Global Risk of Glacial Lake Outburst Floods

Hazard, exposure, and vulnerability.

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Abstract

Globally since 1990, glacial lakes have grown rapidly in response to atmospheric driven deglaciation. Glacial lakes represent a major natural hazard, where dam failure can lead to the sudden release of water and sediment known as Glacial Lake Outburst Floods (GLOFs), causing significant downstream and transnational impacts. Concurrently, exposure of populations and infrastructure to GLOF hazards in high-mountain regions has increased, whilst vulnerability has also changed. Despite this, the global distribution of GLOF risk has never been quantified, nor have GLOF risk drivers been evaluated. This thesis aims to quantify the spatial and temporal variation in GLOF risk at a global scale, and assess the roles of hazard, exposure, and vulnerability as risk drivers. Results show as of 2020 15 million people are at risk of GLOFs. High Mountain Asia has the highest GLOF risk in 2020. Populations here live the closest to glacial lakes globally, with ~1 million people living within 10 km of a glacial lake. Risk in the Andes is increasing rapidly, yet a lack of long-term, complete databases hinders the analysis of past and future GLOF trends. With a long history of GLOF disasters, increasing risk here is concerning, and I strongly suggest the region be targeted for more detailed study. Critically, results show it is not the regions with the largest, most numerous glacial lakes with the highest GLOF risk, instead, the number of people at risk and their capacity to cope plays a vital role. This reaffirms the importance of holistic risk assessments. Finally, this thesis shows GLOF risk will continue to evolve spatially and temporally over the coming decades, driven by hazard and exposure changes. This thesis highlights the complexity of GLOF risk and indicates mitigation will require bespoke, multidisciplinary, and transboundary solutions. By identifying high risk regions and risk drivers, this work could help refine disaster risk reduction strategies and future research priorities to prevent future GLOF disasters.

Acknowledgements

First and foremost I would like to thank my supervisors Thomas Robinson, Stuart Dunning, Rachel Carr, and Matt Westoby for their academic guidance and also their pastoral support throughout. I am grateful for your commitment and patience, your feedback and inspiration, without which this thesis would not have been possible. A special thanks must go to Tom, for staying up late over in New Zealand in order to attend meetings UK time, I am truly grateful you agreed to jump onto my project with such enthusiasm and hope I get to thank you in person soon!

This thesis was made possible by funding from the ONE Planet Doctoral Training Partnership, and I am grateful for the opportunities provided through this scheme. Thanks must also go to all the lecturing and support staff and students within the School of Geography, Politics and Sociology. To the PGR lot (you know who you are) who persuaded me to do the PhD in the first place and who have become close friends, thanks for the laughs both inside and outside the office.

Thanks to Mel, for helping me through what has been a tough year, and to my family, for pretending to be interested in my research - you will be pleased to know it is finally time to 'get a proper job.' Finally to Max, for sticking through it all with me, you're the best.

Declaration

This thesis is the result of my own work done under the supervision of T. R. Robinson, S. Dunning, J. R. Carr, and M. Westoby. It has not been previously submitted for a degree or other qualification in this or any other University. Chapters 3 and 4 are based on published papers in which T. R. Robinson, S. Dunning, J. R. Carr, and M. Westoby are co-authors. The details of these papers are included in *section 1.5 'Author Contributions.'* In all cases I conducted all of the analysis and writing and designed the figures. All co-authors provided editorial inputs and guidance on the development of the research.

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Abbreviations

Abbreviation	Meaning
CPI	Corruption perception index
DEM	Digital elevation model
DTM	Digital terrain model
EWS	Early warning system
GIS	Geographic information systems
GLOF	Glacial lake outburst floods
HDI	Human development index
HMA	High Mountain Asia
HPP	Hydroelectric power projects
MDG	Millennium development goal
MDGL	Moraine dammed glacial lakes
PDGL	Potentially dangerous glacial lakes
PNW	Pacific North-West
SDG	Sustainable Development Goals
SVI	Social vulnerability index

Definition of Terms

Across glacial lake outburst studies, a range of terms including '*hazard,*' '*risk,*' '*susceptibility,*' '*impact,*' '*exposure,*' '*vulnerability*' and *'danger/dangerous'* are used interchangeably and inconsistently (Kougkoulos *et al.,* 2018). Definitions between branches of science can also vary. The lack of consistency in terminology is a challenge within GLOF research, with studies often not comparable or transferable due to the different definitions, methods and parameters chosen. The following section outlines the terminology used in this thesis and explains how they are used in the context of this study, as well as within GLOF literature.

Term	Definition in this thesis
GLOF Danger	Risk can only be accurately evaluated when three parameters, hazard, exposure, and vulnerability are integrated (see 'GLOF risk'). In Chapter 5, both GLOF hazard and GLOF exposure are projected to the year 2060, in order to establish potential future GLOF scenarios. However, projecting change in vulnerability over time is a major challenge, and any projections made based off current vulnerability status, regardless of how detailed, would be subject to a high degree of ambiguity (Huggel et al., 2015). As such, given vulnerability could not be included and to avoid possible confusion in terminology, throughout Chapter 5, we deploy the term 'GLOF danger' rather than 'GLOF risk' which is defined as the function of the normalized values of future GLOF hazard and future GLOF exposure only. Our approach follows that of Mal *et al.*, (2021) who also refrained from including vulnerability in their study. We believe evaluating GLOF danger is still valuable in this context, allowing potential high-danger areas to be identified and could allow future studies to explore how to forecast vulnerability in these high-danger areas. Further, note that the published version of Chapter 3 uses 'GLOF danger' not 'GLOF risk' at the request of a reviewer due to the absence of hazard probability.
GLOF Exposure	Generally, exposure refers to the presence of people, livelihoods, infrastructure, and other assets in places that could be adversely affected

	by physical events and are thereby subject to potential harm, loss, or damage. In this thesis, following the approach taken in previous GLOF studies, we define 'GLOF exposure' as the number of people living within 1 km of any glacial lake-fed river channel, up to a maximum distance of 50 km downstream. We recognise that a 1 km buffer is a crude estimate for identifying potential GLOF impact zones, with population in the upper reaches likely overestimated as people may be above the impacted zone due to steeper topography, whilst in the lower reaches where valleys are flatter and wider, exposed population is likely underestimated. However, at a global scale a 1 km buffer will provide a conservative but consistent and comparable estimate of the potentially exposed population. Other studies (Allen et al., 2018, 2019; Khanal et al., 2015; Reynolds, 2022) have sought to integrate other exposure factors, such as number of buildings, bridges etc. Whilst valuable, integrating such factors at a global scale is beyond the scope of this thesis, thus throughout this work GLOF exposure refers solely to populations. However, in Chapter 5 we begin to discuss the value of integrating other factors, such as hydroelectric infrastructure and make suggestions for possible directions of future work.
GLOF Hazard	Hazard, in natural science studies, is defined as a function of the probability and intensity of an event, i.e., the likelihood that an event will occur from a given site combined with the overall magnitude of the event. Numerous factors can influence the probability of a GLOF occurring at a given point in time (Allen, Linsbauer, et al., 2016; Allen et al., 2019; Dubey & Goyal, 2020; Zheng, Allen, et al., 2021) thus accurately quantifying the probability of GLOFs at a global scale is inherently difficult, and goes beyond the scope of this thesis. Thus here, the term 'GLOF Hazard' refers to the intensity of a potential GLOF and the impacts on the potentially affected population only and does not consider probability of outburst. Consequently, for the publication of Chapter 3 (Taylor et al., 2023) the term 'GLOF lake conditions' was used in place of 'GLOF hazard' at the request of reviewers to avoid confusion in terminology.

GLOF Risk	In natural science studies, risk is generally defined as a function of hazard, exposure, and vulnerability (WMO, 2021; Zheng, Allen, et al., 2021; Allen et al., 2020). As such, throughout this thesis, reference to 'GLOF Risk' is taken to be the normalised results of GLOF hazard, GLOF exposure, and GLOF vulnerability.
GLOF Vulnerability	Vulnerability, in the context of natural hazards generally refers to a person's capacity to anticipate, cope with, resist and recover from the adverse effects of physical events (Wisner et al., 2004; Cutter et al., 2003; Gaillard & Dibben, 2008). Thus GLOF vulnerability depends on a number of physical, social, and environmental factors within the community that exacerbate or lessen the overall impact of a glacial lake outburst flood. Thus, in this thesis we use three indexes that quantify these factors, providing a globally comparable proxy for GLOF vulnerability: the Corruption Perception Index (CPI) at national-scale, the Human Development Index (HDI) at sub-national level (first internal administrative level, e.g. state or province) and a national-scale GLOF-specific Social Vulnerability Index (SVI).

Chapter 1 Introduction

1.1 Background

1.1.1 Glaciers and climate change

Mountain glaciers distributed across the globe (Figure 1.1) represent both a hazard and resource to populations living downstream and are changing rapidly in response to climate warming (Wouters et al., 2019; Hock et al., 2019). The disappearance of mountain glaciers and subsequent expansion of glacial lakes are amongst the most recognisable and dynamic impacts of climate warming and are being observed in almost all glaciated regions globally (Zemp et al., 2009; Bolch et al., 2012; Lei et al., 2018; Rabatel et al., 2013; Veettil & Kamp, 2019; Hugonnet et al., 2021). This enhanced meltwater production from glacier mass loss and growth in glacial lakes increases the risk of cryospheric hazards such as glacial lake outburst floods (GLOFs) (Veh et al., 2019), which can have catastrophic consequences for local communities and infrastructure (Yamada & Sharma, 1993; Rounce et al., 2017; Zheng, Allen, et al., 2021; Allen et al., 2022). Alongside the rise in cryosphere hazards, mountain glaciers around the world provide water resources for more than 1.6 billion people, equating to ~22% of the global population (Immerzeel et al., 2020). Thus, the observed shrinkage of glaciers has major implications for regional water resources, as glacial melt provides a base level of flow during periods of lower water availability, such as the dry seasons observed in the Andes and the Himalaya (Pritchard, 2019; Immerzeel et al., 2020). Between 1961 and 2016 global glacier mass loss was -9,625 ± 7,975 Gt (Zemp et al., 2019) and over the period 2006 to 2016, glacier mass changes were negative in all glaciated regions globally (Zemp et al., 2019). As such, the rapid loss of mountain glaciers is a major global concern.

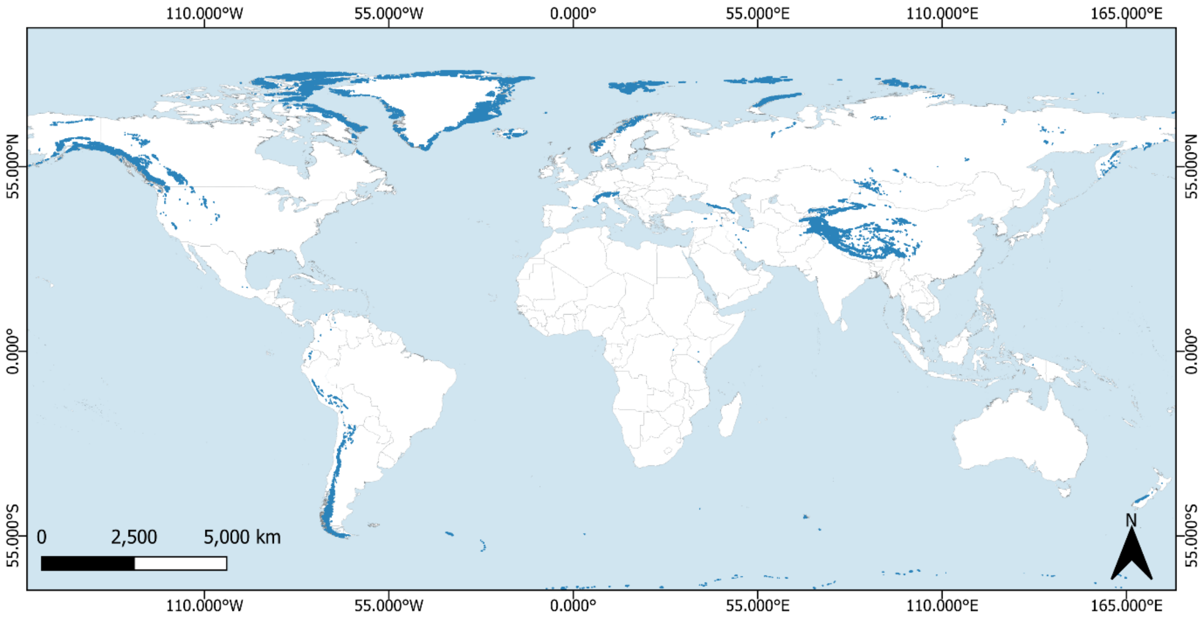


Figure 1.1: Map depicting the global distribution of mountain glaciers. Clusters of high density can be found in Western Canada and the USA, Southern Andes, Asia, European Alps, and Scandinavia. Glacier outlines were obtained from the GLIMS glacier database (GLIMS and NSIDC, 2014).

1.1.2 Glacial lake outburst floods

Since 1990, the number, area, and volume of glacial lakes globally has grown rapidly, increasing by 53%, 51% and 48% respectively (Shugar et al., 2020). As glacial lakes continue to proliferate and expand under a continued warming climate, the hazard of GLOFs increases (Ashraf et al., 2021). GLOFs can be defined as the sudden release of water from glacial lakes that have formed either underneath, at the side, in front, within, or on the surface of a glacier (Allen *et al.*, 2020) and have become emblematic of climate change in mountain regions worldwide (Harrison et al., 2018). GLOFs can have devastating and far-reaching geomorphic and socioeconomic consequences (Zheng, Allen, et al., 2021; Costa & Schuster, 1988; Clague, 2000; Carey, 2005; Huggel et al., 2015; Carrivick & Tweed, 2016) and in the last 70 years, several thousand people have been killed by GLOFs in the Cordillera Blanca alone (Carey, 2008; Emmer et al., 2020). Worldwide, more than 1,300 historical GLOFs have been catalogued (Carrivick & Tweed, 2016), although a recent study by Veh *et al.*, (2021) suggested that the true figure may be much higher, with evidence being found for more than 2,800 GLOFs globally between 1900 and 2021. Thus, we may be markedly underestimating the frequency of GLOFs globally (Carrivick & Tweed, 2016; Emmer, Wood, et al., 2022; Veh et al., 2022) and there remains significant gaps in understanding about the scale of GLOF threat, including where they may occur, their likely magnitude, potential impacts, and, how this may change as glaciers respond to climate warming. Furthermore, as the climate warms and permafrost stores degrade, we expect an increase in the magnitude and frequency of mass movement events, especially in high mountain regions where glacial lakes are located (Kääb et al., 2021; Stoffel et al., 2014), which can trigger GLOFs where they intersect with glacial lakes. Thus, the potential hazard from GLOFs globally is rapidly evolving as the climate is warming and degrading both hillslopes and glacier ice (Kääb et al., 2012; Schaub et al., 2013; Dubey & Goyal, 2020) and therefore requires urgent scientific attention.

1.1.3 Risk of glacial lake outburst floods

In recent years, research interest in GLOF risk has grown (Emmer, 2018; Emmer, Allen, et al., 2022), driven by the urgent need to improve understanding of trends, drivers, and likely future scenarios as the climate warms and exposed populations grow (Harrison et al., 2018; Shugar et al., 2020; Schwanghart et al., 2016; Wester et al., 2019). In natural hazard studies, risk is generally assessed as a function of i) *hazard*, where hazard is a measure of probability and magnitude/intensity of an event/process, ii) *exposure*, defined as the amount of people, infrastructure, and other tangible human assets located in hazard-prone areas, and iii) *vulnerability*, as the conditions determined by physical, social, economic and environmental factors which increase the susceptibility of an individual, community or systems to the impacts of hazards (UNDRR, 2022) (Figure 1.2). Over the past decade, GLOF hazard assessments have been carried out in most high mountain regions globally (Bolch et al., 2012; Wang et al., 2011; Shijin et al., 2015; Allen et al., 2019; Begam & Sen, 2019; Khadka et al., 2019; Zheng, Allen, et al., 2021), however only recently has downstream exposure and socioeconomic vulnerability been recognised as fundamental components of a comprehensive GLOF risk assessment (Huggel et al., 2015). Alongside glacial lake expansion over the past few decades, exposure to GLOF hazard has increased, driven by economic development in mountain regions primarily for tourism, hydroelectric power, and agriculture (Allen et al., 2019; Wester et al., 2019; Schwanghart et al., 2016; Immerzeel et al., 2020), whilst vulnerability has generally declined (Formetta & Feyen, 2019).

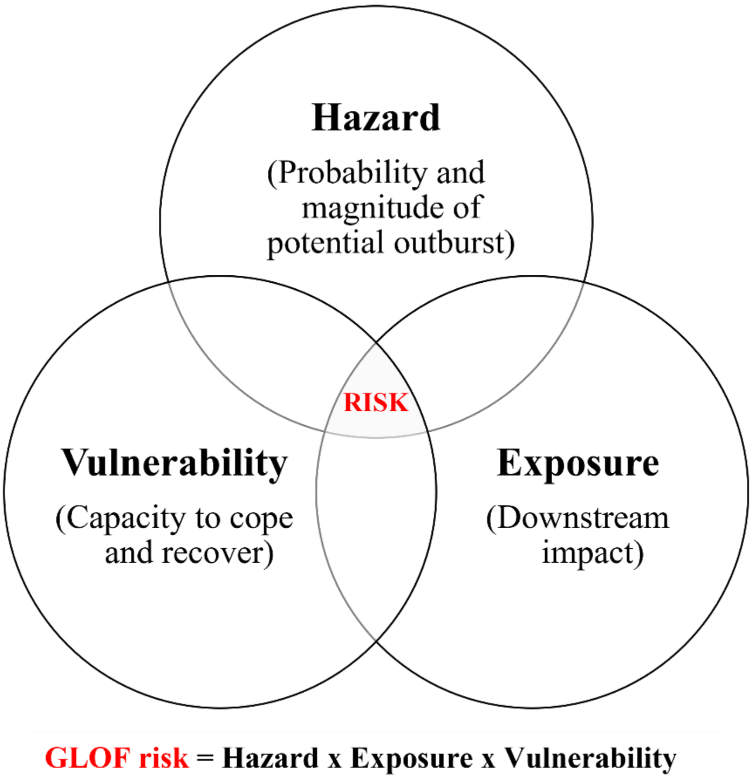


Figure 1.2: Concept of GLOF risk. In natural sciences, 'risk' is generally understood to be a combination of a physical hazard which includes potential outburst magnitude, downstream exposure, and social vulnerability as the capacity for communities to cope with, respond to, and recover from a GLOF hazard.

Over the coming decades, as the number and area of glacial lakes continues to increase, alongside changes to population exposure, the potential social, economic, and geomorphological impacts of GLOFs are likely to change. Thus, it is crucial our understanding of GLOF risk distribution is improved as we look towards potential disaster mitigation or adaptation strategies (Zheng *et al.*, 2021). Thus, knowing *where* and *whether* to target mitigative efforts will be critical, and glacial lake outburst risk assessment must begin to consider larger spatial scales, not restricted by administrative or political boundaries if the highest risk areas are to be identified (Allen et al., 2020). This information can then be fed into policy at global, regional, and local scales and used in the allocation of GLOF adaptation funding to reduce the impacts of GLOF disasters. Historically, GLOF risk studies generally cover small spatial scales, and many are now outdated due to using static data. Therefore, one of the primary motivations of this project is to investigate contemporary GLOF risk at a global scale to identify hotspots of GLOF risk and to target research on the highest risk areas and prioritize disaster risk reduction funding.

Alongside pinpointing static contemporary risk there is an urgent need to better understand the drivers of GLOF risk and how changes to these drivers creates regional differences in GLOF risk, as well as altering GLOF risk trajectories. Thus, this thesis also investigates how hazard, exposure, and vulnerability have changed temporally between 2000 and 2020, and assesses their role on overall GLOF risk changes across that period, providing the first global scale, temporal GLOF risk assessment. Investigating the controls on GLOF risk and how they have changed in the past can provide useful insight into how future GLOF risk could evolve and thus what to address to reduce risk in the future. This work was thus motivated by the absence of holistic, interdisciplinary risk assessments at the global scale, owing to incomplete databases and lack of data sharing across stakeholders, representing a key limitation of managing GLOF risk. In particular, there are few documented holistic risk studies that consider both societal exposure and vulnerability alongside physical drivers of GLOF hazard (Drenkhan et al., 2019; Motschmann, Huggel, Muñoz, et al., 2020; Huggel, Carey, et al., 2020; Emmer, Wood, et al., 2022). Studies on GLOF hazard still far outweigh those that also consider exposure and vulnerability, despite these factors being key elements of risk (Figure 1.2). It is possible to be exposed to a hazard but not vulnerable to it (e.g. through modification of infrastructure and behaviour to mitigate potential losses (WMO, 2021)), whilst similarly it is possible to be highly vulnerable to a hazard even if the hazard itself is deemed relatively low (e.g. due to low socioeconomic development (Carey, 2010)). Thus, assessments conducted without a robust metric for each of hazard, exposure, and vulnerability, are insufficient for quantifying GLOF risk and thus it is important to provide a global dataset of GLOF risk that integrate all three elements of risk.

I recognise that establishing accurate GLOF hazard is complex, owing to the vast number of interacting process-response relationships, and that true risk can only be determined when a measure of hazard probability is included. However, I argue detailed hazard parameterisation is only useful where a potential GLOF would have an impact on downstream communities, and in the absence of probability information it is still possible to obtain useful information on risk, given the underlying assumption that each lake can fail. Thus in this thesis, I reduce the complexity of GLOF hazard by removing any measure of *probability* of outburst, and instead focus equally on the exposure and vulnerability factors in relation to the *magnitude* of GLOF hazard only. From this, areas identified as being high risk could then be targeted for detailed hazard appraisal to more accurately define GLOF risk. Taking this first order approach removes the high degree of uncertainty produced from hazard modelling on such a vast spatial scale where data is incomplete or unavailable, and where the determination of the probability of failure per lake is likely to carry the highest uncertainty. Further to this, in the absence of standardised vulnerability data and high uncertainty in projecting current data given the dynamic nature of vulnerability itself, in Chapter 5**,** I quantify how 'GLOF danger' might change in the future across the entire HMA region rather than GLOF risk. Using the best available proxies for hazard and exposure I quantify future GLOF danger up to 2060 at a scale that has not previously been attempted. Whilst vulnerability metrics are important for ascertaining risk, it is still possible to obtain valuable information relating to how GLOF danger could be expected to evolve in the future, allowing inferences to be made regarding GLOF risk, under different vulnerability scenarios. Chapter 5 therefore provides a starting point from which other research could stem and provides an important contribution to our understanding of glacial lake outburst flood evolution.

1.2 Study area

This thesis identifies glacial lakes where a GLOF could impact human populations, i.e. glacial lakes with non-zero populations downstream. In total, 1089 glacial basins across 31 countries are identified where glacial lakes are present, with the most found in Canada (263) and the least in Uzbekistan (1). To facilitate a global comparison, basins were categorized according to the major mountain range in which they were found and assigned to one of five groups: Pacific Northwest (PNW), Andes, European Alps, High Mountain Asia (HMA) or High Arctic and Outlying Regions (including Scandinavia, New Zealand, Russia, and Iceland) (Figure 1.3). Due to their comparatively small populations, Scandinavia and Iceland were grouped into the High Arctic and Outlying Regions rather than as separate regions.

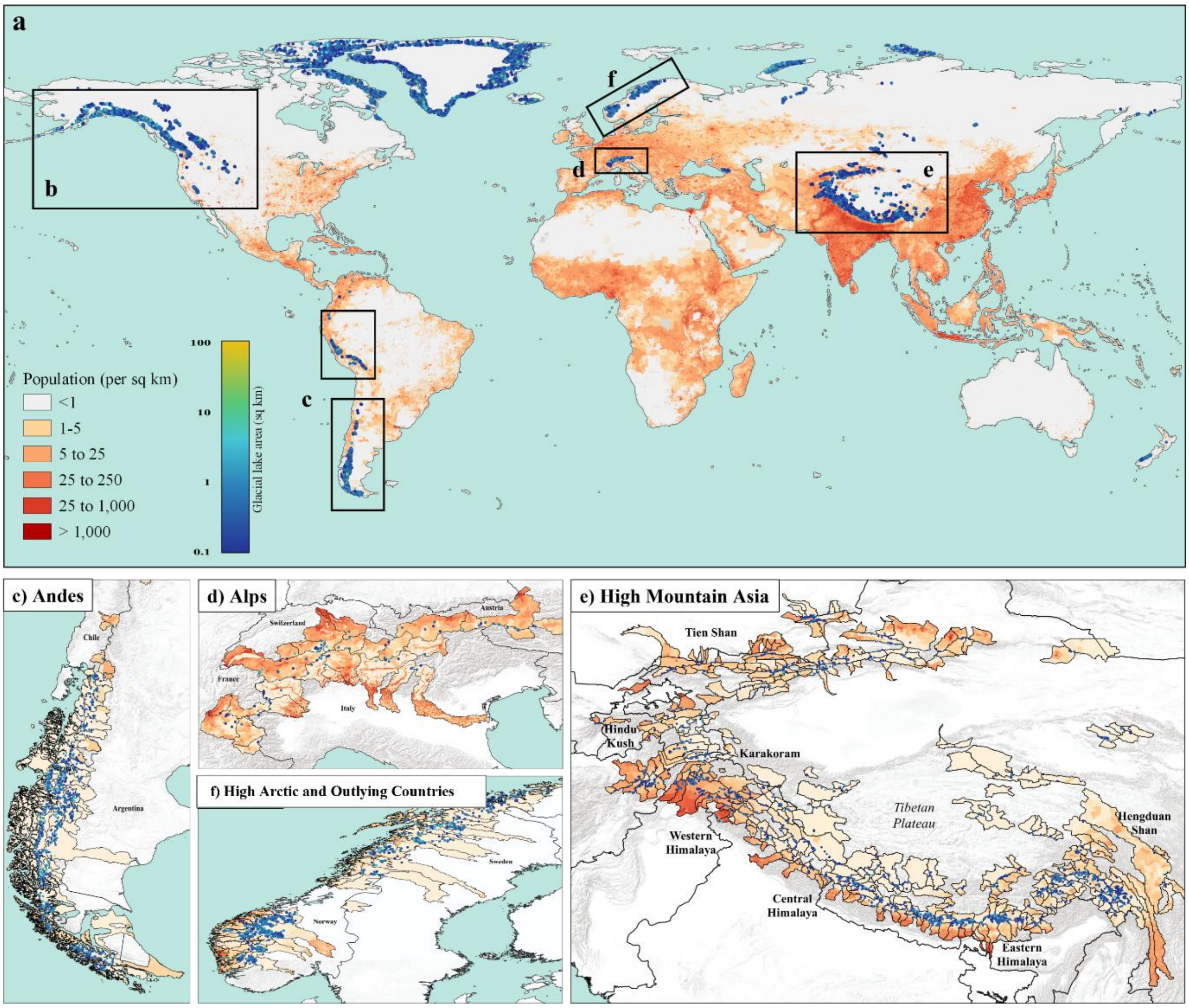


Figure 1.3: Map detailing the study area of this thesis. Map depicts the population (per km^2) and glacial lake area (per km^2) across the globe. Mountain regions identified and analysed in this thesis are as follows; inset (b) PNW, (c) Andes, (d) European Alps, (e) High Mountain Asia, and (f) High Arctic and Outlying Countries. Population data is Gridded Population of the World V4 (CIESIN, 2018), glacial lake shapefiles from Shugar *et al.*, (2020).

1.3 Research aims and objectives

This introduction has highlighted the uncertainty surrounding GLOF risk, with the lack of a global database preventing clear understanding of past, contemporary, and future GLOF risk. I argue that only through quantifying measures of hazard, exposure, and vulnerability, as well as analysing the changes associated with each over the past few decades, can current and future GLOF risk be effectively understood and mitigated. Thus, the overall aim of this thesis is to ***quantify spatial and temporal variations in global GLOF risk and the relative contributions of all three factors of risk (hazard, exposure, and vulnerability).*** This aim will be achieved using the following objectives:

1. To quantify contemporary (2020) global GLOF risk and its spatial variability using a range of remotely sensed and open-access data (Chapter 3).
2. To determine how GLOF risk has changed between 2000 and 2020 and to assess the role of GLOF hazard, exposure, and vulnerability in driving temporal changes in GLOF risk using quantitative analysis (Chapter 4).
3. To investigate potential future GLOF danger in High Mountain Asia using remotely sensed data and statistical projections and evaluate what this could mean for future GLOF risk (Chapter 5).

This thesis investigates GLOF risk changes between 2000 and 2020 from a global to basin scale using remote sensing and open-access data. This approach has several advantages. First, it allows for large spatial and temporal analysis, facilitating comparisons and identification of trends by providing a hierarchy of relative ranked risk. From this, higher risk areas can be prioritised for more detailed, higher-resolution studies, to better understand trends and drivers, but also for risk mitigation and reduction strategies. This also enables resources to be effectively and efficiently deployed to areas of need, such as acquisition of high spatial and temporal resolution satellite data, and logistically complicated field data collection.

As interest surrounding GLOFs has increased over the last few decades, a clear geographical disparity has emerged between where research is being conducted and where GLOFs have been recorded (Emmer, 2018; 2022) (Figure 1.4). Between 1979 and 2021, Iceland, the North American Cordillera, and Himalaya were the most prominent GLOF research hotspots, with 206, 174 and 346 research items respectively (Emmer, 2022) (Figure 1.4). However, in the case of the Himalaya, comparatively few GLOFs have been recorded (see Figure 1.4), with only 50 outbursts on record. Other regions globally have a higher recorded frequency of GLOFs yet comparatively less research; the Karakoram and Patagonian Andes both have at least double the number of outbursts than the Himalaya (111 and 100 respectively), yet both have less than 1/5 the number of studies (70 and 52 respectively). As such, emerging ‘hotspots’ of GLOF risk may not be representative of the global picture, with regions often cited as having high GLOF risk generally those with the most research items attributed to them (e.g. Zheng *et al.,* 2021). Data sparsity across the other regions (e.g. the Andes, Karakoram) may be preventing meaningful assessments of actual GLOF risk in the region, and urgently requires attention. As such, conducting a global scale study could help identify the more overlooked high-risk areas. Finally, it facilitates the identification of knowledge gaps and provides directions for future work.

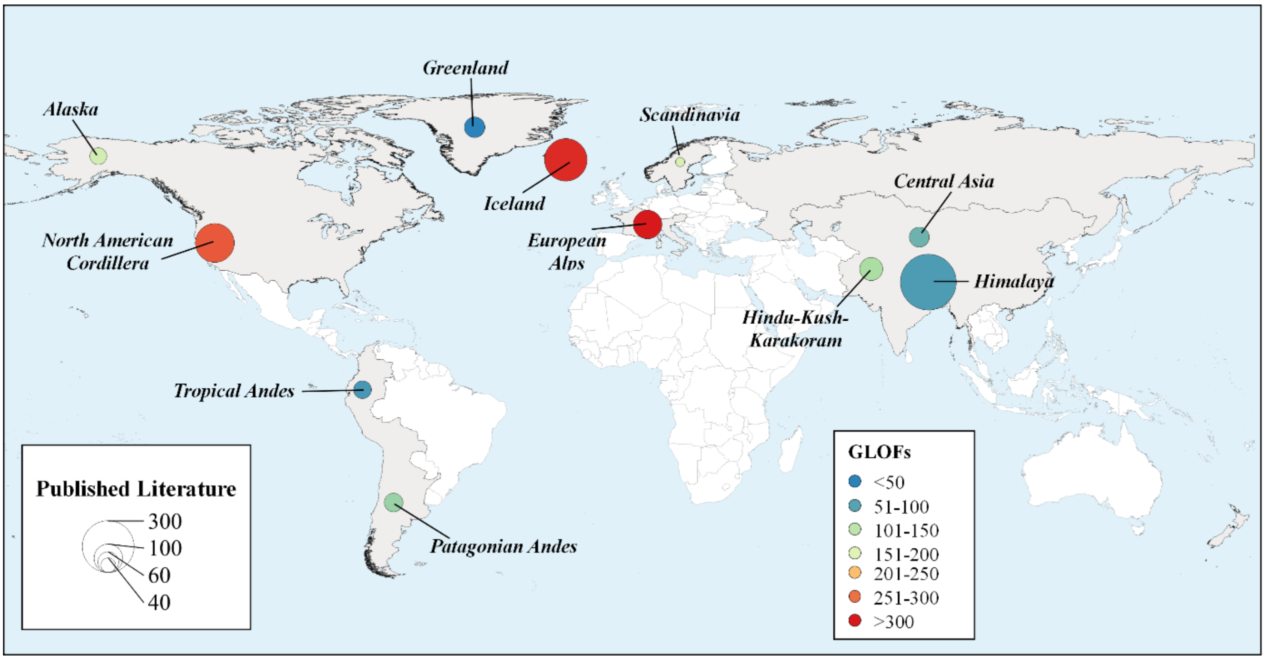


Figure 1.4: Number of published GLOF research items per regions compared to the number of recorded GLOFs between 1979 and 2021. The Himalaya, Iceland and North American Cordillera are hotspots of research, whilst Iceland and the European Alps are hotspots of GLOF activity. Regions in grey indicate those containing glacial lakes and regions in white represent those without. Data (Emmer, 2018; Emmer, Allen, et al., 2022).

1.4 Thesis structure

Chapter 2 provides a review of literature on glacier changes and glacial lake formation, GLOF trigger mechanisms and trends, followed by a detailed discussion of key research gaps in relation to GLOFs, and how the research questions this thesis will address fits within literature. Chapter 3 first establishes contemporary GLOF risk on a global scale for 2020. A methodology was developed to produce a quantifiable measure of risk that accounts for hazard, exposure and vulnerability and is globally comparable. From this, how contemporary GLOF risk is distributed at a regional, national and basin scale is discussed, and hotspots of GLOF risk identified. The distribution of human exposure to glacial lake hazard and the impact this may have on overall risk is also discussed. Chapter 4 determines changes in GLOF risk over a 20-year period (2000-2020). Deploying the robust methods for quantifying GLOF risk developed in Chapter 3, the role of each factor; hazard, exposure, and vulnerability, on driving GLOF risk change is individually assessed. Recommendations for where research should be focussed as well as implications for targeted risk reduction strategies are discussed here. Chapter 5 aims to show how GLOF danger could change in the future and explores how various levels of interventions/mitigation could alter current danger trajectories, with inferences for GLOF risk included. Due to the availability of open access data, and given the region was identified as having the highest GLOF risk in Chapter 3, and with populations shown to be moving closer to glacial lakes than elsewhere globally in Chapter 4, HMA was selected as a case study here. Changes in hazard and exposure are projected to 2060 and used to produce a semi-quantifiable measure of GLOF danger, highlighting areas of high danger that should be prioritised for more detailed study. The differing level of interventions required to alter trajectories from their current path and lower future GLOF danger are discussed, and recommendations for where mitigative efforts should be focussed included. I note here that throughout this thesis the Andes is highlighted as a region of major concern, with rapidly increasing GLOF risk. However, due to limited data availability I could not select this region for future projections, but strongly suggest similar work be done in the region when data becomes available. Methods are described in detail in each chapter rather than a separate methods chapter. Chapter 6 summarises and discusses the key themes of the thesis in the wider context of GLOF risk and identifies useful directions for future research. Chapter 7 outlines the main conclusions of the thesis.

1.5 Author contributions

The following chapters are manuscripts, which I wrote for publication in peer-reviewed journals. I wish to express my gratitude to four co-authors, Thomas Robinson, Stuart Dunning, Rachel Carr, and Matt Westoby, who contributed to the production of these manuscripts.

Chapter 3: Taylor, C., Robinson, T.R., Dunning, S. *et al.* Glacial lake outburst floods threaten millions globally. *Nat Commun* **14**, 487 (2023). https://doi.org/10.1038/s41467-023-36033-x.

C.T., T.R., R.C., and S.D. devised the study. C.T. undertook the computational studies and data analysis. T.R., R.C., S.D., and M.W. supervised the work. C.T. wrote the manuscript, all authors edited the manuscript.

Chapter 4: Taylor, C., Robinson, T.R., Dunning, S. *et al.* The rise of glacial lake outburst flood danger: trends, drivers, and hotspots between 2000 and 2020. Earth's Future (In review).

C.T., T.R., R.C., and S.D. devised the study. C.T. undertook the computational studies and data analysis. T.R., R.C., S.D., and M.W. supervised the work. C.T. wrote the manuscript, all authors edited the manuscript.

1.6 Data availability

All the data used in this study are available from open-source repositories. Glacial lake data files spanning 1990-2018 produced by Shugar *et al.*, (2020) 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/. Data for the indices used to derive SVI (Social Vulnerability Index) are available from the World Bank Open Data at World Bank Open Data | Data. The Global Water Resource Zones produced by Yan *et al.*, (2019) are available from https://doi.org/10.6084/m9.figshare.8044184.v6.

1.7 Notes

All non-peer reviewed chapters in this thesis (**Chapters 1, 2, 5, 6 and 7**) are written in first person. When I refer to contents of published or submitted manuscripts (Chapter 3, Chapter 4) in these chapters, the word "I" includes the work of my co-authors, whose contributions I acknowledge above.

Chapter 2 Literature Review

2.1 Glacier mass loss in a warming climate

Glaciers are highly sensitive to climate change and a key indicator of the impacts of global warming (Roe et al., 2017; Wouters et al., 2019). The balance between inputs (e.g. accumulation) into a glacial system and outputs (e.g. ablation) from a glacial system, termed ‘mass balance,’ can be used to reveal the overall ‘health’ of a glacier, and is thus an essential variable for determining the response of glaciers to climate change (Zemp et al., 2009; Bolch et al., 2012; Zhou et al., 2018). The extent and volume of glacial ice has been in decline since the Little Ice Age (LIA), with increasing temperatures globally resulting in pronounced glacial mass loss and a prevalence of negative mass balance in nearly all glaciated regions of the world (Hugonnet et al., 2021; Rabatel et al., 2013; Veettil & Kamp, 2019). Mass loss across High Mountain Asia (HMA) alone over the last two decades has been estimated at 267±16 Gt yr^{-1}, accounting for 21±3% of the observed sea level rise over the same period (Hugonnet et al., 2021), and a recent study has indicated an apparent end to the Karakoram anomaly, where glacial mass was increasing (Hugonnet et al., 2021). A particularly strong acceleration in ice loss has also been documented in Alaska, northwest America, whilst there are suggestions that Andean glaciers are the highest contributors per unit area to sea level rise (Zemp et al., 2019).

2.1.1 Glaciers as resources and hazards

Glaciers in high mountain regions represent both a natural resource and a hazard. Glacier retreat has not only interrupted natural water flow regimes, altering annual water availability, but also the frequency and magnitude of existing glacial hazards has changed, whilst new hazards have emerged. Glacial hazards can occur over a range of timescales, ranging from rapid onset, short-duration events such as flooding and avalanches, to chronic hazards such as water shortages (Wessels et al., 2002; Bolch et al., 2008). Whilst exposing downstream populations to more frequent and intense hazards, deglaciation has also created new economic opportunities across agriculture, tourism, and the hydropower sector (Cook et al., 2016; Drenkhan et al., 2019; Huggel, Carey, et al., 2020; Huss et al., 2017). As glaciers respond to climate change, the balance between resource and hazard is beginning to change, and life in mountain regions is being reshaped by a cascade of impacts on downstream systems (Rounce et al., 2017; Zheng, Allen, et al., 2021; Allen et al., 2022; Immerzeel et al., 2020).

Globally, glaciated regions represent key water resources (Washakh et al., 2019) and are often referred to as ‘Water Towers’ (Xu et al., 2009; Immerzeel et al., 2020). Throughout the year, contributions of glacial snow and ice melt from these water towers make up large proportions of perennial river flow to many major river systems globally (Xu et al., 2009; Immerzeel et al., 2010; Huss & Hock, 2018; Immerzeel et al., 2020). The importance of this contribution varies throughout the year and is particularly vital during the dry season, for example, in HMA ~70% of summer flow in the Ganges, Indus, Tarim and Kabul Rivers comprises glacial meltwater. Thus, glacier meltwater can be a crucial buffer against drought, particularly when key weather systems (e.g. monsoon) are weak, delayed or fail to materialise (Xu et al., 2009). This is becoming increasingly common as a result of climate change. For instance, changing atmospheric patterns across the Hindu-Kush-Himalaya has resulted in a decrease in the frequency and duration of monsoon rainfall over the last 65 years and an increase in the number of dry days (Burke & Stott, 2017), although this remains spatially and temporally variable. In addition to water resource contributions, the naturally steep slopes of mountainous regions are suitable for harnessing hydroelectric power, with many mountainous regions now heavily dependent on hydroelectric power as a reliable energy source (Washakh et al., 2019). In 2003, 99.5% of the total electricity used throughout Bhutan was generated by hydropower schemes (Tshering & Tamang, 2004), and exports of electricity represented the single major source of revenue, with ~90% energy generated sold to India (Uddin et al., 2007). With changing precipitation patterns reducing glacial contributions to river flow, these hydroelectric schemes will likely become inviable in the coming decades, stunting social and economic development across national borders.

During the 21st century, glacial runoff is likely to diminish rapidly, putting communities at risk of major water shortages; in the Himalaya, runoff is forecast to initially increase by 33-38% during the dry season (Singh & Kumar, 1997), with a peak runoff predicted to occur in 2050 before reducing abruptly as glacial ice continues to be lost, leading to widespread water shortages in just a few decades or less (Barnett et al., 2005; Immerzeel et al., 2010; Nie et al., 2021). For example, in the Shule River Basin in north-western China, the average contribution of glacier meltwater to the total basin runoff is expected to decrease from the current 23% to 15% by 2030 (Wang et al., 2021). Coupled with rapid increases in population, infrastructure, and hydroelectric power plants across mountain regions (Schwanghart et al., 2016; Wester et al., 2019; Immerzeel et al., 2020) this decrease in meltwater supply will have major implications for vulnerability of downstream communities, directly affecting food and energy security; an estimated 70 million people could face food poverty in the Himalaya, potentially as early as 2050 (Immerzeel et al., 2010; Kääb et al., 2012; Soncini et al., 2016). The overall impact on vulnerability is likely to vary nationally, with countries such as Bhutan and Nepal identified as being particularly vulnerable due to relying on hydroelectric power and subsistence farming to drive social and economic development (Uddin et al., 2007; Carrivick &

Tweed, 2016; de Ruiter et al., 2020). Further, water scarcity will also be impacted by quality and access, which differs based on a range of socio-political and economic constraints (Seddon et al., 2020; Lynch, 2012), further altering communities' ability to cope with disaster. Regions where vulnerability is high will be disproportionally affected by these predicted water shortages than elsewhere (Drenkhan et al., 2023). With many glacial-fed rivers crossing international borders, future water shortages are likely to have transnational implications, and we could see a rise in political tensions.

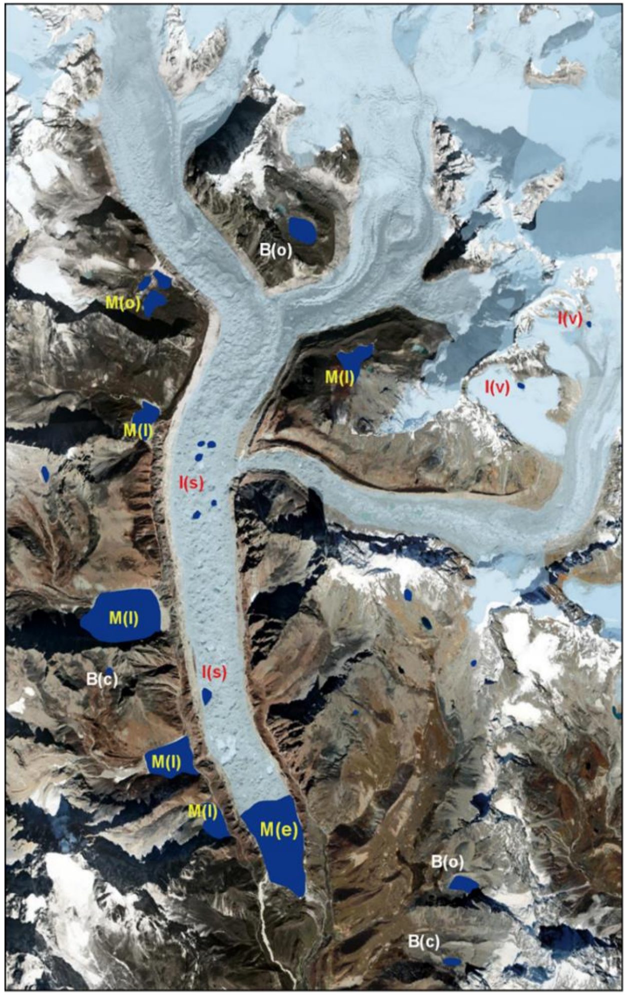
Alongside water shortages that are likely to pose a threat to downstream populations over the coming decades (Barnett et al., 2005; Bookhagen & Burbank, 2006; Immerzeel et al., 2010) the frequency of glacial hazards is also likely to increase (Quincey et al., 2007; Thompson et al., 2012). The widespread and accelerated retreat and thinning of glaciers observed since the 20th century (Hock et al., 2019; Zemp et al., 2019) has led to the exposure of large overdeepenings and subsequently the rapid expansion of numerous, large area glacial lakes (Shugar et al., 2020; Wang et al., 2020; Huggel, Carey, et al., 2020). Since 1990, the number, area, and volume of glacial lakes globally has increasing by 53%, 51% and 48% respectively (Shugar et al., 2020). Such lakes can be categorised according to their impounding barrier, and include: ice-dammed lakes, moraine-dammed lakes, landslide-dammed lakes, and bedrock-dammed lakes (Emmer et al., 2016; Emmer, 2017b; Ives et al., 2010). Globally, ice- and moraine-dammed lakes are the most common, resulting from the first stages of glacier retreat, and are both susceptible to failure by internal and external means, whilst bedrock-dammed lakes form in the later stages of deglaciation and are generally considered stable, with overtopping being the only pathway to failure (Emmer, 2017b; Westoby et al., 2014).

Glacial lakes have previously caused devastating floods across the Andes, Himalaya, and European Alps, with substantial loss of life and costly infrastructural damages (Carrivick & Tweed, 2016; Carey, 2005). Whilst historical records are incomplete, recorded events show glacier floods have directly caused at least 7 deaths in Iceland, 393 deaths in the European Alps, 5745 in South America and 6300 in central Asia (Carrivick & Tweed, 2016). In Peru, perhaps the most prominent and well-documented GLOF occurred on 13th December 1941, when Lake Palcacocha in the Quilcay basin drained, resulting in at least 1600 fatalities and major destruction in the town of Huaráz, 23 km downstream (Mergili et al., 2020). In Bhutan, one of the most destructive outbursts recorded in recent decades occurred in 1994, where 24 people were killed by a significant GLOF from Lugge Tsho (Richardson and Reynolds, 2000). A total of 91 households were affected by the flood in the region, with 12 houses damaged, 5 water mills washed away and major damage reported to pastureland on which the livelihoods of local people depends (Mool et al., 2001).

The continued and accelerated mass loss across mountainous regions has prompted major concerns over future water availability, which impacts peoples vulnerability to other hazards and make disaster more likely (i.e. when coping mechanisms are exceeded), as well as raising concerns regarding the development of potentially dangerous glacial lakes (PDGL), capable of producing large, catastrophic floods (Carrivick & Tweed, 2013, 2016; Schwanghart et al., 2016). Glacial mass loss is likely to continue in a delayed response to climate change, as a glaciers mass balance response time is not in equilibrium with atmospheric forcing leading to a lag-time in mass loss (Marzeion et al., 2018). Thus, with a variable but prevailing negative mass balance globally, glacial lakes are likely to continue to expand, and the frequency and magnitude of GLOFs likely to increase. Alongside this, changes to the frequency and magnitude of triggering mechanisms for GLOFs is likely to change (Haeberli et al., 2017), further adding to the uncertainty of future GLOF activity.

2.2 Glacial lakes

Accelerated glacial mass loss and retreat during the past few decades has resulted in the sustained expansion of existing glacial lakes, as well as facilitating the formation of new lakes (Linsbauer et al., 2016; Nie et al., 2017; Zhang et al., 2015; Khadka et al., 2018; Harrison et al., 2018; Shugar et al., 2020). Glacial lakes now exist across all glaciated regions, forming behind moraines, other glaciers, and landslide deposits, in bedrock depressions, in cirques and through coalescence of supraglacial ponds (Ageta et al., 2000; Sakai et al., 2000; Benn et al., 2001, 2012; Bolch et al., 2012; Thompson et al., 2012; Watson et al., 2016; Brun et al., 2017; Miles et al., 2017; Nie et al., 2017; Song et al., 2017; Bhambri et al., 2019). Various methods have been used to classify the glacial lake types, such as by damming body, relationship with/to neighbouring glaciers and formation (Mool et al., 2001, 2011; Maharjan et al., 2018). Using the most recently updated classification adopted by the 2018 ICIMOD (The International Centre for Integrated Mountain Development) report (Maharjan et al., 2018), glacial lakes can be classified into four main categories based on dam type; moraine, ice, bedrock and other (including landslide-dammed), with a further seven categories based on the process of lake formation (Figure 2.1). Glacial lakes act as 'hydrological buffers' that interrupt the delivery of sediment and meltwater downstream (Carrivick & Tweed, 2013; Irvine-Fynn et al., 2017). Furthermore, proglacial lakes (lakes at the front of a glacier that may be dammed by terminal moraines, bedrock, other glaciers and/or other barriers; Figure 2.1) can amplify ice loss from parent glaciers through processes of mechanical calving and subaqueous melting (Benn et al., 2007; Maurer et al., 2019; King et al., 2019; Watson et al., 2016) with lake-terminating glaciers losing mass more rapidly than land terminating glaciers.



