widespread engineering solutions in place.

Across the Andes, CPI (Corruption Perception Index) scores have remained consistently high over the last 20-years **(Fig. 5a)**. Following the 1941 Huaraz disaster in Peru, lack of dissemination of hazard information and limited socio-economic support pre- and post-disaster, coupled with restricted opportunities for livelihood diversification within the community (McDowell et al., 2013) saw residents rebuilding the city within the designated ‘high hazard zone’ (Carey, 2008). Since 1941, Huaraz’s population has increased from 12,000 residents to over 123,000, with tens of thousands of those living in the direct path of the 1941 GLOF (Motschmann et al., 2020). Coupled with the strong cultural and spiritual significance Andean residents traditionally uphold for the glaciated landscape (Carey, 2010; Motschmann et al., 2020), freedom of movement is limited and populations continue to occupy areas known to be impacted by historic GLOFs (Oliver-Smith, 1996). As a result, managing increasing exposure would be difficult, and would require complex and multifaceted approaches. Instead, given we shown that improving vulnerability can offset increasing GLOF danger **(Fig. S7a)** and that the rate of decrease in vulnerability across the Andes remains one of the lowest globally **(Fig. 5),** we recommend both targeted strategies to reduce vulnerability across the region, to counter rapid increases in GLOF danger, and continued lake mitigation.

The Andes has a long history of GLOF, some disastrous, with the Cordillera Blanca particularly badly affected (Carey, 2005; Emmer, 2017; Lliboutry et al., 1977). As such, the observed increase in GLOF danger over the last 20-years is particularly concerning. Unlike in HMA, where future ice coverage and glacial overdeepenings have been modelled for the entire region (Furian et al., 2021; Linsbauer et al., 2016) in the Andes only a few, small scale studies have been undertaken (Colonia et al., 2017) ). This data sparsity prevents meaningful local-scale assessments as to how GLOF hazard has changed and how it might evolve in the future (Salzmann et al., 2013; Ryan Wilson et al., 2018); it remains unclear how much glacial lake area might increase in the future or how the spatial distribution of lakes might evolve as glaciers retreat (Palomo, 2017). Furthermore, it has been suggested that glaciers and glacial lakes across the Andes may be responding more dynamically to contemporary climate change than elsewhere globally (Veh et al., 2020) and may therefore act as a proxy for future GLOF activity elsewhere. Rapidly growing glacial lakes, in a data-poor environment, coupled with highly vulnerable and increasing populations places the Andes at high risk of GLOF and should be an urgent priority for future research. Furthermore, as populations living along current potential GLOF runout tracks increase (**Fig. 4**), undertaking more detailed studies here may only allow the Andes to prepare for future GLOF scenarios but could also have wider transferable applications for GLOF risk evolution globally.

## 4.2 Role of vulnerability in GLOF danger

Our results show a near-global reduction in vulnerability to GLOFs **(Fig. 5d)** supporting research suggesting vulnerability is reducing globally (Formetta & Feyen, 2019; UNDP, 2020). As changes in vulnerability to natural hazards are often subtle, dynamic and unpredictable (Khanal et al., 2015), it is vital to integrate a measure of vulnerability into GLOF risk assessments to identify the most at-risk areas; the Covid-19 pandemic and the fall of Afghanistan demonstrate two complex events that have significantly impacted vulnerability (Transparency International, 2020; UNDP, 2020), which in turn could have a negative impact on resilience to natural hazards. Furthermore, where GLOF runout tracks cross international borders, the role of vulnerability will play a significant role in determining danger. For example, the Panj River drains several glacial lakes and acts as the border between Tajikistan and Afghanistan, giving the same GLOF hazard in both countries. However, as of 2020, Afghanistan has a far higher vulnerability score (0.919) than Tajikistan (0.836) and given similar levels of exposure suggests potentially far greater impacts would be experienced in Afghanistan as a result.

Despite this, our results indicate any reduction in GLOF impacts globally that may have been gained from declining vulnerability appear to be more than offset by rapidly increasing exposure and glacial lake conditions, such that GLOF danger continues to rise everywhere irrespective of improving vulnerability (**Fig. 6**). Over the past few decades, large amounts of public and private spending have been directed towards improving socio-economic vulnerability (e.g. through the MDGs and SDGs (Vorisek & Yu, 2020)). Whilst clearly successful in reducing vulnerability, our results demonstrate for a climate related hazard such as GLOF, these gains have not been enough to prevent danger increasing. That said, the overall increase in GLOF danger has mostly been slower than increasing exposure and/or GLOF lake conditions in each mountain range **(Fig. 6)**, highlighting that declining vulnerability has dampened the increases in danger since 2000. This is most notable in the PNW region from 2015 onwards, where a marginal rise in vulnerability has driven a more rapid increase in danger than at any other time in the preceding 15 years **(Fig. 6d, e, Table S5)**. Thus, in many regions GLOF danger today could be far higher than present values if not for the investments made through the likes of the MDGs and SDGs, particularly across HMA and the Andes.

The marked increase in vulnerability seen across nations in PNW and the High Arctic and Outlying Countries between 2015 and 2020 could be due to several reasons; in the United States claims of voter fraud and corruption within government operations, amongst the more serious departures from ethical democratic practise, could be responsible for driving corruption levels (Transparency International, 2020, 2021). Like the Fall of Afghanistan to the Taliban, the Ukraine-Russia war or Covid-19 pandemic, these events could all have a negative impact on vulnerability. Regardless of the exact cause, these changes represent largely unexpected perturbations in vulnerability that cannot be predicted and can have a large impact on overall danger should they occur. As such, whilst tackling vulnerability is important, given the uncertainty and inability to forecast events that may change vulnerability, in the context of GLOF danger, we suggest mitigation efforts should equally focus on exposure and hazard moving forwards.