Glacial lake type	Code	Definition
Moraine-dammed lake	**M**	**Lake dammed by moraine following glacial retreat.**
End-moraine-dammed lake	M(e)	Lake dammed by terminal moraines. Usually touches the walls of the side moraines, but the water is held back by the end moraine (dam). Lake is usually, but not necessarily, in contact with the glacier, and may have glacier ice at the lake bottom.
Lateral moraine-dammed lake	M(l)	Lake dammed by lateral moraine(s) (in the tributary valley, trunk valley, or between the lateral moraine and the valley wall, or at the junction of two moraines). Lake is held back by the outside wall of a lateral moraine, i.e., away from the former glacial path.
Other moraine-dammed lake	M(o)	Lake dammed by other moraines (includes kettle lakes and thermokarst lakes).
Ice-dammed lake	I	**Lakes dammed by glacier ice, including lakes on the surface of a glacier, lake dammed by glaciers in the tributary/trunk valley, between the glacier margin and valley wall, or at the junction of two glaciers.**
Supraglacial lake	I(s)	Bodies of water (pond or lake) on the surface of a glacier. This is the most common type of ice-dammed lake in the Nepal Himalaya.
Dammed by tributary glacier	I(v)	Lake dammed by glacier ice with no lateral moraines. Can be at the side of a glacier between the glacier margin and valley wall.
Bedrock-dammed lake	**B**	**Bodies of water that form as a result of an earlier glacial erosion process which accumulate in depressions after the glacier has retreated or melted away.**
Cirque lake	B(c)	A small pond occupying a cirque.
Other glacier erosion lake	B(o)	Bodies of water occupying depressions formed by the glacial erosion process. These are usually located on the mid-slope of hills, but not necessarily in a cirque.
Other glacial Lakes	**O**	**Lakes formed in a glaciated valley and fed by glacial, snow, and permafrost melt, but damming material not directly part of the glacial process, e.g. debris flow, alluvial, or landslide blocked lakes.**

Figure 2.1: Illustration of glacial lake types adapted from Maharjan *et al.*, (2018). M(e)= end-moraine-dammed lake, M(l)= lateral moraine-dammed lake, M(o)= other moraine-dammed lake, I(s)= supraglacial lake, I(v)= valley-glacier ice-dammed lake, B(c)= cirque glacier, B(o)= other bedrock-dammed lake, O= other glacial lake. Background image Google Earth 2021.

2.2.1 Moraine-dammed glacial lakes

After bedrock-dammed lakes, moraine-dammed glacial lakes (MDGLs) are the most common type of lake found globally, and most susceptible to failure (Mool et al., 2001; Komori, 2008; Bajracharya & Mool, 2009; Janský et al., 2010; Bolch et al., 2012; Narama et al., 2017; Ahmed et al., 2022). As a result, moraine-dammed glacial lakes have received the most scientific attention of all glacial lake types (Allen et al., 2022). The majority of lateral and terminal moraine complexes that impound present-day glacial lakes were constructed during the Little Ice Age; a globally synchronous period of glacial advance extending from the 15th century to the end of the 19th century (Clague, 2000; Neupane et al., 2019). Such dams are often un-vegetated, steeper than the angle of repose (the gradient required to hold debris; (Costa & Schuster, 1988)) and composed of unconsolidated, poorly sorted debris across a wide spectrum of clast sizes from silt to large boulders (Clague & Evans, 1994; Clague, 2000). As such, moraine dams are highly unstable and susceptible to failure (Ives et al., 2010; Westoby et al., 2014; Harrison et al., 2018; Neupane et al., 2019). Mapping the distribution of moraine-dammed glacial lakes globally has been carried out extensively in recent years (Fujita et al., 2013; Schwanghart et al., 2016; Nie et al., 2017; Maharjan et al., 2018; Ahmed et al., 2022). Moraine dams are usually classified as one of four types; push moraines, ice-thrust moraines, dump moraines or ice-cored moraines (Figure 2.2, Neupane *et al.,* 2019). Push moraines generally impound small lakes, have a low height, (<9 m) and are the most stable type of moraine (Figure 2.2a). Ice-thrust moraines are formed by the accumulation of sediment and debris eroded from the base of the glacier and excavated internally to the front of the glacier, while dump moraines are developed through the deposition of ice and sediment at the glacier front by the glacier itself (Figure 2.2b, c). Ice-cored moraines form as glaciers retreat, and terminal or marginal ice becomes incorporated into the terminal moraine structure (Figure 2.2d; Bolch *et al.,* 2019; Neupane *et al.,* 2019).

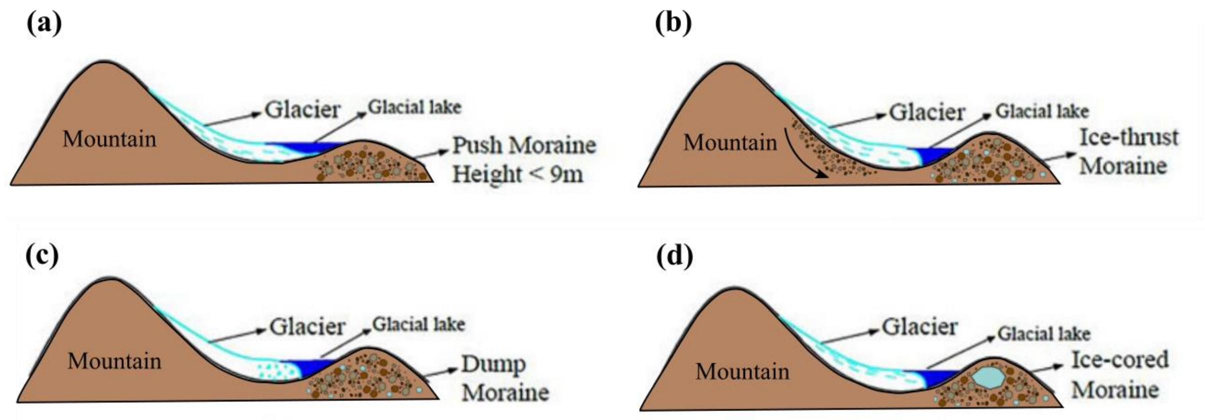


Figure 2.2: Description of key types of moraine-dammed glacial lakes, adapted from Neupane *et al.,* (2019). (a) Push moraine, (b) ice-thrust-moraine, (c) dump moraine and (d) ice-cored moraine.

Generally, moraine-dammed glacial lakes will form via one of two mechanisms: by pooling of meltwater in glacially overdeepened basins or via coalescence of supraglacial ponds. Providing the moraine is sufficiently consolidated and stable (Westoby et al., 2014), as a glacier retreats from its terminal position meltwater will collect in the deglaciated basin between glacier terminus and moraine (Clague, 2000; Frey et al., 2010; King et al., 2017, 2019; Begam & Sen, 2019). Typically, in order for a lake to establish here, an overdeepened glacial bed (the result of prolonged erosion at the glacier bed) must be present (Frey et al., 2010; Linsbauer et al., 2016). More than 5,000 moraine-dammed glacial lakes have been formed via this process across the Himalaya (Veh et al., 2020), with the largest found in central and eastern regions (e.g. Nepal and Bhutan).

In addition to meltwater collecting in overdeepenings following glacier recession, moraine-dammed glacial lakes can also form via supraglacial pond coalescence (Figure 2.3) (Ageta et al., 2000; Komori, 2008; Taylor et al., 2021). The presence of debris cover on glacier tongues causes an inverted mass balance gradient, whereby ablation is supressed at the terminus compared to the mid-elevations of the glacier, which in turn decreases driving stresses and glacier velocity (Benn *et al.,* 2001, 2012). The resulting glacier stagnation promotes the development of surface ponds (Reynolds, 2000; Bolch et al., 2008; Quincey et al., 2007, 2009; Veettil et al., 2016; King et al., 2017; Miles et al., 2017). If drainage through englacial or supraglacial conduits is impeded, ponds may expand and begin to coalesce, eventually forming a 'proto' moraine-dammed lake (Reynolds, 2000; Sakai et al., 2000; Benn et al., 2001; Wessels et al., 2002; Quincey et al., 2007; Röhl, 2008; Benn et al., 2012; Thompson et al., 2012; Tweed & Carrivick, 2015). This process of lake formation is more often associated with heavily debris-covered glaciers (Benn & Lehmkuhl, 2000; Reynolds, 2000; Benn et al., 2001; Thompson et al., 2012) as the uneven glacier surface gradients promotes ponding (Veettil et al., 2016; King et al., 2017). Some of the largest moraine-dammed glacial lakes in the Himalaya have been formed through supraglacial pond coalescence (Figure 2.3) since the early 1950s/1960s (Richardson and Reynolds, 2000a). These include Imja, Lower Barun and Thulagi lakes in Nepal (Haritashya et al., 2018) and Luggye and Thorthomi Tsho in Bhutan (Bajracharya & Mool, 2009; Komori, 2008).

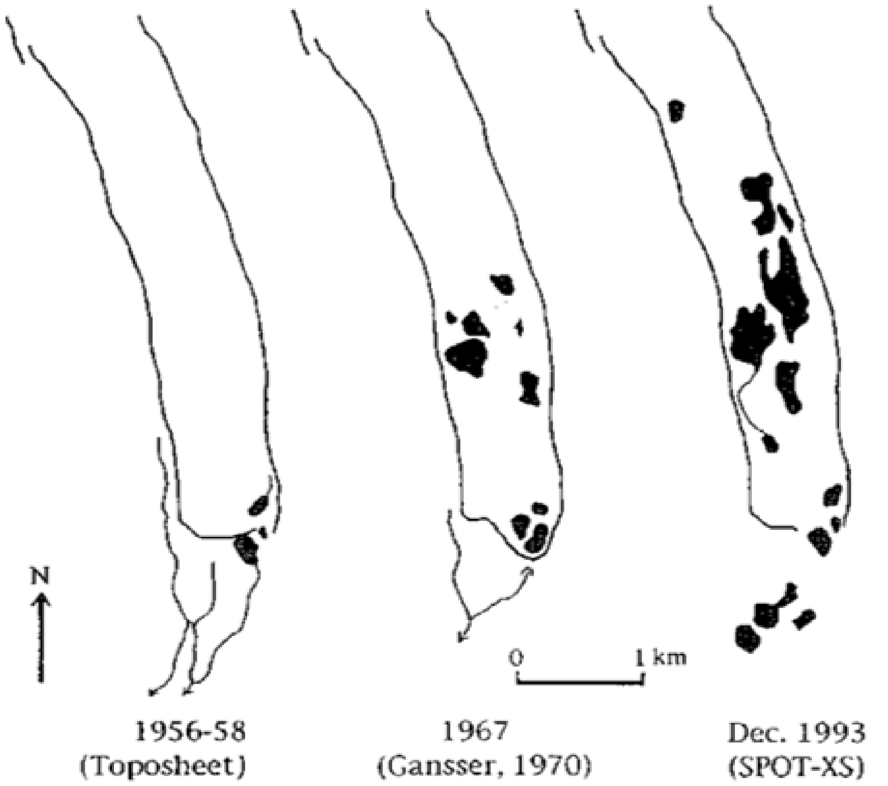


Figure 2.3: Example of supraglacial pond coalescing (Ageta et al., 2000). Visual depiction of the formation of supraglacial lake via pond coalescing on Wachey Glacier, Bhutan.

2.2.2 Ice-dammed glacial lakes

Ice-dammed glacial lakes form as a result of glacier ice loss (Carrivick & Tweed, 2013) and surge activity (Emmer, 2017b). As glaciers advance, they block river valleys resulting in the rapid formation of glacial lakes in tributary valleys (Reynolds, 2014; Round et al., 2017). Ice-dammed glacial lakes vary in size from smaller surface ponds to larger lakes, and are the origin of ~70% of all GLOFs worldwide (Carrivick & Tweed, 2016). Ice-dammed glacial lakes are strongly influenced by their proximity to ice, with their evolution dependant on it, reflected in cycles of formation, drainage, refill, and re-emptying as the damming ice changes (Tweed &

Carrivick, 2015). Regions in western HMA such as Karakoram, Kunlun and Pamir contain a large number of ice-dammed lakes due to the presence of surging glaciers. For instance, the recent surge cycle of Kyagar glacier in the Chinese Karakoram formed an ice-dammed lake on the Yarkant River which subsequently burst, generating a GLOF with volume exceeding 40 million m^3 (Figure 2.4; (Round et al., 2017). Some ice-dammed glacial lakes can evolve into moraine-dammed glacial lakes as they gradually separate from glacial ice due to glacier retreat (Tweed & Carrivick, 2015).

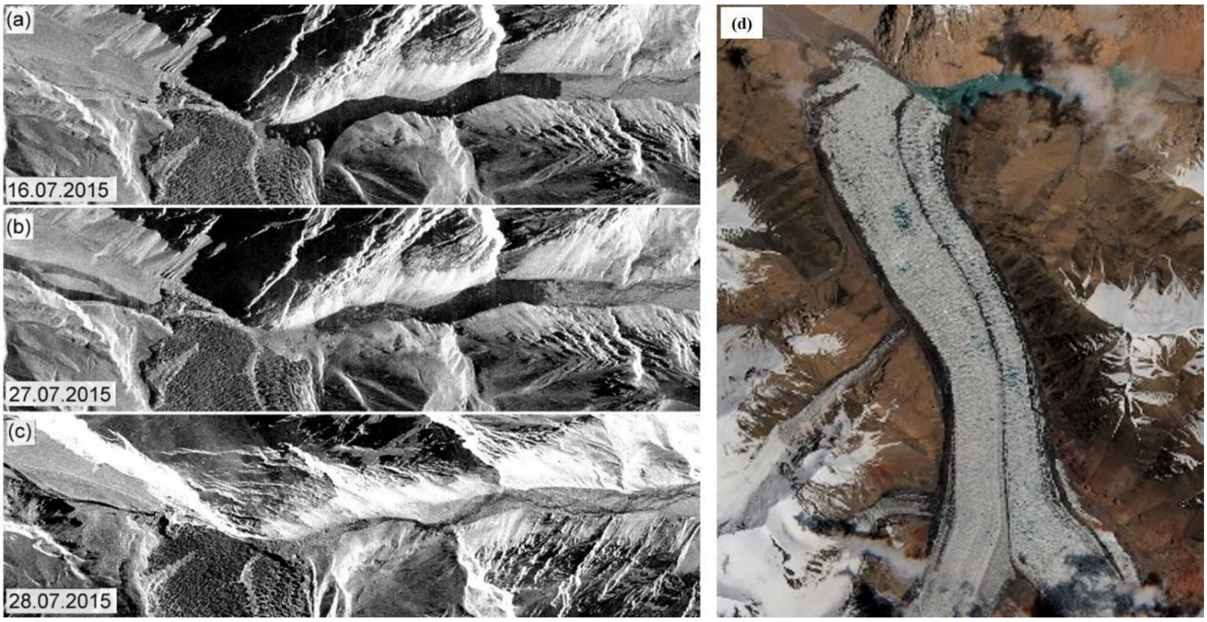


Figure 2.4: Example of ice-dammed lake formation at Kyagar glacier as a result of glacial surging (Round et al., 2017). (a-c) Radar backscatter images of the glacier terminus showing the lake (a) 11 days before drainage, (b) just after drainage began and (c) after the lake drainage. (d) Sentinel-2 optical image from 27.06.2016.

2.2.3 Bedrock and landslide-dammed glacial lakes

Similar to moraine-dammed glacial lakes, bedrock-dammed glacial lakes form as a result of glacier recession (Korup and Tweed, 2007; Emmer *et al.,* 2016; Emmer and Emmer, 2017; Tweed and Carrivick, 2015). As glaciers recede, areas that have been overdeepened by glacial-bed erosion are exposed, allowing meltwater to accumulate in place of the retreating glacier termini forming more stable, bedrock-dammed lakes (Mergili et al., 2013). The number of bedrock-dammed lakes is highly likely to increase, with modelled predictions for ~28,000 glaciers (40,775 km^2) across the HKH (Linsbauer *et al.* (2016)) revealing there are ~16,000 glacial overdeepenings with an area $>10^4$ m^2 and ~5,000 with a volume $>10^6 m^3$ across the mountain range. Landslide-dammed glacial lakes encompass all those impounded by deposits of slope movement, including landslides, rockslides/avalanches, and debris-flows behind which glacial meltwater can accumulate (Emmer, 2017b) and generally form in narrow valleys bordered by steep slopes (Clague & Evans, 1994; Korup & Tweed, 2007). Landslide-dammed glacial lakes are often transient due to poor cohesion of the damming material, leading to rapid erosion (Tweed & Carrivick, 2015).

2.3 Glacial lake outburst floods (GLOFs)

The term 'GLOF' is used to refer to glacially sourced floods, such as from the failure of a moraine-dam (Harrison et al., 2018; Neupane et al., 2019), ice-dam (Walder & Costa, 1996; Tweed & Russell, 1999; Roberts et al., 2003), volcanic 'jökulhlaups' (Carrivick et al., 2004; Russell et al., 2010; Dunning et al., 2013) and/or sub/englacial stores (Korup & Tweed, 2007). In this study, we focus on mountain glaciers, thus the term GLOF(s) is used in reference exclusively to the sudden discharge of stored water and sediment resulting from the failure of mountain glacial lakes. As the number and area of glacial lakes continue to increase globally (Bolch *et al.,* 2012; Gardelle *et al.,* 2011; Carrivick and Tweed, 2013; Brun *et al.,* 2017; Nie *et al.,* 2017; Song *et al.,* 2017; Sharma *et al.,* 2018; Shugar *et al.,* 2020), it has been suggested that the risk from glacial lake outburst floods increases (Rounce et al., 2016). The research interest in GLOFs has thus increased in recent years (Emmer, 2018), particularly in the Himalaya (Nie et al., 2018; Harrison et al., 2018; Veh et al., 2018, 2022, 2023) where the total death toll from all GLOF events is the highest worldwide (Carrivick & Tweed, 2016; Nie et al., 2018; Veh et al., 2018). GLOFs are complex phenomena, and each event is distinct, due to differences in: trigger mechanism(s), the geometry, composition, and structural integrity of the damming body, as well as the topography, geology, and morphology of the flood path (Richardson & Reynolds, 2000a; Emmer & Cochachin, 2013; Reynolds, 2014; Westoby et al., 2014). The peak discharge of a GLOF can reach several times higher than hydro-meteorological floods (Korup & Tweed, 2007; Schwanghart et al., 2016; Cook et al., 2018). As such GLOFs represent a contemporary hazard in high mountain regions (Carrivick & Tweed, 2016; Iwata et al., 2002; Schwanghart et al., 2016; Mal et al., 2021).

Whether a glacial lake produces a GLOF depends on a range of physical and geometric properties of the damming body, as well as characteristics of the surrounding topography and wider meteorological factors (Figure 2.5; Westoby *et al.,* 2014). However, a number of triggering and conditioning factors make some glacial lakes more prone to outburst than others (Westoby et al., 2014). Triggering factors include ice and/or rock avalanches and calving from the terminal glacier, inducing displacement waves (Clague & Evans, 1994; Hubbard et al., 2005; A. C. Byers et al., 2019), rapid inputs of water from glacial or meteorological sources

(Figure 2.5; Clague and Evans, 2000; Richardson and Reynolds, 2000a, 2000b; Korup and Tweed, 2007; Janský, Šobr and Engel, 2010; Worni *et al.,* 2012) or seismic activity (Osti et al., 2013; Gurung et al., 2017). Conditioning factors include lake volume, ice-cored moraine dam degradation and low width to height ratios (Figure 2.5; Westoby *et al.,* 2014; Neupane *et a*l., 2019).

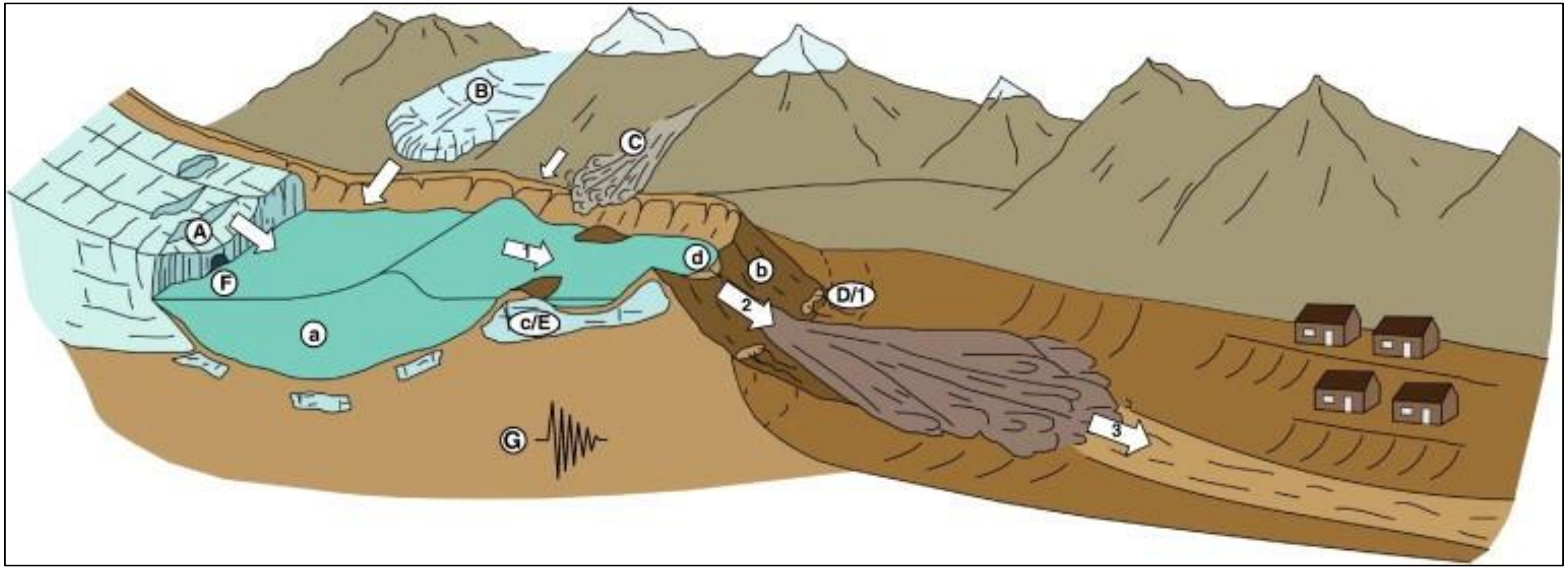


Figure 2.5: GLOF triggers, conditioning factors, and key stages of flood propagation (Westoby et al., 2014). Capital letters are plausible triggering factors for GLOFs: (A) calving glaciers; (B) snow and ice avalanches from hanging glaciers; (C) rockfall, debris flows and landslides; (D) dam settlement and/or piping; (E) melting ice-cores within the moraine; (F) rapid water input from supra-, en-, or subglacial sources; (G) seismic shaking weakening the cohesion of the moraine dam or triggering secondary gravitational mass movements. Lower case letters are conditioning factors for dam failure, including: (a) large lake volumes; (b) low width-to-height dam ratio; (c) degrading moraines from melting ice cores; (d) brim-full lake basins. Numbers are key stages of GLOF propagation: (1) displacement or séiche waves on the lake; (2) breach initiation, dam erosion and incision; (3) propagation of the flood wave(s) downstream.

2.3.1 Frequency, magnitude, and trends

Our ability to detect GLOFs has improved substantially as a result of advances in spaceborne earth observation (Komori et al., 2012), facilitating the compilation of global inventories of GLOFs, including those previously unreported based upon paleo evidence in the landscape (Carrivick & Tweed, 2016; Harrison et al., 2018; Shugar et al., 2020). Until recently, the trends in GLOF frequency had rarely been analysed, with suggestions being speculative and often contradictory. For instance, Richardson and Reynolds (2000a) speculated an increase in GLOFs since 1935, whereas Nie *et al.* (2018) reported an increase from 1975 to 1995 before a slight decrease post-1995. Harrison *et al.* (2018) conducted a global analysis of GLOF occurrence since 1850, reporting a global increase in frequency around 1930, which they attributed to a 'lagged' response to post-little ice age warming, followed by a decline in frequency since ~1975. However, Harrison *et al.*, (2018) also alludes to the successful stabilisation efforts at some moraine dams, such as in Peru and Switzerland, which could also account for the reduced frequency. The most recent analysis of GLOF frequency (Veh, 2019; Veh et al., 2019) reported an unchanged frequency between 1980 and 2017. Whilst their detection algorithms successfully detected existing GLOF cases alongside new cases, they suggest their inventory could have missed ~10% of all GLOFs in the Himalayan region in just the last three decades alone. Thus, contemporary reporting is still likely to miss a significant number of GLOFs, impacting our capacity to detect trends. We still lack context for many of the large floods detected, and many contemporary outbursts do not follow characteristics of historical ones. As such, further work is required.

2.3.2 Triggering mechanisms

Dynamic triggers (e.g. mass movement, calving, and earthquakes) are four times more common than self-destructive causes (ice-core degradation, settlement) for producing GLOFs (Emmer & Cochachin, 2013). The most frequently documented cause of GLOF events globally is by overtopping initiated by a mass movement, which accounts for half of events irrespective of location or dam-type (Lliboutry et al., 1977; Clague, 2000; Emmer & Cochachin, 2013; Westoby et al., 2014; Falátková, 2016; Nie et al., 2018; Neupane et al., 2019) (Figure 2.6). Reported causes show distinct regional patterns, for instance the second most common cause in the North American Cordillera is slope movements, dominated by intensive rainfall or snowmelt, whereas in the Himalaya it is self-destruction (Figure 2.6; Emmer and Cochachin, 2013). This reflects both the difference in climatic setting and conditions of dam formation;

glacial lakes in the North American Cordillera exist between 1,400 - 2,400 m a.s.l., where the intensity of rainfall and snowmelt is likely to be greater than higher elevations, whereas in the Himalaya they are generally found between 4,000 - 6,000 m a.s.l., where dams generally contain more buried ice than lower elevations (Yamada, 1998; Bajracharya *et al.*, 2007; Emmer and Cochachin, 2013).

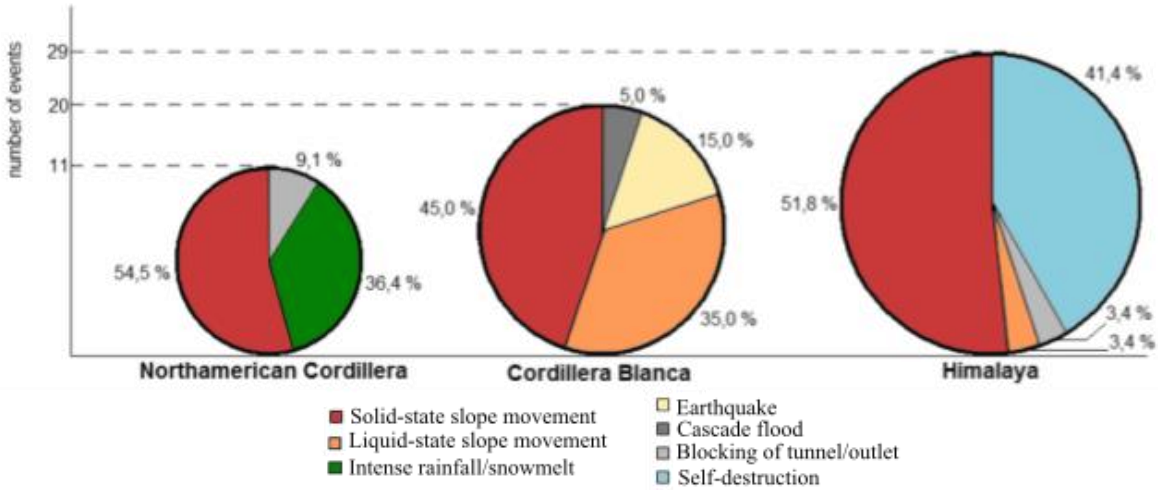


Figure 2.6: Causes of dammed lake failure from Emmer and Cochachin (2013). A representation of the causes of dammed lake failures in the Cordillera Blanca, the North American Cordillera, and Himalaya.

2.3.2.1 Mass movements

The waves generated by mass movements into a glacial lake fall into one of two categories; displacement waves formed by displacing the top of the water column, or 'séiche' waves where the entire water column is mobilised resulting in the repeat run-up of water in the enclosed moraine basin (Westoby et al., 2014; Neupane et al., 2019). Séiche waves are highly effective in eroding the dam structure due to the cyclic effects of waves (Hubbard et al., 2005), however both mechanisms can ultimately result in the failure of the dam (Figure 2.7). Given the mountainous topography in which glaciers exist, the presence of hanging glaciers on steep surrounding slopes and the exposure to erosion and weathering, it is not surprising that mass movement are the primary trigger of GLOFs worldwide. Whilst not all mass movement events can produce displacement waves capable of overtopping a dam, the sedimentation effect of small-scale landslide and rock avalanche events entering a glacial lake can also: (a) block outlets causing water levels to rise and (b) reduce the storage capacity and dam freeboard by raising the lake bed level (Figure 2.7; Ageta *et al.*, 2000; Korup and Tweed, 2007). Thus, there is also a long-term conditioning factor to consider, making documenting the frequency and magnitude of mass movement events critical for GLOF forecasting.

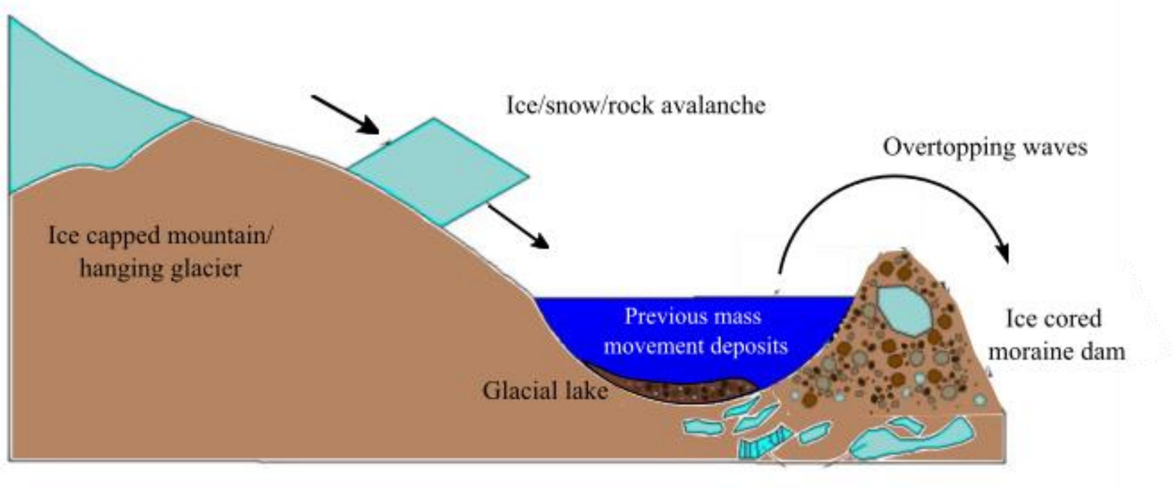


Figure 2.7: Process of wave overtopping mechanism resulting from mass movement entering a lake, adapted from Neupane *et al.,* (2019). The impact results in the generation of waves that overtop the moraine dam.

Climate change is exacerbating glacial retreat and ice loss, as well as increasing precipitation during the ablation season, thus the likelihood of major avalanche events (both ice and rock) and landslide/debris flow events occurring may also be increasing (Clague, 2000; Rounce et al., 2016; Schneider et al., 2011). Furthermore, as the climate continues to warm, glaciers in certain areas may also begin to transition from cold-based to more poly-thermal or in some cases, warm-based conditions in the coming years-to-decades (Reynolds, 2000). This transition could destabilise hanging ice and/or glacial tributaries due to the reduction in basal friction (Huggel, 2009), leading to increased frequency and magnitude of ice falls (Scapozza et al., 2019). Such a transition transition has already been observed in the Peruvian Andes (Vilímek et al., 2005; Kirschbaum et al., 2020). In addition, it has been suggested that as permafrost thaws at high elevations, steep mountain walls may become unstable, allowing more landslides/rock avalanches to detach and enter lakes (Haeberli et al., 2017). However, no study currently exists to test this hypothesis at elevations where it is likely to play a key role in the future (i.e. above 4,000 m a.s.l.; Veh, 2019). As lakes continue to expand up-glacier, they are also more likely to move into potential rock and ice avalanching zones (Lamsal et al., 2016; Linsbauer et al., 2016; Furian et al., 2021, 2022), increasing the possibility of a GLOF. For instance, at Imja Tsho, Nepal, hanging ice from surrounding mountain glaciers is at present too far away from the lake to act as a trigger (Rounce et al., 2016). However, predictions suggest that Imja could expand by 90 x 10^6 m^3 compared to its 2018 volume as Lhotse Shar retreats

(78.4 x 10^6 m^3 (Watson et al., 2020)), meaning the lake is likely to be exposed to mass movement events in the future, as it expands into higher elevations closer to unstable terrain.

2.3.2.2 Glacial calving

For glacial lakes in contact with their parent glacier, calving can become an important component of mass loss (Carrivick & Tweed, 2013; Maurer et al., 2016; King et al., 2019) as well as a potential trigger for GLOFs. Calving at lake-terminating glaciers generally occurs through undercutting, caused by melting and fragmentation at the waterline along crevasses, and occasionally by subaqueous calving of a submerged foot (Figure 2.8; Kirkbride and Warren, 1997; Richardson and Reynolds, 2000a; Watson *et al.,* 2020). Thermo-erosional notches develop at the waterline, creating shear and tensile stress in the overlying ice that leads to calving (Kirkbride & Warren, 1997; Röhl, 2006). Most calving events are minor, producing small scale displacement waves that are not capable of breaching a dam (Lala et al., 2018). However, calving of ice with sufficient mass can produce sizeable displacement or séiche waves capable of overtopping a dam (Neupane et al., 2019). It is worth noting however, that if glacier recession continues on its current trajectory, many lakes will eventually lose contact with their parent glaciers such that glacial calving and avalanching from hanging glaciers may become less relevant triggers for some glacial lakes in the long-term (Nagai et al., 2017; Veh, 2019).

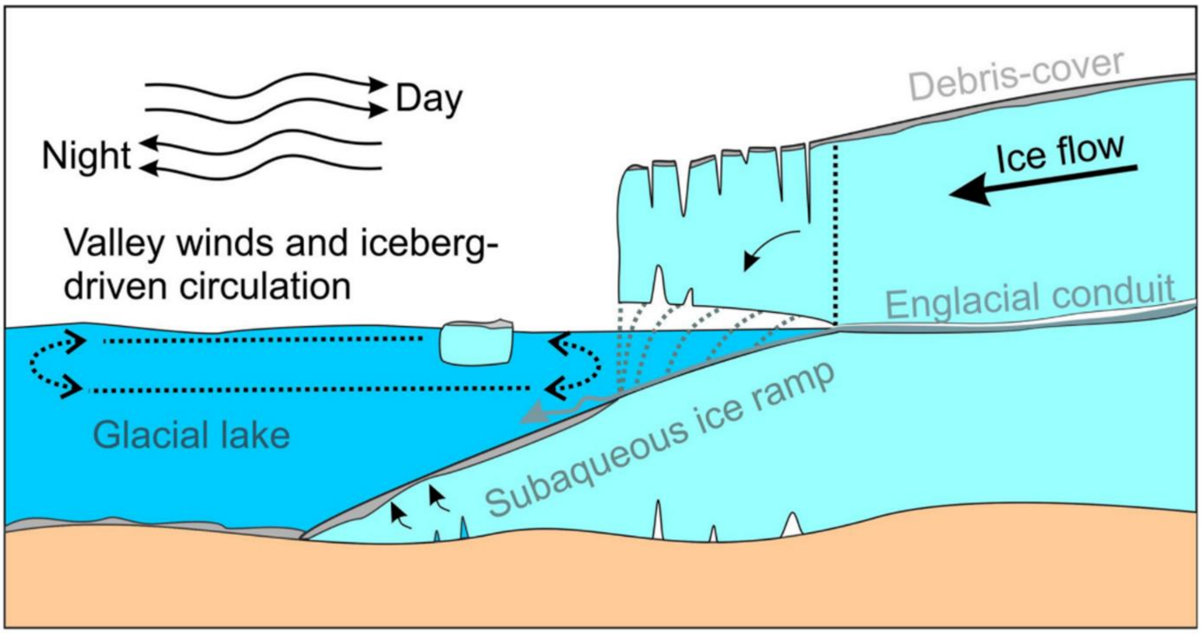


Figure 2.8: Conceptual diagram of glacial calving (Watson et al., 2020).

2.3.2.3 2.3.2.3 Piping

As a dammed glacial lake begins to fill, initial saturation and subsequent seepage of lake water within the dam structure is effective in changing the local physical structure and strength of the dam material (Figure 2.9a, Clague and Evans, 2000; Korup and Tweed, 2007; Liu *et al.*, 2013). This seepage through the dam carries away sediment particles, creating an exit hole in the damming wall (AWAL et al., 2011). Upon creating an exit hole, an elongated cavity will erode backward along a line of highest hydraulic gradient forming a "pipe" through which sediment is dislodged (Figure 2.9b; Liu *et al.*, 2013; Neupane *et al.*, 2019). Overtime this destabilises the structure of the dam, ultimately leading to collapse (Figure 2.9c). Moraine-dams and landslide-dams are made up of heterogeneous mass of unconsolidated or poorly consolidated materials (AWAL et al., 2011), have no through and/or overflow system, often contain massive or interstitial ice and rarely develop effective protective overflow systems (Moore et al., 2011). Furthermore, glacial sediments are readily erodible and become gradually less stable with time (Falátková *et al.*, 2019). As a result, the risk of catastrophic failure is high. In many cases of dam failure, piping is rarely the triggering factor, however the gradually weakening of the dam through removal of fine sediments within the structure by one or more pipes means a less exceptional mass movement event (e.g. smaller ice/snow/rock-avalanche) could initiate moraine dam failure, at a greater speed and magnitude (Clague, 2000; Liu et al., 2013).

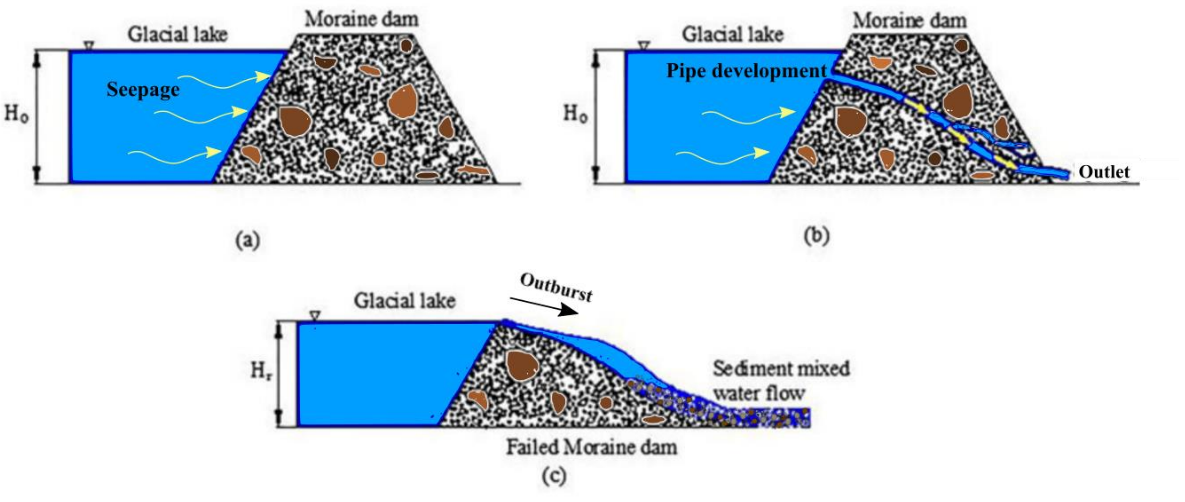


Figure 2.9: Three-step process of moraine-dam piping, adapted from Neupane *et al.*, (2019). (a) Seepage of lake water into the moraine begins to alter internal structure, (b) Formation and propagation of a 'pipe' within the moraine and (c) complete dam failure. (H_0 signifies initial water level and H_r signifies reduced water level after failure

2.3.2.4 Seismic activity

Earthquakes and other seismic activities play a dominant role in creating mass movements capable of triggering GLOFs (Veh, 2019). For instance, although no GLOFs were triggered by the earthquake on this occasion, severe ground shaking during the 2015 M_w 7.8 Gorkha earthquake in Nepal produced multiple landslides that directly hit nine glacial lakes (Kargel et al., 2016), whilst a large ice calving event was observed at Tasman Glacier in New Zealand around 30 minutes after the M_w 6.2 Christchurch earthquake in 2011 (Dykes et al., 2016). Furthermore, the shaking is effective in reducing dam cohesion and causing dam settlement. Thus, earthquakes are capable of triggering GLOFs both directly, via dam settlement and mechanical failure (Osti & Egashira, 2009; Osti et al., 2011), or indirectly through the impact of snow, ice and rock-avalanches leading to overtopping (Veh, 2019).

Seismic activity has been confirmed as the trigger of several lake outbursts (Lliboutry et al., 1977; Clague, 2000), with at least one GLOF in Patagonia (Harrison et al., 2006) and five GLOFs in the Cordillera Blanca (Lliboutry et al., 1977; Emmer, 2017b). By nature, many mountain ranges in which glacial lakes are located are tectonically active (Meyer et al., 2006). Thus, it has been argued that earthquake-triggered dam failure should be automatically considered as a trigger in the majority of GLOF cases (Westoby et al., 2014). Despite this, and their aptitude for causing mass movements, earthquakes are rarely regarded as potential GLOF triggers. This is partly justified, as the incidence of GLOF events only partially corresponds with the spatial pattern of earthquakes; in Nepal, there are many recorded GLOFs and a high number of earthquakes, but Bhutan has a higher number of GLOFs despite having no recorded impactful seismic activity (Veh, 2019). This is unusual given that Bhutan lies in a high earthquake hazard zone and should be more tectonically active; evidence of active faulting can be observed across the Lunana region which may indicate a build-up of stress (Osti et al., 2013; Meyer et al., 2006). The occurrence of a large earthquake here thus has the potential to cause catastrophic dam failure if the glacial lakes were to burst simultaneously (Osti et al., 2013; Meyer et al., 2006). It should be noted that records of earthquakes may be incomplete and observed trends may not be accurate. Additionally, a consideration for seismic gaps should be taken, whereby absence of GLOFs could correspond to absence of seismic activity. However, it remains important that the potential impact of earthquakes is fully accounted for, both for current and future risk models.

2.3.2.5 Meteorological inputs

The influx of glacial meltwater into a dammed glacial lake as a result of the sudden release of a supraglacial, englacial or subglacial reservoir can also lead to failure (Clague, 2000; Worni et al., 2012). Through rapidly increasing the lake volume and water level, the shear resistance of the damming body is temporarily exceeded, leading to the enlargement and downcutting of and existing spillway, the initiation of a new channel or outburst (Clague, 2000). The role of meltwater inputs, particularly from supraglacial ponds/lakes, in triggering GLOFs has received limited scientific attention, and is not usually considered as a criterion for identifying potentially dangerous glacial lakes (Gurung et al., 2017).

The sudden injection of rainwater as a result of heavy or prolonged precipitation, as well as sustained snowmelt associated with a period of increased air temperatures, has been observed to trigger dam failure, the most well-known to be the Chorabari GLOF of 2013, in Kedarnath India (Worni et al., 2012; Das et al., 2015; Gurung et al., 2017; Korup & Tweed, 2007; Janský et al., 2010). Whilst intensive rainfall is rarely documented as the primary trigger of GLOFs outside of the North America Cordillera (Emmer & Cochachin, 2013), and as most lakes exist at elevations too high for precipitation to fall as rain, it is often identified as a contributing factor due to the destabilisation of surrounding slopes, resulting in mass movements that may initiate failure (Emmer & Cochachin, 2013). For instance, two days of continual rainfall prior to the Lemthang Tsho GLOF in July 2015 in Bhutan likely destabilised the steep scarp at the supraglacial ponds that ultimately triggered the outburst (Gurung et al., 2017). Observations of glacial lake and pond activity suggest heightened drainage during summer seasons (Taylor et al., 2021), with 95% of all historical GLOFs in the HMA occurring during spring and summer, which are periods of enhanced ablation and melt of snow and ice in the Northern Hemisphere and monsoonal periods for much of the HMA (Veh, 2019). Thus, atmospheric triggers, along with inputs from supra-, en- and sub-glacial sources remain an important source of uncertainty for GLOF hazard and risk studies.

2.3.3 Conditioning mechanisms

While the failure of a glacial lake dam is most commonly considered a result of external triggers, a number of conditioning factors can also predispose glacial lake dams to fail, such as: low dam freeboard (vertical distance from the surface of the lake to the dam crest (Reynolds, 2009)); a high height-to-width ratio (Huggel et al., 2002; Quincey et al., 2007; Emmer & Vilímek, 2013); sedimentological and structural characteristics (e.g. loosely consolidated, saturated sediment); and the presence of degrading permafrost and/or a massive, buried ice core (Richardson & Reynolds, 2000b). These factors generally operate over long periods of time (years to decades) and can result in the gradual degradation of the dam eventually leading to failure without any obvious external trigger, often referred to as 'self-destructive' (Emmer & Cochachin, 2013; Yamada, 1998). In the Himalaya, 'self-destruction' is cited as the second most common cause of GLOFs (Emmer & Cochachin, 2013).

In such cases, failure is most often initiated when the hydrostatic pressure (the pressure a column of water exerts on the moraine) exceeds the structural capacity of the dam (Richardson & Reynolds, 2000b; Emmer & Vilímek, 2013; Rounce et al., 2016). Hydrostatic pressure can be altered in a number of ways, but primarily through an increase in lake level (Yamada, 1998; Vilímek et al., 2005). Whilst the disruption of the structural integrity enables rupture by hydrostatic pressure, it also decreases the ability of the dam to withstand external triggers (e.g. landslides, avalanches etc.) (Emmer & Cochachin, 2013). Thus, solely self-destructive dam failure is a function of time, constituting not one single process but rather a group of processes (Emmer & Cochachin, 2013). However, these conditioning factors result in a continued decrease in dam stability, such that a relatively minor trigger is needed to cause failure.

Particularly for moraine-dammed glacial lakes, during periods of glacier downwasting, ice at the glacier margins often becomes insulated by thick debris cover, and can be incorporated within terminal-moraine structures forming substantial ice cores within an 'ice-debris complex' (Figure 2.7, Bolch *et al.,* 2019). Cores can represent up to 90% of the moraine volume (Costa & Schuster, 1988; Richardson & Reynolds, 2000b) and represent weak points within the moraine structure that have been observed to thaw with changing temperature conditions (Richardson & Reynolds, 2000a, 2000b). Over time these buried ice cores begin to degrade by ablation and/or thermokarst development, via the degradation of permafrost (Figure 2.10), creating conduits for dammed water to drain through (*piping,* see Figure 2.9) which undermines the structural integrity of the dam and therefore increases the propensity for failure (Figure 2.10b; Richardson and Reynolds, 2000a, 2000b). This was observed at Lugge Tsho, Bhutan, where a large-scale failure of its terminal moraine slope was caused by ice core degradation (Ageta et al., 2000). As the moraine degrades, settlement and thus lowering of the dam crest decreases the *dam freeboard* (Figure 2.10; Reynolds, 2009) decreasing the minimum amplitude required for a displacement wave to overtop the dam, and/or reducing the capacity of the dam to influxes of water from melting or rainfall (Huggel et al., 2002; Westoby et al., 2014; Neupane et al., 2019). As a result, the role of buried ice and the unpredictability of subsurface drainage channel development within moraines has been highlighted as being particularly important in the context of outburst susceptibility (Falátková et al., 2019).

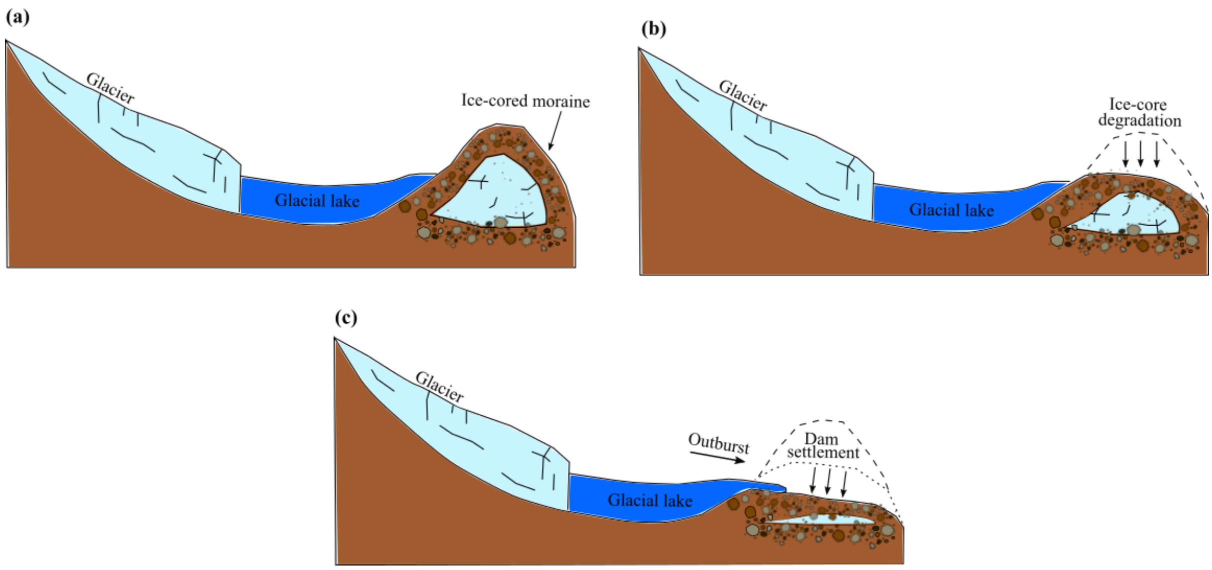


Figure 2.10: Process of dam settlement caused by ice-core degradation. (a) ice-cored moraine, (b) ice begins to degrade, lowering the moraine as material is redistributed and (c) settlement of the dam reduces the dam freeboard and thus leads to outburst.

2.3.4 Detecting and forecasting outbursts

The capabilities of remote sensing and Geographic Information Systems (GIS) have improved markedly over recent years. Coupled with wide availability and affordability of multi-temporal imagery and topographic data from space and airborne platforms, this has facilitated the growth of remotely sensed natural hazard-based assessments (Rounce et al., 2017; Begam & Sen, 2019; Bazai et al., 2021; Ahmed et al., 2021; Allen et al., 2019). Studies are generally focussed on individual glaciers or regions, with most based in mountainous regions. With such regions normally inaccessible for field studies due to terrain, working conditions and cost, remote sensing has allowed research to be conducted in previously unstudied areas, substantially expanding our understanding, and consolidating our knowledge base.

2.3.4.1 Determining trigger mechanisms

Mass movement events with the potential to trigger GLOFs, such as avalanches or landslides with initiation zones in close proximity to glacial lakes, can be identified using spectral band segmentation, thresholding, and DEM-derived slope classification in combination with detailed aerial photography or high-resolution satellite imagery (Margreth & Funk, 1999; Salzmann et al., 2004; Quincey et al., 2005; Allen et al., 2008). For instance, potential trigger zones for mass movement (avalanche and/or landslide) have been identified from Landsat imagery, in both glacierised and non-glacierised areas (Rounce et al., 2016) by considering snow/ice avalanche prone areas that have slopes >45° (Alean, 1985) but <60°, as mass is unlikely to accumulate past this threshold (Osti et al., 2011; Shea et al., 2015), and rockfall areas that have slopes >30° (Bolch et al., 2012). The location of potential contemporary detachment from hanging glaciers has also been carried out using satellite imagery, by identifying crevasses and faults in the ice (Schneider et al., 2010; Komatsu & Watanabe, 2014), as well as future potential trigger zones through mapping topography surrounding glacial lakes (Frey et al., 2010). This process is laborious however and relies on high-resolution data that is not always available.

GIS based methods remain the most viable option for predicting mass movement events due to their remote locations (e.g. Frey *et al.,* (2010)). However, the identification of more subtle features such as bedrock tension cracks, overhanging glacier seracs or landslide scars remains challenging (Huggel et al., 2006), even with the use of modelling and fine resolution spaceborne and airborne imagery available. The use of feature tracking to assess slope movement has been used successfully post-event in the Chamoli district, Uttarakhand, India (Van Wyk De Vries et al., 2022), demonstrating the potential of high-resolution optical satellite image feature tracking for monitoring the stability of high-risk slopes as precursors to GLOF events, however has this approach has not be used widely yet. Furthermore, for time-series analysis or live tracking, satellite imagery is limited by artefacts such as cloud cover and shadowing, which is especially prevalent in the mountainous terrain that often surround glacial lakes, making identification and travel trajectories difficult to assess and forecast. More research is needed to quantify the volume of ice that may detach from hanging glaciers (similar to estimates for rock avalanches achieved by Hubbard *et al.* (2005)) in order to determine the potential characteristics of ensuing displacement waves, dam failure and related flood pathways. This has been successfully simulated for hanging Alpine glaciers (Pralong & Funk, 2005), but not over larger spatial scales.

Modelling the response of a glacial lake-dam to an earthquake (Dai et al., 2005) is especially difficult due to the unpredictability associated with estimating the timing and magnitude of seismic events, as well as the uncertainties in dam composition and response to shaking. However, deploying geotechnical field investigations can provide an indication of how a moraine dam may respond to different levels of ground shaking. The uncertainties associated with accurately forecasting ground shaking mean accurate estimates of the probability of dam failure in a future earthquake are difficult. The projected warming of 2.1 ± 0.1°C in the

Himalayan regions until the end of the 21st century (Kraaijenbrink et al., 2017) will likely form new lakes, particularly moraine-dammed and landslide-dammed (Linsbauer et al., 2016), as well as destabilise ice cores within moraine-dammed lakes (Haeberli et al., 2017), meaning that more lakes, with less stable moraines are likely to be exposed to shaking due to earthquakes. The likelihood of GLOFs may increase with climatic change, due to increased avalanching, more intense rainfalls and warmer temperatures degrading moraine dams. Precisely how and when the frequency of GLOFs will change in the future remains uncertain.

2.3.4.2 Monitoring conditioning mechanism

Quantifying dam settlement through surface lowering has been achieved by both in-situ monitoring (Reynolds, 1992; Bolch et al., 2011; Scapozza et al., 2019) and through the assessment of high-resolution digital terrain models (DTM) (Irvine-Fynn et al., 2011; Bennett & Evans, 2012; Sawagaki & Lamsal, 2013). However, both methods present disadvantages; in-situ monitoring is challenging logistically, whilst the use of DTMs is often impaired by errors that prevent meaningful results (Westoby et al., 2014). Currently, the most effective method of monitoring changes in dam structure is by deploying geophysical techniques. Carrying out geophysical investigations on debris-covered glaciers and large moraine-dams in particular is a significant logistical and scientific challenge (Reynolds, 2006) but has been successfully used to identify ice cores. For instance, Tshering (2009) deployed ground penetrating radar (GPR) on the terminal moraines of Lugge Tsho, whilst both GPR and Electrical Resistivity Tomography (ERT) have been used at Tsho Rolpa (Reynolds, 2006). Geophysical methods like GPR and ERT are highly effective in mapping the presence of buried ice, as well as identifying areas of piping (Reynolds, 2006). Obtaining such 3D information is of significant importance for hazard assessments, and essential for integrating into dam-breach models. Modelling moraine dams with interstitial ice, ice lenses, ice cores or permafrost (Hambrey et al., 2008; Worni et al., 2012) is challenging (Westoby et al., 2014). Following an in-situ assessment of the extent of ice within the moraine using geophysical techniques (Reynolds, 2006, 2013), dams can be treated as composite structure (i.e. assume simple composition) for overtopping failure simulations, removing the need for more complex internal ice modelling (Westoby *et al.*, 2014). However, this information is rarely available for glacial lakes due to their remoteness and the labour-intensive nature of conducting geophysical field surveys on dams.

Drainage over a dam can be detected using high resolution imagery, however outflows, through-flows or piping currently cannot be addressed through remote sensing studies (Bolch *et al.*, 2012; Rounce *et al.*, 2016). Given the composition of the dam could indicate the likelihood of piping, field investigations are important and increasingly deployed. For instance, Liu, Tang, and Cheng (2013) analysed the composition of moraine-dams at Guangxieco Lake and found a poorly graded terminal moraine indicative of piping mechanism. This is particularly important for lakes where seepages have already been observed, like Thorthormi Tsho in Bhutan (Ageta et al., 2000; Komori et al., 2012). Other methods for identifying pipe development in the field include a transition from 'normal' clear-water seepage outflow to a cloudy seepage with minimal discharge variation (Wahl, 2004).

2.3.4.3 Spatial and temporal trends

The amount of information available on outburst events varies considerably globally (Carrivick & Tweed, 2016); due to their remote location, many GLOF events occur unnoticed (Bajracharya *et al.,* 2007), making it difficult to determine the exact cause. The analysis of multi-temporal satellite imagery in recent years has revealed many unnoticed, even large, GLOFs (Emmer, 2017b; Komori et al., 2012; Nie et al., 2018; Veh et al., 2018). This suggests the current GLOF inventories significantly underestimate the true number of events, making it difficult to establish trends in trigger mechanisms around the globe. This is particularly true of High Mountain Asia, where an analysis of just 10% of the Hindu-Kush-Himalaya revealed 10 previously unreported GLOFs between 1988 and 2016 (Veh et al., 2018), indicating current records have captured a fraction of historic events.

A number of studies have highlighted an apparent temporal pattern in GLOF occurrence globally, with outbursts generally occurring during warmer, wetter periods (Bhargava et al., 2008; Yamada, 1998; Kattelmann, 2003; Mool et al., 2001; Emmer & Cochachin, 2013; Carrivick & Tweed, 2016; Falátková, 2016; Harrison et al., 2018; Nie et al., 2018; Veh, 2019; Taylor et al., 2021). For instance, one study found that of 128 known GLOF events in the Himalaya almost all occurred in June-September (Falátková, 2016), while Nie *et al.,* (2018) found 18 of 27 occurred in June-August and Veh (2019) found 20 of 22 newly detected GLOFs occurred between June and September. Given the most frequent cause of moraine-dammed glacial lakes failure is mass movement (Clague, 2000; Richardson & Reynolds, 2000a; Emmer & Cochachin, 2013; Westoby et al., 2014; Falátková, 2016) and the frequency of such triggers has been seen to increase during the ablation season (Richardson & Reynolds, 2000a) this trend is unsurprising. Despite this, the seasonal variability inherent in GLOF hazard has been largely ignored in holistic GLOF risk assessments.

In summary, the majority of existing methods for monitoring mechanisms for GLOFs exist for either local or regional studies but are all subject to uncertainty. As such, there is a preference to combine methods to produce more accurate local scale studies, with regional studies less popular and global studies near non-existent. Further, studies are generally static, with few considering temporal variation in hazard. This is a key limitation of current GLOF studies.

2.4 Hazard, vulnerability, exposure, and risk

The proliferation of glacial lakes in high mountain regions, coupled with increases in both population and infrastructure at higher elevations (Schwanghart et al., 2016), has resulted in increased exposure to GLOFs over the last 30 years (Bajracharya *et al.,* 2007). As such, there has been an intensification of research into GLOF hazard, vulnerability, and risk (Emmer & Vilímek, 2013). Previous studies have estimated hazard and risk of individual glacial lakes and/or for glacial lakes within specific regions such as; North America (Clague, 2000), South America (Emmer & Vilímek, 2013; Iribarren Anacona et al., 2015; Cook et al., 2016; Emmer et al., 2016; Motschmann, Huggel, Muñoz, et al., 2020), Central Asia (Bolch et al., 2008; Janský et al., 2010; Dubey & Goyal, 2020) and the Himalaya (Ives et al., 2010; Mool et al., 2011; Ashraf et al., 2012; Worni et al., 2013; Aggarwal et al., 2017; Rounce et al., 2016, 2017; Kougkoulos et al., 2018; Washakh et al., 2019). A range of terms are used interchangeably and inconsistently in GLOF studies. The lack of consistency in terms is a challenge for GLOF research, with studies often not comparable or transferable due to the different definitions, methods and parameters chosen. However, most studies seek to determine which glacial lakes have the potential for outburst, in order to inform, mitigate and prevent socio-economic impacts (e.g. Rounce *et al.,* 2017). In this thesis, GLOF risk is defined as a function of hazard, exposure, and vulnerability, with the relative importance of each on driving GLOF risk the key focus. In Chapter 5, the phrase 'GLOF danger' is used rather than risk, given no metric of vulnerability is included.

2.4.1 Hazard

Generally defined as the potential occurrence of a natural physical process or phenomenon that may cause disruption, damage and/or loss of life (Reynolds, 1992, 2009; GAPHAZ, 2017; UNDRR, 2022) hazard is assessed as the function of the probability that an event will occur and its expected magnitude (GAPHAZ, 2017). Whether glacial lakes represent a significant hazard depends on their '*probability'* of outburst, i.e. how likely they are to outburst, as well as their potential flood '*magnitude,'* i.e. volume of outburst, distance of travel, inundation depths (Quincey *et al.,* 2007). Thus, hazard assessments seek to analyse the factors increasing a glacial lake's probability for outburst, as well as determine the magnitude of any subsequent outburst (Dubey & Goyal, 2020; Mool et al., 2011).

2.4.1.1 Probability of outburst

There are numerous factors that can alter a glacial lake's probability to outburst, including; characteristics of the lake, the moraine dam, the parent glacier, and surrounding topography (Richardson and Reynolds, 2000; Kougkoulos *et al.,* 2018). A wide range of parameters that make glacial lakes prone to outburst are commonly evaluated in hazard studies (Table 2.1; Figure 2.11). These parameters are then examined in sequence to determine if the condition(s) in question are met or whether a parameter exceeds a set threshold (Rounce *et al.,* 2016). Following the analysis of selected parameters, glacial lakes are then assigned to a pre-defined category qualifying their potential hazard (e.g. Figure 2.12). Establishing GLOF hazard is still difficult, despite decades of research and advances in data. Several parameters are generally used for inferring probability of outburst, yet only a few are used consistently; there is no standardised categorisation that exists within the discipline, with studies each defining their own categories or using adaptations of previous. For instance, the approach of Worni *et al.,* (2013), which categorised lakes as 'critical,' 'potentially critical' or 'not-critical,' was updated and defined as 'very-high,' 'high,' 'medium,' 'low' or 'no' hazard by Rounce *et al.,* (2016).

Panel ID	Int.	Mag	Parameter	ID	Source
a) Glacier			Crevassed snout above lake	2	2, 3, 4, 5, 16
			Distance between lake and glacier	4	2, 4, 5, 6, 13, 14, 17, 23, 24, 28, 30
	*	*	Glacier activity (advance/retreat, calving)	6	2, 5, 14, 16, 30
			Glacier area	5	5, 13, 16, 17
			Presence of stagnant ice at glacier snout	8	13, 14
			Reaction to climate	7	11
			Snout steepness	3	17, 20
			Supra- and en-glacial drainage	1	2, 4, 5, 11, 13, 17, 28
			Slope between glacier snout and lake		5, 8, 27
b) Lake	*	*	Lake area	3	4, 5, 10, 14, 16, 17, 20, 23, 24, 29, 30
			Lake area change	4	4, 5, 11, 14, 15, 16, 17, 25, 30
			Lake depth	1	4, 21, 24
	*	*	Lake volume	2	4, 8, 13, 21, 24, 28
	*	*	Dam freeboard	5	2, 3, 4, 6, 15, 18, 19, 21, 27, 28
c) Surrounding Lake	*	*	Calving from hanging glaciers	1	5, 16
			Compound risk	6	8,
	*	*	Hydro-meteorological situation	4	4, 5, 9, 13, 16, 19, 28, 30
	*	*	Mass movements (snow/ice/rock avalanches/landslides)	2	1, 2, 3, 4, 5, 8, 9, 11, 13, 14, 15, 16, 18, 19, 21, 23, 25, 29
	*		Permafrost	5	16
	*		Seismic activity	3	4, 5, 15, 16, 19, 25, 28
			Steepest slope surrounding lake		7, 11, 14, 28
d) Moraine Dam			Armoured overflow channel (natural or technical)		2, 3, 5, 12, 16
	*		Dam composition	8	5, 10, 17
			Dam distal flank steepness		1, 4, 13, 15, 17
			Dam top width	5	13, 20
	*	*	Dam type	6	4, 5, 8, 12, 15, 17, 18, 26, 27, 28
			Dam width and/or height ratio	3	1, 3, 4, 9, 10, 12, 13, 15, 16
			Piping and/or seepage	4	2, 3, 4, 5, 8, 12, 13, 15, 16, 20
	*		Presence of buried ice/ ice core	7	1, 2, 5, 8, 9, 10, 11, 13, 14, 16

	*	Presence of stabilising vegetation	2	1
	*	Slope of lateral moraine	1	2, 5, 16, 29
e) Downstream				
		Evidence of previous GLOF	4	2, 5, 16
		Infrastructure	2	22, 25
		Land-use	1	22
	*	River channel morphology	3	5
		Population		25

1: Costa and Schuster (1988); 2: Grabs and Hanisch (1992, 1993); 3: Clague and Evans (2000); 4: Zapata (2002); 5: Mool *et al.* (2001); 6: O'Connor *et al.* (2001); 7: Huggel *et al.* (2002); 8: Reynolds (2003); 9: Huggel *et al.* (2004); 10: McKillop and Clague (2007a, 2007b); 11: Bolch *et al.* (2008); 12: Hegglin and Huggel (2008); 13: Wang *et al.* (2008); 14: Bolch *et al.* (2011); 15: Mergili and Schneider (2011); 16: Mool *et al.* (2011); 17: Wang *et al.* (2011, 2012); 18: Worni *et al.* (2013); 19: Emmer and Vilímek (2013); 20: Emmer and Vilímek (2014); 21: Vilímek *et al.* (2015); 22: Wang *et al.* (2015); 23: Allen *et al.* (2016); 24: Cook *et al.* (2016); 25: Rounce *et al.* (2016); 26: Carrivick and Tweed (2016); 27: Petrov *et al.* (2017); 28: Kougkoulos *et al.* (2018); 29: Allen *et al.* (2019); 30: Fischer *et al.* (2020).

Table 2.1: Review of the parameters used in GLOF hazard assessments. The table collates to Figure 2.11. Each parameter has a matching panel ID (a-e), and an assigned number ID that matches the figure. For example, Panel ID *a*, number ID *2* points to a visual representation of a glacier-based parameter – Crevassed snout above lake. Parameters marked with a * denote factors that can influence GLOF intensity and magnitude.

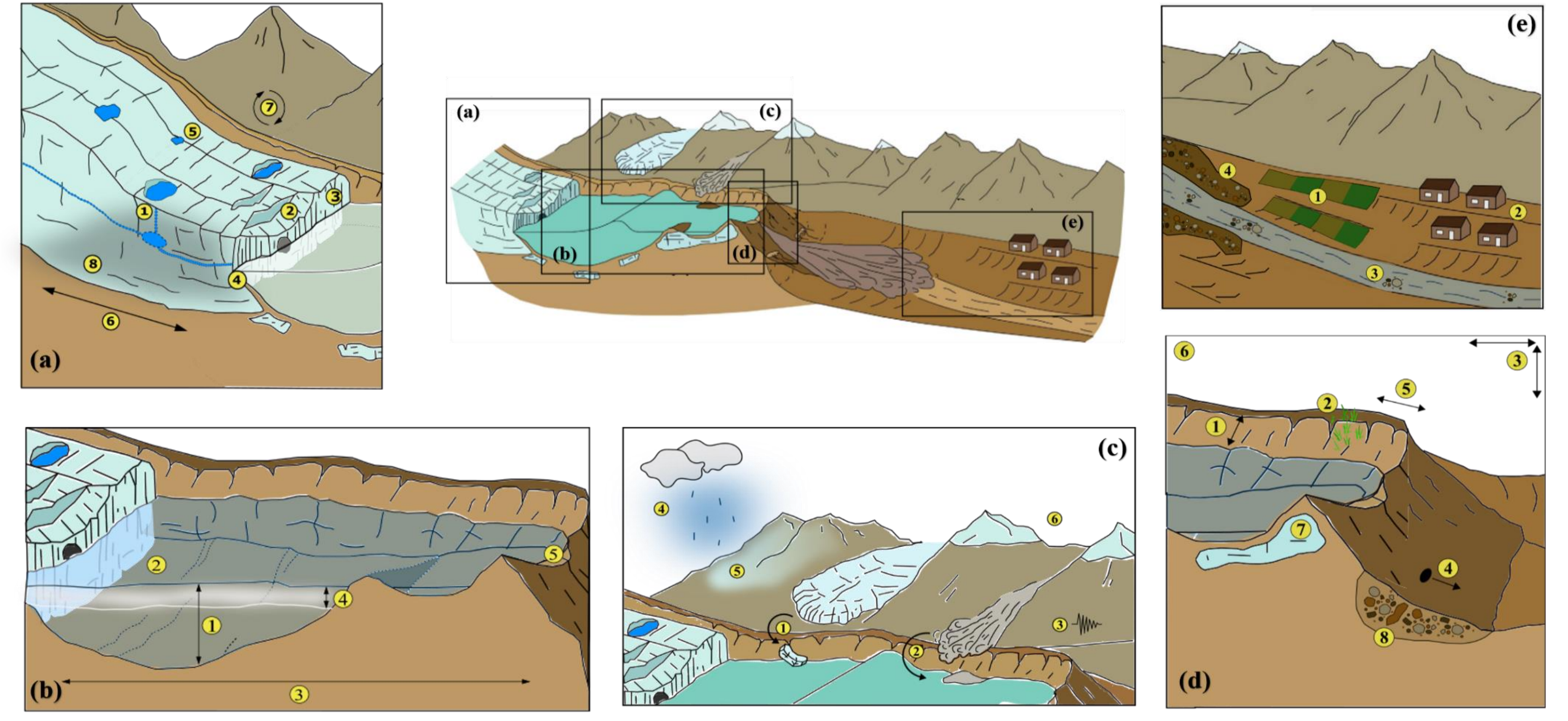


Figure 2.11: Conceptual diagrams showing GLOF triggers mechanisms grouped according to origin, adapted from Westoby *et al.*, (2014). Clockwise from top left; (a) key glacier parameters; 1) supra- and englacial drainage, 2) crevassed snout above lake, 3) snout steepness, 4) distance between glacier and lake, 5) glacier area, 6) glacier activity (advance, retreat etc.), 7) reaction to climate change, 8) stagnant ice at glacier snout. (b) key lake parameters; 1) lake depth, 2) lake volume, 3) lake area, 4) lake area change and 5) dam freeboard. (c) key surrounding parameters; 1) calving from hanging glaciers, 2) mass movements and/or ice, snow, and rock avalanches, 3) seismic activity, 4) hydro-meteorological setting, 5) permafrost degradation, 6) compound risk. (d) key moraine parameters; 1) slope of lateral moraine, 2) presence of stabilising vegetation, 3) width/height radio, 4) piping and/or seepage, 5) dam top-width, 6) dam type, 7) presence of buried ice, 8) dam composition. (e) Key downstream parameters; 1) land-use, 2) infrastructure, 3) river channel morphology, 4) evidence of past GLOF/debris-flows/flash-floods.

The process of parameterisation is further complicated by the fact parameters are often interconnected and a GLOF can be caused by multiple triggers (Fujita *et al.,* 2013; Falátková, 2016; Rounce, Watson and McKinney, 2017). For instance, rockfall/landslide susceptibility is controlled by a composition of multiple parameters (e.g. slope steepness, seismic activity, permafrost) therefore each individual criteria must be assessed to avoid bias (Kougkoulos *et al.,* 2018). Previous studies have often failed in this regard, neglecting key criteria that could have altered a lakes hazard 'score' (e.g. Costa and Schuster, 1988; Bolch, 2008; Emmer and Vilímek, 2013; Rounce *et al.,* 2016; Aggarwal *et al.,* 2017). Equally, it is vital that closely related parameters are not over-evaluated; for instance, glacier snout steepness and presence of a crevassed glacier snout can both greatly increase the probability of calving and thus enhance hazard (Wang et al., 2011). However, by nature glaciers with steeper snouts generally flow faster, leading to enhanced crevassing and subsequently increased calving meaning it is unnecessary for both parameters to be included in the same hazard analysis (Kougkoulos et al., 2018). Very little is known as to how triggers interact with each other, and how this interconnection may affect hazard susceptibility (Dubey & Goyal, 2020). Thus, it is often difficult to quantitatively assess hazards by assigning weight or values to individual parameters (e.g. Bolch *et al.,* 2011) since it is unknown how many GLOFs are caused by specific triggers (Rounce et al., 2017). Emmer and Cochachin (2013) highlighted this shortcoming through combining the effects of hydrostatic pressure, buried ice and time into one group termed 'self-destructive' failure due to the difficulty in separating the processes.

Advances in modelling over recent years have improved our understanding of GLOF hazard markedly (Westoby et al., 2015; Mergili et al., 2018; Zheng, Allen, et al., 2021), yet hazard analysis remains full of uncertainties and inferences. Empirical models (e.g. BASEMENT) developed through regression analysis using data from historical dam failures cannot be replicated at all lakes due to lack of available data and show major variation depending on the input parameters selected (Somos-Valenzuela et al., 2016). In comparison, hydrodynamic models depend on the definition of numerous lake-specific parameters, which if not available can lead to a high degree of uncertainty in outcomes (Fischer et al., 2022). Further, many existing hazard assessments have been developed for glacier-scale studies, where obtaining in-situ or high-resolution remotely sensed data is a viable option and greatly enhances the accuracy of outcomes; a study by Mckillop and Clauge (2007) suggested 18 parameters are needed to predict the probability of a GLOF, with the majority of these based on high resolution satellite imagery or in-situ field observations. Further, where historical data are available, back-analysis modelling can, and has, been used to determine contemporary GLOF hazard. However, such approaches cannot be replicated over a larger spatial scale, as in-situ data collection is unfeasible and databases sparse (Kougkoulos et al., 2018). For instance, bathymetric data is needed to accurately deduce glacial lake volume (Veh et al., 2020) however, is not available for all lakes globally, thus is often estimated using empirical relationships developed from small bathymetric datasets.

2.4.1.2 Magnitude of outburst

Expected magnitude of an outburst generally refers to the likely extent of flooding. Magnitude is often referred to as the 'intensity,' based on numerous physical properties of the outburst floodwaters, including; discharge velocities, inundation heights, runout distance, arrival time (GAPHAZ, 2017; Zheng, Allen, et al., 2021). On the most basic level, the most common method for quantifying GLOF magnitude at the regional- and local-scale uses glacial lake volume, by applying simple depth-area-volume relationships to convert mapped lake area to assumed lake volume (Huggel et al., 2002; Zheng, Mergili, et al., 2021). Here, larger volume lakes have the potential to produce larger, higher magnitude GLOF events. However, for studies covering larger spatial scales, such as national- or global-scale, conducting depth-area-volume relationships becomes challenging, with studies preferring to use lake area, which provides an often used proxy for lake depth (and volume) and thereby potential flood magnitude (Huggel et al., 2004). Glacial lake volume rarely equates directly to GLOF outburst volume; complete lake drainage is rare with lower magnitude outbursts more likely than larger magnitude outbursts (Hagg et al., 2021; Huggel et al., 2004; Fischer et al., 2022). As such, studies often take a semi-qualitative approach, whereby scenarios of varying magnitudes are given (e.g. small, medium, and large, Figure 2.12) (GAPHAZ, 2017). Conducting these scenario testing is important for disaster planning, enabling hazard zoning maps to be created, evacuation routes to be established and allowing communities to prepare for a range of outburst events effectively.

Aside from glacial lake volume, GLOF magnitude can also be influenced by handful of other factors (Table 2.1), for instance runout track slopes, erosion depth along runout tracks, and precipitation. Each factor can alter outburst discharge volumes, velocities, inundation extent etc. and thus overall magnitude. For studies wishing to model GLOF magnitudes, it is essential these factors be included in testing.

2.4.1.3 Hazard assessments

At the global scale, records of historical GLOFs remain incomplete (Veh et al., 2022); stream gauge records are sparse at most glacial lakes globally (Allen et al., 2018) and most outbursts occur unnoticed. Our ability to parameterise GLOF hazard has improved significantly for a handful of well-documented areas, with complex modelling and statistical analyses successfully identifying glacial lakes with high GLOF hazard. Yet for the majority of glacial lakes globally, we lack the fundamental data required for such approaches, leading to a high degree of uncertainty. As a result, in this thesis, I take a consequence-based approach, whereby the probability of GLOF failure is treated as unknown, on the assumption the lake will fail at some point, removing the need for parameterisation at a global scale. Thus GLOF hazard here reflects the impacts or effects on the potentially affected population only (i.e. magnitude of outburst), in the form of glacial lake area as a proxy for volume.

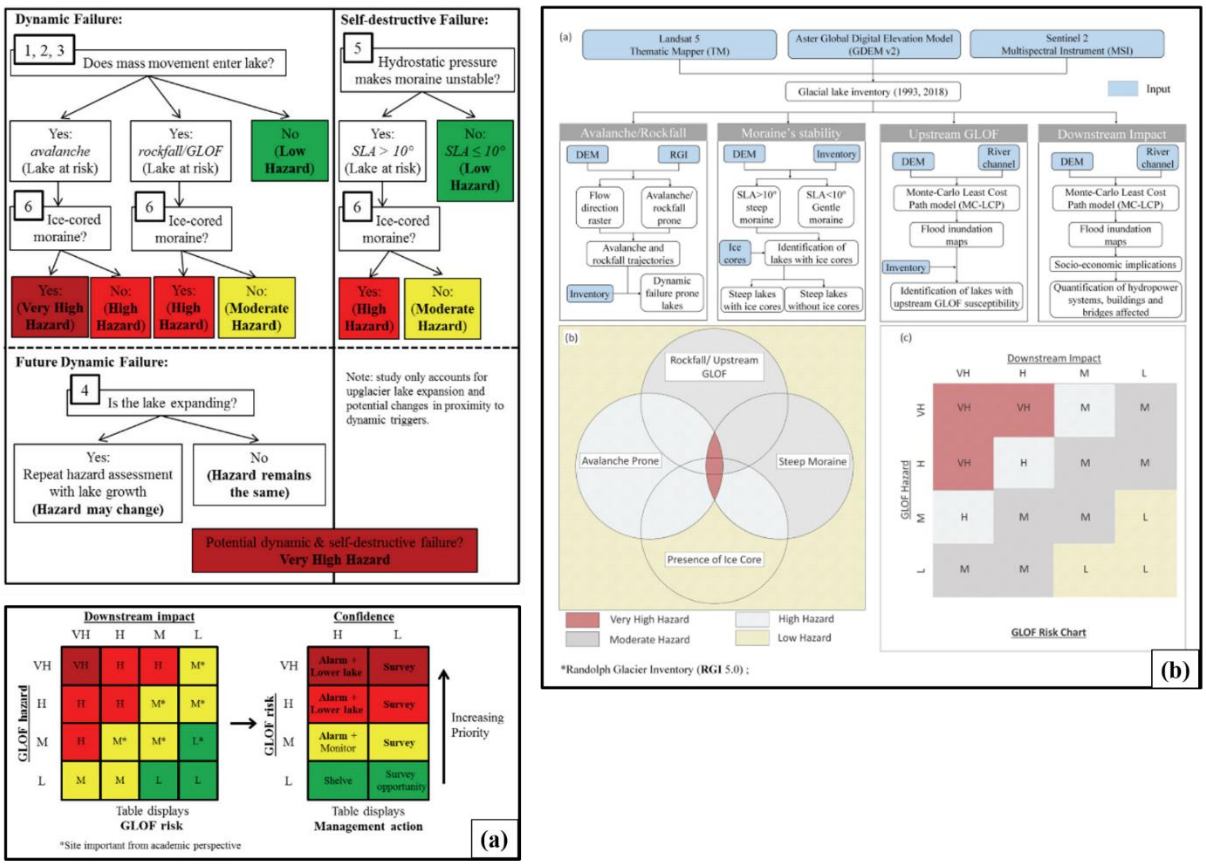


Figure 2.12: Example workflows of existing hazard/risk assessments, from (a) Rounce *et al.*, (2016) and (b) Dubey and Goyal (2020). (a) Top: hazard classification flow chart for determining the hazard associated with a glacial lake, Bottom: risk management and action framework. (b) Top: workflow of method, Bottom left: hazard classification flowchart represented using Venn diagrams, Bottom right: risk chart represented as a function of downstream impact and GLOF hazard.

2.4.2 Exposure

Exposure to GLOFs measures the human population and level of infrastructure facilities that are likely to be directly impacted by GLOF events (Allen, Linsbauer, et al 2016). Concurrent with the rapid growth of glacial lakes, population, infrastructure, and hydroelectric power schemes have experienced rapid and large increases globally (Allen *et al.*, 2019; Zheng *et al.* 2021; Schwanghart *et al.*, 2016; Shugar *et al.*, 2020). Thus, the presence of people, livelihoods, environmental services and resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected by physical events (i.e., subject to potential harm, loss, or damage) has increased (Lavell *et al.,* 2012). As a direct result of this, GLOF risk likely changes irrespective of changes to the hazard.

Only recently has the downstream impact been recognised as a fundamental component of a comprehensive GLOF risk assessment (ICIMOD, 2011; Strozzi *et al.*, 2012; Fujita *et al.*, 2013). At regional to global scales, exposure is hard to directly quantity, however, collating downstream information such as settlement size, number and type of bridges, distance from HEP sites, area of agricultural land and other infrastructure or activity of economic value (Khanal et al., 2015) coupled with GLOF routes and run-out modelling (e.g. Rounce, Watson and McKinney, 2017; Dubey and Goyal, 2020) is becoming more common practise (Allen *et al.,* 2018; 2019). The flood inundation extents, depths, and potential flood volume (PFV) produced through modelling approaches are then used in conjunction with the downstream information, to quantify the impact to provide an assessment of socio-economic exposure that can then be sorted into classes. Once human exposure is considered, the spatial extent of GLOF danger can be constrained, allowing for areas where humans are most likely to be adversely impacted by an outburst event to be prioritised (Allen *et al.,* 2019).

GLOF runout distances vary globally based on a range of factors (e.g. outburst volume, stream gradient, runout topography), thus it is difficult to determine inundation zones from which to extract exposure from, particularly on large spatial scales. Documented GLOFs across the Himalayas have been seen to travel further than 120 km (Osti & Egashira, 2009) whereas of the 29 recorded GLOF events in the Cordillera Blanca, only nine had impacts reaching further than 10 km (Emmer, 2017a). As a result, studies vary in their runout thresholds making it difficult to compare impacts across spatial scales.

Metrics used to quantify exposure also vary between studies depending on data availability and focus of the study. For instance, some studies use only total population (Tellman et al., 2021) whilst others integrate other factors such as hydroelectric power plants, land-use type, number of buildings, total number of livestock etc. (Schwanghart et al., 2016; Mal et al., 2021; Rinzin et al., 2023). Obtaining accurate population data is challenging, with most databases limited to regional or national scales and presented at resolutions that do not allow for more granular analysis (Smith et al., 2019). Further, estimates of population density from various global gridded data sets (e.g. Gridded Population of the World and WorldPop) vary markedly (Hay et al., 2005). As a result, determining exposure is challenging and highly dependent on the resolution of data selected and which parameters are chosen by researchers. As such, studies are often local-scale and not comparable.

Exposure is, by nature, highly variable across spatial and temporal scales, however existing studies often treat it as static. For instance, Rounce *et al.,* (2016) assumed mapped buildings had permanent occupants which is likely not the case, whilst Huggel *et al.,* (2020) found the total population in the high-hazard zone of lake Palcococha, Peru increased by more than 50,000 people during the day. Seasonal tourism also increases the number of people exposed to GLOFs each year (Khanal et al., 2015; Palomo, 2017). In turn, these temporal changes could have an impact on overall GLOF risk yet are rarely considered in GLOF risk assessments given the difficulties in obtaining suitable data. Despite these challenges, determining exposure to natural hazards, in this case GLOFs, is crucial for risk reduction, allowing communities likely to be directly impacted by an outburst to fully prepare. In some areas, as is being implemented across Bhutan (Dorji, 2021), exposure analysis has led to the implementation of land-zoning policies, preventing building on, and inhabiting likely inundated zones but still enabling social and economic development along river basins with potentially dangerous glacial lakes in their headwaters to continue.

2.4.3 Vulnerability

Vulnerability, in the contexts of natural hazards, is generally defined as an individual's or community's capacity to anticipate, cope with, resist and recover from the adverse effects of physical events (Wisner et al., 2004; Cutter et al., 2003; Gaillard & Dibben, 2008; UNDRR, 2022). Thus, the impact a hazard could have on a community depends not only on the proximity to the potential natural hazard (the exposure), but also on a number of physical, social, and environmental factors within the community that exacerbate or lessen the overall impact of a hazard (Cutter et al., 2000, 2003; Gaillard & Dibben, 2008; Zhou et al., 2014) (Table 2.2).

Historically, people knowingly inhabit areas exposed to GLOFs (Huggel, Cochachin, et al., 2020); some are forced into these areas due to economics or work prospects (Carey et al., 2012; Orlove, 2016), others select GLOF sites due to historical and cultural connections (Sherry et al., 2018) or for religious and tourism related reason (Allen, Rastner, et al., 2016). In contrast, in other areas, outmigration from rural areas into urban developments has resulted in reduced exposed populations (Ziegler et al., 2014). Although the socio-economic vulnerability to climate-related hazards is thought to have decreased (Formetta & Feyen, 2019), this decrease in vulnerability is spatially heterogenous and it remains unclear if this is sufficient to offset increases in exposure. As a result, changes in exposure and societal vulnerability could potentially lead to different risk scenarios, especially where political, economic, and social conditions facilitate or impede disaster risk reduction (Zheng, Allen, et al., 2021). For instance, generally, women are more vulnerable to GLOF hazards than males, given their lower levels of education and other social, religious, and political conditions (Shrestha et al., 2016). As a result, women's ability to prepare for, respond to, and recover from GLOFs is significantly reduced even when effective evacuation and response plans exist (Cutter et al., 2003). Temporally, vulnerability can also vary, with tourists known to increase collective vulnerability due to their lack of awareness and familiarity with local hazards and evacuation plans leading to delayed responses and dependence on locals (Ritchie, 2008; Drabek, 1999; Allen, Rastner, et al., 2016; Kala, 2014). In contrast, other factors can decrease vulnerability to GLOFs markedly; improving access to safe drinking water and sanitation, increasing access to communication devices, making improvements to infrastructure, and increasing literacy levels in both males and females can all enhance the ability of individuals, communities, and governments to prepare for, react to, and recover from an outburst, collectively reducing vulnerability. As such, assessing vulnerability is critical for accurately determining risk.

There are very few examples of studies that seek to understand the relationship between vulnerability and the impact of natural flood disasters (Hofflinger et al., 2019). Of those that do exist, most are local scale and rely on comprehensive questionnaires and face-to-face interviews to gather relevant data (Medina & Moraca, 2016; Henry et al., 2017). Further, few consider the interrelationship among variables used to quantify social vulnerability leading to double counting (Hofflinger et al., 2019). Thus, due to difficulty in quantifying factors, conducting accurate vulnerability assessments at even the regional-scale is challenging, with global-scale evaluations near-impossible. As a result, many risk studies focus on the physical dimension of natural hazards alone and disregard the human aspects (Hofflinger et al., 2019). To combat these issues, Cutter (1996) developed what is now widely known as a Social Vulnerability Index (SVI), making it possible to compare the spatial variability in socioeconomic vulnerability using a single index value across multiple spatial scales. Additionally, and importantly, the index can be constructed using census data, which is more readily available and removes the need for in-situ fieldwork. From this, there are examples of studies that have adapted the SVI to directly reflect specific natural hazards; Hofflinger *et al.*, (2019) successfully produced an index designed to evaluate response to flooding in Huaraz, Peru. Using this approach, it is possible to determine potential vulnerability to GLOFs at a global scale using open-access census data.

Changes in vulnerability to natural hazards are often subtle, dynamic, and unpredictable (Khanal et al., 2015). The war in Ukraine, fall of Afghanistan and Covid-19 pandemic are all examples of events that have significantly impacted vulnerability (Conceição & UNDP, 2020; Transparency International, 2020) and are all events that could not have been forecasted or prepared for. Given this, establishing a 'baseline' measure of vulnerability using data that is available to us from census data is crucial. Whilst is a static measure of vulnerability, it does provide at least some idea of how things have changed and the impact they could have on overall risk and is essential for accurate risk appraisals.

Indicator	Justification	References
Race and ethnicity	Imposes language and cultural barriers that affect access to post-disaster funding and residential locations in high hazard areas. Temporary residents of local communities (e.g. foreign workers, tourists) are highly vulnerable to flooding.	(Cutter et al., 2003; Lee & Van Zandt, 2019)
Religion and cultural beliefs	Alters how people perceive risk, how they respond to authorities and warnings. Impacts location of people.	(Allen, Linsbauer, et al., 2016)
Age	Age impacts the ability for evacuation out of harm's way. Elderly population and children are harder to evacuate due to mobility constraints, which increases their vulnerability during flooding. Children and the elderly are more susceptible to diseases, increasing vulnerability after flooding. Extremes of the age spectrum typically lack resilience.	(Cutter et al., 2000)
Gender	Women generally have significantly lower levels of flood awareness and a lack of knowledge about GLOF evacuation procedures. Differences in literacy between genders, making women highly vulnerable during natural disasters. Differences in resource access, opportunities, rights, power, and greater caring responsibilities. High proportion of women working in informal sectors and low rates of participation in economic activities make recovery more difficult.	(Shrestha et al., 2016; Cutter et al., 2003)
Rural/Urban setting	Rural residents may be more vulnerable due to lower incomes and more dependent on locally based resource extraction economies (e.g. farming, fishing). High-density areas (urban) complicate evacuation.	(Cutter et al., 2000)

Residential property	The value, quality, and density of residential construction affects potential losses and recovery; expensive homes are costly to replace; mobile homes are easily destroyed and less resilient	(Cutter *et al.*, 2000, 2003)
Infrastructure and lifelines	Loss of sewers, bridges, water, communications, and transportation infrastructure compounds potential disaster losses. The loss of infrastructure may place financial burden on smaller communities that lack resources to rebuild. Villages with no road access are significantly more at risk from flooding. Road access is critical during emergency evacuations and for post-flood assistance. Isolated communities have no access to relief and aid. Access to communication channels is critical before, during and after a disaster, particularly to receive warning information.	(Cutter et al., 2003)
Renters	Housing tenure is an important determinant of social vulnerability. Many characteristics of renters correlate with aspects of social vulnerability. Renters may not have insurance to protect against the loss of their belongings. Renters lack resources prior to a disaster and during post-disaster recovery e.g. may have issues finding affordable temporary housing or shelter after flooding. Renters have no home ownership and often lower financial resources. They may lack legal rights to influence rebuilding, which puts them at a heightened risk of displacement after flooding.	(Cutter et al., 2003)
Occupation	Some occupations, especially those involving resource extraction, may be severely impacted by a hazard event. Self-employed suffer when their means of production is lost and may not have the requisite capital to resume work in a timely fashion and thus will seek alternative employment. Those migrant workers engaged in agriculture and low-skilled service jobs (housekeeping, childcare, and gardening) may similarly suffer, as disposable income fades and the need for services declines. Immigration status	(Cutter et al., 2003)
Education	Education is intrinsically linked to socioeconomic status, with higher levels of education resulting in greater lifetime earnings. Lower levels of education reduce understanding of warning information and access to recovery information.	(Cutter et al., 2003; Lee & Van Zandt, 2019)
Population growth	Counties experiencing rapid growth lack good quality housing. Social services network may struggle to adjust to increased populations. Language barriers and unfamiliarity for obtaining relief or recovery information of new migrants increase vulnerability.	(Cutter et al., 2000, 2003)
Social dependency	Those people who are dependent on social services for survival are already economically and socially marginalized and require additional support in the post-disaster period.	(Cutter et al., 2003)
Special needs populations	Special needs populations (infirm, institutionalised, transient, homeless) are disproportionately impacted during	(Cutter et al., 2003)

	disasters. Lack of visibility within communities leads to lack of inclusion during recovery.	

Table 2.2: Social vulnerability indicators used to quantify GLOF-specific vulnerability in this study.

2.4.4 Risk

In natural hazard studies, risk is generally assessed as a function of hazard, exposure, and vulnerability (Worni *et al.*, 2013; Rounce *et al.*, 2016, 2017; Allen *et al.*, 2018; Dubey and Goyal, 2020). Several methods for assessing risk of GLOFs can be found in the literature (e.g. Bolch *et al.*, 2011; Wang *et al.*, 2011; Shijin, Dahe and Cunde, 2015; Allen *et al.*, 2019; Begam and Sen, 2019; Khadka *et al.*, 2019; Zheng *et al.*, 2021). Some are regionally focussed or adjustable, but often limited by their subjectivity (Washakh et al., 2019), with each differing in method structure, quantity and range of characteristics assessed, the required input data and percentage of subjectivity in the process (Emmer & Cochachin, 2013). Risk assessments are generally conducted in order to identify glacial lakes that need further investigation, and to assist decision making regarding intervention. Most studies seek to balance the economic and social impacts, however prioritising one over the other changes the risk levels (Rounce et al., 2017; Dubey & Goyal, 2020). For instance, in one study of 131 glacial lakes in Nepal (Rounce et al., 2017), favouring economic impacts over social impacts results in the identification of two 'high-risk' lakes whereas prioritising social impacts above economic impacts finds six different lakes.

Studies focussing on GLOF hazard still dominate the literature (Figure 1.4; Emmer, 2018, 2022) and the science behind GLOF hazard is well established, if still uncertain. Less well known are the socio-economic, cultural, and institutional drivers, with few holistic studies integrating exposure and vulnerability (Carey et al., 2012; Huggel et al., 2015; Motschmann, Huggel, Muñoz, et al., 2020). Effective risk assessments and risk management strategies need to be based on sound understandings of risk drivers- that is hazard, exposure, and vulnerability (Kreibich et al., 2014; de Ruiter et al., 2020). Through identifying which driver(s) are responsible for the observed changes in risk, mitigation efforts can be more effectively directed, with funding and research more efficiently distributed. For instance, in one location, hazard might be driving increasing risk, thus lake engineering might be more suitable compared to another location where exposure is the main driver of risk increase, where land use zoning could be more effective. This understanding will be particularly useful in areas where funding and resources are limited (Carrivick & Tweed, 2016; Shaw, 2016). Furthermore, evaluating how drivers of risk have changed over time could allow predictions for future trends to be ascertained, providing an opportunity for stakeholders (communities, governments, Non-

Governmental Organisations (NGOs)) to prepare for future GLOF risk scenarios and ultimately prevent disaster. Ascertaining the effect of these drivers on overall risk continues to be hampered by a lack of empirical data (Bouwer, 2011; Ward et al., 2020).

GLOFs are multivariate hazards, being a composite of multiple conditioning and triggering factors (Figure 2.11) and leading to a variety of local and far-reaching potential impacts, thus are challenging to categorise. However, as the number of glacial lakes increases with deglaciation, and as the flow of people and goods along river valleys increases due to the growth of tourism and trade (Khanal et al., 2015) there is a pressing need for clear understanding and communication of risk, particularly to communities situated downstream where the hazard perception is often low (Thompson et al., 2020; Aslam et al., 2022). Currently there is a tendency to focus on hazard, as well as the potential impacts of a potential GLOF, which in turn are presented as ‘risk.’ This practise is dangerous and should be widely discouraged (Dubey & Goyal, 2020); a hazardous lake alone does not translate directly to a high risk lake if exposure and vulnerability are low. Furthermore, Rounce, Watson and McKinney (2017) highlight how easily changing the weighting of parameters can impact the classification of the glacial lakes. In the past this has led to the same lake receiving different ‘risk’ categorisations; Imja Lake in the Mt. Everest region, Nepal has been variously identified as being ‘safe’ (Watanabe et al., 2009; Fujita et al., 2013), a ‘very-low hazard’ (Hambrey et al., 2008) and a ‘high risk’ with recommendations for being the priority for further investigation and hazard reduction (Mool et al., 2011). This conflicting classification can be both confusing and misleading for stakeholders and exposed communities, proving actively unhelpful in the targeting of mitigation and emergency planning measures (Rounce et al., 2016). (Carrivick & Tweed, 2016). Thus, it is vital risk assessments are designed with stakeholders and communities in mind such that the appropriate response can be obtained.

2.4.5 Spatial and temporal change in risk

What is often missing from risk assessments is the consideration that hazard, exposure, vulnerability and, by extension, risk of a GLOF changes temporally. A number of studies have highlighted the temporal trend in GLOF *occurrence* (Yamada, 1998; Kattelmann, 2003; Mool et al., 2001; Emmer & Cochachin, 2013; Carrivick & Tweed, 2016; Falátková, 2016; Harrison et al., 2018; Nie et al., 2018; Veh, 2019) but how this temporal variation is translated to or interacts with changes to hazard, exposure, vulnerability, and risk is rarely assessed. Changes to glacial lake hazards have received more attention in recent years. For example, Veh *et al.* (2019) has suggested glacial meltwater contributions could be enough to raise GLOF risk two-or threefold even if the exposure and vulnerability to an outburst were to remain unchanged. However there seems to be no consideration of how changes to exposure and/or vulnerability could alter risk classification. Exposure and vulnerability can change more frequently than hazard; population change is generally more dynamic on an hourly, daily, seasonal, and annual timescale than lake expansion for instance. In existing risk assessments, exposure is often taken as static and vulnerability often not quantified (Mal et al., 2021; Zheng, Allen, et al., 2021). Yet, alongside physical changes, cultural changes associated with landscape character, identity and religion are all being altered (Dunbar & Marcos, 2012; Milner et al., 2017). Thus, the spatial and temporal changes in exposure and vulnerability may have a significant impact on the overall risk across daily, seasonal, annual, and longer timescales. This demonstrates the variability in GLOF risk, which if risk minimizing efforts are to be more efficiently directed and overall more effective, must be included in risk assessments.

2.5 Chapter summary

In the face of warming climates across high mountain regions globally, the growth of glacial lakes and migration of people, infrastructure, and services to higher elevations close to glacial lakes is of significant concern for GLOF risk. Currently however, changes in hazard remains the main focus of many studies, with few studies integrating exposure and vulnerability metrics alongside hazard to quantifying GLOF risk. As a result, there is a tendency to talk in terms of GLOF risk, when generally only the hazard has been established. This practise is dangerous and needs to be addressed; a hazardous lake alone does not translate directly to a high risk if exposure and vulnerability are low. This thesis aims to address this by assessing exposure, vulnerability, and hazard together to establish GLOF risk (Section 1.3). In addition, there is a vital need to establish an accurate global picture of GLOF risk; regions often cited as having high GLOF risk are generally those with the most research items attributed to them, with lesser studied areas (e.g. the Andes, Karakoram) overlooked, despite having higher GLOF frequencies and often more severe GLOF impacts. Thus, this thesis seeks to establish GLOF risk at the global scale, in order to identify hotspots of risk which can then be used to inform and direct future research. Managing GLOF risk will become increasingly important over the coming decades if future disasters are to be avoided and sustainable development in mountain regions progress. Thus, this thesis is primarily focussed on adding to our understanding of this contemporary glacial hazard.

Chapter 3 Global distribution of contemporary glacial lake outburst flood risk

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Key words

GLOF, risk, exposure, hazard, vulnerability, spatial distribution

ABSTRACT

Glacial lakes represent a major hazard as failure of the dams impounding lakes can lead to an unpredictable and sudden release of water and sediment known as glacial lake outburst floods (GLOFs). This can result in significant loss of life and transnational impacts (Allen et al., 2019; Zheng, Allen, et al., 2021). Globally, since 1990, the number, area and volume of glacial lakes has grown rapidly (Shugar et al., 2020). Concurrent with this glacial lake growth, large increases in downstream population and infrastructure have occurred, particularly across High Mountain Asia (HMA) (Schwanghart et al., 2016), while socio-economic vulnerability has decreased (Formetta & Feyen, 2019). Despite this, the global distribution of contemporary GLOF risk has never been quantified. Here we show that 15 million people globally are exposed to direct impacts from potential GLOFs. Populations living in HMA are at highest risk of GLOF impacts, and on average, live the closest to glacial lakes, with ~1 million people living within 10 km of a glacial lake. More than half of the globally exposed population are found in just four countries: India, Pakistan, Peru, and China. At the basin scale, the Khyber Pakhtunkhwa basin in Pakistan, Santa basin in Peru, and Beni basin in Bolivia stand out as those most at-risk of GLOF impacts. Importantly, these are not home to the largest, most numerous, or most rapidly expanding glacial lakes. Instead, we show it is the high number and proximity of people to a glacial lake, and their capacity to cope with outburst impacts that is a key factor. We rank GLOF risk at the basin level, which we use to highlight locations to prioritise for detailed local-scale analyses and risk mitigation and identify the Andes as a primary region of concern.