### 4.3 Implications for Early Warning Systems

Globally, over the past 20 years, populations across HMA have moved closer to glacial lakes **(Fig. 4).** Driven by major agricultural expansions, HEP developments (Drenkhan et al., 2019) and continued growth of tourism (Carey, 2008), this trend is expected to continue in the next few decades (Furian et al., 2021; GAPHAZ, 2017). Historically, the construction of Early Warning Systems (EWS) has been deployed for GLOF risk management (Nie et al., 2018), with the aim of detecting impending GLOF in sufficient time to relay a warning to exposed downstream populations to evacuate. However, as populations continue to move closer to glacial lakes, the effectiveness of EWS as a risk reduction strategy may reduce, potentially providing insufficient time for warning messages to be communicated (Maurer et al., 2020) and acted upon. Thus, analysing the spatial distribution of exposed populations, as presented here, is vital if alternative risk reduction strategies are to be implemented. This will be particularly valuable in countries where resources and funding are limited (Carrivick & Tweed, 2016).

Where GLOF danger is high, and where populations have moved closer to glacial lakes, the dissemination of information to end-users is increasingly important, to effectively relay warnings and messages where EWS are still applicable, and to ensure a constant state of preparedness and understanding of how to respond to an impending GLOF (Shrestha et al., 2016; UN, 2006). Countries across HMA have the lowest literacy rates globally **(Fig. S3, Table S2)** thus communicating risk to inhabitants is a major challenge; downstream from Tsho Ropla in Nepal, inhabitants have been reported as having almost no understanding of how their EWS worked, or what to do on receipt of an evacuation notice, despite information leaflets and signs being distributed (Byers et al., 2017). Thus, even the most sophisticated warning system or disaster plan loses its significance if it fails to reach all members of the community (Shrestha et al., 2016) and future education must be inclusive and target the most vulnerable. As glacial lakes continue to grow, areas previously unaffected by GLOF may be impacted. Perceptions of risk have been found to vary within communities downstream of glacial lakes; immediately below Tsho Ropla, Nepal, villagers who have experienced previous flooding are vastly more aware of and willing to listen to warnings than those living further downstream who have no previous experience of GLOF (Dahal, 2008). Further, as populations move closer to glacial lakes **(Fig. 4)** the proportion of people never having experienced a GLOF will likely increase. Therefore, education should be extended to communities further downstream within glacial catchments identified as high danger.

Implementing effective GLOF monitoring and mitigation involves the collaboration of a wide range of actors and institutions, including local communities, national governments, regional organisations, NGO’s, the private sector and science community (IPCC, 2012; UN, 2006). The presence of ineffectiveness, corruption or political tensions in any of these bodies could result in inefficiency (Zheng et al., 2021) as observed in the 1941 Huaraz disaster (Carey, 2005). As the proximity of people to glacial lakes increases in HMA, it will be vital that local communities, governments, NGOs, and international research communities work together to prevent and mitigate damages and losses from GLOF, particularly where GLOF runout tracks cross international borders, as observed in the Gongbatongshaco GLOF in 2016 (Nie et al., 2018; Zhang et al., 2021) and by modelling of future potential GLOFs by Allen et al (2022). Currently, transboundary risk mitigation and disaster recovery is inescapably (and detrimentally) linked to global politics and finance.

## 5 Conclusions

Over the past 20 years, GLOF danger has increased in almost all countries where glacial lakes are found. Our results show that the drivers of this increase vary both between regions and within regions, and importantly, increasing danger does not mirror increasing glacial lake area or number. As such, we urgently need a more holistic approach to GLOF risk assessments, encompassing changes in exposure to identify areas most likely to experience substantial GLOF impacts, and allow effective mitigation to be implemented. The HMA has the highest GLOF danger, but we highlight the Andes as an area of rapidly increasing GLOF danger and data scarcity, which makes the Andes a key priority for future GLOF research. Populations are beginning to move away from contemporary glacial lakes except across

HMA, where people are living closer to lakes than ever before. This will inevitably alter the effectiveness of current mitigation strategies such as EWS and requires immediate attention. Our results show that reduced vulnerability has partly offset increases in exposure and lake growth, but, despite this, GLOF danger has continued to increase. We suggest a greater focus on exposure will be integral to managing GLOF danger in the future, and funding should be directed accordingly. The distribution of both glacial lakes and populations will undoubtedly change over the coming decades as deglaciation continues and regions develop. Thus, many regions have a unique opportunity to establish effective and targeted mitigation strategies now to prevent future GLOF disasters. We hope our initial database of GLOF danger drivers, alongside the recommendations given within this paper could be used to help better inform policy makers, direct funding to the key drivers of danger and lead to the implementation of more effective, long term mitigation strategies.

## Acknowledgements

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## Open Research

All the data used in the study are available from open-source repositories. Glacial lake data files spanning 1990-2018 are available from https://nsidc.org/data/HMA_GLI/versions/1. Population data are available at https://doi.org/10.7927/H4X63JVC. National corruption scores are available from Transparency International at http://www.transparency.org/en/cpi/2019. Sub-national human development scores are available from the United Nations Development Programme (UNDP) at https://hdi.globaldatalab.org/areadata/. The Global Water Resource Zones are available from https://doi.org/10.6084/m9.figshare.8044184.v6.

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