3.1 Introduction

Mountain glaciers are particularly sensitive to changes in climate (Kraaijenbrink et al., 2017; Roe et al., 2017; Wouters et al., 2019) and are highly visible indicators of climate warming (Pachauri & Meyer, 2014; Hock et al., 2019; Wouters et al., 2019). Over the last three decades there have been substantial decreases in global glacier mass, with total global ice loss between 2006 and 2016 estimated at -332 ± 144 Gt y^{-1} (Zemp et al., 2019). This decline is likely to persist through the 21st century as most glaciers are out of balance with the present climate; ~36 ± 8% of current mass loss is a 'lagged response' to past climate forcing (Marzeion et al., 2018). In many areas, overdeepenings in former glacier beds are being uncovered during glacier retreat, facilitating the formation of glacial lakes as melt water collects in natural depressions (Carrivick & Tweed, 2013; Allen, Linsbauer, et al., 2016; Lei et al., 2018). Glacial lakes can also form via the growth and coalescence of supraglacial ponds on debris-covered glaciers (Benn et al., 2012; Watson et al., 2016), and in other ice-marginal settings such as at the glacier termini, tributary junctions, or along glacier margins (Hewitt & Liu, 2010; Bhambri et al., 2019). The formation of glacial lakes can trigger positive feedback loops, whereby lakes promote further ice loss through calving and subaqueous melting, causing additional melt and retreat, and further lake expansion (King et al., 2019; Maurer et al., 2019; Watson et al., 2020). Thus, glacial lake formation and expansion can have, and is already having, major implications for glacial ice loss globally.

Importantly, these glacial lakes represent a substantial hazard in the form of glacial lake outburst floods (GLOFs). GLOF triggering is complex, with dam breach initiation caused by mass movement-induced impulse waves (Emmer & Cochachin, 2013; Rounce et al., 2016), lake overfilling due to pluvial, nival and glacial runoff (Allen, Rastner, et al., 2016), and moraine or ice dam degradation being variably important, depending on the setting (Neupane et al., 2019; Majeed et al., 2021). GLOFs can be highly destructive and can arrive with little prior warning, causing significant damage to property, infrastructure, and agricultural land, and result in extensive loss of life (Zheng, Allen, et al., 2021). However, the impact varies significantly across the globe; in the last 70 years, several thousand people have been killed by GLOFs in the Cordillera Blanca alone (Carey, 2008; Emmer et al., 2020), most from a small number of events (Evans et al., 2009; Mergili et al., 2013) whilst only 393 deaths in the European Alps can be directly linked to GLOF activity over the last 1000 years (Carrivick & Tweed, 2016). The continued ice loss and expansion of glacial lakes due to climate change therefore represents a globally important natural hazard that requires urgent attention if future loss of life from GLOF is to be minimised (Dubey & Goyal, 2020; Shugar et al., 2020) and the UN's Sustainable Development Goals (particularly Goal 11- Disaster Risk Reduction) are to be met.

Since 1990, the number, area, and volume of glacial lakes globally has grown rapidly, increasing by 53%, 51% and 48% respectively (Shugar et al., 2020). Concurrent with the rapid growth of glacial lakes, many catchments downstream have experienced rapid and extensive increases in population, infrastructure, and hydroelectric power (HEP) schemes, whilst agriculture has also intensified (Schwanghart et al., 2016; Haeberli et al., 2017; Allen et al., 2019; Wester et al., 2019; Immerzeel et al., 2020). However, the socio-economic vulnerability to climate-related hazards is thought to have decreased due in part to the success of the Millennium Development Goals (MDGs) and succeeding Sustainable Development Goals (SDGs) (Formetta & Feyen, 2019). Yet this decrease is spatially heterogenous and it remains unclear if this heterogeneity is sufficient to offset potential increases in hazard and exposure. Contemporaneous changes in downstream exposure (i.e. the proximity of population to a potential outburst), vulnerability (the exposed populations likelihood to be impacted by the GLOF), and hazard mean that GLOF risk is rarely static (Wisner et al., 2004; Allen, Linsbauer, et al., 2016; Schwanghart et al., 2016; Wang et al., 2015). However, how the recent observed changes in each combine to produce contemporary global GLOF risk remains unclear (Emmer et al., 2020). Whilst regional scale GLOF risk assessments have been undertaken (Zheng, Mergili, et al., 2021; Khanal et al., 2015) to our knowledge, no global scale study has been attempted that considers not just the physical drivers of GLOF hazard, but also societal exposure and vulnerability that directly influence GLOF risk (Huggel, Carey, et al., 2020).

Here, for the first time, we combine the most up-to-date hazard, exposure, and vulnerability data available to quantify and rank contemporary (2020) impact potential from GLOFs at a global scale, adding to similar recent approaches for hydrometeorological floods (McDermott, 2022; Tellman et al., 2021). We analyse the spatial distribution of population exposure to determine where populations are in relation to glacial lakes, using necessarily simple estimates of potential GLOF runout paths (50 km runout, with potentially affected populations located within 1 km of a river course), therefore identifying potentially higher priority zones for mitigation or adaptation, and further, local-scale research. While this study captures hazard, exposure, and vulnerability as they were in 2020, the methods presented provide a framework to capture changing GLOF risk through time.

3.2 Methods

3.2.1 Hazard, exposure, and vulnerability

3.2.1.1 Hazard

Hazard is a critical component of risk and is generally defined as a function of the probability and intensity of an event, i.e., the likelihood that an event will occur from a given site based on intrinsic properties and dynamic characteristics of that site combined with the overall magnitude of the event (GAPHAZ, 2017). The probability of a GLOF occurring at a given point in time is dependent on specific local conditions, including, but not limited to; potential topographic triggers (ice/rock/snow avalanche etc), lake-dam geometries, and lake area/volume etc (Allen, Rastner, et al., 2016; Allen et al., 2019; Dubey & Goyal, 2020; Zheng, Allen, et al., 2021). Further, the likelihood of lake failure will almost certainly vary temporally. Attempts to quantify the probability of GLOFs have been undertaken at regional-scale using simple proxies for the likelihood of landslide and/or ice avalanches into lakes (Zheng, Allen, et al., 2021; Furian et al., 2021). However, to be applied globally, these approaches require globally consistent, high-resolution DEMs, which are known to suffer from considerable artefact issues in high mountain regions where GLOFs originate (Bolch & Loibl, 2017). Furthermore, this only accounts for one of many potential triggers, ignoring internal conditioning factors that can lead to dam self-destruction, for instance. Therefore, quantifying the probability of failure is inherently difficult at a global scale, given factors that contribute to failure can be stable, change very slowly, or very rapidly. Here, I take a consequence-based approach and focus on quantifying only the intensity of a potential GLOF. I do this by using the total lake number and area as a proxy for intensity, where a larger number and higher area lakes have the potential to produce larger, more intense GLOFs. Previous regional-scale work (Zheng, Allen, et al., 2021) has sought to use lake volume as a proxy for GLOF intensity by applying simple area-volume relationships to convert mapped lake area to assumed lake volume. However, for this study any area-volume relationship would need to be globally consistent, scaling all lake hazard values consistently, and thus I prefer to use simply mapped lake number and area instead.

By treating the probability of failure as unknown and instead focussing on quantifying the impacts or effects on the potentially affected population, locations are ranked in terms of the potential damage that may be caused, as opposed to probability weighted impacts. Thus here, the hazard scoring system highlights conditions that may yield more intense GLOFs should a failure occur. When combined with exposure and vulnerability, the basins with the largest potential impacts can then be targeted for more detailed local studies to ascertain the probability of a GLOF occurring in the first place, allowing those with the highest potential losses to be prioritised for more local studies. While probability is a key element of risk, I note that basins with high potential impact would still be considered comparatively high risk if the probability of failure were found to be low (low probability, high impact event), while basins with low potential impacts would only suffer marginal increases in comparative risk if the probability of failure were found to be high (Figure 3.1).

		GLOF Impact			
		Low	Medium	High	Very High
GLOF Probability	Unlikely	Low	Low	Medium	Medium
	Possible	Low	Medium	Medium	High
	Likely	Medium	Medium	High	Very High
	Very Likely	Medium	Medium	Very High	Very High

Figure 3.1: Simple qualitative risk matrix comparing GLOF probability to GLOF impact. Here, a low probability but high impact event is considered the same risk as a high probability but low impact event.

To identify glacial lake basins (i.e. those basins containing one or more glacial lakes), I use the Level 4 Global Water Resource Zones shapefiles (Yan et al., 2019) and the most recently available global inventory of glacial lakes (Shugar et al., 2020) identifying a total of 1089 glacial basins worldwide (Figure 3.2). Note that these Water Resource Zones do not represent true river catchments, instead showing regions that contain several associated rivers flowing into a lake or ocean, with Level 4 representing rivers that have no tributaries larger than 100 km^2. This can cause strange effects, particularly in large coastal or plains areas, such as in Chile (Figure 3.12). However, to my knowledge there is no suitable global dataset of river catchments, and regional and national datasets are too inconsistently derived for a globally consistent study. To aid spatial discussions basins are grouped into four main mountain ranges; European Alps, Andes, High Mountain Asia (HMA) and Pacific Northwest (PNW), with the remaining 131 (12%) basins outside of these ranges referred to as 'High Arctic and Outlying Countries'. I then extract the raw number and area of glacial lakes per basin/country/region to act as proxies for GLOF hazard intensity, before performing a linear transformation function to produce a normalised value for each indicator (Equation 3.1):

$$y_{N/A} = \frac{(\mathbf{X})}{(\mathbf{Max})}$$

Equation 3.1

Where **x** is the absolute number/area of glacial lakes per basin/country/region, **Max** is the maximum number/area of glacial lakes found out of all basins/countries/regions, and **y** is the normalised value of glacial lake number/area per basin/country/region. Individual normalized values of glacial lake number ($\mathbf{y_N}$) and area ($\mathbf{y_A}$) are then multiplied to produce a singular score between 0 and 1, with higher values relating to the greatest GLOF hazard intensity.

Finally, the potential downstream spatial extent of GLOFs is considered by evaluating their expected reach. Generally, communities located closer to glacial lakes are more likely to be directly impacted by GLOFs than areas further downstream (Allen et al., 2020). 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). Defining a runout distance or reach angle from which to assess exposed population on a global scale is therefore difficult. Previous research (Dubey & Goyal, 2020) set a runout cut-off distance of 50 km, to facilitate a standardized comparison between glacial lakes. This 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). Further, comparisons of likely GLOF discharges with that of meteorological floods (Cook et al., 2018) suggest many (50%) of likely GLOFs that exceed the 100-year meteorological flood discharge do so to only ~20 km downstream, with only 1% theoretically reaching > 85 km (Schwanghart et al., 2016). However, with lake sizes increasing due to climate change, runout of future GLOFs may well exceed those previously observed distances due to the larger volume of water potentially involved or have higher impacts within the same distance due to faster arrival times or greater inundation depths for instance. Nevertheless, although I recognise runout distances vary considerably, with some GLOF events showing runout lengths > 200 km (Richardson & Reynolds, 2000a), considering such distances at a global scale could lead to major overestimations of downstream impacts in many locations (Dubey & Goyal, 2020). Thus, following sensitivity testing in which distances of 25 km, 50 km, and 100 km were considered as potential run outs, and following the approach of Dubey and Goyal (2020), I use a path-dependant cut off distance of 50 km, which should encapsulate the majority of GLOF runouts globally and provide a conservative estimate of potential GLOF reach, accounting for potentially larger runout GLOFs in the future, whilst avoiding overestimations by using observed but rare extreme runout distances. Using a 50 km cut off distance also accounts for issues arising from the use of Water Resource Zones, as only the region within 50 km of a glacial lake is assessed. Water Resource Zones closely resemble true river catchments in the upper reaches, and only vary in the lower reaches in coastal/plain zones. In most of the major mountain regions considered here, these upper reaches are likely to extend further than 50 km, this ensures that only the area and population downstream and in proximity to glacial lakes are included in our calculations.

3.2.1.2 Exposure

GLOF runout pathways tend to follow river channels (Carrivick & Tweed, 2016; Veh et al., 2019) so impact increases with proximity to the channel (Takenaka et al., 2012). Similar to previous approaches (Veh, 2019) the GLOF hazard footprint is further constrained to estimate exposed populations by applying a 1 km buffer either side of any main river channel (Yan et al., 2019) with a glacial lake in its upper reaches, up to a distance of 50 km (Figure 3.2). Here, populations were rounded to the nearest whole number. Using the 2020 Gridded Population of the World version 4 (GPWv4) (CIESIN, 2018) to sum the population count per 1 km^2 cell within this buffer, 2020 exposed population was obtained (Figure 3.2). I recognise that a 1 km buffer is a crude estimate for identifying potential GLOF impact zones; exposed population is likely overestimated in the upper-most 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 impacted zone, whilst in the lower-most reaches where valleys are flatter and wider, exposed population is likely underestimated as flood waters can spread many kilometres from the active channel. However, as the overall impact of a GLOF wanes with distance from the river channel and downstream (Veh, 2019; Takenaka et al., 2012), and given the resolution of the population data used (CIESIN, 2018), at a global scale a 1 km buffer will provide a conservative but consistent estimate of the potentially exposed population. These areas identified as a concern can then be targeted for further, more detailed analysis using more complex GLOF runout modelling and higher resolution population data to refine our initial estimates. A linear transformation function is used to produce a normalised value of exposure for each basin (Equation 3.2).

$$\boldsymbol{E} = \frac{(\boldsymbol{P})}{(\boldsymbol{Max})}$$

Equation 3.2

Where E is the normalised exposure score, P is the total exposed population per basin/country/region, and Max refers to the maximum exposed population per basin/country/region, respectively. To add further granularity, we split the 50 km buffer into

5 km intervals and sum the population within these intervals, to determine how population is distributed along these likely GLOF runout tracks.

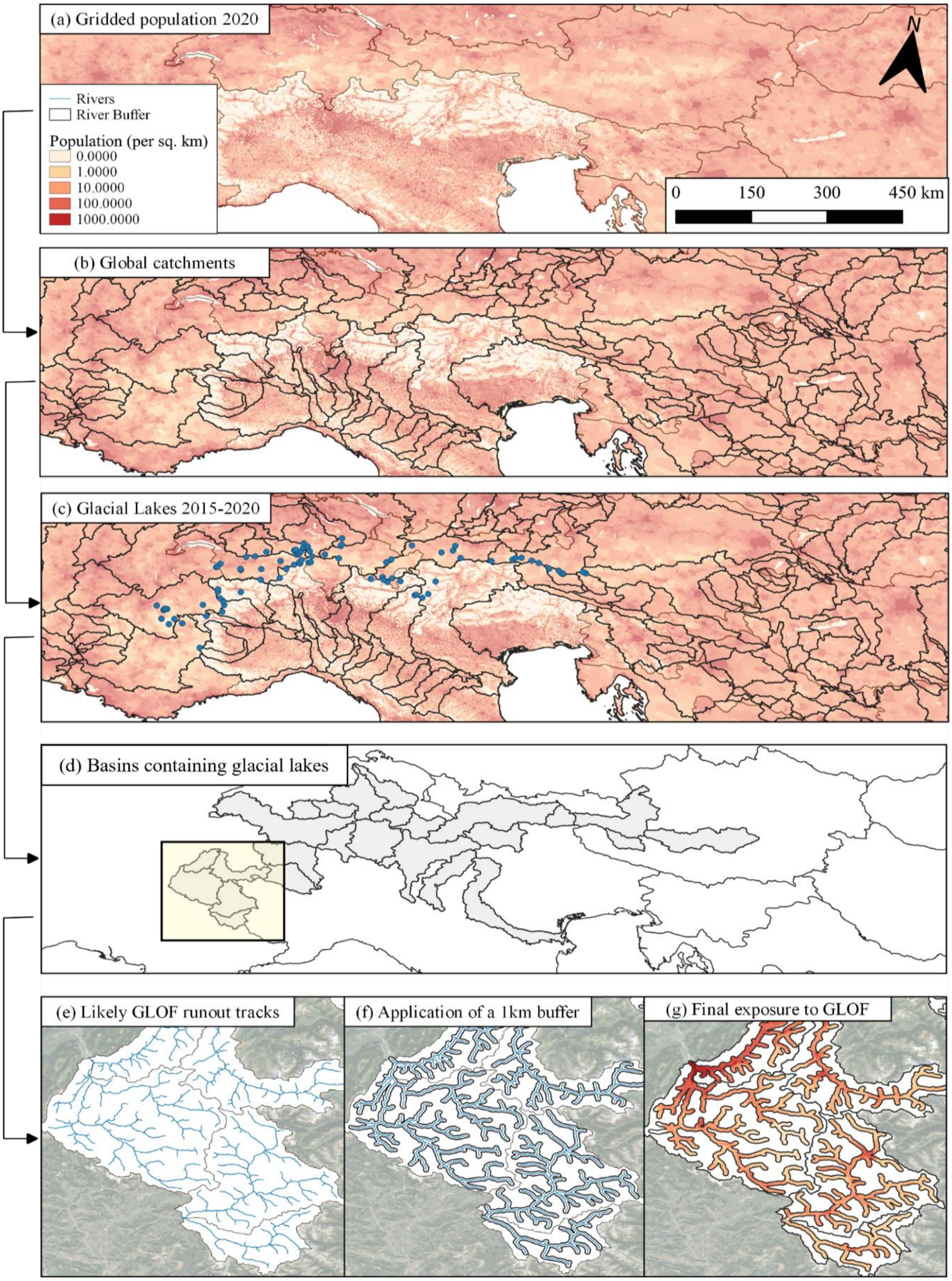


Figure 3.2: Extraction of hazard and exposure used in this thesis. Workflow detailing the extraction of GLOF hazard and exposure; a) global gridded population 2020, b) level 4 river basins, c) glacial lake shapefiles 2015-2018, d) identification of basins containing glacial lakes, e) extracted population within glacial basins, f) glacial-fed river channels as proxies for likely GLOF runout tracks up to 50 km from glacial lakes, g) application of 1 km buffer either side of river channels and h) final exposed population extracted. Background of f-h Google Earth 2021.

3.2.1.3 Vulnerability

Many factors influence human vulnerability to natural hazards (Cutter et al., 2003; Gaillard & Dibben, 2008; Zhou et al., 2014), and yet, due in part to the absence of sufficient data, few GLOF studies have considered vulnerability (Huggel et al., 2015). Since the implementation of the Millennium Development Goals (MDGs) and succeeding Sustainable Development Goals (SDGs), there has been a vast improvement in the amount, quality, and availability of vulnerability data globally. Here, I combine qualitative information obtained from the Corruption Perception Index (CPI) at national scale (Transparency International, 2020) and Human Development Index (HDI) at sub-national level (first administrative level, e.g. state or province) (Conceição & UNDP, 2020) with a novel national-scale, GLOF-specific 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; Schmidtlein et al., 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 (Figure 3.3). The HDI is a summary measure of three key dimensions of human development: health, education, and standard of living (Conceição & UNDP, 2020), and is comprised of normalised indices of: life expectancy, expected years of schooling, mean years of school and Gross National Income (GNI) per capita (Figure 3.3). Both the CPI and HDI have been successfully used in previous large-scale risk assessments for other natural hazards (Drenkhan et al., 2019; Robinson et al., 2019).

While both the CPI and HDI provide a useful metric for assessing physical vulnerability of a country/territory (Robinson et al., 2019), they do not reflect on many factors that influence social vulnerability (Cutter et al., 2003). Thus, to assess the coping capacity of downstream communities and the ability of the affected nation to effectively respond to the event, an Social Vulnerability Index was developed. Drawing upon an existing flood vulnerability assessment proposed by Tascon-Gonzalez *et al.* (2020), the SVI used in this study initially analysed nine indicators that either reduce or enhance a populations and nation’s capacity to cope with a GLOF disaster. To avoid double counting, a correlation study (matric-plot and correlation-matrix) was conducted to ensure variables were independent from other indicators as well as those used to calculate the HDI and CPI (Figure S3. 1). To keep the sample size valid, preference was given to variables with the lowest number of missing values. As a result, four variables were not included when calculating the final SVI score: percentage of safe drinking water and percentage of good sanitation as well as percentage illiterate population and percentage unemployment. The former two were highlighted both for double counting and lack of datapoints, and the latter two for double counting with data used to calculate the HDI. Consequently, the final SVI score was based on 5 unique indicators (Equation 3.3).

$$\boldsymbol{SVI = \frac{\left(\frac{reducing\ indicators}{enhancing\ indicators}\right)}{5}}$$

Equation 3.3

I acknowledge that the relative importance of each indicator on social vulnerability will change with location, with studies often assigning weights using an analytic hierarchy process and expert knowledge to fit the specific context of the study (Tascón-González et al., 2020). Given the global scale of this study and considering vulnerability data at finer resolution is largely absent globally, an equal weighting approach was selected with the understanding that outputs should be taken as a baseline value, and exact values per country may vary. I also note that while the vulnerability of the immediately exposed population is critical to understanding the eventual impacts from a disaster, the capacity of the country as a whole to adequately respond to the disaster is also a crucial factor. As such, the vulnerability indicators used here attempt to capture both the physical vulnerability of the directly exposed populations, and the capacity of the country/region as a whole to cope with the event. In this study, all three indicators (HDI, CPI and SVI) are normalised and combined with equal weighting (Equation 3.3) to produce a single proxy for vulnerability (Equation 3.4). Final values range between 0 and 1, where 1 equates to the highest vulnerability. No scores of absolute 0 were recorded.

$$\boldsymbol{Vulnerability = 1 - [HDI\ x\ (1 - CPI)\ x\ SVI]}$$

Equation 3.4

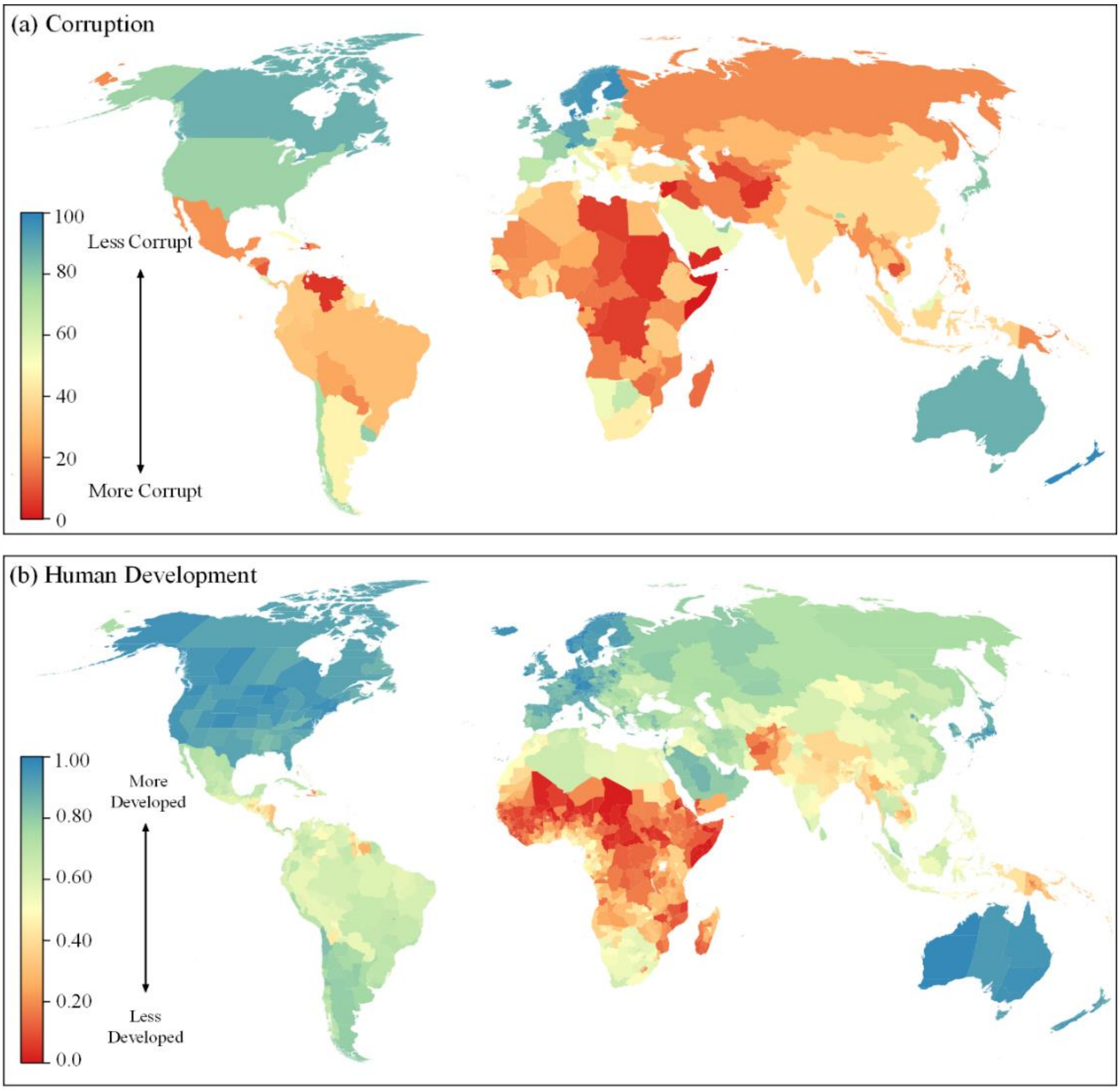


Figure 3.3: Global distribution of Corruption Perception Index and Human Development Index used in this thesis. a) global maps of national corruption scores, b) subnational human development scores.

Category	Indicator	Description	Impact	Justification	Refs
Demographic	% Population growth	The percentage change in total population.	Increase	Countries with rapid growth lack good quality housing, social services may not be adjusted to cope with increased populations. Language barriers and unfamiliarity for obtaining relief or recovery information of new migrants increase vulnerability.	[1], [2]
	% Urban population	The percentage of the total population living in urban areas *(as defined by each country).*	Decrease	Rural residents may be more vulnerable due to lower incomes, higher dependency on locally based resources and lower frequency of communicative/transport infrastructures. While urban areas can complicate evacuation, in the context of flooding from glacial lakes rural communities are more likely to be heavily disrupted.	[1]
	% Young children	The percentage of the total population aged 0-5.	Increase	Age impacts the ability for evacuation out of harm way. Elderly population and children are harder to evacuate due to mobility constraints, which increases their vulnerability during flooding. Children and the elderly are more susceptible to diseases, increasing vulnerability after flooding. Extremes of the age spectrum typically lack resilience.	[1], [3], [4]
	% Elderly	The percentage of the total population aged over 65.	Increase		
Education	% Illiterate	The percentage of the total population aged over 6 years classified as illiterate.	Increase	Elevated levels of education results in greater lifetime earnings whilst lower education levels reduce individuals' ability to understanding warning and recovery information. Higher literacy rates of women result in significantly higher levels of flood awareness and ability to obtain information before, during and after disaster, thus reducing vulnerability.	[2], [5], [6]
	% Literate females	The percentage of the total female population aged over 25 with some education to secondary school level.	Decrease		
Work and employment	% Unemployed	The percentage of the total labour force out of employment	Increase	Lower socioeconomic status households are disproportionately impacted during and after flooding. Wealth enables communities to absorb and recover from loss more quickly e.g. insurance, safety nets, entitlement programmes. Those economically inactive are less likely to recover after a flood e.g. from the loss of housing.	[2], [3]
Socio-economic sustainability	% Households with access to clean	Percentage of the population drinking water from an improved source* that is accessible on premises, available when needed and free from contamination.	Decrease	Housing conditions can determine the quality of life of a population. Those with poor quality housing are less likely to be able to recover after a flooding event. Loss of sewers and water compounds disaster losses and reduces capacity to recover.	[2], [7], [8]

	drinking water				
	% Households with access to good sanitation	Percentage of the population using an improved sanitation facility** that is not shared with other households, where excreta are safely disposed of in situ or treated off site.	Decrease		
Communication	% Population with mobile phones	The percentage of total population with access to a mobile phone.	Decrease	Access to communication channels is critical during a before, during, and after a GLOF, particularly to receive warning information. Higher access increases community resistance and decreases vulnerability	[2]

*Improved water sources include piped water, boreholes, or tube wells, protected dug wells, protected springs, and packaged or delivered water.
**Improved sanitation facilities include flush/pour flush toilets connected to piped sewer systems, septic tanks, or pit latrines; pit latrines with slabs (including ventilated pit latrines, and composting toilets.
Refs: [1] Cutter, Mitchell, and Scott, 2000; [2] Cutter, Boruff and Shirley, 2003; [3] Rufat *et al.*, 2015; [4] Orlove, 2016; [5] Lee and Van Zandt, 2019; [6] Shrestha *et al.*, 2016; [7] Watanabe and Rothacher, 1996;[8] Rohe, Van Zandt and McCarthy, 2013.

Table 3.1: Description and justification of the proposed indicators used to analyse the social vulnerability to GLOF impacts in this study. Indicators included in the SDG (Sustainable Development Goals) are identified, as well as an indication of whether each lead to an increased or decreased GLOF impact.

3.2.1.4 Risk

The normalised results of all three parameters (GLOF hazard, exposure, and vulnerability), were then combined to produce a quantitative metric for GLOF risk (Equation 3.5). Basins were then ranked from highest (1) to lowest (1089) risk to identify hotspots of GLOF risk.

$$\boldsymbol{GLOF\ risk = [Hazard\ x\ Exposure\ x\ Vulnerability]}$$

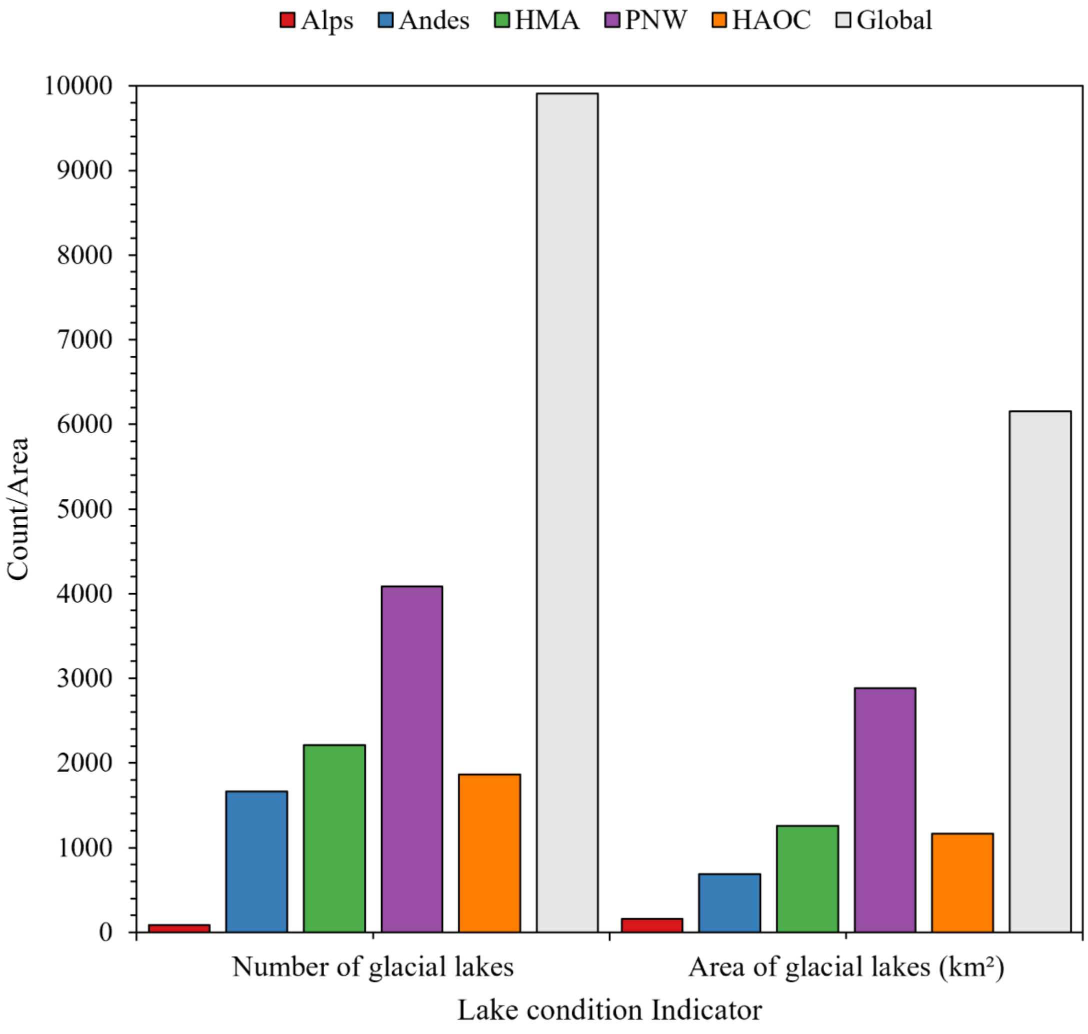
Equation 3.5

3.3 Results

3.3.1 Hazard

As of 2020, glacial lakes were found in 30 countries, with the highest area and number of glacial lakes found in the Pacific Northwest (PNW: area = 2884.05 km^2, n = 4083) and the lowest in the European Alps (area = 159.51 km^2, n = 87) (Figure 3.4; note Greenland was excluded given exposure is zero and its large number and area of lakes, plus the large seasonal variations in both could skew results unnecessarily). Within these regional trends there is significant national variation, with Canada containing the highest area and number of glacial lakes (area = 1941.05 km^2, n = 3034), whilst Iceland contains the least total area (0.79 km^2) and Ecuador the least total number (3) of glacial lakes (Figure 3.4). The biggest range in number of glacial lakes within a mountain range is found in the Andes, ranging from 1200 lakes in Chile to just three in Ecuador, whilst HMA has the highest range in lake area, from 1094 km^2 in China to 34.89 km^2 in Nepal.

As of 2020, regional normalised GLOF hazard represented in terms of the total number and area of glacial lakes was highest in the Pacific Northwest (PNW; 1.000), and lowest in the European Alps (0.041) (Figure 3.4). Within this regional trend there was high variability between nations, with individual GLOF hazard highest in Canada (0.685) and lowest in Ecuador (0.001). The largest range in intra-regional GLOF hazard scores was seen in High Mountains Asia (HMA), ranging from a high hazard score in China (0.319) to a low hazard score in Mongolia (0.006). Generally, normalised national GLOF hazard scores in HMA are below 0.100, with the exception of China.



ID	Number of glacial lakes	Area of glacial lakes (km²)	GLOF Hazard Score
Alps	87	159.51	0.041
Andes	1662	686.87	0.334
HMA	2211	1256.09	0.405
PNW	4083	2884.05	1.000
HAOC	1862	1166.09	0.447
Global	9905	6152.60	

Figure 3.4: Global distribution of GLOF hazard as of 2020. Number and area of glacial lakes and normalised hazard score for each mountain range in the study.

3.3.2 Exposure

In total, as of 2020, 90 million people across 30 countries live in 1089 basins containing glacial lakes (Figure 3.5). Analyses indicates that of these, 15 million (16.6%) live within 50 km of a glacial lake and 1 km of potential GLOF runout tracks (Figure 3.5). Results show that the majority of those exposed (62%) are located in the HMA region, with ~9.3 million people

(Figure 3.5). Globally, the proportion of exposed population varies significantly between countries; India and Pakistan contain the highest number of exposed people (~3 million and 2 million respectively, or one-third of the global total exposed population combined), whilst Iceland contains the lowest (260 people) (Figure 3.5). Just four highly populous countries account for >50% of the globally exposed population: India, Pakistan, Peru, and China (Figure 3.6). Meanwhile, Kyrgyzstan and Bhutan have the highest percentage of total national population exposed to GLOF (16% and 12% respectively), whilst in Sweden, < 1% of the national total is exposed to GLOF (Figure 3.5). As a result, regionally HMA has the highest normalised exposure score (1.000) whilst the HAOC scores the lowest (0.019). India and Pakistan are the highest individually scoring nations (1.000 and 0.701), and Sweden the lowest (0.001).

Generally, the population exposed to GLOFs increases with distance from a glacial lake, with almost half (48%) of exposed populations globally located between 20 km and 35 km downstream of glacial lake (Figure 3.6). Only 2% (300,000) of the global population exposed to GLOFs live within 5 km of one or more glacial lakes (Figure 3.6), with the majority of these (66%; 198,000) found in HMA (Figure 3.6). Populations in HMA live, on average, closer to glacial lakes than anywhere else, with ~1 million people living within 10 km downstream of a glacial lake, where any early warning time is likely to be low, and uncertainty in GLOF magnitude high. In contrast, populations across the PNW and High Arctic and Outlying Countries are generally situated further than 35 km downstream from glacial lakes (Figure 3.6). Analysis of exposure at the national scale reveals considerable sub-regional variability (Figure 3.7). In the European Alps, populations in Italy and Switzerland are living closer to glacial lakes than Austria and France (Figure 3.7). In the Andes, 1/5 of the total exposed population in the region (~0.5 million) can be found within the first 20 km in Bolivia and Peru, whereas in Ecuador exposed population is generally concentrated from >20 km, with < 25,000 people living closer to glacial lakes (Figure 3.7). Across HMA, populations in Pakistan are living closest to glacial lakes, with 0.8 million people living within the first 15 km, whereas in Nepal, populations are generally located more than 30 km from lakes (Figure 3.7). Whilst India has the highest exposed population globally, with ~3 million people living within 1 km of likely GLOF runout tracks up to 50 km (Figure 3.6) < 16% are found before 30 km (Figure 3.7). In the High Arctic and Outlying Countries, more than 60% of the total population found within each 5 km buffer is accounted for by Georgia (Figure 3.7) with the relative contribution of exposure in the remaining six nations much lower.

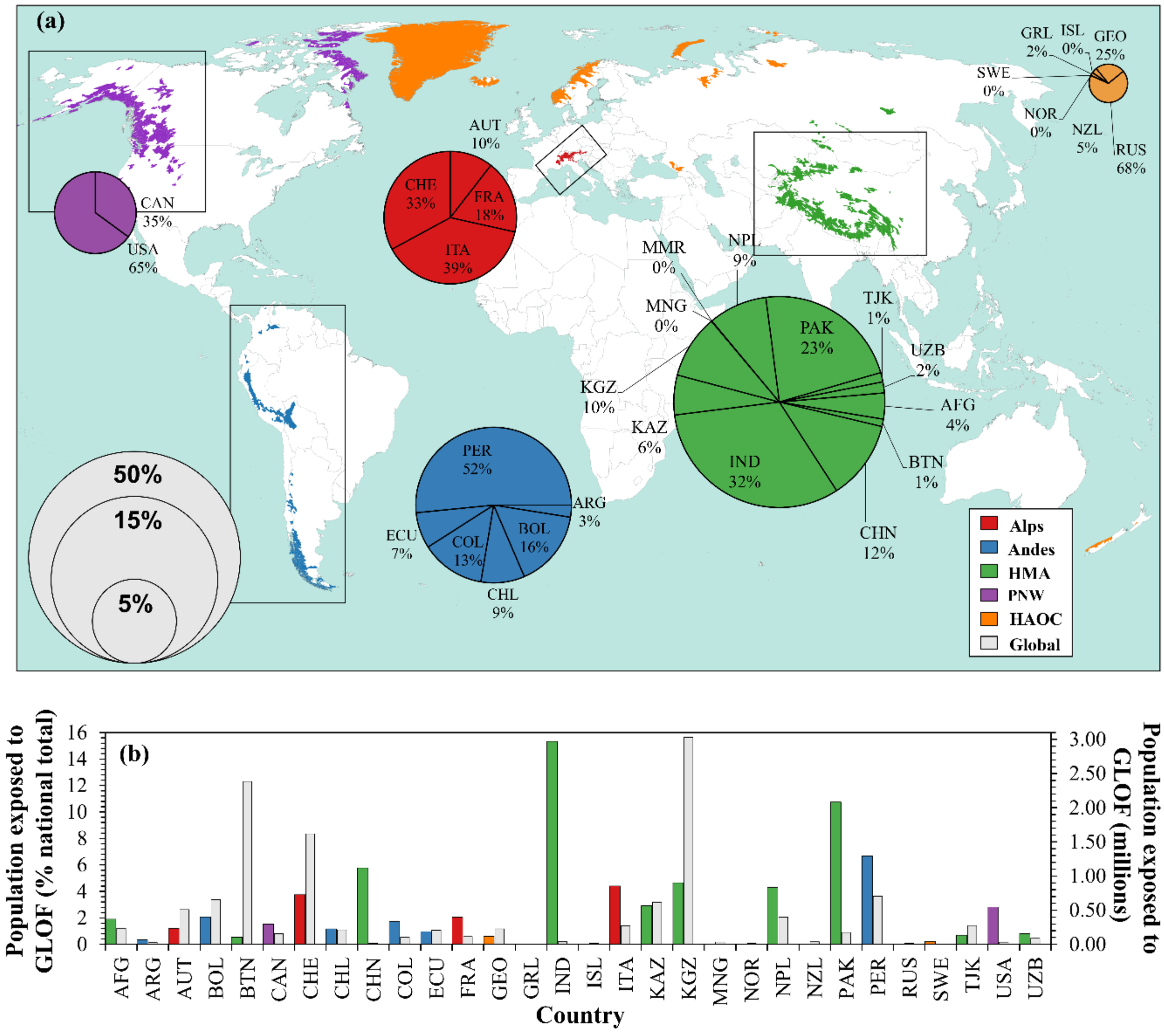


Figure 3.5: Global distribution of GLOF exposure as of 2020. (a) Global distribution of glacial basins, colour-coded according to mountain range (Alps, Andes, HMA, PNW and High Arctic and Outlying Countries). Pie charts show the proportion of exposed population within each mountain range for individual country contributions as of 2020, whilst size of the pie indicates the percentage contribution to the global total (b) Grey bars show exposed population as a percentage of the national total (left axis). Coloured bars show the total exposed population per country (right axis).

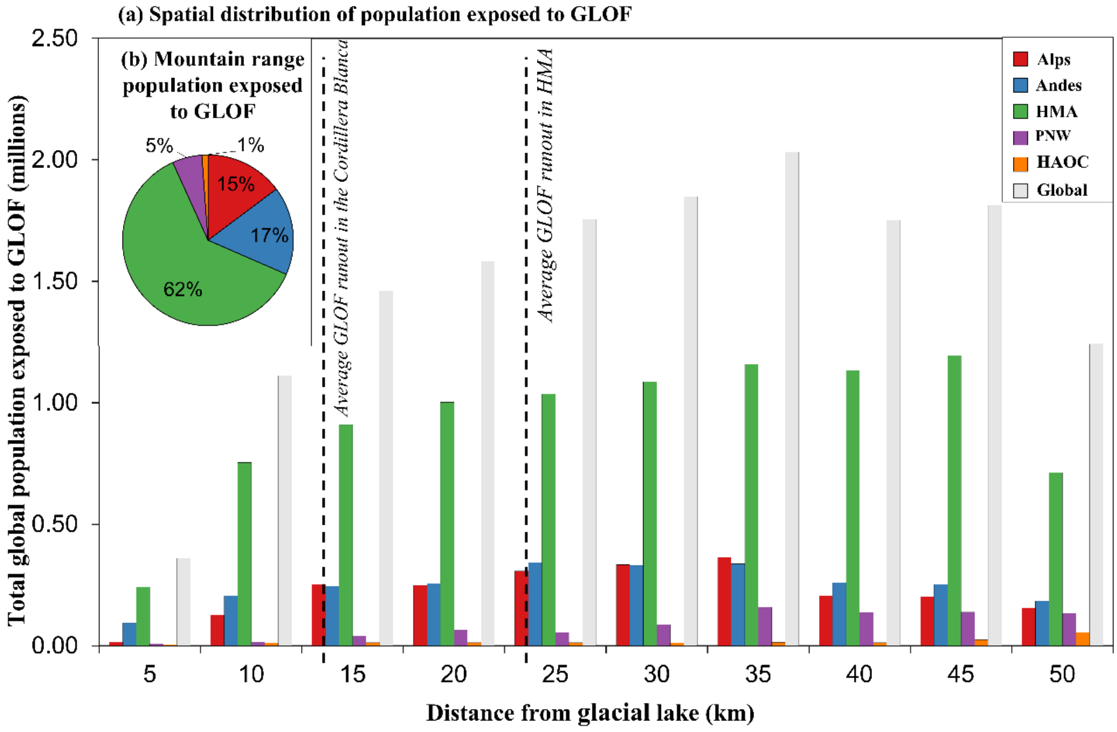


Figure 3.6: Global spatial distribution of GLOF exposure as of 2020. (a) Spatial distribution of exposure within GLOF runout tracks up to 50 km from a glacial lake, at 5 km intervals at the global and mountain range scale (b) Contribution of mountain range to the global total exposed population. Countries are coloured according to mountain range.

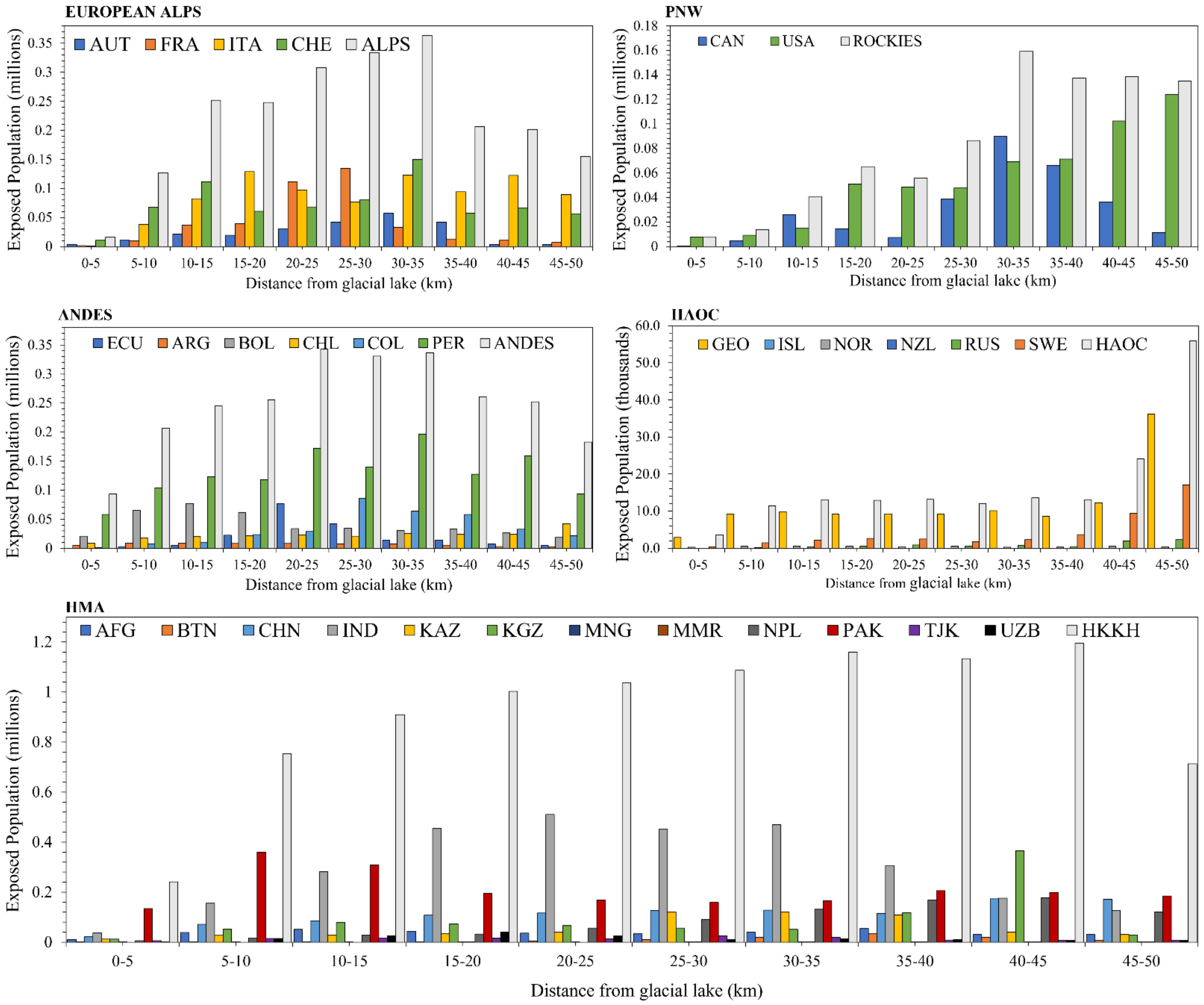


Figure 3.7: National spatial distribution of GLOF exposure as of 2020. Spatial distribution of exposure to GLOF within 1 km of likely GLOF runout tracks up to 50 km from a glacial lake, at 5 km intervals for each mountain range. Mountain range totals are given alongside national totals for comparison.

3.3.2.1 Exposure in HMA

Globally, exposure to GLOFs in 2020 is highest in HMA, with ~9 million people living within 1 km of likely GLOF flood corridors up to 50 km from a glacial lake (Figure 3.5). With ~1 million of these people living within 10 km of a glacial lake (Figure 3.6), populations across the region are living the closest globally to glacial lakes as of 2020. The sub-regional spatial distribution within these overall regional trends is interesting and shows marked variation (Figure 3.8b); of the total exposed population across the region, most (42%) are found in the Himalayan sub-region (3.9 million) and the least in the Altay and Sayan sub-region (< 1%, ~ 6000 people). Populations in the Hindu-Kush-Karakoram sub-region live the closest to glacial lakes (Figure 3.8b) with > 0.5 million exposed people residing between 0 and 10 km, accounting for 22% of the sub-regional total. Comparing the covariance in the rates of glacial lake (area/number) and population change within sub-regions between 1990 and 2018 highlights their role on overall GLOF risk (Figure 3.8a). Of concern is the Himalayan sub-region, as the population, area and number of glacial lakes are growing rapidly (by 2.63%, 3.47% and 6.88% annually), indicating both the hazard and exposure are increasing. Comparatively, in the sub-regions of Altay and Sayan, whilst population is increasing (1.66% a^{-1}) both the area and number of glacial lakes is in decline (-1.60% a^{-1} and -1.49% a^{-1} respectively), suggesting currently hazard is not growing (Figure 3.8a). Although the change in the area and number of glacial lakes is low in the Hindu-Kush-Karakorum (0.25% a^{-1} each), the sub-region has the highest rate of population growth across HMA (2.81% a^{-1}). Thus, should the number and area of glacial lakes increase in the future (thus increasing GLOF hazard), GLOF risk in this sub-region could increase.

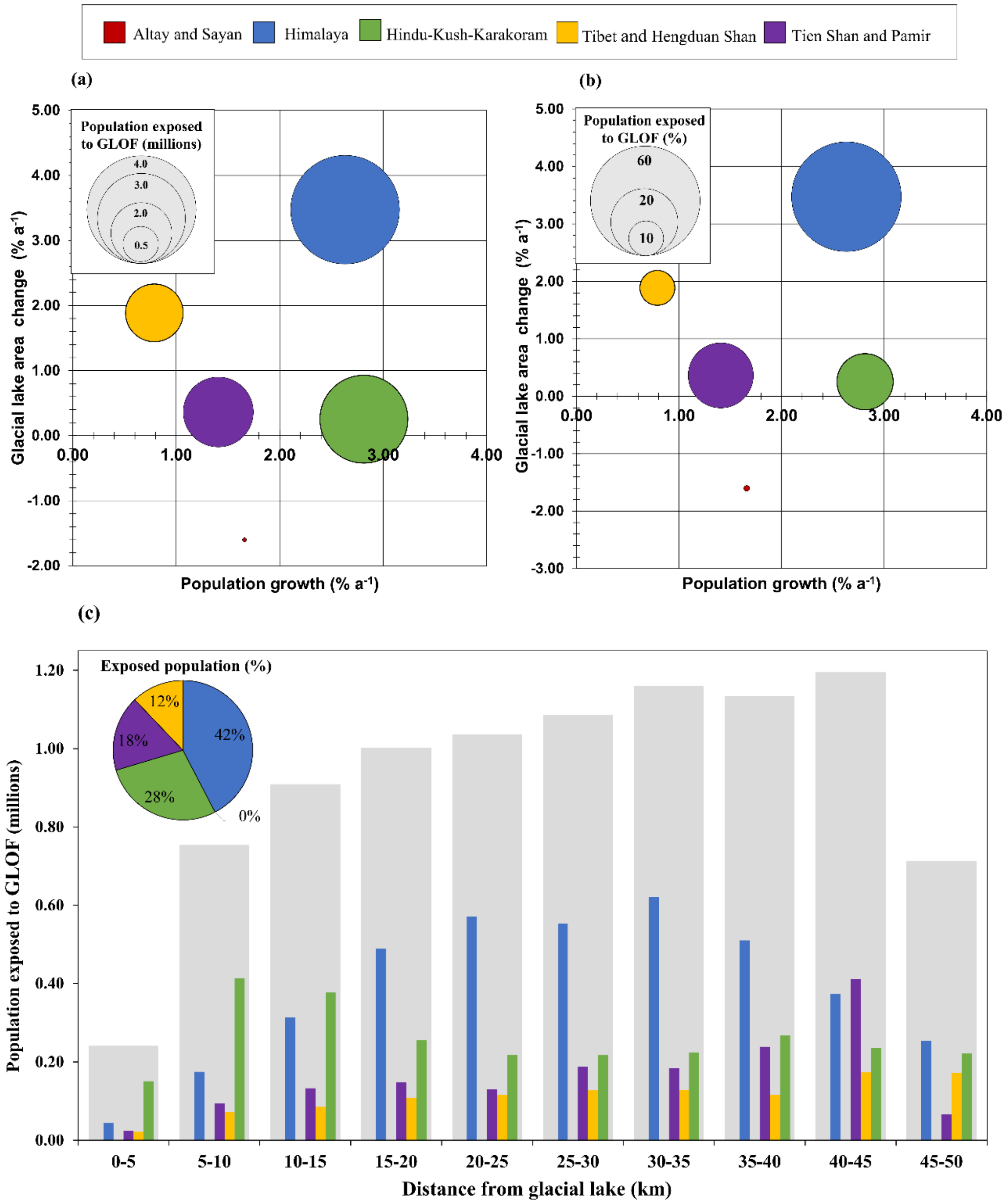


Figure 3.8: Sub-regional spatial exposure to GLOFs in HMA as of 2020. (a) Rate of change in population and area of glacial lakes with absolute exposed population across HMA (b) Rate of change in population and area of glacial lakes with percentage exposed population across HMA (as percentage of the total population in glacial basins in HMA) and (c) Spatial distribution of exposed populations across HMA according to sub-region. Pie chart shows the relative contribution of each sub-region to the regional total.

3.3.3 Vulnerability

Each of the three indices used to calculate vulnerability (CPI, HDI and SVI) showed marked variation between regions as well as within regions. As of 2020, HMA has the lowest HDI and CPI (0.671 and 35 respectively), whilst the PNW has the highest (0.928 and 72 respectively). However, this masks national trends. For instance, whilst most nations in HMA score below the global average in HDI (0.799), Kazakhstan scores higher (0.825). Similarly in the Andes, although average CPI score is 51, national scores range from high corruption in Ecuador (88) to low corruption in Bolivia (31). Globally, Norway has the highest HDI (i.e. most developed; 0.957) and New Zealand the highest CPI (i.e. least corrupt; 88). Afghanistan has both the lowest HDI and CPI globally (0.511 and 19 respectively), making it the least developed and most corrupt nation where glacial lakes are found. Generally, the European Alps and PNW score well in the SVI (Figure 3.9); for indicators that reduce vulnerability to GLOF (literate females, urban population, access to safe water, good sanitation, and internet) >70% of population across the PNW are accounted for (Table 3.2). In contrast, across HMA and the Andes the percentage of population accounted for in factors increasing vulnerability to GLOFs are above the global average, whilst scores for factors decreasing vulnerability to GLOFs are below the global average (Figure 3.9, Table 3.2). As a result of the combination of these three indices (CPI, HDI and SVI), HMA is identified as the most vulnerable region to GLOFs as of 2020 (0.768) and the PNW the least (0.336). Overall, Afghanistan and Pakistan are the most vulnerable nations (0.919 and 0.837 respectively) whilst Switzerland and New Zealand are the least (0.194 and 0.186 respectively).

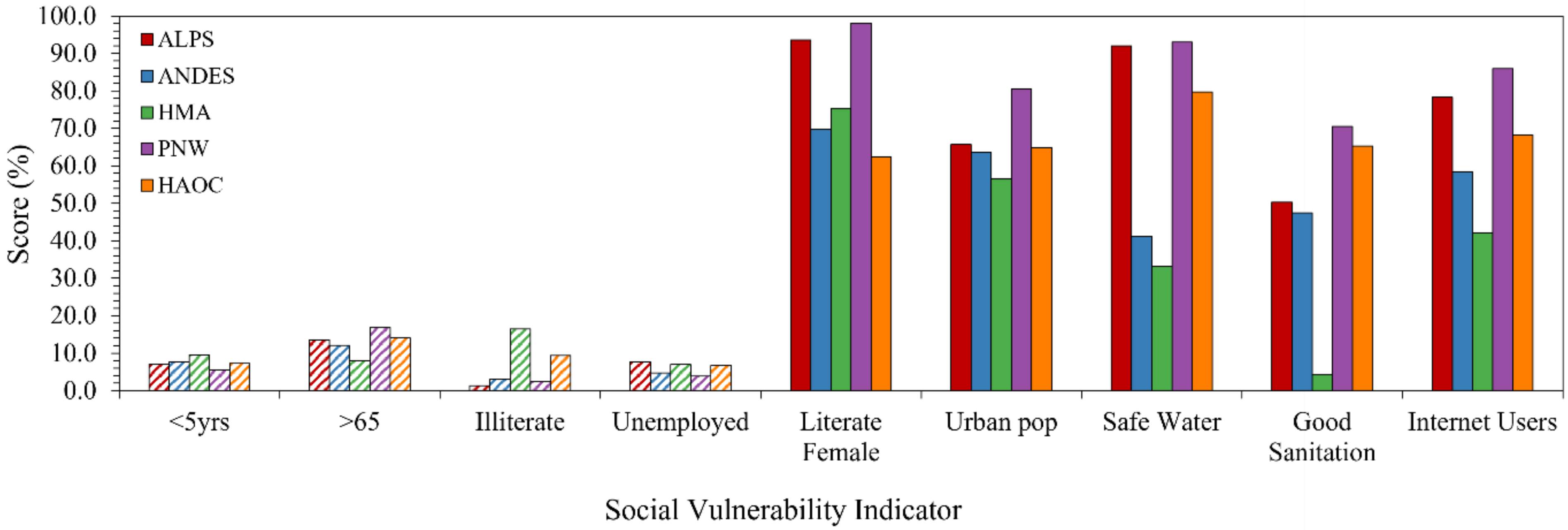


Figure 3.9: Mountain range Social Vulnerability Index scores for 2020. Mountain range totals for indicators used to the calculate the social vulnerability index used in this study. From left to right; percentage population < 5 years of age, percentage population > 65 years of age, percentage population illiterate, percentage population unemployed, percentage female population with some literacy, percentage urban population, percentage population with access to safe drinking water, percentage population with access to good sanitation, percentage population with access to internet. Dashed bars show factors that increase vulnerability to GLOFs, and solid bars show factors that decrease vulnerability to GLOFs.

Country ID	Population <5 yrs	Population >65 yrs	Illiterate Population	Unemployed Population	Literate Female Population	Urban population	Safe Drinking Water	Good Sanitation	Internet Users
AFG	14.8	2.6	57.0	11.1	13.2	25.8			13.5
ARG	8.4	11.2	1.0	9.8	59.2	92.0			71.8
AUT	4.9	19.4	1.0	4.7	100.0	58.5	99.0	97.0	87.7
BOL	10.3	7.3	7.5	3.5	53.1	69.8		23.0	43.8
BTN	8.3	6.1	33.5	6.8	23.3	41.6	36.0		48.1
CAN	5.3	17.6	1.0	5.6	100.0	81.5	99.0	82.0	91.0
CHL	6.2	11.9	3.6	7.1	77.8	87.6	99.0	77.0	82.3
CHN	5.4	11.5	3.2	4.3	76.0	60.3		72.0	54.3
COL	7.4	8.8	4.9	9.7	55.7	81.1	73.0	17.0	62.3
ECU	9.6	7.4	7.2	4.0	52.5	64.0	75.0	42.0	57.3
FRA	5.6	20.4	1.0	8.4	81.7	80.7	98.0	88.0	82.0
GEO	6.9	15.1	0.6	14.4	97.2	59.0	80.0	27.0	64.0
GRL	5.2	20.0	1.0	4.9	91.2	88.0	97.0	95.0	97.6
IND	8.5	6.4	25.8	5.4	27.7	34.5			34.5
ISL	6.1	15.2	1.0	2.8	100.0	93.9	100.0	82.0	99.0
ITA	3.9	23.0	0.8	9.9	75.9	70.7	95.0	96.0	74.7
KAZ	10.5	7.7	0.2	4.6	99.3	57.5	90.0		78.9
KGZ	12.0	4.6	0.4	6.3	99.1	36.6	68.0		38.0
MNG	11.6	4.2	1.6	6.0	91.5	68.5	24.0		23.7
NOR	5.2	17.3	1.0	3.3	95.4	82.6	98.0	76.0	96.5
NPL	9.5	5.8	32.1	1.4	29.3	20.2	27.0		34.0
NZL	6.3	16.0	1.0	4.1	97.4	86.6	100.0	89.0	90.8
PAK	12.8	4.3	40.3	4.5	27.6	36.9	35.0		15.5
PER	8.6	8.4	5.6	3.3	58.9	78.1	50.0	43.0	52.5
RUS	6.4	15.1	0.3	4.6	96.3	74.6	76.0	61.0	80.9
SWE	6.0	20.2	1.0	6.5	89.3	87.7	100.0	93.0	92.1
CHE	5.2	18.8	1.0	4.6	95.6	73.8	95.0	100.0	89.7
TJK	14.4	3.1	0.2	11.0	93.3	27.3	48.0		22.0
USA	6.0	16.2	1.0	3.7	96.1	82.5	99.0	90.0	87.3
UZB	10.4	1.3	0.0	5.9	99.9	50.4	44.0		52.3

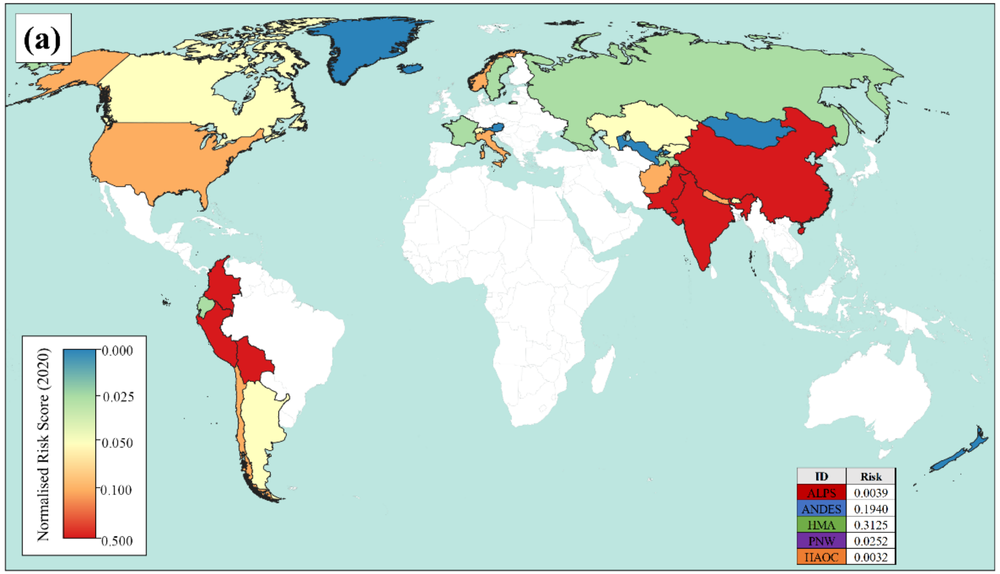
Table 3.2: Values used to calculate the Social Vulnerability Index for the vulnerability proxy. Values are given as percentages of total population. Metrics in red increase vulnerability to GLOF, those in green reduce vulnerability to GLOF. Blank indicates no data available. Countries are coloured according to mountain range, where; Alps = yellow, Andes = orange, HMA = blue, PNW = green and High Arctic and Outlying Countries = purple.

3.3.4 Risk

The combined normalised scores of hazard, exposure, and vulnerability reveal the HMA has the highest GLOF risk as of 2020 (0.313), with a total of 9.3 million people exposed to 2211 glacial lakes covering an area 1256.09 km^2. Comparatively, the High Arctic and Outlying Countries have the lowest GLOF risk (0.032) with <200,000 people exposed, albeit to a similarly high number and area of glacial lakes (1862 lakes covering an area 1166.09 km^2)(Figure 3.10). As with the individual components, there is substantial sub-regional variation in GLOF risk (Figure 3.13). China and Pakistan are the most at-risk nations globally (0.863 and 0.751 respectively) (Figure 3.10). Pakistan has near double the exposed population of China (2.1 million and 1.1 million respectively) and is significantly more vulnerable (0.837 compared to 0.683 in China). However, with more numerous glacial lakes, and of larger area

(1109 lakes covering 1094.44 km^2) the GLOF hazard score in China is large enough to more than offset these differences.

When all 1089 glacial basins are ranked from highest to lowest risk (1 – 1089), the top three are found in Pakistan (Khyber Pakhtunkhwa basin), Peru (Santa basin) and Bolivia (Beni basin) (Figure 3.11, Figure 3.12, Table 3.2) containing, respectively, 1.2 million, 0.9 million and 0.1 million people who could be exposed to GLOF impacts. Interestingly, Canada and USA contain just 3 basins in the top 50 globally (Table 3.3, Table S3.1) as well as the lowest ranking basin (Tyers basin, Canada), where exposure is negligible as potential GLOF runout tracks are largely unpopulated. However, at the national level Canada and USA have relatively high GLOF risk (0.321 and 0.059) ranking 4^{th} and 6^{th} respectively, mainly because they host a large number of catchments with generally high hazard scores, highlighting the importance of spatial scale in these analyses. Of the top 50 catchments in 2020, 44% are found in HMA (Figure 3.13iii, Table 3.3). Nationally, Bhutan stands out, with four of five glacial catchments placing within the top 50 (Figure 3.13iii, Table 3.3).



ID	Exposure	Hazard	Vulnerability	Risk
CHN	0.377	0.319	0.683	0.863
PAK	0.701	0.024	0.837	0.751
PER	0.435	0.031	0.708	0.400
CAN	0.099	0.685	0.289	0.321
IND	1.000	0.032	0.755	0.257
USA	0.184	0.285	0.383	0.059
CHL	0.077	0.137	0.434	0.048
ITA	0.287	0.026	0.532	0.042
NPL	0.280	0.017	0.810	0.041
COL	0.112	0.047	0.704	0.039
KGZ	0.303	0.015	0.786	0.037
RUS	0.039	0.088	0.754	0.027
AFG	0.124	0.017	0.919	0.021
BOL	0.135	0.015	0.781	0.016
KAZ	0.189	0.008	0.689	0.011
ARG	0.021	0.078	0.650	0.011
TJK	0.045	0.011	0.836	0.004
BTN	0.035	0.020	0.572	0.004
CHE	0.245	0.008	0.194	0.004
FRA	0.134	0.001	0.652	0.001
AUT	0.078	0.003	0.304	0.001
NZL	0.003	0.108	0.186	0.001
NOR	0.001	0.111	0.201	0.000
ECU	0.063	0.001	0.339	0.000
MNG	0.002	0.006	0.745	0.000
GEO	0.015	0.001	0.446	0.000
SWE	0.000	0.096	0.203	0.000
ISL	0.000	0.012	0.292	0.000
GRL	0.000	1.000	0.477	0.000
UZB	0.052	0.000	0.814	0.000

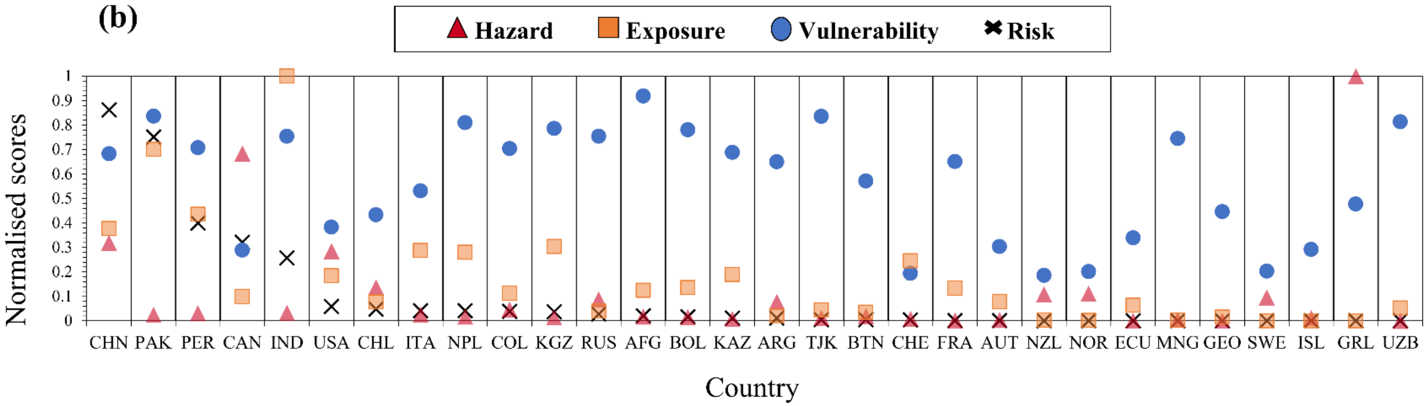


Figure 3.10: Global GLOF risk as of 2020. (a) Spatial distribution of GLOF risk as of 2020 and (b) final normalised scores of hazard, exposure, vulnerability, and risk for each country. Countries are listed from highest risk score (left) to lowest (right). Note that risk scores are shown to three decimal places and with the exception of Uzbekistan no scores of absolute zero were recorded.

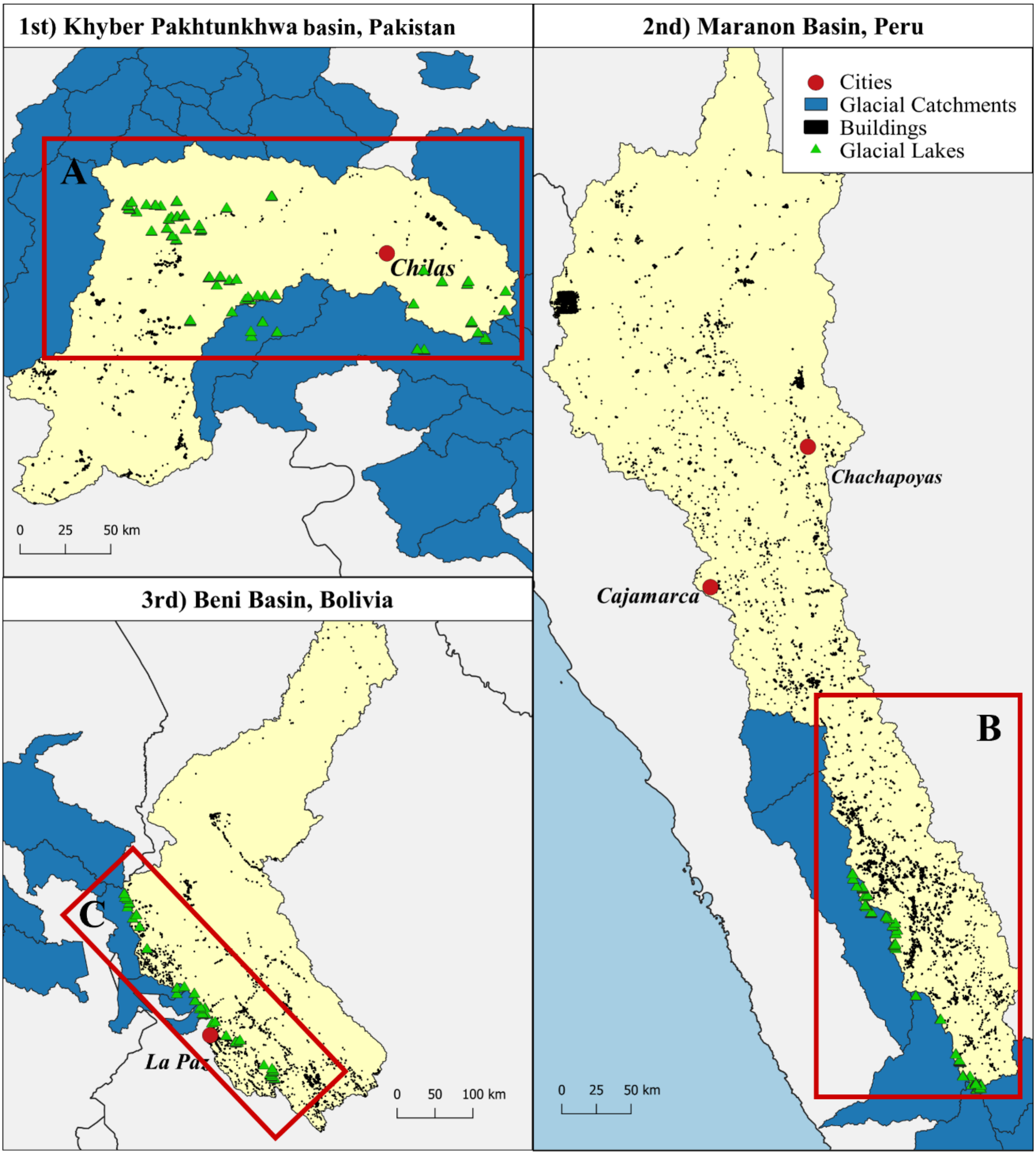


Figure 3.11: Top 3 most at-risk glacial basins. Location of the three most at-risk glacial basins as of 2020; 1st - Khyber Pakhtunkhwa basin, Pakistan, 2nd - Santa basin, Peru, and 3rd - Beni basin, Bolivia. Inset panels A-C correlate to Figure 3.12. Key cities and buildings are shown alongside the location of glacial lakes as of 2020. Population as of 2020 is given.

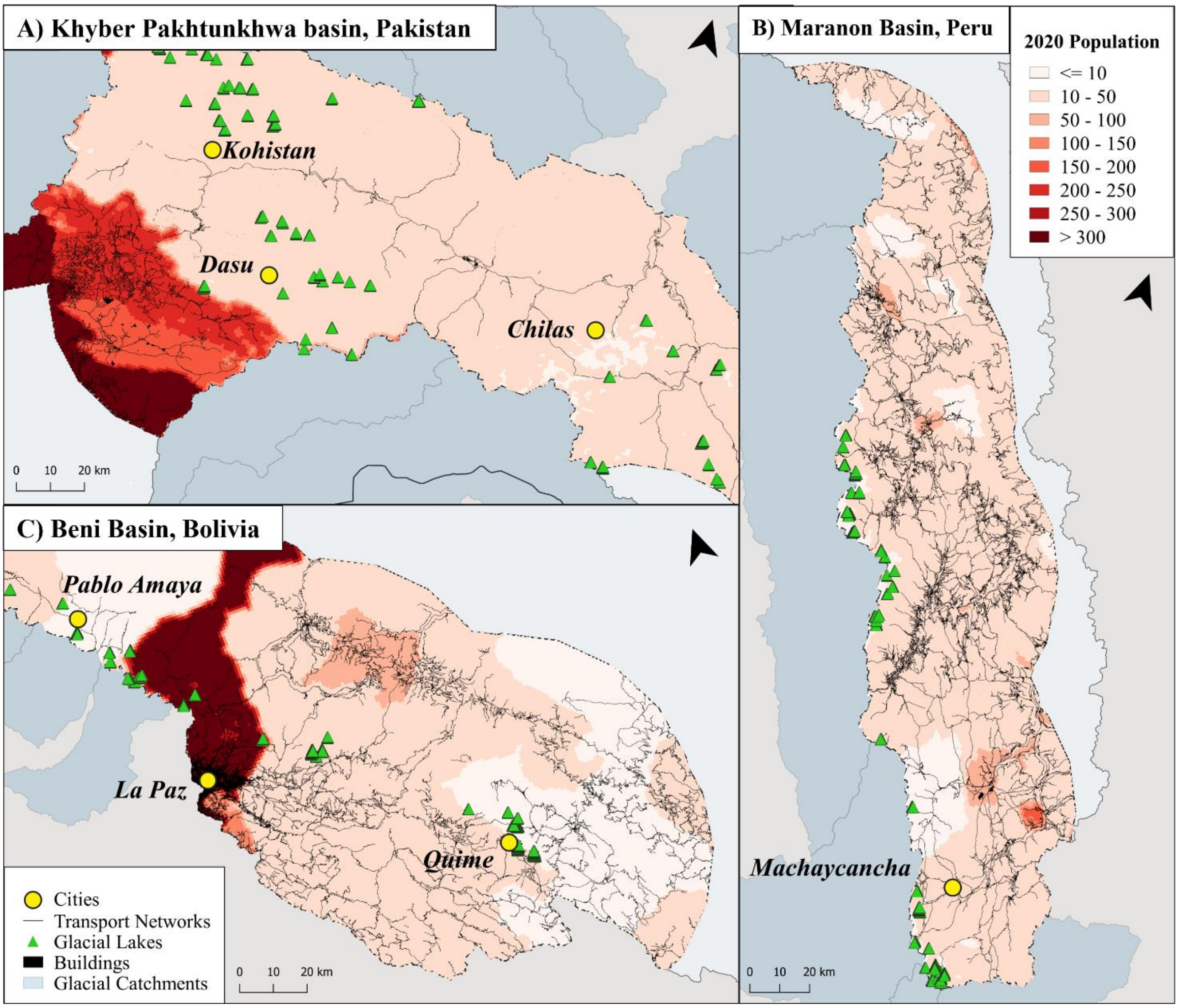


Figure 3.12: Exposure in the Top 3 most at-risk glacial basins. Areas of higher exposure within the top 3 most at-risk basins (within <50 km of a glacial lake); A) Khyber Pakhtunkhwa basin, Pakistan, B) Santa basin, Peru, and C) Beni basin, Bolivia. Panels correlate to Figure 3.11. Key cities, transport networks (railways/roads) and buildings are shown alongside the location of glacial lakes as of 2020. Population as of 2020 is given.

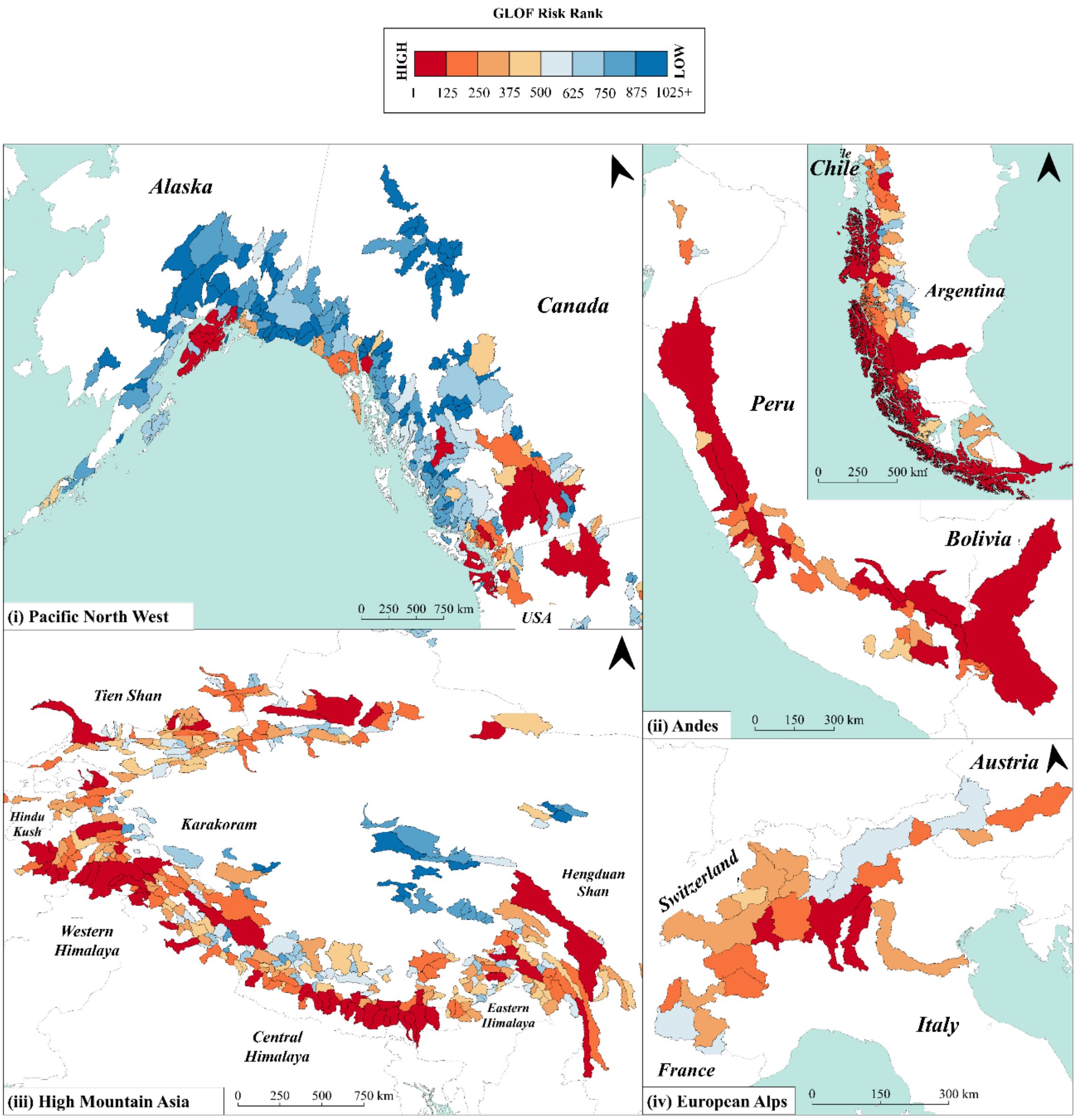


Figure 3.13: Basin-scale GLOF risk ranking. 2020 GLOF risk for each of the 1089 glacial basins from high (red) to low (blue) risk.

Country	Basin ID	Normlaised Risk	Risk Rank	Basin Name*
PAK	11411000000	1.47E-03	1	Khyber Pakhtunkhwa
PER	50432000000	3.43E-04	2	Santa
BOL	50411230301	3.40E-04	3	Beni
BTN	11501060201	2.61E-04	4	Punatsangchhu
IND	11501050200	1.75E-04	5	
CHL	51203030111	1.69E-04	6	
PAK	11410040300	1.60E-04	7	
ARG	51202010101	1.40E-04	8	
USA	30101130110	1.39E-04	9	
USA	30403131201	1.31E-04	10	
NOR	41001010201	1.10E-04	11	Glomma
PER	51502040200	9.47E-05	12	
PAK	11410040201	9.40E-05	13	
PAK	11406150100	7.95E-05	14	Sutlej
CHN	11504090000	7.78E-05	15	
NOR	41001010211	7.33E-05	16	Møre og Romsdal
IND	11406190000	7.17E-05	17	Jhelum
NPL	11504080301	6.83E-05	18	TamaKoshi
NPL	11504080500	6.55E-05	19	BhoteKoshi
NPL	11506070000	5.37E-05	20	Trishuli
CHE	40210100400	5.07E-05	21	Rhône
ITA	40208060200	4.44E-05	22	
CHL	51202050211	4.39E-05	23	
NPL	11506050100	4.07E-05	24	Marsyangdi
NPL	11504080101	3.95E-05	25	DudhKoshi
AFG	10907220101	3.92E-05	26	
TJK	10907330101	2.89E-05	27	Pyanj and Kyzylsu
IND	11406190100	2.83E-05	28	Chenab
CHL	51301020211	2.80E-05	29	
NPL	11504070100	2.75E-05	30	Tamor
NOR	41001050911	2.49E-05	31	Rogaland
PER	50426270600	2.25E-05	32	
ARG	51301060200	2.23E-05	33	Santa Cruz
IND	11406180100	2.16E-05	34	Indus
PER	50426221300	2.12E-05	35	
CHN	11002030201	1.80E-05	36	Heihe
CAN	30401070401	1.73E-05	37	
PER	51502030101	1.70E-05	38	
PER	50411231301	1.68E-05	39	
BTN	11501110301	1.65E-05	40	Drangmechhu
CHN	12517000000	1.65E-05	41	Jinsha
CHN	11002031101	1.52E-05	42	
BTN	11501110201	1.48E-05	43	Mangdechhu
NOR	41001051211	1.38E-05	44	
IND	11501050101	1.29E-05	45	
PER	51401160500	1.26E-05	46	
PER	51401160101	1.25E-05	47	
AUT	40515060000	1.21E-05	48	
ITA	40208140000	1.19E-05	49	
BTN	11501060500	1.11E-05	50	Amochhu

Table 3.3: Top 50 basins at highest risk of GLOF impacts as of 2020. Countries are coloured according to mountain range, where; Alps = red, Andes = blue, HMA = green, PNW = purple and HAOC = orange. *Very few of the basins included have clearly identifiable names within literature, and for some of the smaller basins the names vary between local populations and across languages. Thus, basin names are given where possible alongside basin ID numbers that can be used to identify others if needed.

3.4 Discussion

3.4.1 Global distribution of GLOF risk

With an increase in interest surrounding GLOFs over the last few decades, a clear geographical disparity has emerged between where GLOFs are occurring and the hotspots of research (Emmer, 2018; Emmer, Allen, et al., 2022) (Figure 3.14). Between 1979 and 2021, the Hindu-Kush-Karakoram, Iceland, and the North American Cordillera were the most prominent GLOF research hotspots with 346, 206 and 174 research items respectively (Emmer, Allen, et al., 2022) (Figure 3.14). Since 2015, however, the Himalayas have emerged as the primary research focus, accounting for 36% of the studies undertaken between 2017 and 2021 (Emmer, Allen, et al., 2022). As such, these 'hotspot' regions are often cited as having the highest GLOF risk (e.g. Zheng *et al.,* 2021). Whilst true in part, our results also indicate that as of 2020, the potential for large GLOF impacts is also high across the Andes (Figure 3.10), and as a nation, risk in Peru is third highest globally whilst the second and third highest risk basins globally are found in Peru and Bolivia (Figure 3.10, Figure 3.11).

Over the last two decades, glaciers across the Andes have undergone rapid deglaciation in response to climate change (Wilson et al., 2018; Masiokas et al., 2020) leading to the growth of numerous large glacial lakes and consequently a growth in GLOF hazard; the number of glacial lakes across the region increased by 93% compared to just 37% in HMA over the same period (Figure 3.4). Concurrent with this increase, populations living in close proximity to glacial lakes has grown (Figure 3.5, Figure 3.6), increasing the overall exposure to GLOF; since 1941 the population in Huaraz, Peru alone has increased by > 100,000 (Motschmann, Huggel, Carey, et al., 2020). At the same time, regional vulnerability remains high as a result of deep-rooted corruption and poor standards of living (Figure 3.9). Compared to the other study regions, the number of GLOF research items across the Andes are few; less than 8% (< 100 items) of the English-language published research items between 1979 and 2021 were undertaken in this region (Emmer, Allen, et al., 2022) (Figure 3.14). I suggest this data sparsity across the Andes is preventing meaningful assessments of actual GLOF risk in the region, and urgently requires attention. Further, our results show in locations where GLOF research is prolific, such as Iceland, GLOF risk is much lower; Iceland places 28th out of 30 when nations are ranked in order of risk. Identifying locations with high GLOF risk, as presented here, could help address the disparity between where GLOF risk is high (e.g. HMA, the Andes) and where research is being undertaken (e.g. Iceland) by directing research efforts to regions where it is urgently needed. Further, a better understanding of who is funding research and collation of the resultant outputs could help here. I acknowledge continued monitoring globally is important, and should be continued, however suggest a greater focus and a redirecting of research funding to areas of higher risk would be beneficial for long-term risk reduction.

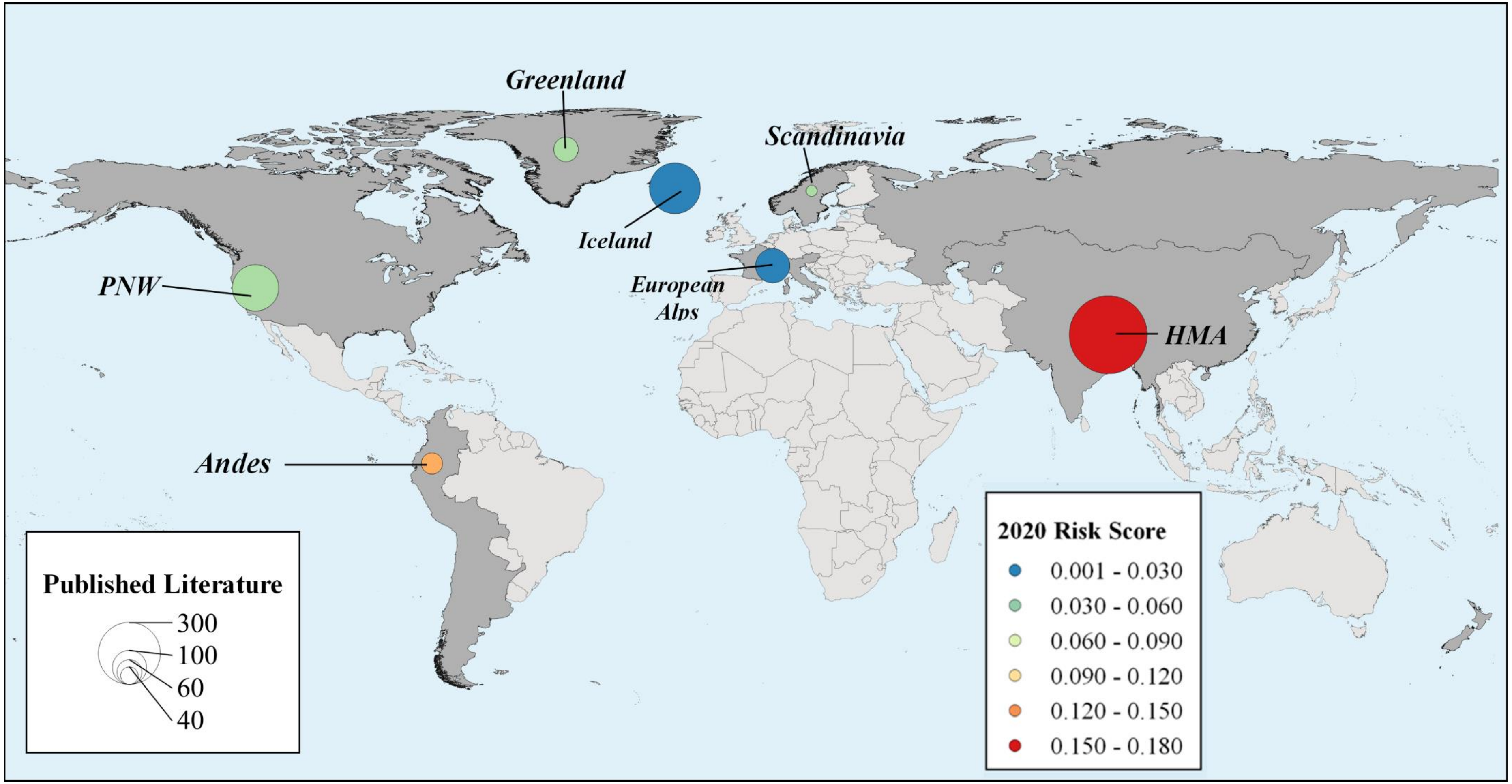


Figure 3.14: Comparison of locations of GLOF research and calculated GLOF risk score (data collated from Emmer, 2018; Emmer, Allen, *et al.*, (2022). Number of GLOF research items per regions where glacial lakes are found (dark grey) compared to calculated 2020 GLOF risk in the same areas. Generally, regions with lower risk (e.g. Iceland, PNW) have been highly studied, whereas the high-risk regions (e.g. the Andes) have fewer studies.

3.4.2 Populations in HMA live closest to glacial lakes

Compared to hydrometeorological floods, GLOFs can have exceptional discharges, reaching >120 km downstream (Osti & Egashira, 2009; Richardson & Reynolds, 2000a). Here, anyone living within 1 km of likely GLOF runout tracks up to a maximum distance of 50 km from a glacial lake was considered to be at risk of either direct (e.g. death or injury) or indirect (e.g. loss of land, damaged infrastructure) impacts. However, peak discharge attenuates rapidly from the flood source (Schwanghart et al., 2016), meaning that risk impacts are generally greatest with increasing proximity to a glacial lake (Allen et al., 2019, 2020). Results show populations in HMA (Figure 3.5), and particularly those in Pakistan (Figure 3.7) are living closest to glacial lakes globally. With the expansion of agriculture, development of new HEP sites (located at increasing proximity to glacial lakes), and growth of the tourism sector expected to increase in this region over the next few decades, it follows that exposure is only likely to increase as people move to higher elevation to support the aforementioned development, as has been observed in other mountain regions globally (Drenkhan et al., 2019; Carey, 2008; GAPHAZ, 2017; Furian et al., 2021). The characteristically rapid onset and high discharge of GLOFs means there is often insufficient time to effectively warn downstream populations and for effective action to be taken, particularly for populations located within 10-15 km of the source lake (B. Bajracharya et al., 2007; Maurer et al., 2020). Improvements are urgently needed to Early Warning Systems (EWS) alongside evacuation drills, plus other forms of community outreach that are sympathetic to potential social and cultural barriers, to enable more rapid warnings and emergency action in these highly exposed areas.

Across HMA resources for mitigation are often limited (Carrivick & Tweed, 2016), and residents' lack of awareness, or lack of means to affect change, inhibits their ability to prepare for, and recover from, potential GLOF disasters sourced from remote glacial lakes (Wang & Jiao, 2015). Thus, analysing the spatial distribution of exposure as presented here not only highlights where advances are needed (e.g. EWS) but could also allow for more effective mitigation strategies (e.g. land zoning, education) to be implemented. Similar to findings for the Andes, whilst Pakistan is a global hotspot of GLOF risk, there is a comparative lack of published research occurring here, despite large-scale investment (>US$30 million) in GLOF vulnerability projects from the United Nations Development Programme (UNDP, 2021). As population across Pakistan continues to increase rapidly (3.12% a^{-1}), and with the number and area of glacial lakes here predicted to increase over the coming years, (Linsbauer et al., 2016; Furian et al., 2021), Pakistan could become a major hotspot for GLOF impacts in the future. I suggest the area should be targeted for more fundamental research to underpin national adaptation projects.

Evaluating the spatial distribution of exposure not only allows for areas of concern to be identified, but it can also reveal locations within high-risk areas that could be lower priority for mitigation strategies. In the Cordillera Blanca, only 5 out of 29 documented GLOFs (17%) have impacted further than 10 km downstream. Therefore, although the GLOF risk in the Andes is second highest globally (Figure 3.10, Figure 3.11) and should be targeted for more detailed studies and intervention, when placed in a regional context, only 12% of the total number of people exposed to GLOF across the mountain range (~300,000 people) are in the likely direct-impact zone (within 10km), with the majority of those located in Peru (54%) and Bolivia (29%) (Figure 3.7). This knowledge means priority areas for risk mitigation can be accurately identified, which is particularly important for regions where resources are limited.

3.4.3 Role of exposure and vulnerability

Glaciers are exhibiting negative mass balance in nearly all glaciated regions of the world (Hock et al., 2019), and over the past three decades the number, area and volume of glacial lakes has increased rapidly (Shugar et al., 2020). Data show that countries (and basins) with the largest, or most numerous, glacial lakes do not always equate to having the highest GLOF risk. Instead, our results show that it is exposed population that greatly elevates the potential impact of GLOFs globally, particularly across HMA and the Andes (Figure 3.5). For instance, Greenland has the highest number and area of glacial lakes of any nation in this study, thus has the highest hazard score (1.000) yet no people reside along likely GLOF runout tracks thus it has a risk score of zero. Documenting changes in glacial lakes and highlighting areas where GLOF hazard may be increasing, while valuable, does not therefore provide an accurate indication in terms of risk trajectories, since contemporaneous changes in population exposure may more than offset changes in hazard. For instance, Norway has one of the highest rates of lake growth globally, both in terms of area (4.58% a^{-1}) and number (15.93% a^{-1}), yet population growth is just ~1% a^{-1} (Figure 3.15). In comparison, Nepal has far lower rates of lake growth (area: 1.26% a^{-1}; number: 1.73% a^{-1}) but annual population growth is at ~4% a^{-1} (Figure 3.15). Since Nepal has a substantially higher exposed population than Norway (0.8 million compared to ~4000) risk may well be growing faster in Nepal, despite substantially slower growth in hazard. Thus, whilst a higher number and/or area of glacial lakes may increase overall GLOF hazard by (i) increasing the exposure of lakes to potential external triggers (e.g. rock/ice avalanching) and (ii) increasing the overall volume of meltwater likely to be released during an outburst (Allen, Linsbauer, et al., 2016; Rounce et al., 2016; Linsbauer et al., 2016), results demonstrate that this does not automatically translate to higher GLOF risk and it is vital that exposure be integrated if risk is to be accurately assessed.

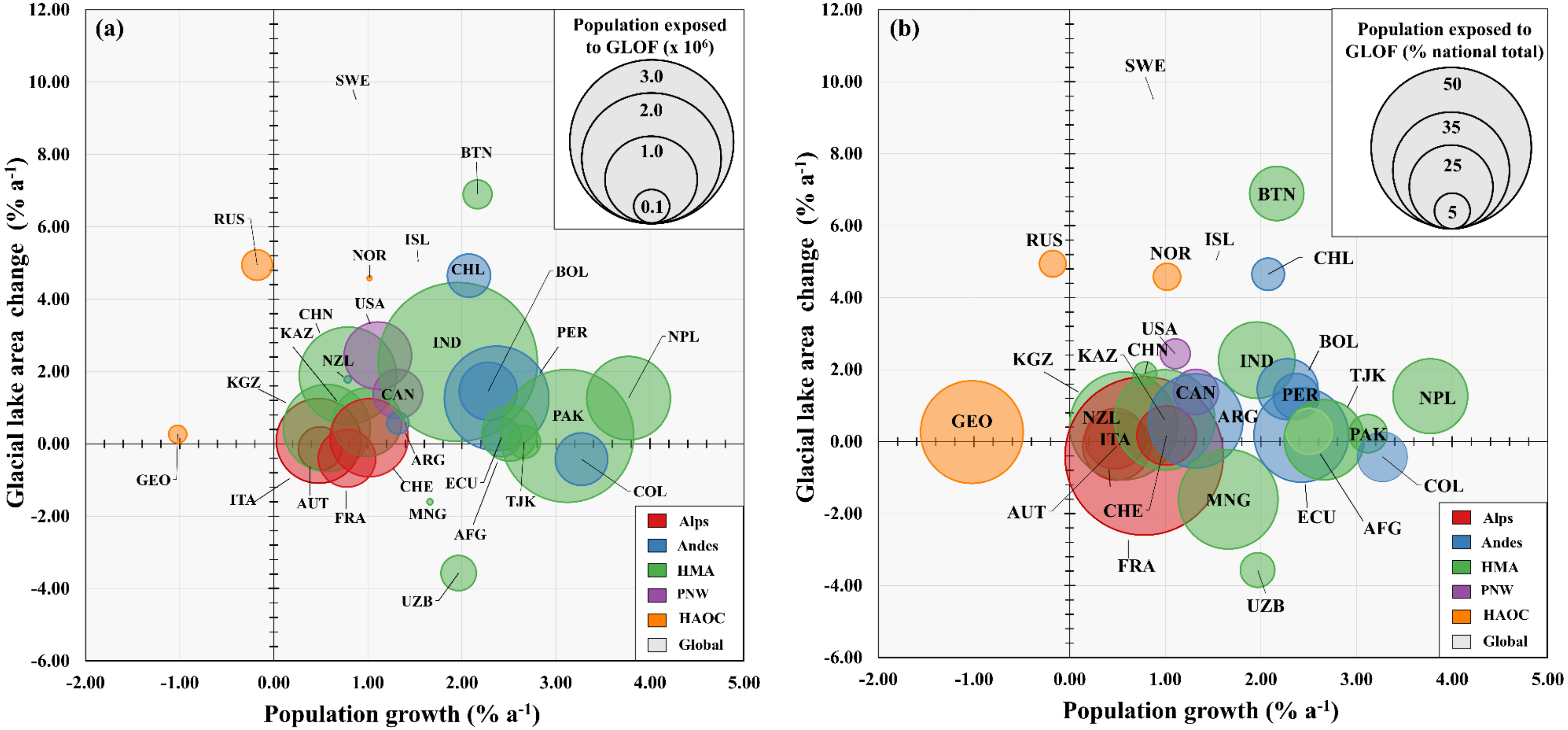


Figure 3.15: Rate of change in glacial lake area and total population. Rates of population change between 1990 and 2020 and glacial lake area change between 1990 and 2018 as a) absolute population exposed to GLOF and b) percentage of national population exposed to GLOF in each country. Countries are colour coded according to Mountain Range.

It is well-established that variations in vulnerability alter the degree to which natural disasters impact people (Carey, 2005, 2008, 2010; Carrivick and Tweed, 2016; Bajracharya *et al.*, 2007). As such, two outburst events affecting the same number of people with the same material impact (e.g. a footbridge or road washed away) can have fundamentally different consequences depending on the social, political, cultural, and economic context of the country, or even basin, in which they occur (Carey, 2005, 2008, 2010; Carrivick and Tweed, 2016; Bajracharya *et al.*, 2007). Results reaffirm this relationship; Bolivia and Canada have similar exposure (400,000 and 300,000 people exposed within 1 km of likely GLOF flood corridors up to 50 km respectively) yet a substantially higher vulnerability factors in Bolivia results in an overall higher risk score (0.781) than Canada (0.289) despite hazard being much higher in Canada. This highlights the crucial role of exposure and vulnerability in determining the impact, and thus the risk, of GLOFs. Whilst hazard assessments dominate GLOF risk studies (e.g. Kougkoulos *et al.*, 2018), exposure, and vulnerability assessments within the context of GLOF risk remain relatively unexplored topics that urgently need addressing, particularly in developing countries (Vuille et al., 2018) where GLOF risk is generally highest (Figure 3.10, Figure 3.11).

3.4.4 Future research

This chapter quantified GLOF exposure using only the total population within likely runout zone buffers up to 50km (Figure 3.5, Figure 3.6). Whilst this approach is useful, and provides a good proxy for exposure, including measures of ‘damage’ to the likes of buildings, roads and bridges would add further granularity. Within the top 3 most at-risk basins in this study (Table 3.3) there is a vast network of roads and large numbers of buildings within the likely impacted zones (Figure 3.12, Figure 3.11). Including these measures would give a more refined picture of potential GLOF impact, allowing communities to better prepare for outbursts and as a result recover faster. At a global scale this would be challenging, and goes beyond the scope of this study, but could be integrated into future research for the high-risk basins identified here.

Whilst this chapter shows the global picture of contemporary (2020) GLOF risk, it remains unclear how this risk is changing temporally and whether such changes are being driven by changes in hazard, exposure, vulnerability, or some combination. This distinction is important, as it would allow the factor responsible for driving risk changes at the basin scale to be isolated, meaning future risk reduction and mitigation efforts could be tailored accordingly, making risk management more effective and efficient. This would be most beneficial in areas where resources and finding are limited, particularly where corruption within governments and funding bodies exist and where vulnerability within communities is high. Thus, research that evaluates the temporal changes in hazard, exposure, and vulnerability over a prolonged period and the relationship to changing GLOF risk is needed.

3.5 Conclusions

How GLOF risk might change in the future remains subject to debate. As glaciers continue to recede existing glacial lakes will expand, and many new lakes will form (Zheng, Allen, et al., 2021), altering the spatial pattern of GLOF hazard (Sattar et al., 2019). At the same time, we will see spatiotemporal changes in populations and their vulnerability as people, goods and services migrate in response to various socioeconomic drivers, and development related to the growth of tourism, HEP and agriculture continues to expand into higher elevations closer to glacial lakes and other forms of natural hazard (GAPHAZ, 2017). This chapter has shown the most at-risk basins, mainly across HMA and the Andes do not always host the most, or the largest, glacial lakes and rather it is the high number of people and the reduced capacity of those people to cope with disaster that plays a key role in determining overall GLOF risk. This finding highlights the need for a more holistic approach to GLOF risk assessment, where each component, hazard, exposure, and vulnerability are accounted for. Results highlight the value of global-scale spatial danger analysis and I envisage findings to be a starting point for more targeted risk assessments at the national-and basin-scale. The findings of this chapter are important, as they not only identify countries and basins that rank highly in terms of GLOF risk, which can allow for more targeted GLOF risk management, but also regions where more research is urgently needed to understand risk at a fundamental level. In particular, the Andes is highlighted as an under-studied hotspot of GLOF risk, and suggest the region be targeted for more detailed study.

Chapter 4 Trends, drivers, and hotspots of GLOF risk between 2000 and 2020

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Key words

GLOF, risk, exposure, vulnerability, temporal variability.

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 effect of these changes on the overall risk posed by GLOFs, as well as the relative importance of each factor remains contentious, making the implementation of targeted risk reduction strategies challenging. Results show that globally, since 2000, the number of people at direct risk of GLOF impacts has increased by 3.2 million (27%), to a total of 15 million as of 2020. The largest increase in GLOF risk occurred across the Andes, while only nine countries experienced a decrease in GLOF risk, most notably in Nepal and Kyrgyzstan. Importantly, contrary to the notion presented in current research, findings show the changes in GLOF risk have not been universally driven by either GLOF hazard, exposure, or vulnerability; instead, the primary driver varies both at regional- and national-scales. Further, 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 population. The Andes is highlighted as a global hotspot for high and rapidly increasing contemporary GLOF risk, and the region suggested as a target for further research. Critically, results show that mitigating GLOF impacts will require bespoke solutions depending on the relative effect of hazard, exposure, and vulnerability on changing GLOF risk.

4.1 Introduction

The accelerated formation and expansion of glacial lakes, as a result of climate driven ice loss, represents both an important resource in mountain regions and a major natural hazard (Shugar et al., 2020; Dubey & Goyal, 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 (Zheng, Allen, et al., 2021; Emmer et al., 2020). Most notably, in the last 70 years, estimates suggest as many as 30,000 people have been killed by GLOFs in the Cordillera Blanca alone (Emmer et al., 2020; Carey, 2008).

The risk posed by GLOFs to downstream communities depends on a complex interplay between hazard, exposure, and vulnerability (Wisner et al., 2004; IPCC, 2019). Since 1990, the number, area and volume of glacial lakes has increased rapidly (Shugar et al., 2020), whilst at the same time many glacial catchments have experienced a rapid growth in exposure through increases in population, infrastructural developments, and implementation of hydroelectric schemes, as well as an increasing intensification of agriculture (Allen et al., 2019; Wester et al., 2019; Immerzeel et al., 2020). Concurrent with these changes, socio-economic vulnerability to climate-related hazards has 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). Chapter 3 (Taylor et al., 2023) highlighted the importance of including exposure and vulnerability alongside hazard in GLOF assessments. However, the relative effect that changes to these factors have had on the total global risk from GLOFs remains unclear. If current and future GLOF risk is to be effectively managed, we urgently need a better understanding of the past and present trajectory of global GLOF risk (Zheng, Allen, et al., 2021; Emmer, Allen, et al., 2022). Furthermore, there is a critical need to establish which factor(s) is/are responsible for driving changes in GLOF risk at regional, national, and local scales, in order to better direct mitigation efforts and ultimately save lives and reduce impacts. This is particularly important for transboundary GLOF management, where runout paths from a single lake can cross borders that separate populations with very different vulnerabilities.

Here, how GLOF hazard, exposure and vulnerability have changed at a global, regional, and basin-scale is assessed for the period 2000 and 2020. Results are then combined to quantify the change in GLOF risk over the same period. The rates of change in each factor (hazard, exposure, vulnerability) are then compared to establish the primary driver(s) of changing GLOF risk, thus systematically identifying which aspects of risk should be reduced in order to best mitigate overall GLOF risk on a location-specific basis. Finally, regions with a rapidly increasing trajectory of GLOF risk are highlighted, to objectively identifying priority locations for future work.

4.2 Methods

4.2.1 Changing hazard, exposure, and vulnerability

4.2.1.1 Hazard

Here, I adapt the approach defined in Chapter 3 (see section 3.2.1.1; Taylor *et al.,* 2023), to quantify and rank hazard, population exposure, vulnerability, and resulting risk from GLOFs globally. This analysis is conducted at 5 yearly timesteps: 2000, 2005, 2010, 2015, and 2020, allowing both contemporary values and trends since 2000 to be calculated. Results are evaluated at the national-scale, mountain range scale, and basin-scale using the same mountain range definitions set out in Chapter 1; European Alps, Andes, High Mountains Asia (HMA), Pacific Northwest (PNW), and High Arctic and Outlying Countries. 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, Allen, et al., 2021). However, GLOF triggers are multiple and complex (Dubey and Goyal, 2020; Allen, *et al.*, 2016) and the quality of global DEMs in the regions where glacial lakes are present is highly variable (Bolch & Loibl, 2017). Consequently, results 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. Thus, reference to GLOF hazard here refers solely to intensity of outburst and includes no measure of probability. Nevertheless, this approach is intended to be adaptable to facilitate future inclusion of probability into the hazard part of the calculation.

Data on the number and area of glacial lakes from the Cooperative Institute for Research and Environmental Sciences (CIRES) National Snow and Ice Data Centre were used 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. A linear transformation function is used to produce a normalised value for both lake number and area (Equation 4.1);

$$\boldsymbol{y_{N/A}} = \frac{(\boldsymbol{X})}{(\boldsymbol{Max})}$$

Equation 4.1

Where **x** is the absolute number/area of glacial lakes per basin, **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 ($\mathbf{y_N}$) and area ($\mathbf{y_A}$) are then multiplied to produce a singular score between 0 and 1, with 1 relating to high intensity GLOF (high hazard). No scores of 0 were recorded in any location during any epoch.

4.2.1.2 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. Following the approach detailed in Chapter 3 (see section 3.2.1.2), a maximum runout distance of 50 km was considered as per previous research (Dubey & Goyal, 2020; Taylor et al., 2023), which should encapsulate the majority of runouts globally, whilst avoiding overestimations by excluding major outliers. Further, following previous approaches (Veh, 2019; Taylor et al., 2023) exposed populations were further constrained by applying a 1 km buffer either side of any main river channel (level 1 channel (Yan et al., 2019). Using the 2000-2020 Gridded Population of the World version 4 (GPWv4) (CIESIN, 2018) at 5 yearly static intervals, population count per 1 km^2 cell was summed within this buffer to obtain exposed population (Figure 4.1). Here, the number of people per cell was rounded to the nearest whole number. This 50 km buffer was then split into 5 km intervals and population within each interval summed, to add further spatial granularity (See Figure 3.2). This was repeated for each 5-yearly timestep, to obtain exposure over time between 2000 and 2020. Once the total exposed population had been calculated for each region and country, the same linear transformation function as Equation 4.1 was deployed, using $\mathbf{y_E}$ (where **E** is exposed population) to produce a normalised exposure score for each region/country.

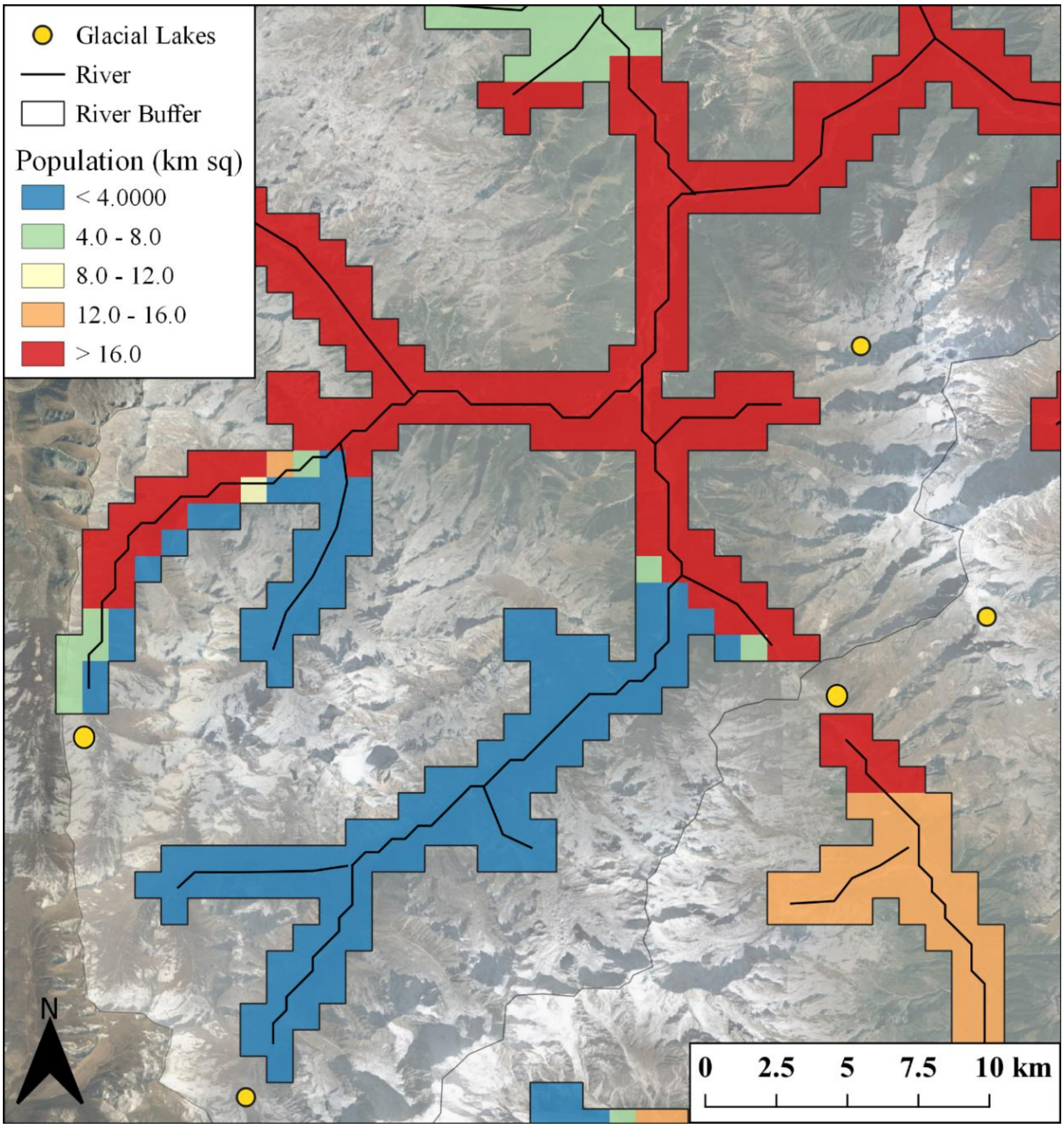

Figure 4.1: Method of extracting population exposure along river buffers. Population extraction within the 1 km river buffer. River centrelines (± 0.08 km) were extracted where glacial lakes exist in their upper reaches and a buffer of 1 km applied either side. Population within this buffer was then extracted to obtain total exposed population for each of the time periods. Example from a basin in the Hengduan Shan region, China. Background image Google Earth 2021.

4.2.1.3 Vulnerability

Here, qualitative information obtained from the Corruption Perception Index (CPI) and Human Development Index (HDI) is combined with a GLOF-specific Social Vulnerability Index (SVI) to provide a proxy for GLOF vulnerability (see Chapter 3 (Taylor et al., 2023)). 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 (Conceição & UNDP, 2020). The HDI has been successfully used in previous GLOF risk assessments in the Andes (Drenkhan et al., 2019) and globally (Taylor *et al.,* 2023) and data can be obtained annually from 1990. To accompany the CPI and HDI, an SVI was calculated, adding another dimension of vulnerability. Drawing upon an existing flood vulnerability assessment (Tascón-González et al., 2020) and a time-invariant assessment of global GLOF risk (Taylor *et al.,* 2023) the SVI integrates five indicators 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 4.2);

$$\boldsymbol{SVI = \frac{\left(\frac{reducing\ indicators}{enhancing\ indicators}\right)}{5}}$$

Equation 4.2

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. All three indicators (HDI, CPI and SVI) at each time-step are normalised and combined with equal weighting (Equation 4.1) to produce a single proxy for vulnerability (Equation 4.3). Final values range between 0 and 1, where 1 equates to the highest vulnerability. No scores of 0 were recorded in any location during any epoch.

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

Equation 4.3

4.2.1.4 Risk

The normalised results of all three parameters (hazard, exposure, and vulnerability) at each time-interval 5-yearly intervals were then combined with equal weighting to produce a semi-quantitative metric for GLOF risk between 2000 and 2020 (Equation 4.4):

$$\boldsymbol{GLOF\ risk = [Hazard\ x\ Exposure\ x\ Vulnerability]}$$

Equation 4.4

4.3 Results

4.3.1 Changing hazard, exposure, and vulnerability

4.3.1.1 Hazard

Over the 20-year study period, glacial lakes (>0.05 km^2) were identified in 31 countries. Data show substantial increases in the number (+53%) and area (+51%) of glacial lakes globally, although there was marked spatial variation in these changes across different mountain ranges and countries (Figure 4.2). Between 2000 and 2020, glacial lake area increased the most in the PNW (924 km^2) whilst the number of glacial lakes increased the most across the High Arctic and Outlying Countries region, with an increase of 1221 lakes. The European Alps saw the lowest increase in both area (92 km^2) and number (9) of glacial lakes over the study period (Figure 4.2). 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 (Figure 4.3). Within these broader mountain range trends, the area 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) (Figure 4.2). Overall, the area of glacial lakes increased the most in Sweden, from 5.52 km^2 to 20.25 km^2 (267%), while the number of lakes increased the most in Bhutan, from 29 to 161 (455%) (Figure 4.2).

Consequently, the score for GLOF hazard increased the most across the High Arctic and Outlying Countries region (+0.027) and the least across the Alps (+0.002) (Figure 4.4). Within this are substantial national variations (Figure 4.4), e.g. increases in Sweden and Norway accounted for the majority of increase in the High Arctic and Outlying Countries region. The glacial lake hazard score (Equation 4.1) reduced in 13 countries, remained unchanged in Greenland, and increased in the remaining 14 countries (Figure 4.4). The largest increase in glacial lake hazard score occurred in Norway (+0.077) and China (+0.075) and the largest decrease was in Canada (-0.012) (Figure 4.4). GLOF hazard scores 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 0.685 respectively) (Figure 4.4).

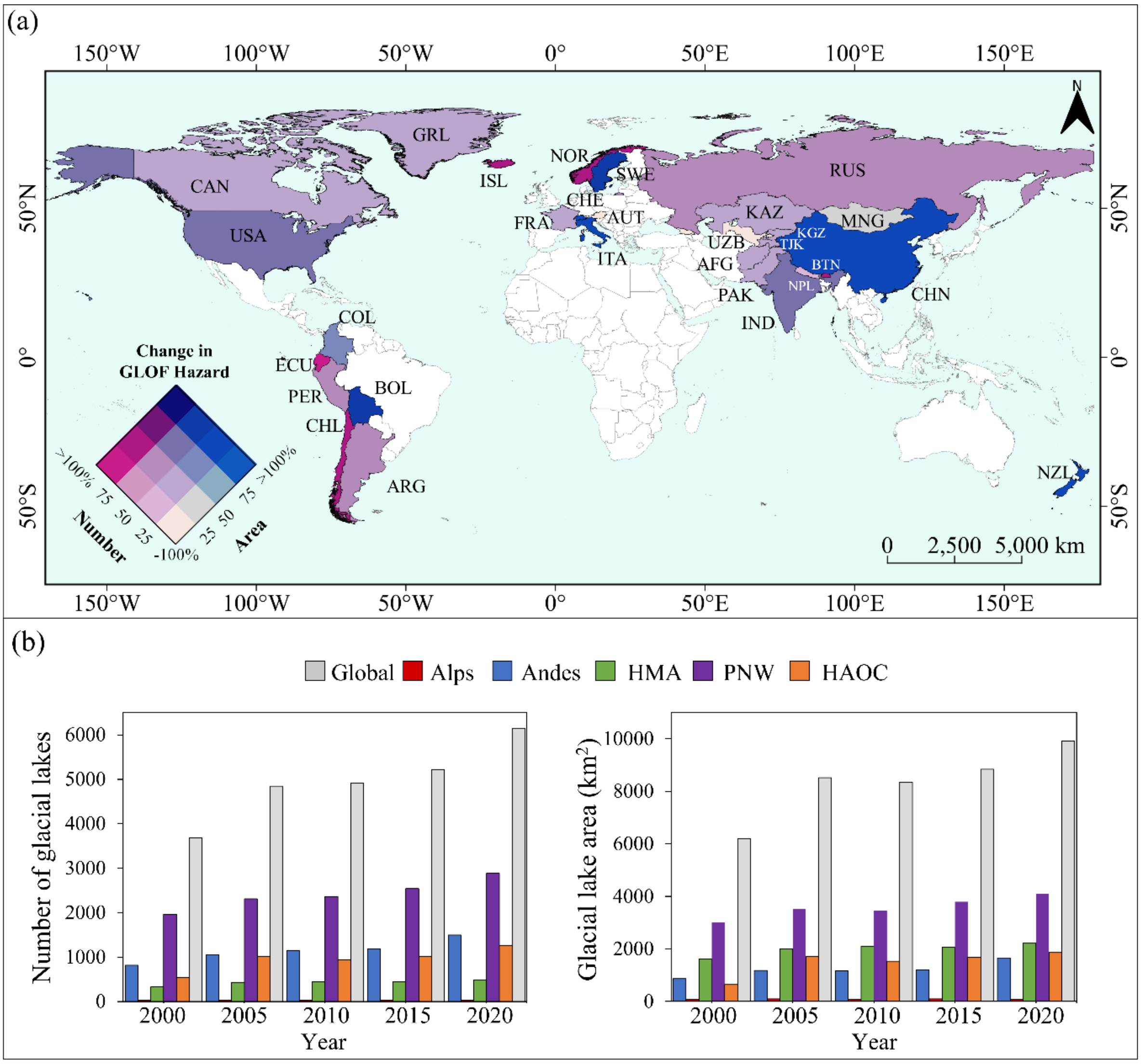

Figure 4.2: Global change in GLOF hazard 2000 to 2020. Change in the number and area of glacial lakes for the period 2000-2020 grouped by mountain range at 5-yearly intervals, where each interval represents the average of the 5-year period. Greenland was not included in the bar charts as its large number and area of glacial lakes skewed results.

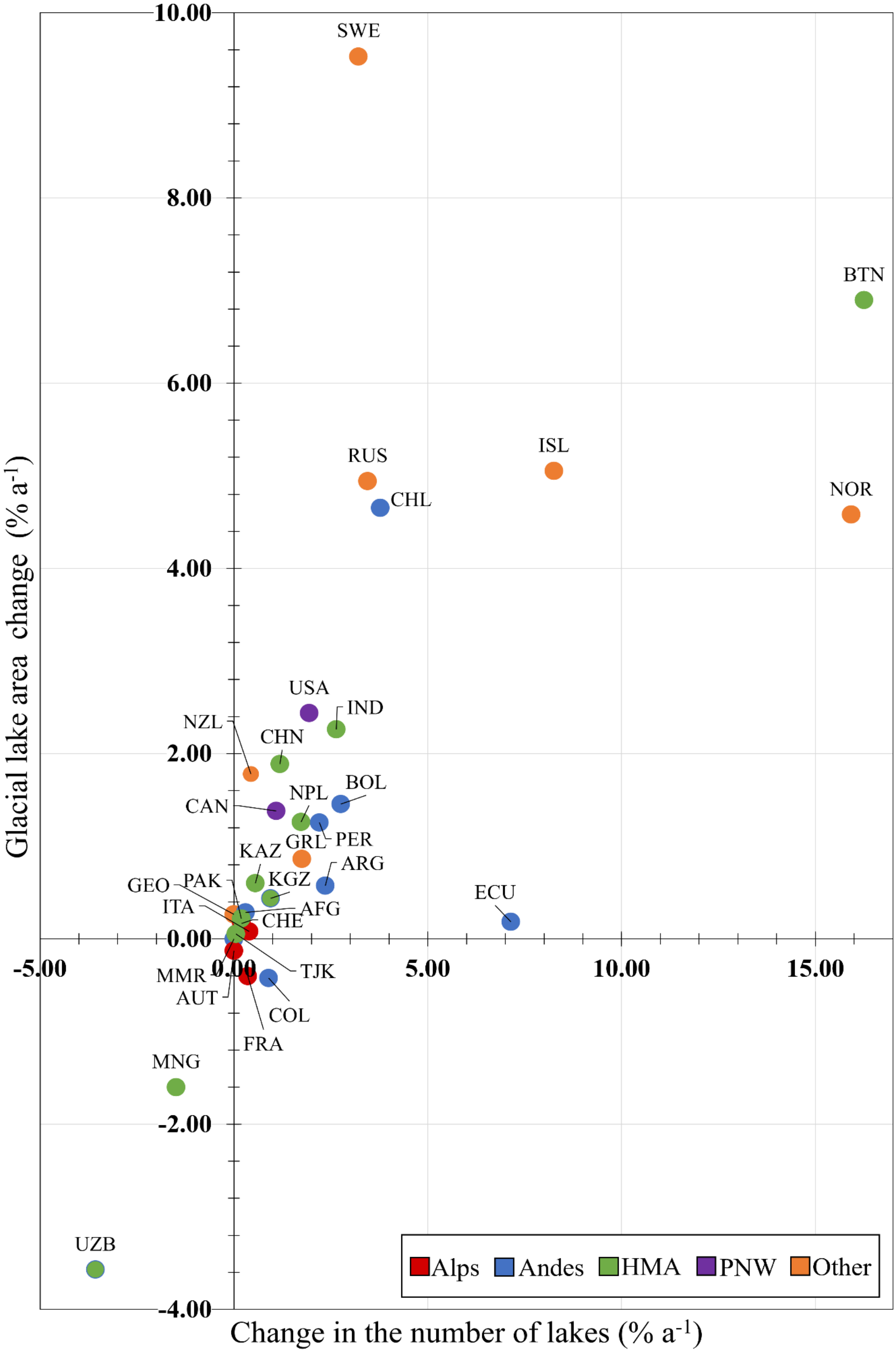

Figure 4.3: Hazard rate of change 2000 to 2020. Rate of change in the number and area of glacial lakes for the period 2000-2020. Countries are colour coded according to mountain range.

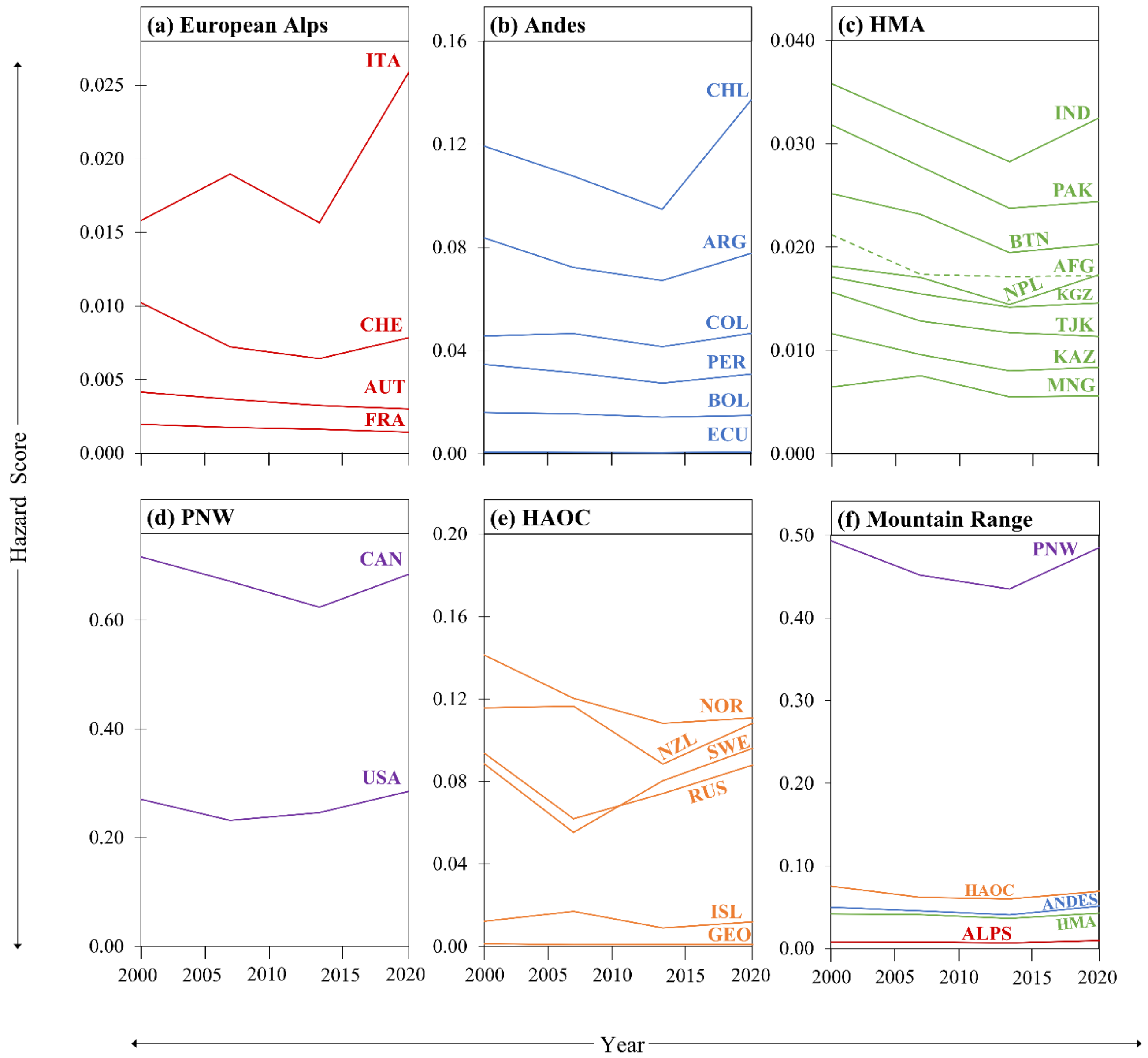

Figure 4.4: National-scale change in GLOF hazard. Change in GLOF hazard from 2000-2020. Values are given as the normalization of glacial lake number and area per country. Colour coded according to mountain range. ID of each nation is given above the lines. Note that the y-axis values are different for each mountain range to aid visualisation. Dotted line of AFG used for clarity only.

Exposure					
ID	**2000**	**2005**	**2010**	**2015**	**2020**
AFG	0.0873	0.0973	0.1087	0.1219	0.1369
ARG	0.0137	0.0153	0.0172	0.0195	0.0223
AUT	0.0691	0.0705	0.0719	0.0735	0.0752
BOL	0.1498	0.1525	0.1561	0.1608	0.1670
BTN	0.0281	0.0309	0.0341	0.0376	0.0415
CAN	0.0687	0.0733	0.0783	0.0837	0.0896
CHE	0.2097	0.2197	0.2305	0.2423	0.2551
CHL	0.0786	0.0856	0.0934	0.1022	0.1121
CHN	0.3036	0.3222	0.3427	0.3655	0.3907
COL	0.0955	0.0987	0.1027	0.1076	0.1135
ECU	0.0467	0.0503	0.0542	0.0585	0.0631
FRA	0.0826	0.0848	0.0873	0.0900	0.0932
GEO	0.0232	0.0199	0.0171	0.0148	0.0129
GRL	0.0028	0.0028	0.0029	0.0030	0.0031
IND	0.6890	0.7548	0.8280	0.9093	1.0000
ISL	0.0024	0.0024	0.0024	0.0023	0.0023
ITA	0.1373	0.1405	0.1440	0.1479	0.1522
KAZ	0.0955	0.1057	0.1177	0.1318	0.1483
KGZ	0.2238	0.2298	0.2360	0.2425	0.2492
MNG	0.0026	0.0025	0.0024	0.0023	0.0022
NOR	0.0859	0.0867	0.0876	0.0886	0.0898
NPL	0.4442	0.3625	0.3248	0.3082	0.3027
NZL	0.0022	0.0022	0.0023	0.0024	0.0024
PAK	0.5299	0.6022	0.6848	0.7790	0.8866
PER	0.3861	0.4067	0.4327	0.4654	0.5072
RUS	0.0415	0.0412	0.0409	0.0407	0.0406
SWE	0.0032	0.0031	0.0031	0.0030	0.0030
TJK	0.0442	0.0470	0.0502	0.0540	0.0583
USA	0.0811	0.0873	0.0942	0.1019	0.1104
UZB	0.0380	0.0415	0.0454	0.0496	0.0542
Alps	0.2567	0.2541	0.2462	0.2360	0.2288
Andes	0.2605	0.2633	0.2620	0.2595	0.2670
HMA	1.0000	1.0000	1.0000	1.0000	1.0000
PNW	0.0620	0.0670	0.0703	0.0723	0.0749
HAOC	0.0301	0.0271	0.0241	0.0214	0.0194

Hazard					
ID	**2000**	**2005**	**2010**	**2015**	**2020**
AFG	0.0231	0.0212	0.0174	0.0172	0.0172
ARG	0.0801	0.0837	0.0723	0.0672	0.0777
AUT	0.0043	0.0042	0.0037	0.0032	0.0030
BOL	0.0092	0.0160	0.0155	0.0142	0.0148
BTN	0.0069	0.0252	0.0232	0.0195	0.0203
CAN	0.6964	0.7167	0.6716	0.6239	0.6847
CHE	0.0072	0.0102	0.0072	0.0064	0.0078
CHL	0.1010	0.1193	0.1077	0.0948	0.1372
CHN	0.2439	0.2786	0.2872	0.2580	0.3190
COL	0.0381	0.0456	0.0466	0.0415	0.0466
ECU	0.0005	0.0007	0.0005	0.0004	0.0006
FRA	0.0019	0.0020	0.0017	0.0016	0.0014
GEO	0.0013	0.0013	0.0008	0.0009	0.0009
GRL	1.0000	1.0000	1.0000	1.0000	1.0000
IND	0.0270	0.0358	0.0320	0.0283	0.0325
ISL	0.0055	0.0122	0.0170	0.0090	0.0119
ITA	0.0152	0.0158	0.0190	0.0157	0.0259
KAZ	0.0107	0.0116	0.0096	0.0080	0.0084
KGZ	0.0170	0.0171	0.0155	0.0142	0.0146
MNG	0.0085	0.0065	0.0076	0.0055	0.0056
NOR	0.0343	0.1413	0.1203	0.1082	0.1108
NPL	0.0177	0.0182	0.0171	0.0145	0.0173
NZL	0.0629	0.1157	0.1165	0.0884	0.1082
PAK	0.0317	0.0318	0.0278	0.0238	0.0244
PER	0.0297	0.0347	0.0314	0.0274	0.0309
RUS	0.0681	0.0938	0.0620	0.0741	0.0879
SWE	0.0517	0.0886	0.0553	0.0803	0.0960
TJK	0.0158	0.0156	0.0128	0.0117	0.0114
USA	0.2372	0.2705	0.2319	0.2461	0.2853
UZB	0.0002	0.0003	0.0004	0.0004	0.0000
Alps	0.0308	0.0328	0.0348	0.0309	0.0410
Andes	0.2762	0.3027	0.3038	0.2828	0.4340
HMA	0.4030	0.4644	0.5003	0.4627	0.4070
PNW	1.0000	1.0000	1.0000	1.0000	1.0000
HAOC	0.2416	0.4578	0.4122	0.4155	0.4470

Vulnerability					
ID	**2000**	**2005**	**2010**	**2015**	**2020**
AFG	0.9875	0.9829	0.9742	0.9574	0.9192
ARG	0.7403	0.7380	0.7143	0.7349	0.6501
AUT	0.4701	0.4514	0.3804	0.3094	0.3041
BOL	0.7936	0.7808	0.7777	0.7671	0.7809
BTN	0.7000	0.7165	0.6629	0.6088	0.5720
CAN	0.2600	0.2366	0.2485	0.2409	0.2895
CHE	0.2333	0.2176	0.1945	0.1891	0.1937
CHL	0.4241	0.3924	0.4266	0.4147	0.4339
CHN	0.7858	0.7622	0.7309	0.7293	0.6834
COL	0.7711	0.7631	0.7412	0.7233	0.7042
ECU	0.4086	0.3807	0.3550	0.3118	0.3389
FRA	0.7311	0.7167	0.7210	0.7161	0.6515
GEO	0.4948	0.4776	0.4746	0.4545	0.4460
GRL	0.5941	0.5791	0.5263	0.5181	0.4771
IND	0.8676	0.8484	0.8077	0.7774	0.7546
ISL	0.2581	0.2339	0.2675	0.2653	0.2921
ITA	0.6935	0.6745	0.6342	0.6158	0.5316
KAZ	0.8175	0.8007	0.7880	0.7762	0.6888
KGZ	0.8720	0.8736	0.8432	0.8092	0.7862
MNG	0.8053	0.7827	0.7527	0.7169	0.7452
NOR	0.2281	0.2138	0.2059	0.1724	0.2011
NPL	0.9086	0.8938	0.8679	0.8519	0.8104
NZL	0.2181	0.1989	0.1903	0.1676	0.1857
PAK	0.9010	0.8872	0.8708	0.8484	0.8369
PER	0.7473	0.7321	0.7294	0.7295	0.7076
RUS	0.8074	0.7986	0.7830	0.7670	0.7545
SWE	0.2122	0.2102	0.2046	0.1715	0.2027
TJK	0.8963	0.8895	0.8620	0.8338	0.8357
USA	0.3662	0.3562	0.3362	0.3045	0.3833
UZB	0.9134	0.9062	0.8874	0.8680	0.8143
Alps	0.5320	0.5150	0.4825	0.4576	0.4202
Andes	0.6922	0.6789	0.6635	0.6533	0.6364
HMA	0.8595	0.8494	0.8225	0.7979	0.7679
PNW	0.3131	0.2964	0.2923	0.2727	0.3364
HAOC	0.4018	0.3874	0.3789	0.3595	0.3656

Risk					
ID	**2000**	**2005**	**2010**	**2015**	**2020**
AFG	0.0209	0.0213	0.0193	0.0210	0.0228
ARG	0.0085	0.0099	0.0093	0.0101	0.0118
AUT	0.0015	0.0014	0.0011	0.0008	0.0007
BOL	0.0115	0.0200	0.0197	0.0184	0.0203
BTN	0.0014	0.0059	0.0055	0.0047	0.0051
CAN	0.0898	0.1084	0.1042	0.0975	0.1164
CHE	0.0037	0.0051	0.0034	0.0031	0.0041
CHL	0.0354	0.0421	0.0450	0.0422	0.0701
CHN	0.6110	0.7183	0.7556	0.7222	0.8945
COL	0.0295	0.0361	0.0373	0.0339	0.0391
ECU	0.0001	0.0001	0.0001	0.0001	0.0001
FRA	0.0012	0.0013	0.0012	0.0011	0.0009
GEO	0.0002	0.0001	0.0001	0.0001	0.0001
GRL	0.0172	0.0172	0.0161	0.0163	0.0156
IND	0.1695	0.2409	0.2249	0.2098	0.2573
ISL	0.0000	0.0001	0.0001	0.0001	0.0001
ITA	0.0151	0.0157	0.0182	0.0150	0.0220
KAZ	0.0088	0.0103	0.0093	0.0086	0.0090
KGZ	0.0349	0.0360	0.0323	0.0292	0.0300
MNG	0.0002	0.0001	0.0001	0.0001	0.0001
NOR	0.0071	0.0275	0.0228	0.0173	0.0210
NPL	0.0751	0.0618	0.0505	0.0398	0.0446
NZL	0.0003	0.0005	0.0005	0.0004	0.0005
PAK	0.1587	0.1786	0.1740	0.1650	0.1902
PER	0.1306	0.1305	0.1371	0.1321	0.1864
RUS	0.0240	0.0324	0.0208	0.0243	0.0282
SWE	0.0004	0.0006	0.0004	0.0004	0.0006
TJK	0.0066	0.0069	0.0058	0.0055	0.0058
USA	0.0739	0.0883	0.0771	0.0802	0.1268
UZB	0.0001	0.0001	0.0002	0.0002	0.0000
Alps	0.0042	0.0043	0.0041	0.0033	0.0039
Andes	0.0498	0.0541	0.0528	0.0480	0.0547
HMA	0.3464	0.3945	0.4115	0.3692	0.3110
PNW	0.0194	0.0199	0.0205	0.0197	0.0248
HAOC	0.0029	0.0048	0.0038	0.0032	0.0031

Table 4.1: Normalised values of exposure, hazard, vulnerability, and risk between 2000 and 2020. All raw values were normalised between 0-1 to allow comparison

4.3.1.2 Exposure

The number of people residing within 1 km of potential GLOF runout tracks and within 50 km from a glacial lake increased by 3.2 million (+27%) over the 20 years between 2000 and 2020: increasing from ~11.8 million in 2000 to ~15 million in 2020 (Figure 4.5; Table 4.2). The greatest change in population occurred across HMA (+2.2 million; >68% of total global change) followed by the Andes (+0.5 million; >15% of total global change) (Figure 4.5b;Table 4.2), while populations exposed to GLOFs in the High Arctic and Outlying Countries region decreased by ~30,000 (Figure 4.5b). At the national 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) (Figure 4.5a). Mongolia, Georgia, Nepal, and Sweden were the only countries where exposed population decreased, with the largest absolute decrease of ~400,000 (-32%) in Nepal (Figure 4.5a).

Outside of HMA, most of the change in exposed population occurred at distances >30 km from glacial lakes (Figure 4.5This is particularly notable in the PNW, where little change in population occurred until 40 km downstream (Figure 4.5c). 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 (Figure 4.5c) Within the mountain range trends there are interesting national-scale changes. For instance, both Pakistan and Bolivia had large numbers of people living within 15 km of a glacial lake over the study period, however, in Bolivia exposure generally increased from >25 km, with a marginal decline in the first 20 km downstream (Figure 4.6). In contrast, the exposed population in Pakistan increased within the first 15 km (Figure 4.6). In Nepal, the number of people living within 50 km of a glacial lake decreased in all spatial intervals, with the largest decline between 25 km and 40 km downstream (Figure 4.6). These three national examples demonstrate the value of more granular analysis, where patterns of exposure within countries can be masked by regional scale trends. 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, Table 4.1). In total, 23 countries (76%) increased in overall population exposure (Figure 4.7)

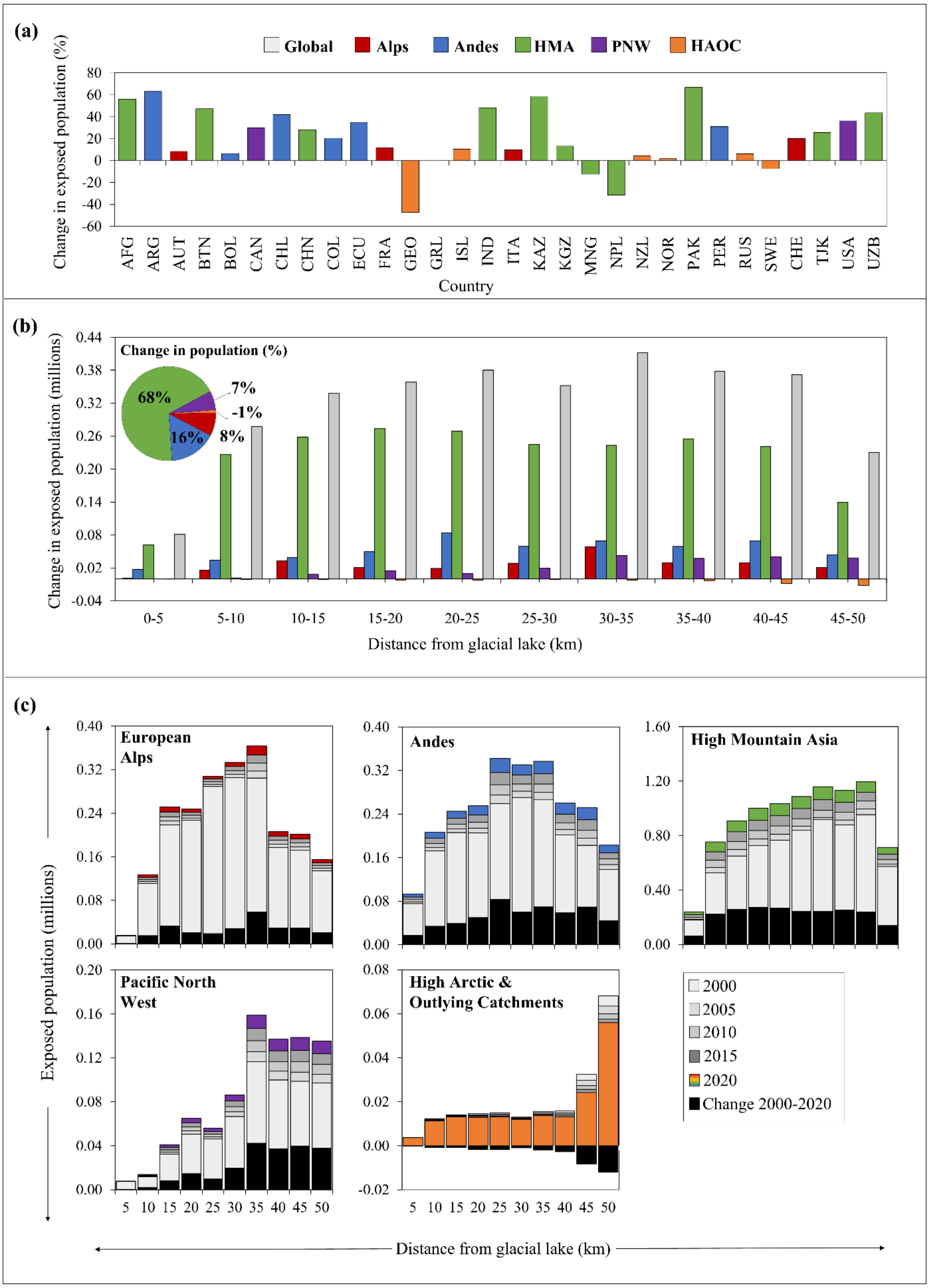

Figure 4.5: Global change in GLOF exposure 2000 to 2020. (a) Change in population per country living within the 1 km river buffer between 2000 and 2020 up to a distance of 50 km. (b) Overall change in population within the first 50km from a glacial lake, given at 5 km intervals per mountain range (coloured 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. Total change over the 20-year period is shown in black.

Exposed Population						
ID	**2000**	**2005**	**2010**	**2015**	**2020**	**Change**
AFG	236300	263000	293500	328500	368600	132300
ARG	38500	43000	48400	54800	62800	24300
AUT	214300	218300	222600	227200	232200	17900
BTN	71100	78300	86200	95000	104700	33600
BOL	377600	380900	385800	392700	401900	24300
CAN	226700	241700	257900	275500	294500	67800
CHL	160400	174300	190000	207700	227800	67400
CHN	872600	925600	983800	1048000	1118900	246300
COL	277000	287700	300600	315800	333500	56500
ECU	139400	150100	161600	174100	187600	48200
FRA	356200	364700	374300	385000	397100	40900
GEO	82400	69700	59200	50600	43400	-39000
GRL	0	0	0	0	0	0
ISL	200	200	200	300	300	100
IND	2003300	2206200	2432700	2686000	2969500	966200
ITA	777800	794300	812400	832200	853700	75900
KAZ	354400	394900	442100	497500	562300	207900
KGZ	795400	820100	845900	872700	900700	105300
MNG	6700	6500	6300	6100	5900	-800
NPL	1215600	1000900	899200	851900	832000	-383600
NZL	7600	7600	7600	7700	7900	300
NOR	4200	4300	4300	4300	4300	100
PAK	1247000	1416300	1609300	1829500	2080600	833600
PER	986000	1039100	1105200	1187900	1292100	306100
RUS	110100	111500	113100	114900	116900	6800
SWE	300	300	300	300	300	0
CHE	604900	632100	661400	693100	727400	122500
TJK	105700	111200	117400	124600	132800	27100
USA	400400	431100	465200	503200	545600	145200
UZB	107500	117700	128800	141000	0	-107500
Alps	1953100	2009400	2070700	2137600	2210400	257300
Andes	1978900	2075100	2191700	2333000	2505500	526700
HMA	7015700	7340500	7845300	8480800	9076000	2060300
PNW	627100	672700	723000	778600	840100	213000
HOAC	204800	193500	184700	178000	173100	-31700
Global	**11779600**	**12291300**	**13015500**	**13908000**	**14959600**	**3180000**

Table 4.2: Static population exposed to GLOFs between 2000 and 2020. Population exposed to glacial lakes between 2000 and 2020. Here population is taken as the number of people living within 1 km of a likely GLOF runout track up to 50 km from a glacial lake and is rounded to the nearest 100.

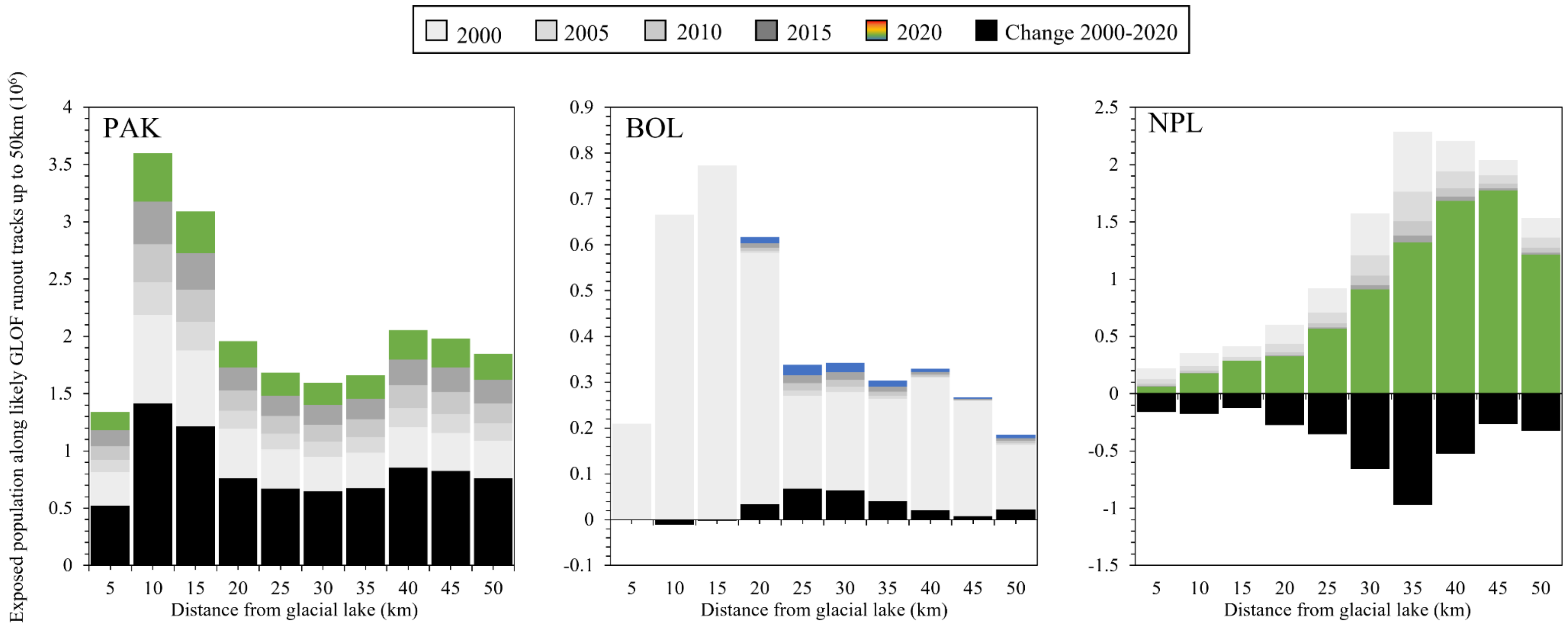

Figure 4.6: Example national population distributions along GLOF runout tracks. Change in population living along likely GLOF runout tracks within 50 km from a glacial lake for the period 2000 to 2020 for Pakistan, Bolivia, and Nepal at 5-yearly intervals. Total change over the 20-year period is shown in black.

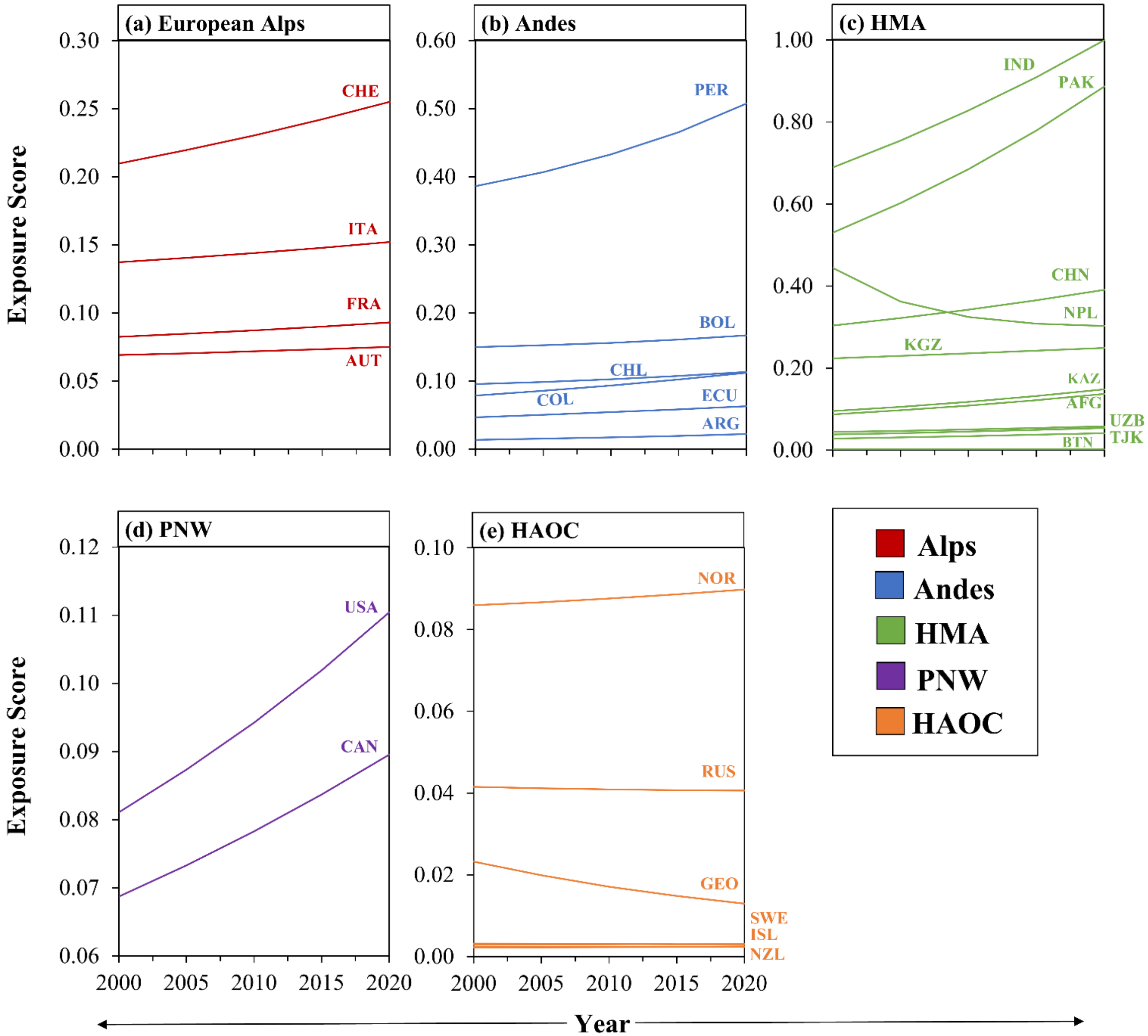

Figure 4.7: National-scale change in GLOF exposure 2000 to 2020. Change in GLOF exposure from 2000-2020. Values are given as the normalization of population per 50 km of a glacial lake. ID of each nation is given above the lines. Note that the y-axis values are different for each mountain range to aid visualisation.

4.3.1.3 Vulnerability

Over the 20-year period all three indicators of GLOF vulnerability (CPI, HDI, and SVI), showed marked variability (Figure 4.8, Figure S4. 1, p. 248). All regions have experienced improvement in levels of development since 2000 (Figure 4.8), indicating an increase in life expectancy, education, and annual income (Figure 4.8). HMA improved the most (Figure 4.8) with Afghanistan and Pakistan scoring the lowest in HDI consistently across the 20-year period, while countries in the PNW had the highest average development score as of 2020 (Figure 4.8b). 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 (Figure 4.8).

Despite clear improvements, particularly in development and social vulnerability, such that overall vulnerability decreased 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. Countries across HMA consistently have the lowest female literacy rates; only 13%, 23% and 28% of females were classed as literate in Afghanistan, Bhutan, and Pakistan respectively in 2020 (Figure 4.9). Further, whilst the largest improvements to total literate population were made in Nepal and Bhutan globally, where literacy rates increased by 73% and 59% respectively (Figure 4.9), as of 2020 less than half the population of Afghanistan are classed as literate (43%). Improvements in access to safe drinking water and good sanitation occurred in all but three countries globally between 20000 and 2020, but HMA (alongside the Andes) substantially lags the global average; 75% (and 49%) of the population can access safe supplies compared to >90% of populations elsewhere (Figure 4.9). Globally, ~71% of the population living in countries with glacial lakes have good sanitation (Figure 4.9), whilst in HMA, on average less than 50% of the population residing here accessing good sanitation.

Conversely, the PNW was the least vulnerable region on average across all time intervals, despite an increase in vulnerability since 2015 (Figure 4.8). Countries already scoring highly in SVI across the PNW, and High Arctic and Outlying Countries saw little improvement, due to most having almost 100% in the factors that reduce vulnerability; for instance, by 2020 four highly scoring countries attained 100% female literacy rates (Iceland, Austria, Canada, and Uzbekistan) while three attained 100% access to safe drinking water (Iceland, New Zealand, and Sweden) (Figure S4. 1, p. 248). Thus, changes here were mainly driven by increases in unemployment and percentage of dependant populations; the largest increases in over 65s occurred across the European Alps and PNW, with a rise of 5% and 4% respectively between 2000 and 2020 (Figure S4. 1, p. 248).

Overall, vulnerability to GLOF impacts reduced in 25 countries, with the largest reduction taking place in Austria (-35%) (Figure 4.9, Table 4.1). 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 to GLOF impacts over the whole 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.

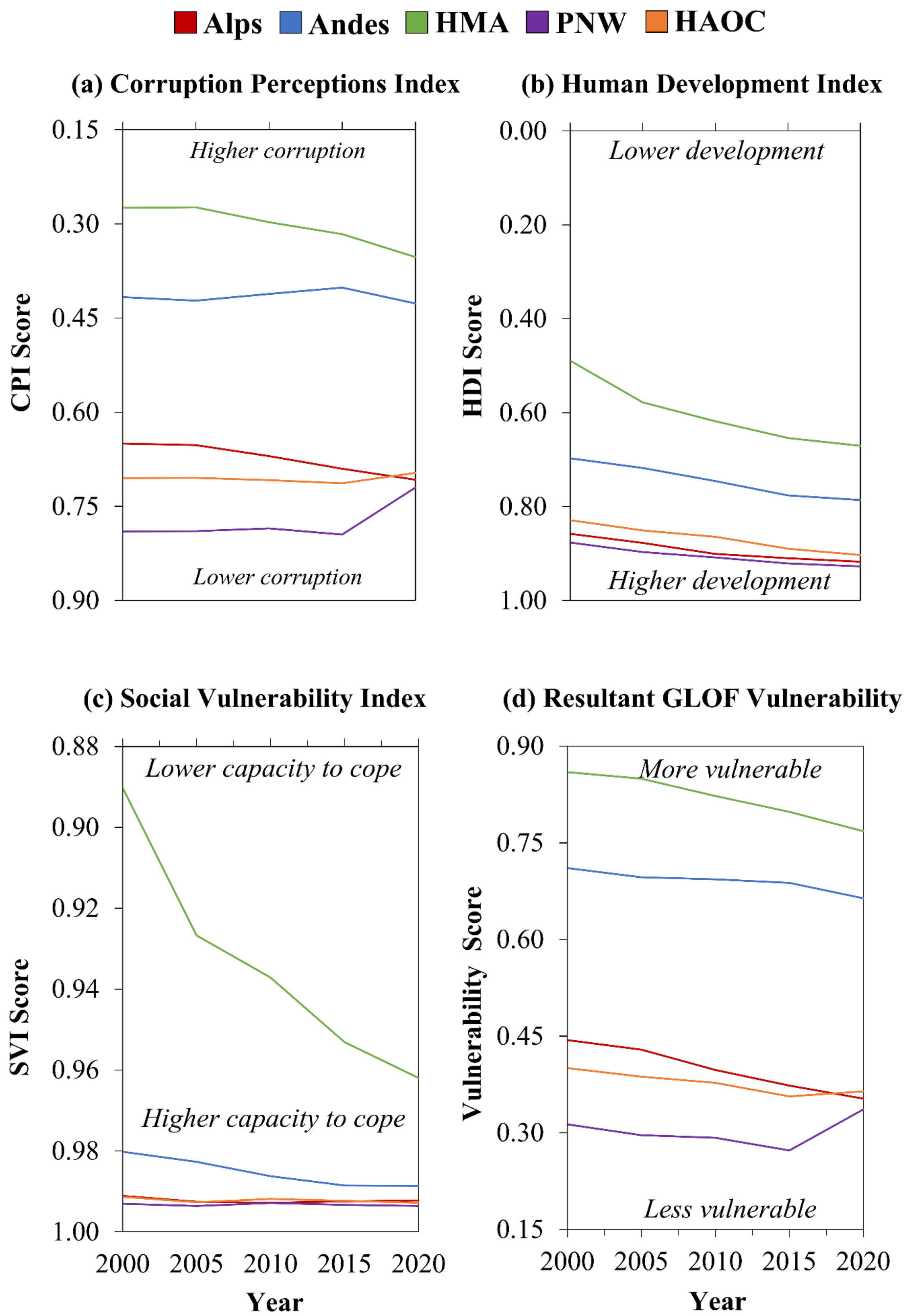

Figure 4.8: Global GLOF Vulnerability scores 2000 to 2020. Change in a) corruption perceptions index, b) human development index c) GLOF social vulnerability index and d) resulting overall GLOF vulnerability per mountain range for the period 2000-2020.

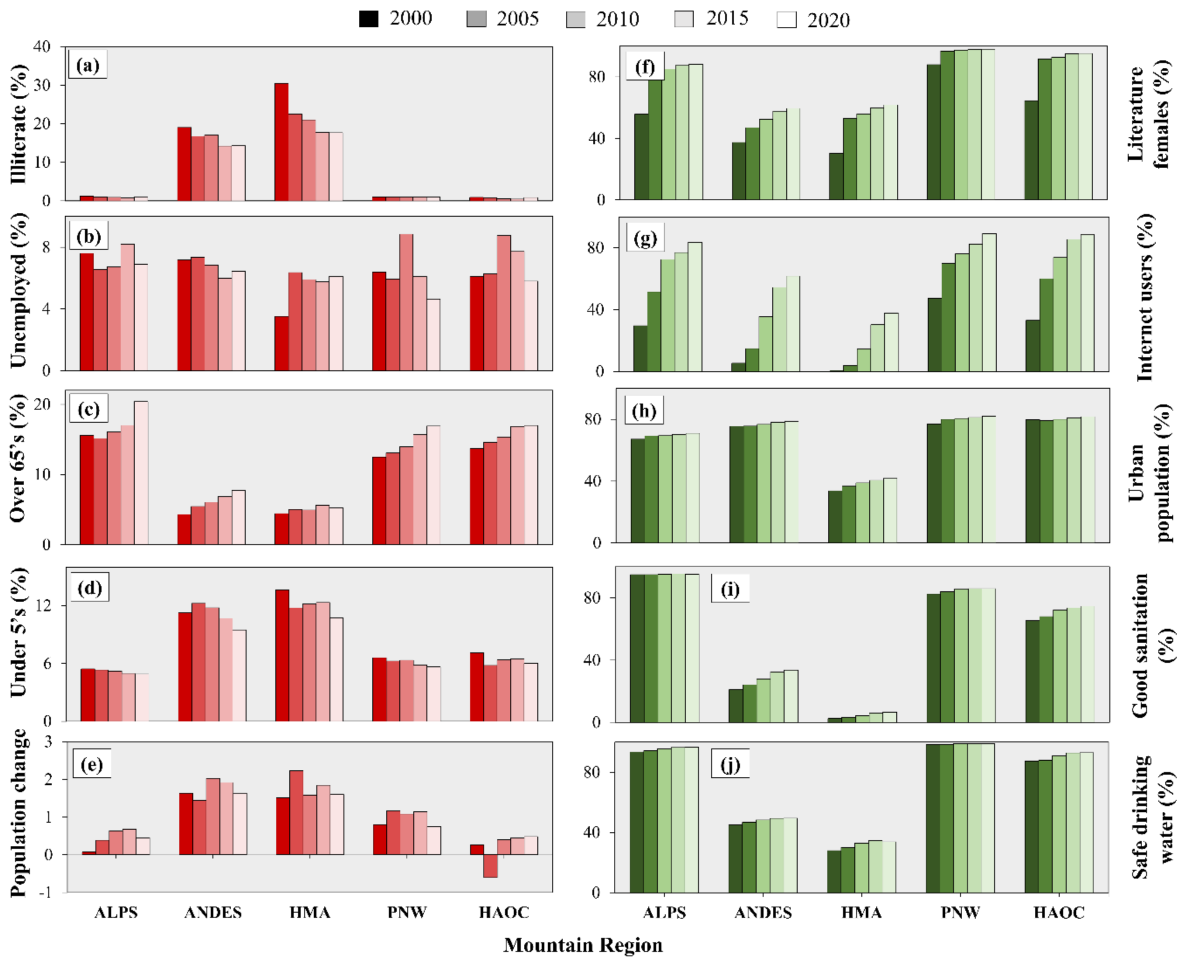

Figure 4.9: Changes in SVI indicators 2000 to 2020. Changes in all 10 indicators used to calculate SVI between 2000 and 2020. a) Percentage of population that are illiterate. b) Percentage of population unemployed. c) Percentage of population over 65 years. d) Percentage of population under 5 years. e) Rate of population change. f) Percentage of the female population over 25 that have some formal education to secondary standard. g) Percentage of the population that use the internet. h) Percentage of urban population. i) Percentage of population with access to good sanitation. j) Percentage of population with access to safe drinking water. Data in red represents factors that increase social vulnerability to GLOF, while data in green represents factors that decrease social vulnerability to GLOF. Data is grouped according to mountain range. Note that not all 10 indicators were used in the final GLOF vulnerability score (see section 3.2.1.3 for more details).

4.3.2 Change in GLOF risk

As of 2020, HMA has the highest GLOF risk globally (0.133 average) and the Alps the lowest (0.007) (Table 4.1). The biggest absolute change in GLOF risk 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 risk (+52% and +49% respectively) (Table S4.3, p.262). In the European Alps and PNW, GLOF risk increased the most between 2015 and 2020 (Figure 4.10). In the Andes and HMA, the most rapid increase in GLOF danger occurred between 2000-2005 and again between 2015-2020. Within this regional picture, GLOF risk increased in 22 countries and declined in nine (Figure 4.12). The largest absolute increase in risk 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 risk (relative to the 2000 score) was observed in China (+0.283), however again, Bhutan saw the largest percentage increase (+256%). China and India remained the highest risk countries throughout the study period (Table 4.1).

Within the 50 highest ranked basins, 39 (78%) were found in HMA and the Andes, with the top three found in Pakistan, Peru, and Bolivia at each time-interval Basins in Kazakhstan, Afghanistan and India increased in risk ranking the most over the study period, while basins in Nepal decreased the most (Figure 4.13). Across the European Alps GLOF risk ranking decreased in 92% of basins, with only two basins in Switzerland increasing in rank, whilst in the PNW three quarters of basins decreased in ranking, 15% increased and the remaining 20% did not change. The lowest ranking basins were consistently found in the USA, Canada, and China (Figure 4.13). In the Andes, 50% of basins increased in GLOF ranking. Here, higher risk basins continue to increase in ranking while lower risk basins decreased (Figure 4.13). Of the 395 basins across HMA, 30% (119) increased in ranking, with the majority of this increase occurring in lower-risk basins (Figure 4.13). Basins in Kazakhstan, Afghanistan and India increased in ranking the most, while the majority of those in Nepal (~80%) decreased. With one exception, Bhutanese basins consistently ranked within the top 10% globally and continued to increase in GLOF ranking over the 20 years. Most basins across China decreased in ranking, apart from in the Hengduan Shan region where there were notable increases.

4.3.2.1 Change in drivers of risk

The rate of change in GLOF hazard, exposure and vulnerability varied markedly between and within regions over the 20-year period. Whilst hazard scores increased everywhere over the 20-year period (Figure 4.10b, i), in the PNW the overall increasing trend is the result of changes over the last 5 years only (2015-2020). In the European Alps, hazard remained comparatively stable until 2015, where there was a notable increase to 2020. Despite this increase, risk in the European Alps remains the lowest globally as of 2020 (Figure 4.10b, i). The rate at which exposure to GLOFs increased over the 20-year period grew in all regions except High Arctic and Outlying Countries (Figure 4.10b, ii) with the most rapid change occurring across HMA, almost double that of the next fastest (the Andes) (Figure 4.10b, ii). Vulnerability decreased everywhere globally, with the exception of the period 2015-2020 in the PNW and High Arctic and Outlying Countries regions, where vulnerability increased (Figure 4.10b, iii).

Taken together, GLOF risk globally has increased since 2000 (Figure 4.10b, iv) and changes have been most rapid in HMA followed by the Andes. Risk in the European Alps and the High Arctic and Outlying Countries increased between 2000 and 2005 and remained at similar levels thereafter (Figure 4.10b, iv). Risk in the PNW decreased between 2005 and 2015 and then increased markedly between 2015 and 2020, due to the combination of increases in hazard, exposure, and vulnerability (Figure 4.10b, iv).

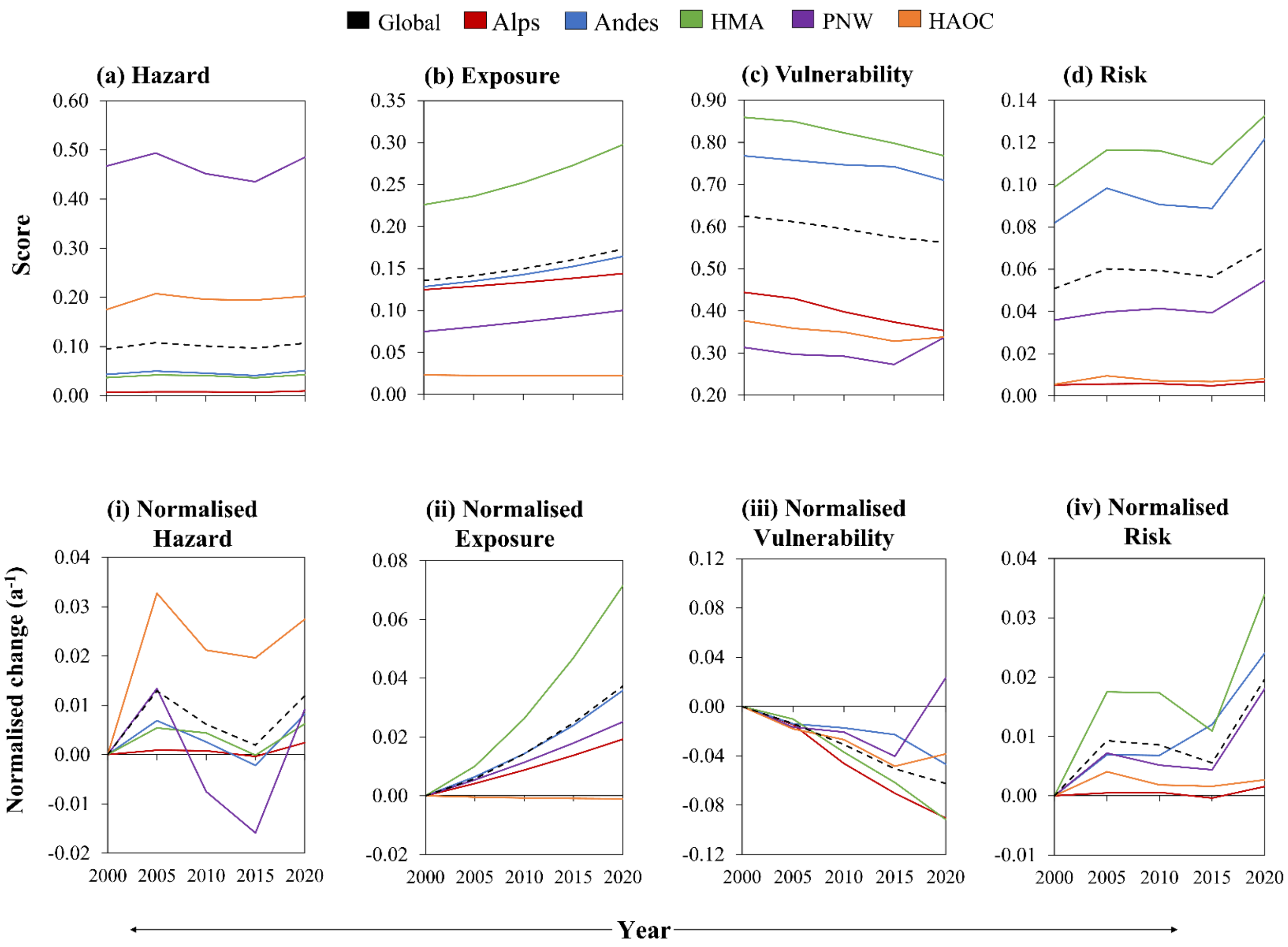

Figure 4.10: Change in normalised GLOF risk metrics 2000 to 2020. a-d Normalised scores between 2000-2020 for hazard, exposure, vulnerability, and risk and (i-iv) Normalised scores against the 2000 values between 2000 to 2020 for hazard, exposure, i vulnerability and risk, summarised by mountain range. The global average (dashed black) is given for comparison.

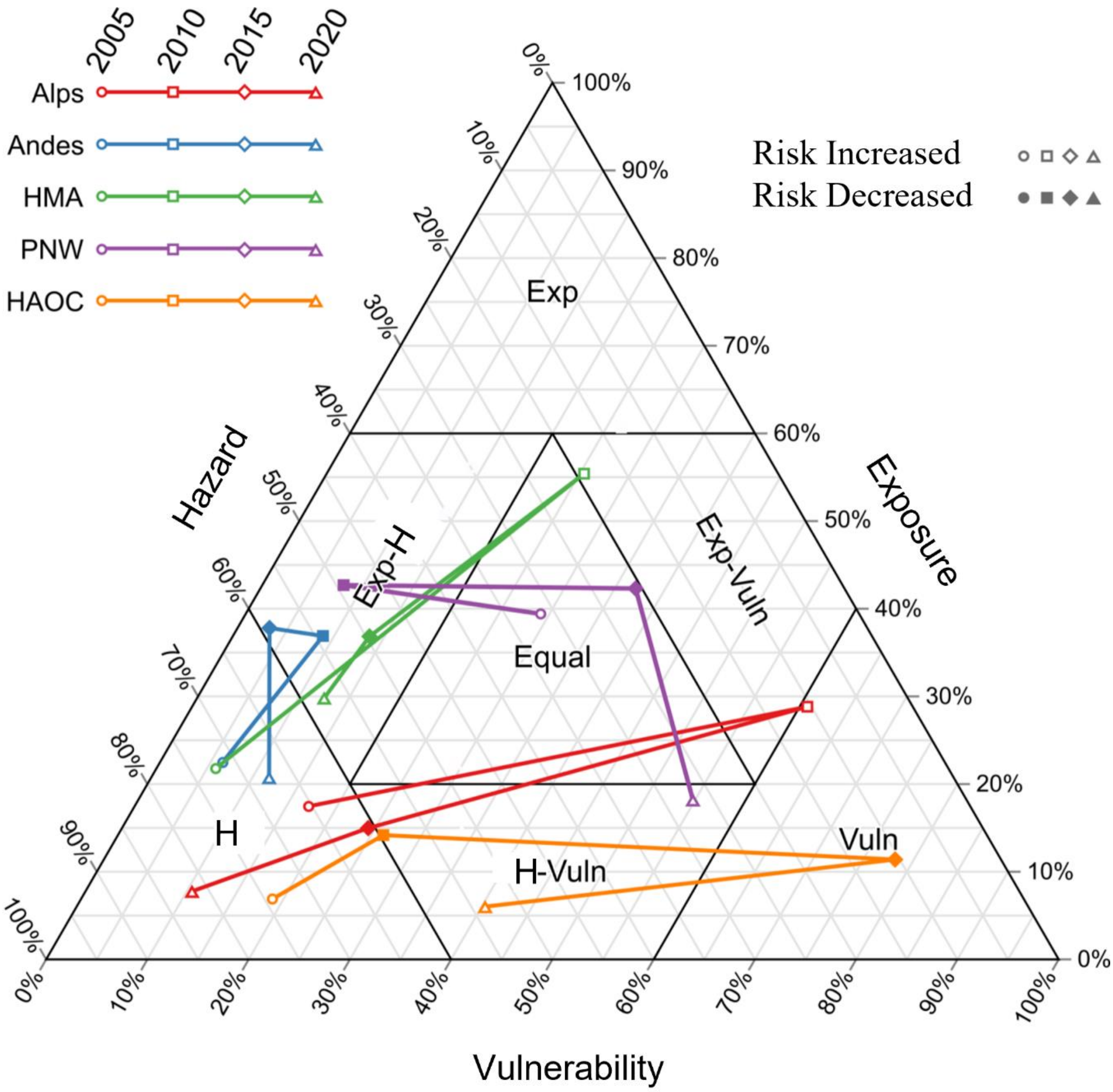

Figure 4.11: Ternary plot showing the combined relative weight of changes in hazard, exposure, and vulnerability in the overall change in risk since the previous time period. The position on the plot indicates which metric(s) have had the biggest effect in changing the overall risk score for the corresponding epoch; Exp- primarily exposure, H- primarily hazard; Vuln- primarily vulnerability; Exp-H- combined exposure and hazard; Exp-Vuln- combined exposure and vulnerability; H-Vuln- combined hazard and vulnerability; Equal – all three metrics contributed equally. Hollow symbols indicate risk increased and filled symbols indicate risk decreased compared to the pervious time period.

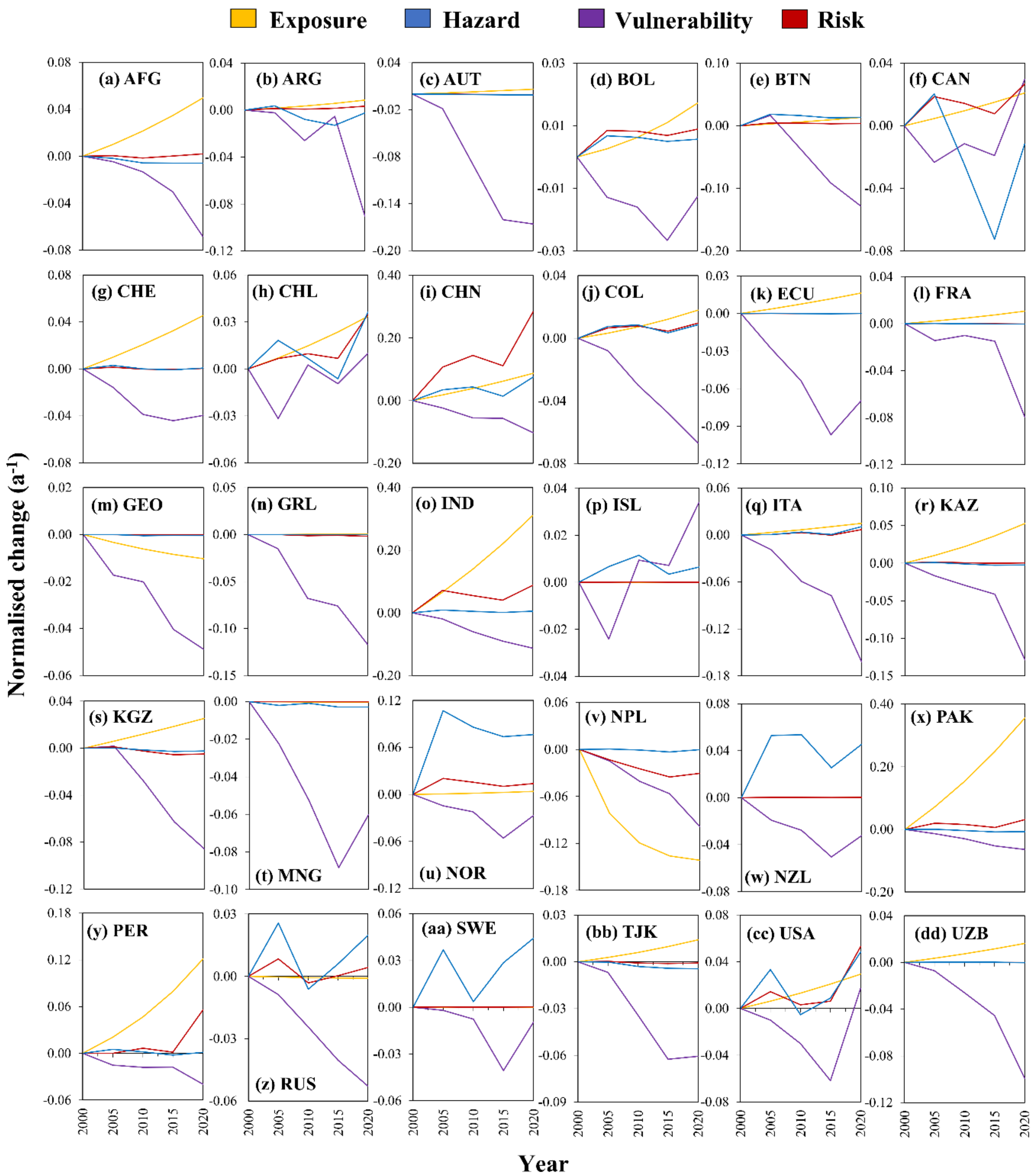

Figure 4.12: National-scale change in normalised GLOF risk metrics 2000 to 2020. Change in exposure, hazard, vulnerability, and risk for the period 2000 to 2020 for each country in this study. Values are normalised against 2000 values.

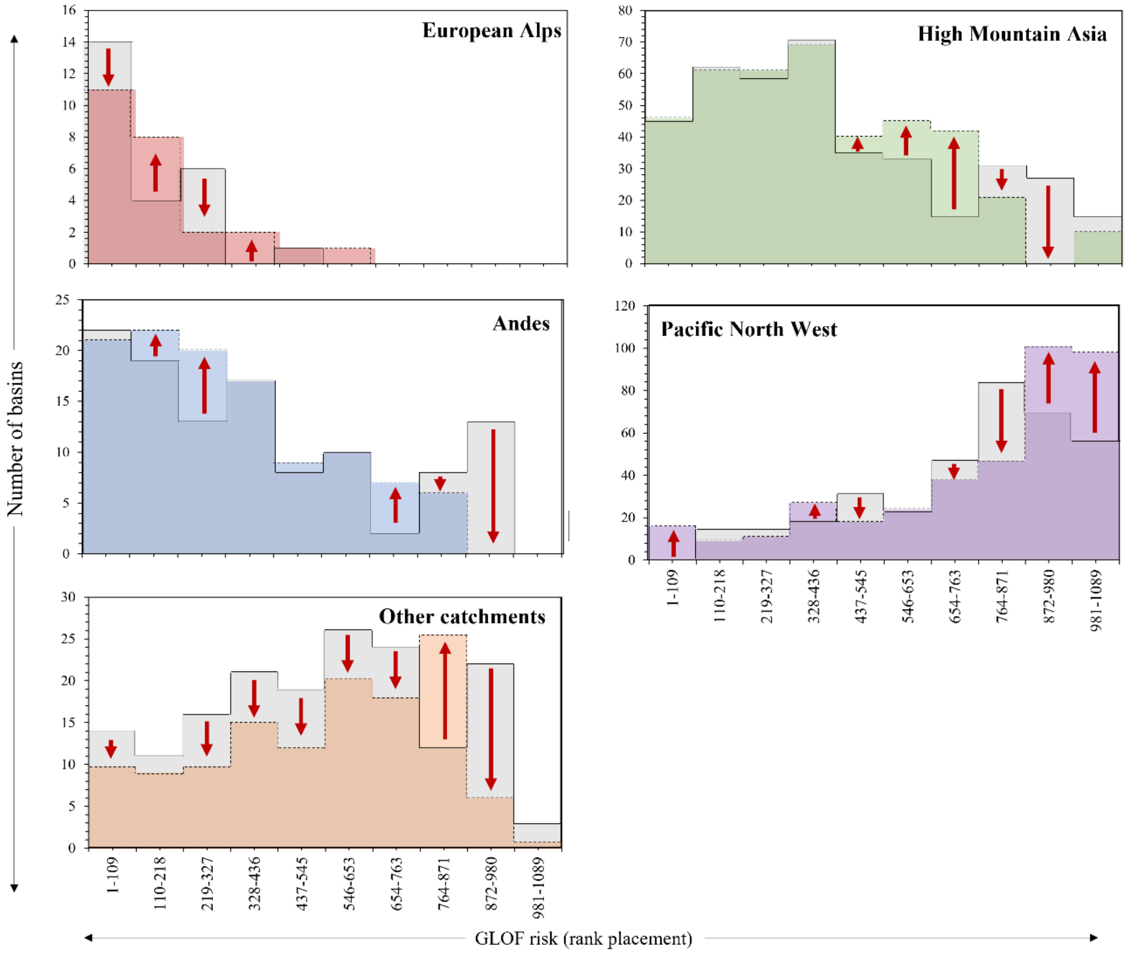

Figure 4.13: Distribution of basin-scale risk 2000 to 2020. Change in the distribution of basin-scale GLOF risk grouped according to mountain range for the period 2000-2020, with 2000 rank distribution shown in grey and 2020 rank distribution in colour. Arrows denote increases or decreases in risk from the 2000 value. Marginal changes are seen in the European Alps. Most basins in the PNW and HAOC decreased in rank. Most basins in the Andes and HMA increased in rank.

4.4 Discussion

4.4.1 Mitigating GLOF risk

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 risk globally (Bolch et al., 2012; 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, ***results here clearly show GLOF risk does not universally mirror hazard***. Instead, comparisons of risk with changes in hazard, exposure, and vulnerability over the past 20 years show the primary driver of GLOF risk varies between and within regions (Figure 4.12; Figure 4.11). As a result, the most effective mechanisms for mitigating GLOF risk will also vary between and within regions. Without knowing the primary driver of changes in GLOF risk it is difficult to accurately direct funding and implement policy to mitigate increases. These results therefore provide the first global scale indication of which mitigation pathways may have the greatest impact on reducing the rate of risk growth, and thus greatest potential to decrease GLOF risk at the regional and basin scale, and could be used to inform future policies, strategies, and funding.

Broadly, where hazard is the key driver of increasing risk, such as across the European Alps and in some nations in High Arctic and Outlying Countries (Figure 4.11; Figure 4.12, Figure 4.14) implementing hard engineering solutions may have the greatest effect to lower hazard scores and thus reduce risk. However, where increasing exposure is the main driver, such as across the Andes and HMA (Figure 4.11; Figure 4.14) hard engineering solutions would provide more marginal, and perhaps cost-ineffective, improvements in overall risk. Results clearly highlight the significant role of changing exposure in driving changes in GLOF risk; the High Arctic and Outlying Countries is the only region without an increase in exposure over the 20-year period and the only region where risk largely remains static (Figure 4.14). Thus, a focus on hazard avoidance through land use planning or relocation of communities has the greatest potential to slow the growth in, and potentially reduce, risk, particularly for nations across the Andes and HMA. Hazard avoidance is difficult for existing communities given the range of political and social factors that must be considered. However, knowing which factor to focus mitigation or adaptation efforts towards would help reduce GLOF risk moving forward and should be a consideration of all future strategies.

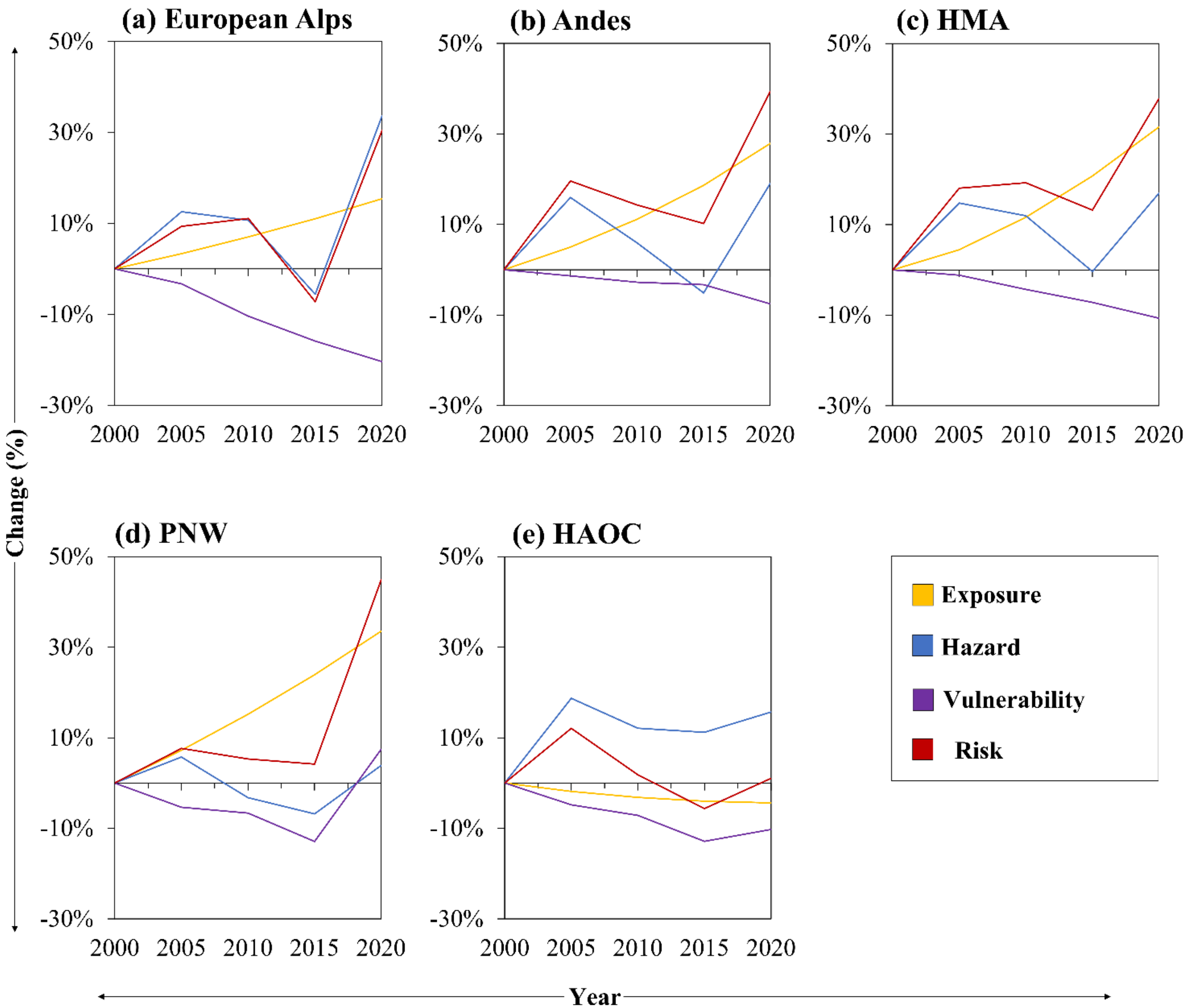

Figure 4.14: Percentage change in GLOF risk drivers. Change in the three drivers of GLOF risk (Exposure, Hazard, and Vulnerability) as well as GLOF risk for each mountain range over the period 2000 to 2020. Values are normalised against the 2000 value. Note the y-axis varies between panels.

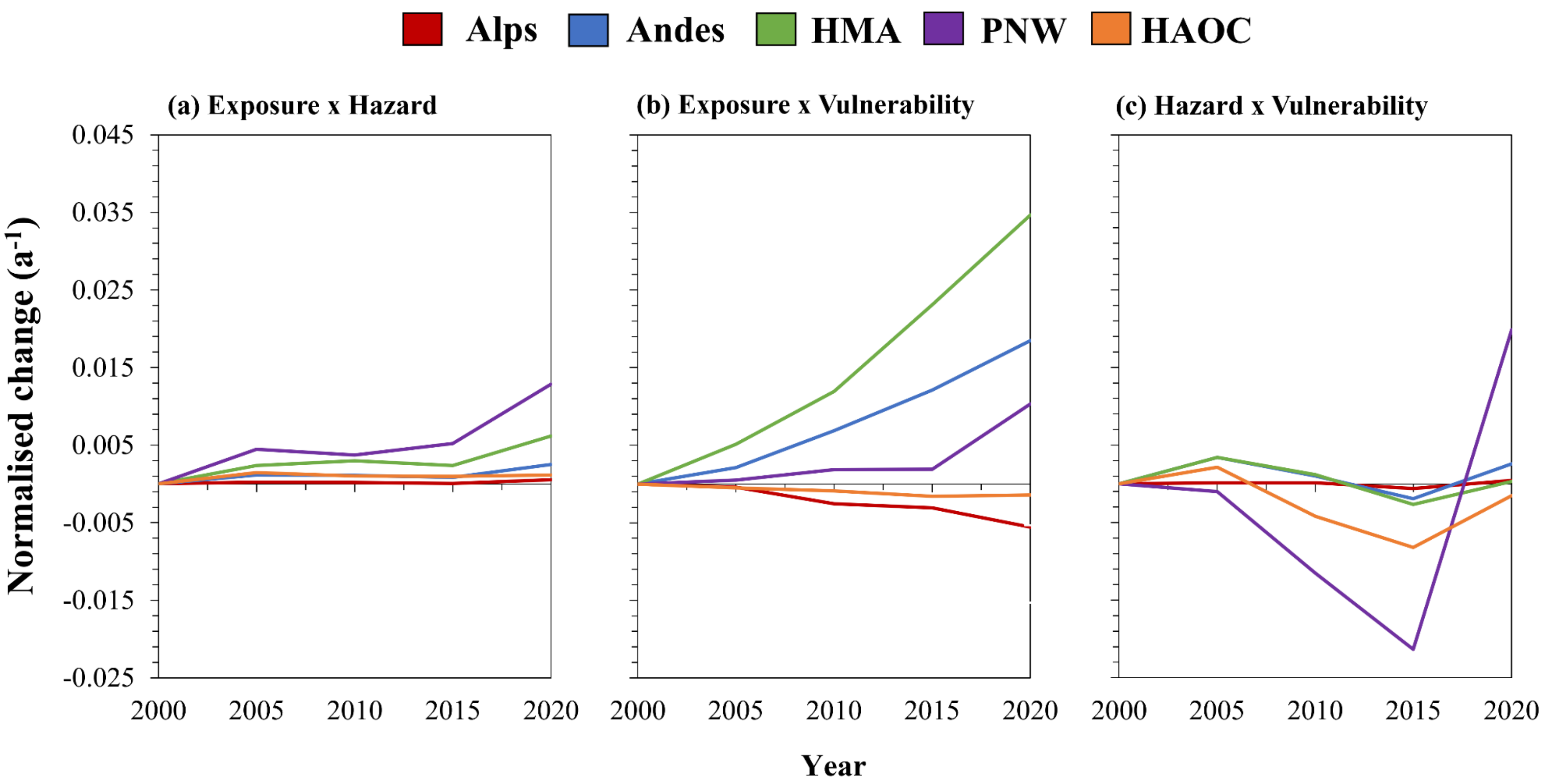

Figure 4.15: Change in GLOF risk derived from residual drivers. Here one driver is assumed equal in all regions and risk derived from the combination of the remaining two drivers. a) exposure and hazard, with constant vulnerability b) exposure and vulnerability with constant hazard and c) hazard and vulnerability with constant exposure.

4.4.1.1 High Mountain Asia

Across HMA, results show increasing exposure plays a much larger role in driving changes in GLOF risk than hazard (Figure 4.11; Figure 4.14b); although risk does appear to mirror the trend in hazard, risk scores are exacerbated by rapidly growing exposure. As the region develops, populations are moving into higher elevations for tourism, agriculture and for settlements around new HEP (Bajracharya *et al.*, 2007; Schwanghart *et al.*, 2016; Allen *et al.*, 2019; Zheng *et al.*, 2021), and over the last 20 years, the population exposed to GLOFs in HMA has increased by 2.2 million (Figure 4.7; Table 4.2). Had population exposure across HMA not changed since 2000 (Figure 4.10), by 2020 it would have had the second lowest GLOF risk globally, due to the comparatively slower rate of hazard change and rapid decrease in vulnerability (Figure 4.15). Thus, although monitoring and quantifying changes in glacial lakes is important, particularly for identifying new exposure corridors, across HMA a greater focus on forecasting, managing, and limiting the increasing exposure to existing lakes may prove more effective for GLOF risk management over the coming decades.

Findings demonstrate that exposure is a vital driver of GLOF risk, yet many reduction strategies do not focus on managing 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. dams, spill ways, tree plantation), introduce monitoring stations (weather, flood gauges), undertake hydrological modelling, and install early warning systems (Conceição & UNDP, 2020). Whilst all these methods may reduce GLOF hazard and thus risk, results indicate that for Pakistan, it is not hazard that is the primary driver of increasing risk, but exposure (Figure 4.12). Over the 20-year study period, Pakistan's population increased by 57%, but 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% (Figure 4.6). In short, Pakistan's population in GLOF exposed areas is rising faster than elsewhere within the country. Thus, results suggest a focus on managing exposure in glacial basins across Pakistan may be more valuable than hazard management. Whilst more difficult to implement, directing more funding to issues such as land-use zoning or relocation costs could be more effective than approaches that focus on reducing the frequency and magnitude of outburst events.

I acknowledge that reducing exposure may be more technically and/or politically challenging to implement than hazard mitigation, and that focusing on hazards may therefore be more favourable socially and politically. However, given exposure is identified as the key driver of GLOF risk and considering reducing exposure can bring broader co-benefits especially if communities are subject to multi-hazards, I suggest research, funding, and policy across the region be directed towards managing exposure changes and not just strategies to reduce the frequency/magnitude of events, which may have less impactful reductions on overall risk. I 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 SDGs, such as access to clean drinking water and adequate sanitation (Table S4.2), is a pressing issue that may outweigh the risk from GLOFs. Further, deglaciation may present other hazards, such as water scarcity issues, which will further compound quality and access issues, with more vulnerable groups disproportionally impacted (Seddon et al., 2020; Lynch, 2012; Drenkhan et al., 2023). Nevertheless, future GLOF events will almost certainly exacerbate both issues.

4.4.1.1.1 National trends in HMA

Trends in hazard, exposure, vulnerability, and risk varied markedly between nations, with Afghanistan and Bhutan emerging as interesting cases. Vulnerability in Afghanistan decreased but remained the highest globally for the duration of the study period (Table 4.1), and given the recent fall to the Taliban, is likely to remain as such. For the time being, hazard from glacial lakes here remains low; lakes are not growing rapidly in area or number (Figure 4.2; Figure 4.3). However, exposure did increase between 2000 and 2020 and this growth was sufficient to drive an increase in risk (Figure 4.5, Figure 4.14). Modelled overdeepenings for HMA indicate that in an environment with strongly reduced ice extent due to climate change, the largest glacial lakes will be found in the western Himalaya and Karakoram (Linsbauer et al., 2016; Furian et al., 2021). Hence, GLOF hazard is likely to increase in Afghanistan in the future. Coupled with already rising exposure and high socioeconomic vulnerability, future GLOF risk could be much higher than present, thus ***I strongly suggest Afghanistan become a key study area for more detailed analysis of GLOF risk*** today and in the future, although recognise studies will likely be limited to remote sensing only at least for the time being.

Although exposure to GLOFs appears to be driving the increase in GLOF risk across the HMA region as a whole (Figure 4.14), in Bhutan, rapidly increasing hazard was the main driver of changes in GLOF risk. Over the last two decades, GLOF risk in Bhutan has increased consistently, and as of 2020, is one of the highest globally, with all five basins in the top 10% when ranked in order of risk. Due to the long history of GLOFs across the nation, several GLOF risk reduction strategies are already in place; in the Punakha-Wangdue valley a total of six EWS with 17 sirens have been installed along the Pho-Chhu river, whilst education and awareness programmes for communities likely to be impacted by GLOF have been delivered in the Punatsang Chhu river basin with positive results (Shrestha et al., 2016). Since 1955, 11 GLOF have been recorded across Bhutan (Veh, 2019), however only two outbursts have occurred in since 2000 (Veh et al., 2022). Thus, as lakes continue to increase in both number and area (Figure 4.2) there a pressing need to identify when and how these lakes are likely to burst, to ensure the most appropriate mitigation strategies are implemented alongside those already in place. Given hazard continues to increase despite the interventions already in place at the lakes themselves, an alternative route could be to reduce exposure and vulnerability, via land zonation and education. With 40% of the population illiterate, and only 23% of women in Bhutan with some formal education as of 2020 (Figure 4.9), communicating GLOF risk information is difficult (Dhungel & Ojha, 2012; Shrestha et al., 2016), therefore any communication materials must be designed to engage even the most vulnerable members of community, such as using pictures and illustrations.

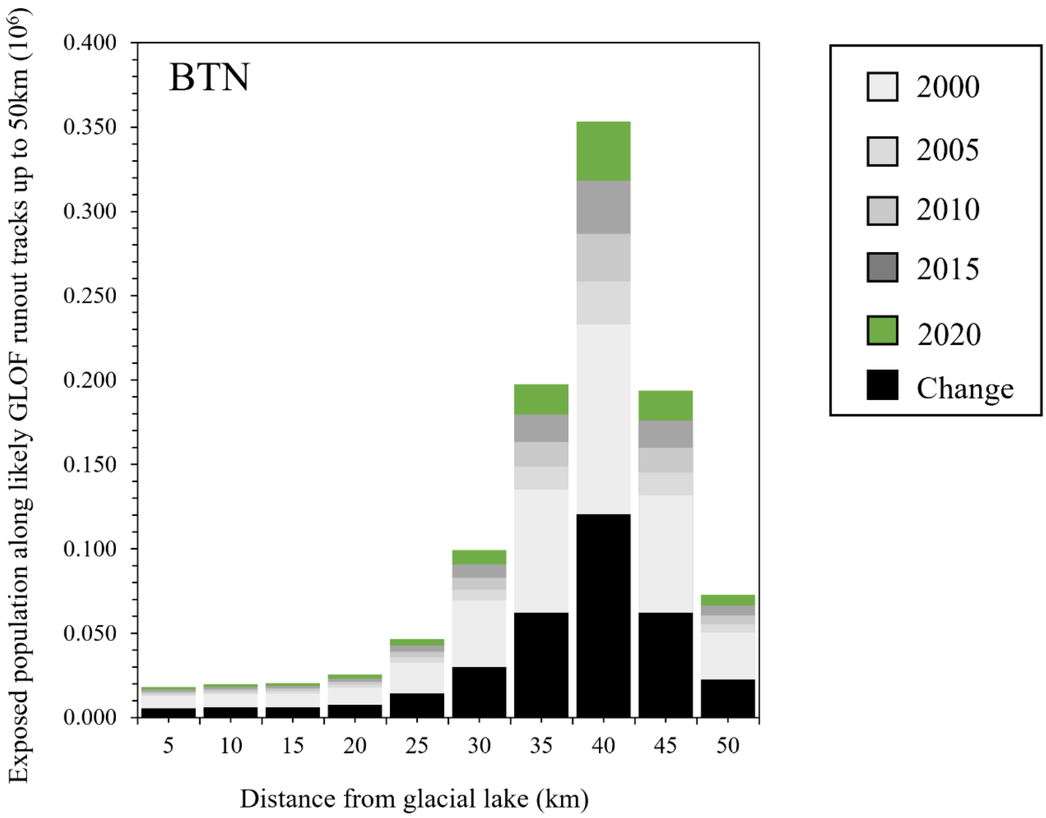

Figure 4.16: Spatial exposure to GLOFs in Bhutan between 2000 and 2020. Changes in spatial exposure to GLOFs in Bhutan between 2000 and 2020 at 5 km intervals. Total change over the 20-year period is shown in black.

4.4.1.2 European Alps

It is difficult to separate the relative roles of different factors on the observed increase in GLOF risk across the European Alps (Figure 4.11; Figure 4.14a), however the risk trend appears to closely mirror the hazard trend. Whilst GLOF in the region are general 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 (Pfeffer et al., 2014; Salzmann et al., 2004). Whilst exposure increased 15% between 2000 and 2020 (Figure 4.7), vulnerability decreased by 20%, which is more than sufficient to offset the exposure increase and thus made hazard, which increased by 34%, the primary driver of risk. As such, in order to manage future changes in GLOF risk across the Alps a focus on engineering solutions to mitigate the magnitude and frequency of GLOF hazard is recommended. Given the higher economic development and political stability in the region, the construction of spillways, artificial lake lowering, levee strengthening etc. should be highly achievable and effective in managing further increases in GLOF risk 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 hazard and exposure in this region. Implementing engineering solutions now to mitigate risk may allow for long-term management as the number and size of lakes changes over the coming years.

4.4.1.3 Pacific Northwest and High Arctic and Outlying Countries

In the PNW and High Arctic and Outlying Countries, relatively static risk between 2000 and 2015 was controlled by a combination of increasing GLOF hazard and/or exposure, with a sufficient counter effect from declining vulnerability (Figure 4.11; Figure 4.14). However, between 2015 and 2020, risk increased rapidly in both regions, particularly in PNW, due to a sharp increase in both hazard and vulnerability (Figure 4.11; Figure 4.14). Whilst changes in vulnerability are not forecastable, countries in both regions typically have well developed 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, and reflected by the few recorded GLOF related deaths; there are no records of loss of life from GLOFs 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 one single GLOF from Cirenmaco on the Tibetan Plateau in 1981 (Wang et al., 2018). Thus, although overall GLOF risk in the PNW was the third highest globally in 2020, this was primarily due to the vulnerability increase in the period 2015-2020. Therefore, glacial lake expansion, both in terms of lake area and number, should continue to be monitored, but data indicate that GLOF risk 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 likely to be key to managing GLOF risk in these regions.

4.4.2 The Andes as a region of concern.

HMA is often cited as having one of the highest GLOF risks globally (e.g. Carrivick and Tweed, 2016; Zheng *et al.*, 2021; Emmer, 2018), and over the past 20-years results show the region did have the highest, and most rapidly increasing GLOF risk (Figure 4.14). However, results also show the Andes experienced the second most rapid increase in GLOF risk globally, as well as a percentage increase in risk nearly 1.5 times that of HMA (Figure 4.14; Table 4.1). Until 2005, this increase can be attributed almost solely to increasing GLOF hazard (Figure 4.11; Figure 4.14b), reflecting the rapid and accelerated deglaciation observed across the Andes over the past two decades (Wilson et al., 2018; Masiokas et al., 2020). During this period, increases in exposure were offset by reductions in vulnerability (Figure 4.14). 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, Huggel, Carey, et al., 2020). Despite these interventions, GLOF risk continues to increase during the study period, although such interventions have not been accounted for (Figure 4.4). Since 2005, GLOF hazard in the Andes appears to have declined, but GLOF risk has continued to increase (Figure 4.14). This is due to increasing rates of growth in exposure that have outpaced the combined decreases in hazard and vulnerability. As such, here, mitigating the changing exposure could be beneficial for managing future GLOF risk.

Across the Andes, CPI (Corruption Perception Index) scores have remained persistently high over the last 20-years (Figure 4.8a). Following the 1941 Huaraz disaster in Peru, a 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, some rebuilding on outburst deposits (Motschmann, Huggel, Carey, et al., 2020). Coupled with the strong cultural and spiritual significance Andean residents traditionally uphold for the glaciated landscape (Carey, 2010; Motschmann, Huggel, Carey, et al., 2020), freedom of movement is limited, and populations continue to occupy areas known to be impacted by GLOFs (Oliver-Smith, 1996). As a result, although results indicate exposure as a key driver of GLOF risk, managing increasing exposure here would be difficult, and would require complex and multifaceted approaches. Instead, given results show that improving vulnerability can offset increasing GLOF risk (Figure 4.15a) and that the rate of decrease in vulnerability across the Andes remains one of the lowest globally (Figure 4.8), I recommend both targeted strategies to reduce vulnerability across the region, to counter rapid increases in GLOF risk, as well as continued lake mitigation to control GLOF hazard.

The Andes has a long history of GLOFs, some disastrous, with the Cordillera Blanca particularly badly affected (Lliboutry et al., 1977; Carey, 2005; Emmer, 2017b; Ahmed et al., 2022); a recent study documented 160 GLOFs across the glacierized Cordilleras of Peru and Bolivia, tripling the number of previously reported events (Emmer, Wood, et al., 2022). As such, the observed increase in GLOF risk over the last 20-years is particularly concerning, although unsurprising. Unlike in HMA, where future ice coverage and glacial overdeepenings have been modelled for the entire region (Linsbauer et al., 2016; Furian et al., 2021) in the Andes only a few, small scale studies have been undertaken (e.g. Colonia *et al.*, 2017; Emmer *et al.*, 2020). This data sparsity prevents meaningful local-scale assessments as to how GLOF hazard has changed and how it might evolve in the future (Vuille & Bradley, 2000; Salzmann et al., 2013; Wilson et al., 2018; Harrison 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 (Figure 4.5), undertaking more detailed studies here may not only allow the Andes to prepare for future GLOF scenarios but could also have wider transferable applications for GLOF risk evolution globally.

4.4.3 Role of vulnerability in GLOF risk

Results show a near-global reduction in vulnerability to GLOFs, albeit at varying rates (Figure 4.8d), supporting research suggesting vulnerability is reducing globally (Formetta & Feyen, 2019; Conceição & UNDP, 2020). As changes in vulnerability to natural hazards are often subtle, dynamic, and unpredictable (Khanal et al., 2015), it is vital a measure of vulnerability is integrated 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 at global and national-scales (Conceição & UNDP, 2020; Transparency International, 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 the ultimate impacts and therefore the risk, particularly where less vulnerable nations are upstream of more vulnerable nations. 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 higher vulnerability score (0.919) than Tajikistan (0.836) and given similar levels of exposure suggest potentially greater impacts would be experienced on the Afghan side of the border as a result.

Despite this, results indicate any reduction in GLOF impacts globally from declining vulnerability are more than offset by rapidly increasing exposure and/or hazard, such that GLOF risk continues to rise irrespective (Figure 4.8; Figure 4.10). 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, results demonstrate for a climate related hazard such as GLOFs, these gains have not been enough to prevent risk increasing. That said, the overall increase in GLOF risk has mostly been slower than increasing exposure and/or hazard in each mountain range (Figure 4.10; Figure 4.12), highlighting that declining vulnerability has been effective in dampening increases in risk 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 risk than at any other time in the preceding 15 years (Figure 4.14d, e). Thus, in many regions, GLOF risk could be far higher that present values if not for the investments made through the likes of the MDGs and SDGs, particularly across HMA and the Andes. If continued and increased investment in reducing vulnerability globally can lead to even larger reductions than experienced since 2000, it is possible that growing exposure and hazard could be offset sufficiently to reduce risk. However, at the current growth rates this appears to present a significant challenge.

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 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 risk should they occur. As such, tackling vulnerability is important, and current decreases should at least be maintained, in addition to reversing trends in exposure and hazard through mitigation strategies.

4.4.4 Implications for early warning systems

Globally, over the past 20 years, populations across HMA have moved closer to glacial lakes (Figure 4.5). 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 (GAPHAZ, 2017; Furian et al., 2021). 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 GLOFs in sufficient time to relay a warning to exposed downstream populations to evacuate (Bajracharya *et al.*, 2007). 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). 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 risk 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 (UN, 2006; Shrestha et al., 2016). Countries across HMA have the lowest literacy rates globally (Figure 4.9, Table S4.2) 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 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 and make use of local and indigenous knowledge. As glacial lakes continue to grow in area and number, 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 GLOFs (Dahal, 2008). Further, as populations move closer to glacial lakes (Figure 4.5) 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 risk.

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 (UN, 2006; IPCC, 2012). The presence of ineffectiveness, corruption, or political tensions in any of these bodies could result in inefficiency (Zheng, Allen, 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 GLOFs (Zhang et al., 2021), particularly where GLOF runout tracks cross international borders, as observed in the Gongbatongshaco GLOF of 2016 (Kougkoulos et al., 2018; Nie et al., 2018) and by modelling of future potential GLOFs (Allen et al., 2022). Currently, transboundary risk mitigation and disaster recovery is inescapably (and detrimentally) linked to global politics and finance as well as water security, issues that requires careful unpicking over the coming decades.

4.4.5 Future research

4.4.5.1 Holistic risk assessments

This chapter shows the value of integrating hazard, exposure, and vulnerability into assessments of risk, highlighting their varying roles on GLOF risk between nations and within them. Emmer *et al.* (2022) identified a clear imbalance in research focussed on individual GLOF risk components, where hazard studies still largely outweigh those on vulnerability or exposure. As such, we need to encourage interdisciplinary cooperation, to create an integrated and holistic approach to GLOF research that considers all aspects of GLOF risk and promotes the inclusion of all stakeholders. In particular, encompassing changes in **a)** exposure, to identify areas most likely to experience substantial GLOF impacts, and allow effective mitigation to be implemented and **b)** vulnerability, so that factors responsible for lowering a nation, community, or individuals, ability to respond to GLOF disaster can be targeted, should be a key focus for future research. With populations across HMA shown to be moving closer to glacial lakes, the effectiveness of current risk reduction strategies such as EWS may well be reduced, and new strategies or adaptations of current strategies will be required in order to support development in high mountain regions without also increasing GLOF risk. Here, obtaining realistic GLOF scenario models would be beneficial for future planning (Emmer, Allen, et al., 2022). I hope this initial database of GLOF risk drivers, alongside the recommendations given within this chapter, could be used to help better inform policy makers, direct funding to key drivers of risk and lead to the implementation of more effective, long term mitigation strategies.

The distribution of both glacial lakes and populations will undoubtedly change over the coming decades as deglaciation continues and regions develop. Whilst studies have attempted to project the future spatial extent of glacial lakes (Furian et al., 2022; Linsbauer et al., 2016; Magnin et al., 2020), as yet there have been no studies that seek to determine how GLOF risk may evolve over the coming decades. This information would be invaluable, allowing regions to establish effective and targeted mitigation strategies before the threat of GLOFs fully emerges, to prevent future disasters.

4.4.5.2 Outburst frequency and magnitude

Understanding GLOF magnitude is crucial for determining overall impact, particularly in areas where populations are moving closer to glacial lakes such as in HMA (Figure 4.5). Here, modelling the likes of runout distance, inundation depths and extent and arrival times would enable more effective mitigation and reduce risk. Whilst substantial progress has been made in understanding the underlying processes of GLOF initiation and propagation (e.g. Pudasaini, 2012; Pudasaini and Fischer, 2020) as well as in the advancement of full 3D models (Cicoira et al., 2022), there remain gaps in understanding, particularly for defining realistic scenarios in modelling future GLOFs, and is a key research challenge that needs addressing.

Deploying GLOF mitigation strategies effectively also relies on an understanding of GLOF occurrence. Whilst here GLOF hazard refers solely to the intensity of outburst and includes no measure of probability, knowing how often outbursts may occur is crucial for future planning; an area experiencing low-magnitude, but high-frequency events may require different strategies to an area where GLOFs are high-magnitude but low-frequency. A recently compiled database (Veh et al., 2022) reveals a total of 752 GLOFs occurred across 24 of the nations included in this study between 2000 and 2020 (Figure 4.17), whilst six nations had no documented outburst during this period: Columbia, Ecuador, France, Georgia, Mongolia, and Uzbekistan (Figure 4.17). This information, when paired with the findings of this chapter, could be used to better understand which mitigation strategies would be most suitable for each location. Exposure and vulnerability in Pakistan are high (Table 4.1) thus frequent GLOFs are likely to impact large numbers of people even if interventions within the community (e.g. education, evacuation rills) are undertaken. With 49 documented outbursts over the 20-year period, here engineering strategies that control the magnitude and frequency of outbursts may be necessary alongside managing exposure changes. In comparation in Bhutan, only two outbursts were documented between 2000 and 2020, thus deploying land-zoning policies may be more cost-effective. An updated GLOF inventory for Peru and Bolivia (Emmer, Wood, et al., 2022) revealed an increasing occurrence of low-magnitude GLOFs in recent decades. In the Andes, increasing GLOF risk is driven by exposure (Figure 4.14), yet populations are not moving closer to glacial lakes (Figure 4.7). As such, low-magnitude GLOFs are unlikely to directly impact downstream communities, thus lake engineering may not be the most cost-effective mitigative strategy. This type of analysis would be highly beneficial for regions were funding is limited, allowing GLOF risk mitigation to be individually tailored. Updated GLOF inventories (e.g. Veh *et al.*, 2022) have highlighted the incompleteness of existing GLOF records (e.g. Emmer, Wood, *et al.*, 2022; Zheng *et al.*, 2021; Baťka *et al.*, 2020; Veh *et al.*, 2019; Nie *et al.*, 2018), with the number of recorded GLOFs underestimated in some regions because of the availability of remote sensed and documentary data or low research activity, whilst vanishing geomorphological GLOF imprints of historical events means some events may be missed completely. As such, there remains a lack of understanding as to how the frequency of GLOFs has changed over the last few decades, or how it might be expected to change over the coming decades and importantly, how this relates to GLOF risk. More comprehensive GLOF inventories are essential for better understanding the frequency of GLOF occurrence in mountain environments and enabling GLOF risk reduction and should be a priority for future research.

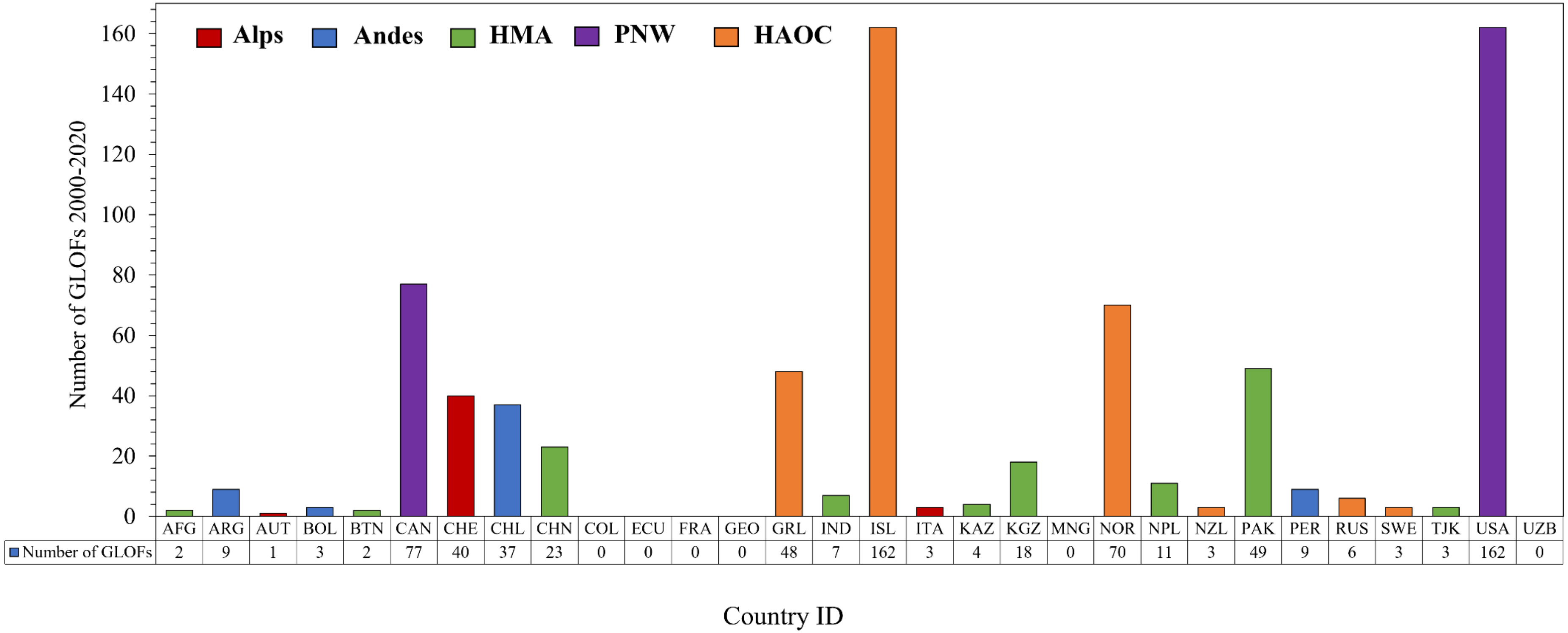

Figure 4.17: GLOF occurrence 2000 to 2020 from Veh *et al.*, (2022). Total number of glacial lake outburst events that occurred in each nation during the study period (2000-2020). Bars are coloured according to mountain range.

4.5 Conclusion

Over the past 20 years, GLOF risk has increased in almost all countries where glacial lakes are found. The results show that the drivers of this increase vary both between regions and within regions, and importantly, increasing risk does not mirror increasing glacial lake number and/or area. HMA has the highest GLOF risk, but results highlight the Andes as an area of rapidly increasing GLOF risk. Populations are beginning to move away from contemporary glacial lakes except across HMA, where people are living closer to lakes than ever before. The results show that reduced vulnerability has partly offset increases in exposure and hazard, but, despite this, GLOF risk has continued to increase.

Chapter 5 Future glacial lake outburst flood danger in High Mountain Asia

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Key words

GLOF, danger, exposure, vulnerability, HMA, cascade events

ABSTRACT

Extensive and rapid deglaciation since the 1970s has resulted in the formation and expansion of glacial lakes across High Mountain Asia (HMA). These lakes pose a significant threat to downstream communities in the form of glacial lake outburst floods (GLOFs). GLOFs can be highly destructive, often arriving with little warning, causing significant damage and extensive loss of life. Concurrent with this glacial lake growth, rapid regional development across HMA is increasing the exposure to GLOF impacts as people move closer to glacial lakes. The number and spatial extent of glacial lakes is predicted to increase with continued glacier shrinkage, but it is uncertain how the risk from GLOFs may evolve across HMA over the coming decades. Here, UN population projections are used to show that the number of people exposed to GLOF impacts could increase by 3.9 million by 2060, representing an increase of 20% compared to 2020 exposure. Results show potential GLOF danger is likely to shift northwest towards the Karakoram, with Pakistan identified as a hotspot of high future danger. With most glacial lakes predicted to form where there are currently no existing lakes (Furian *et al.*, 2021), results highlight the importance of risk perception and education, which should be addressed urgently. Further, with future lakes likely to form at higher elevations above existing lakes, results indicate an increased need to understand cascading events, which will require more targeted management if large scale, transnational disasters are to be avoided.

5.1 Introduction

High Mountain Asia (HMA), which comprises the Tibetan Plateau and its surrounding mountain ranges (including the Himalaya, Karakoram, Tien Shan, and Pamir) contains the largest concentration of glacier ice outside of the polar regions (Wang et al., 2020). Most glaciers in the central and eastern Himalaya receive ~80% of their annual accumulation from the summer monsoons (Bookhagen & Burbank, 2006), while glaciers in the western Himalaya and Karakoram receive ~60–70% from westerly extratropical cyclones (Bolch et al., 2012;

Kapnick et al., 2014; Mölg et al., 2014). Glaciers across HMA have experienced extensive shrinkage in ice mass over recent decades, with observations of negative mass balance (−19.0 ± 2.5 Gt yr^{-1} between 2000 and 2018), declines in glacial length and substantial glacier fragmentation widespread across the region (Song et al., 2017; Maurer et al., 2019; Shean et al., 2020). This trend is expected to continue throughout the 21st century in response to climate warming (Huss & Hock, 2018).

Particularly in the central and eastern Himalaya, glacier down-wasting and mass loss in response to the prevailing negative mass balance conditions, has resulted in the sustained expansion of existing glacial lakes, as well as facilitating the formation of new glacial lakes (Harrison et al., 2018; Song et al., 2017; Maurer et al., 2019; Mal et al., 2021). Glacial lakes can form behind moraines, other glaciers, landslide deposits, in bedrock depressions, in cirques, and, through coalescence of supraglacial ponds, with the latter being the most frequent formation mechanism in HMA (Ageta et al., 2000; Sakai et al., 2000; Benn et al., 2001, 2012; Thompson et al., 2012; Watson et al., 2016; Miles et al., 2017; Song et al., 2017). Between 1990 and 2018, the area of glacial lakes in HMA increased by ~45%, with glacial lakes in the eastern Himalaya (Nepal, Bhutan, and Southwest China) almost doubling in area during this time (Shugar et al., 2020). These lakes form as glaciers recede, exposing more topographic overdeepenings, and allowing glacial meltwater to collect. Furthermore, increased surging activity of glaciers as basal temperatures rise is enabling the formation of ice-dammed glacial lakes (Round et al., 2017). At the same time, glacier retreat is exposing weakened and/or over-steepened slopes, which increases the likelihood of mass movements occurring that can form landslide dammed glacial lakes. These glacial lakes may pose a significant threat to downstream communities in the form of glacial lake outburst floods (GLOFs) (Mal et al., 2021), whereby large volumes of water and sediment are suddenly released downstream (Begam & Sen, 2019). GLOFs are amongst the most impactful natural hazard in high mountain areas: they arrive with little prior warning and can cause substantial damage to residential and commercial infrastructure, agricultural land, as well as resulting in loss of life (Zheng, Allen, et al., 2021; Emmer et al., 2020; Mohanty & Maiti, 2021).

HMA has a long history of GLOFs; a review by Carrivick and Tweed (2016) found historical outbursts have claimed the lives of 6300 people since the early 1990s, whilst other studies have documented the considerable damage to infrastructure, hydropower stations, livestock, and farmland caused by outbursts (Kattelmann, 2003; Richardson & Reynolds, 2000a; Yamada & Sharma, 1993; Veh et al., 2020; Mohanty & Maiti, 2021; Harrison et al., 2018). Compared to other natural hazards, large, impactful GLOF events are rare and hard to predict, both spatially and temporally. As such, the economic implications of GLOFs across HMA have been substantial, with regions underprepared for events. It is thought that countries in the east of the region, namely Nepal and Bhutan, have suffered the highest socio-economic impacts by historic GLOFs worldwide (Carrivick & Tweed, 2016), primarily due to the increasing number of hydroelectric power schemes (Schwanghart et al., 2016; Fischer et al., 2022). For example, in August 1985, a GLOF event from Dig Tsho in eastern Nepal destroyed bridges, homes, agricultural land and the nearly completed Namche Small Hydropower Plant just two weeks before its inauguration, resulting in an estimated loss of US$1.5 million (Kattelmann, 2003; Horstmann, 2004). With glacial lakes expanding and populations moving into higher elevations closer to these lakes across the region ((Schwanghart et al., 2016) see Chapter 3), future GLOFs could have even greater economic implications as the land-use, infrastructure and industry develops. For example, a GLOF from Tsho Rolpa, Nepal, could cause major damage to the Khimti Hydropower project – a 60 MW complex located below the glacial lake. Due to reliance on the plant for energy security, employment and more, damage or destruction from an outburst has been estimated to cost the nation US$22 million (Horstmann, 2004). As such, there is a need to understand where these events could happen, as well as estimate their potential impact so communities can mitigate the effects.

Since 2000, GLOF risk has been increasing rapidly (Chapter 4) and as of 2020, HMA has the highest GLOF risk globally (Chapter 3; (Taylor et al., 2023)). Whist elsewhere globally populations are beginning to move away from glacial lakes, across HMA more people than ever before are moving into higher elevations closer to glacial lakes (Chapter 4; Taylor *et al.*, (in review)) mainly for tourism, agricultural and hydroelectric-driven opportunities (Bajracharya, Shrestha and Rajbhandari, 2007; Schwanghart *et al.*, 2016; Allen *et al.*, 2019; Drenkhan *et al.*, 2019; Zheng *et al.*, 2021; Taylor *et al.*, in review). Consequently, over the last 20 years (2000-2020), exposure to GLOFs in HMA increased by 2.2 million, with 13% of this increase occurring along likely GLOF runout tracks within 10 km of a glacial lake (see Chapter 4, section 4.3.1.2; Taylor *et al.*, in review). This trend is expected to continue in the next few decades (GAPHAZ, 2017; Furian et al., 2021). Alongside these changes in exposure, between 2000 and 2020 vulnerability across HMA declined (Chapter 4), with nations making clear improvements to the likes of education, access to safe drinking water and employment, all of which reduce how acutely the potential impacts of a future GLOF might be felt (Carey, 2010; Cutter et al., 2003; Lee & Van Zandt, 2019; Allen et al., 2018). Nevertheless, populations in

HMA remain the most vulnerable to GLOF impacts as of 2020 (Chapter 3), with factors that increase vulnerability to GLOF impacts above the global average across all factors (Figure 3.8) (e.g. percentage illiterate, percentage under 5 years old). Thus, it is vitally important we understand how exposure to existing and potential future lakes might change in HMA in the future, allowing communities time to prepare.

Modelling shows the glaciated area of HMA will likely reduce by ~50% by 2060 (Farinotti et al., 2019) with rates of change faster in some areas; the Karakoram subregion could lose between 50% and 75% of its 1985 mass by as early as 2035 (Cogley, 2011). This reduction in glacier area will likely expose new overdeepenings and thus promote formation of new glacial lakes, beneath more newly exposed, steep, mountainsides, meaning that the spatial distribution of GLOF hazard, exposure and risk is expected to change over the coming decades (Emmer, Allen, et al., 2022; Allen et al., 2022). At the same time, the spatial distribution of people, infrastructure and services is also likely to change (Furian et al., 2021). These spatial changes raise questions regarding current mitigative strategies, such as Early Warning Systems (EWS) and lake engineering. Historically, EWS have been installed to limit the impact of GLOFs on human lives (Nie *et al.*, 2018), with the aim of detecting impending GLOFs in sufficient time to enable ample warning to be relayed to people who might be affected so they can move to safer ground (Bajracharya *et al.,* 2007). Similarly, lake engineering solutions (e.g. artificial lowering, creation of spillways, moraine reenforcing) aim to control the magnitude and frequency of outbursts in order to minimise societal impact. However, as populations continue to move closer to glacial lakes the effectiveness of such strategies could reduce (Maurer *et al.,* 2020) and other mitigation strategies may be needed. Whilst projections have been made for the future of glacial lakes across HMA (Frey et al., 2010; Furian et al., 2021; Magnin et al., 2020; Linsbauer et al., 2016), there are few studies that integrate potential changes to exposure or vulnerability, thus future GLOF risk remains uncertain. The results of this chapter are therefore crucial; understanding how GLOF hazard, exposure and vulnerability may evolve over the next few decades is vital for implementing effective and targeted mitigation strategies to prevent future GLOF disasters across HMA.

Here, I use the number and area of glacier bed overdeepenings comprised by Furian *et al.,* (2021) as a proxy for future GLOF hazard per basin. Note that glacial lakes formed by other methods (see Figure 2.1) are not included here. Using the UN probabilistic projections of population increase (United Nations, Department of Economic and Social Affairs, 2022), exposure is extrapolated along likely GLOF runout tracks (50 km, Chapter 3) from 2020 to

2060. This time period was selected for two main reasons; first a forty-year period is long enough to demonstrate change in both hazard and exposure, and second, the time period in question is easily visualised, thus results could be useful for future policies. Results are then used to determine how exposure to potential GLOFs across HMA might change by 2060. From this, locations of potential future high GLOF exposure are highlighted, thus objectively identifying priority locations for future work in HMA.

I note that whilst Chapter 3 and 4 highlight the Andes as a region of concern, the lack of data availability prevented further exploration in this region. Thus, given HMA has the highest GLOF risk globally (Chapter 3) and an abundance of readily available data, HMA was selected to act as a case study in this instance, with a suggestion for a similar study to be conducted in the Andes when data allows.

5.2 Methods

5.2.1 Future GLOF hazard

To identify potential future glacial lakes, a dataset of overdeepenings by Furian *et al.,* (2021) was used. The dataset was composed using DEM data, glacier ice thickness data and glacier outlines, creating a DEM 'without glaciers' to assess bedrock morphology. All subglacial overdeepenings were then filled using a hydrological GIS tool to represent potential future glacial lakes. Guided by previous studies (Linsbauer et al., 2016; Colonia et al., 2017), a threshold of 10^5 m^2 was used to exclude smaller overdeepenings likely to fill with sediment rather than water (see Furian *et al.,* (2021) for full methodology). Building on the methodology defined in Chapter 3 (see section 3.2.1.1; (Taylor et al., 2023)) and using the dataset from Furian *et al.,* (2021), the number and area of potential future glacial lakes is used to provide a proxy for future GLOF intensity between 2020 and 2060, at 5-yearly intervals assuming current rates of retreat continue unchanged. Here, the probability of outburst is treated as unknown with the reasonable assumption that a GLOF will occur, with the results then used to target more detailed local studies. A linear transformation function was then used to produce a normalised value for both the number and area of glacial lakes per basin (Equation 5.1):

$$\boldsymbol{y_{N/A/E}} = \frac{(\mathbf{X})}{(\mathbf{Max})}$$

Equation 5.1

Where **x** is the absolute number/area of glacial lakes per basin, **Max** is the maximum number/area of glacial lakes found out of all 1089 basins (Figure 1.3, Figure S3. 1), and **y** is the normalised value of glacial lake number/area per basin. Individual normalized values of glacial lake number ($\mathbf{y_N}$) and area ($\mathbf{y_A}$) (and exposure ($\mathbf{y_E}$)) are then multiplied to produce a singular score between 0 and 1, with 1 relating to the greatest GLOF hazard. No scores of 0 were recorded. It should be noted that this study focusses on future glacial lakes forming in bedrock depressions only and does not account for glacial lakes that may form via other means (supraglacial coalescing prior to deepening, landslide damming, glacial surging etc.), as these are difficult to predict from available datasets. Thus, these results indicate a minimum estimate of future GLOF hazard. Further, here the disappearance of existing glacial lakes is not considered, and I assume all lakes present in 2020 remain as such throughout the study period. This approach is justifiable, given over the previous 20 years (2000-2020), the number of glacial lakes only decreased in two nations (Mongolia and Uzbekistan, by 10 and one respectively, Figure 4.2).

5.2.2 Future GLOF exposure

With the aim of identifying areas across HMA that are most likely to have the highest future potential GLOF danger (under current population trajectories), here a 'worst case scenario' was assumed, where all projected glacial lakes have formed by the end of the study period (2060). Given projections show glaciated area might have reduced by 50% by 2050 and given recent climate change scenarios appear to be nearer the worst-case projections of past climates than of the median (IPCC, 2023) this assumption, whilst likely an overestimation for the Western Himalaya and Karakoram region (Zheng *et al.,* 2021), could be feasible for at least some of the already highly deglaciated regions in the east. By adopting a worst-case scenario approach, these results provide an upper estimate on the potential danger to communities from glacial lakes situated in upstream overdeepenings, and therefore will highlight where action is needed to avoid this worst-case exposure possibility. As such, considering projected glacier bed overdeepenings as sites where existing lakes can expand and/or new lakes could develop (Furian et al., 2021) overdeepenings were combined with the UN probabilistic projections of population (United Nations, Department of Economic and Social Affairs, 2022) to calculate the total population exposed to potential future glacial lakes up to 2060. Following the same approach as set out in Chapter 3 (Taylor et al., 2023), the 2020 Gridded Population of the World version 4 (GPWv4) (CIESIN, 2018) was used to calculate the population count living within

1 km of likely GLOF runout tracks (using level 1 channels as defined by Yan *et al.,* (2019)) up to a maximum distance of 50 km (see Figure 3.2, section 3.2.1.2). This threshold should encapsulate the majority of GLOF runouts globally, whilst avoiding further overestimating of impacts by excluding rare events. To add further granularity, exposed population along potential GLOF runout tracks at 5-yearly intervals from 2020 to 2060 was also calculated.

The UN probabilistic projections are comprised using data concerning the population size and age structure of each country, as well as data on fertility, mortality, and international migration, with the majority of data taken from census or civil registration databases (see United Nations, Department of Economic and Social Affairs (2022) for a full methodology description). In the absence of data, estimates for some countries in recent years were obtained by projecting forward from the last available data point, based on assumptions about trends in the demographic components of population change (fertility, mortality, and migration), while also reflecting uncertainty about future changes based on the past experiences of other countries under similar conditions. Analyses show projections to be increasingly accurate, with total population projections from 1950-1980 on average, 2% lower than observed (Keilman, 2001), with population in 1990 projected to be 5.44 billion compared to the actual observed total of 5.3 billion (Khan & Lutz, 2008). The future population of each country was projected from 1 July 2020 assuming population growth is constant across the entire country. Here, I take the nationwide estimate and assume it is applicable to a smaller spatial subset (glacial basins) whilst acknowledging rates of population are unlikely to be universal across nations. I use a linear transformation function to produce a normalised value of exposure for each catchment with final values between 0 and 1, where 1 equates to the highest exposure (Equation 5.1).

5.2.3 Potential GLOF danger

Risk is a function of hazard, exposure, and vulnerability (WMO, 2021; Zheng, Allen, et al., 2021; Allen et al., 2020). Many factors influence human vulnerability to natural hazards (see Table 3.1, section 3.2.1.3) (Cutter et al., 2003; Gaillard & Dibben, 2008; Zhou et al., 2014). Whilst research indicates vulnerability is in decline globally (Formetta and Feyen, 2019; Conceição and UNDP, 2020; Taylor *et al.,* 2023; Taylor *et al.,* In review) (see Chapter 4, section 4.3.1.3), changes in vulnerability at all spatial scales are often subtle, dynamic, and unpredictable (Khanal et al., 2015). The ongoing war in Ukraine, the civil war in Syria and Fall of Afghanistan exemplifies this, where progress has been halted and vulnerability significantly altered. Thus, I acknowledge projecting change in vulnerability over time is a major challenge, and any projections made based on current vulnerability status, regardless of how detailed, would be subject to a high degree of ambiguity (Huggel et al., 2015). However, without a robust prediction for vulnerability it is impossible to accurately quantify GLOF risk. I recognize that it is possible to be exposed to a hazard but not vulnerable to it (e.g. through modification of infrastructure and behaviour to mitigate potential losses (WMO, 2021)), however by quantifying future exposure to GLOF hazard it would be possible to identify where the most people are likely to be impacted by a future GLOF. As such, due to the absence of vulnerability metrics, here GLOF risk is not determined. Instead, following the approach of Mal *et al.*, (2021) and to avoid possible confusion in terminology, the term ‘‘potential GLOF danger’’ is used, defined as, and calculated by, multiplying the normalized values of hazard and exposure for each basin to produce a quantitative measure of future potential GLOF danger (Equation 5.2). Areas identified as having particularly high GLOF danger could then be targeted for more detailed study where development to reduce vulnerability in order to offset changing hazard and/or exposure may be needed. However, at present this is beyond the scope of this study.

$$\textbf{Potential GLOF danger} = [\textbf{Hazard x Exposure}]$$

Equation 5.2

5.3 Results

5.3.1 Future GLOF hazard

Using modelled glacial bed overdeepenings as a proxy for the location of future glacial lake formation, and under the assumption that all overdeepenings develop into glacial lakes, the number of glacial lake basins (i.e., basins containing at least one glacial lake) is projected to increase from 397 to 658 (Figure 5.1), a 66% increase on the number of glacial basins present in 2020. Most new glacial lake basins are found in China, with 208 of the total number of new basins (62%). The remaining are in Kyrgyzstan (44), Tajikistan (24), India (21), Pakistan (19), Nepal (7) and Kazakhstan (5). Of the future glacial lakes, 36% (9,064) are found in glacial lake basins with no pre-existing glacial lakes, with the remaining 64% located in the 397 existing glacial lake basins across HMA (Figure 5.1). No additional glacial lakes are expected to form in 59 glacial lake basins that already contain glacial lakes in 2020.

Based on the modelling from Furian *et al.*, (2020) three main types of overdeepenings are identified across HMA (Figure 5.2); **(a)** those located directly beneath pre-existing glacial lakes (suggesting future expansion of existing lakes either vertically or horizontally), **(b)** those located beneath glaciers where glacial lakes are already present but where overdeepenings are not directly beneath current lakes (suggesting formation of new lakes and/or potential coalescence with existing lakes), and **(c)** those located beneath glaciers with no pre-existing lakes (suggesting formation of new lakes) (Figure 5.2). Out of all the projected overdeepenings, 446 are located directly beneath existing glacial lakes (Figure 5.2a), with the majority of these lakes (71%) being proglacial lakes. Projected overdeepenings located beneath glaciers with existing glacial lakes (proglacial and/or supraglacial), but not directly beneath current glacial lakes account for 14% (3457) of the total (Figure 5.2b). The remaining 84% of overdeepenings (21,379) are located beneath glaciers with no pre-existing glacial lakes (Figure 5.2c).

The total number of glacial lakes across HMA is projected to increase by 25,282 (1043%) to reach an area covering 2682.6 km^2 (Figure 5.3a, b). The largest absolute increase in the number and area of glacial lakes is again found in China, with projections suggesting a further 10,947 lakes could form here, increasing the total glacial lake area to 1175.60 km^2 (Figure 5.3a, b). Mongolia was the only nation where no overdeepenings were identified (Figure 5.3). The number and area of glacial lakes in Uzbekistan and Bhutan is expected to change the least, increasing by 13 and 274 glacial lakes (0.22 km^2 and 58.60 km^2) respectively (Figure 5.3a, b). Whilst China will have the largest absolute increase in glacial lakes, compared to 2020, Tajikistan and Pakistan will see the largest percentage increase in number and area of glacial lakes (Figure 5.3c, d); the number of glacial lakes is expected to increase more than 30-fold in Tajikistan while the area of glacial lakes will increase almost 20-fold in Pakistan. Currently, the east of the HMA region contains the most numerous and the largest area glacial lakes (Figure 5.4a), particularly Bhutan and eastern Nepal. However, this distribution is expected to shift west towards Pakistan, Afghanistan and Tajikistan as glacial ice is lost and new glacial lakes form (Figure 5.4b). A shift of lakes to higher elevations can also be expected (Figure 5.5); in 2020 no glacial lakes exist above 6000 m a.s.l., however most future glacial lakes (65%) are expected to be found above 5000 m a.s.l. (Figure 5.5) with 15% likely to exist above 6000 m a.s.l.

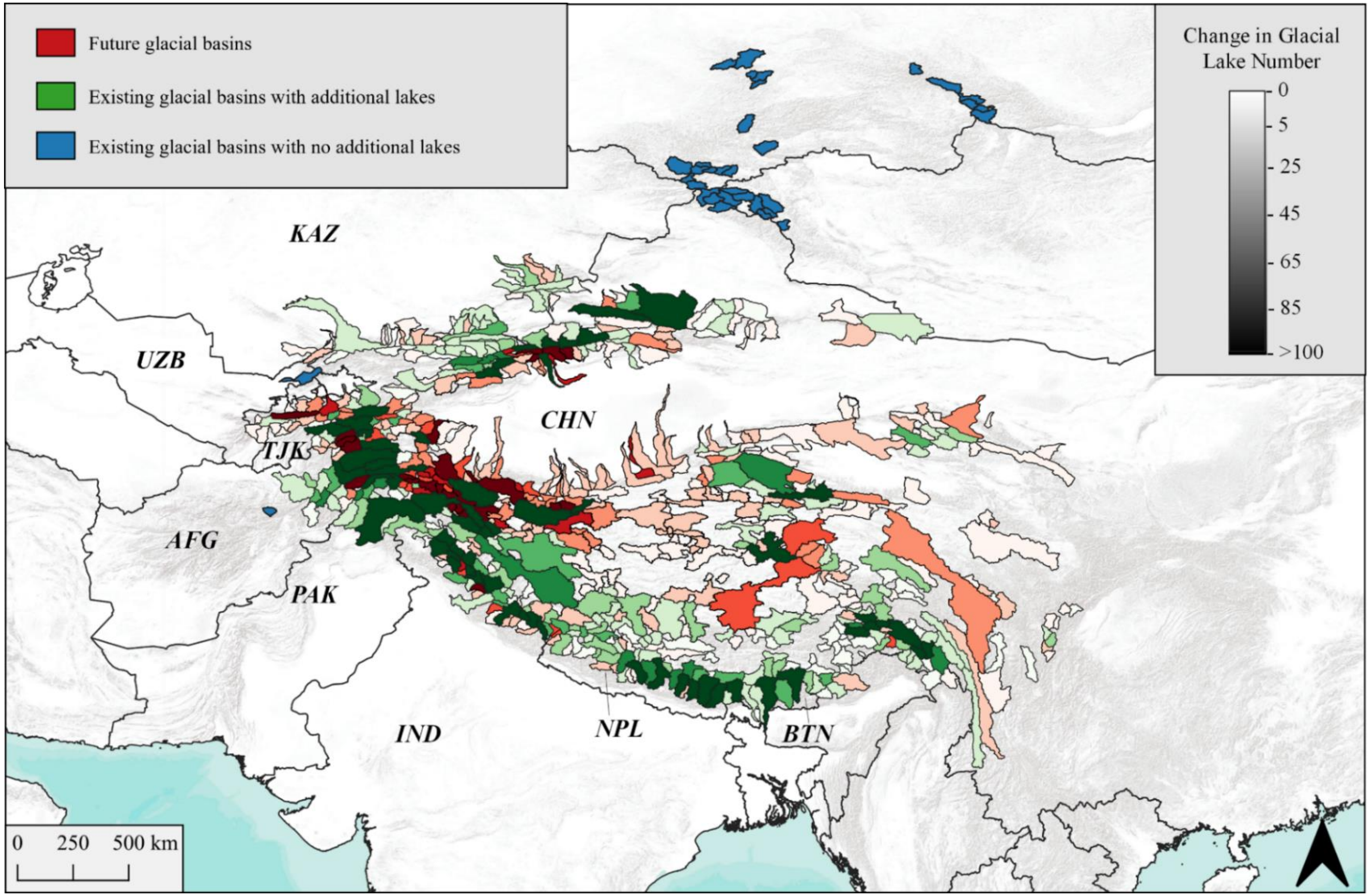

Figure 5.1: Spatial distribution of future glacial lake basins. Basins containing one or more glacial lakes across HMA for existing glacial lake basins (blue), projected new glacial lake basins (red) and existing glacial lake basins with additional future lakes (green). Colours are graded to show the change in number of glacial lakes, with light colours representing lower numbers and darker colours representing higher numbers. Basins are defined as Level 4 watersheds according to Yan *et al.*, (2019).

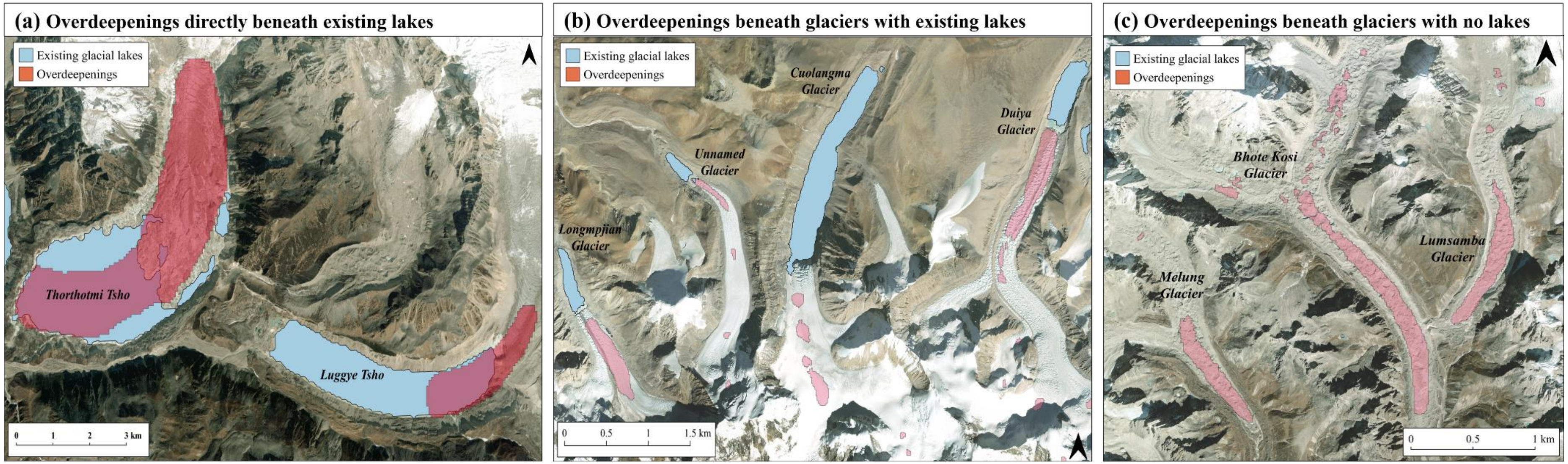

Figure 5.2: Three types of future overdeepenings. Examples of the types of projected overdeepenings found across HMA. (a) Overdeepenings directly beneath existing glacial lakes (the majority of which are proglacial), (b) Overdeepenings beneath glaciers with existing lakes but not directly underneath existing glacial lakes, and (c) Overdeepenings beneath glaciers with no pre-existing glacial lakes. Existing glacial lakes are shown in blue and overdeepenings in red. Examples shown are (a) Lunana, Bhutan, (b) Central Himalaya and (c) Khumbu region, Nepal. Background imagery Google Earth 2020.

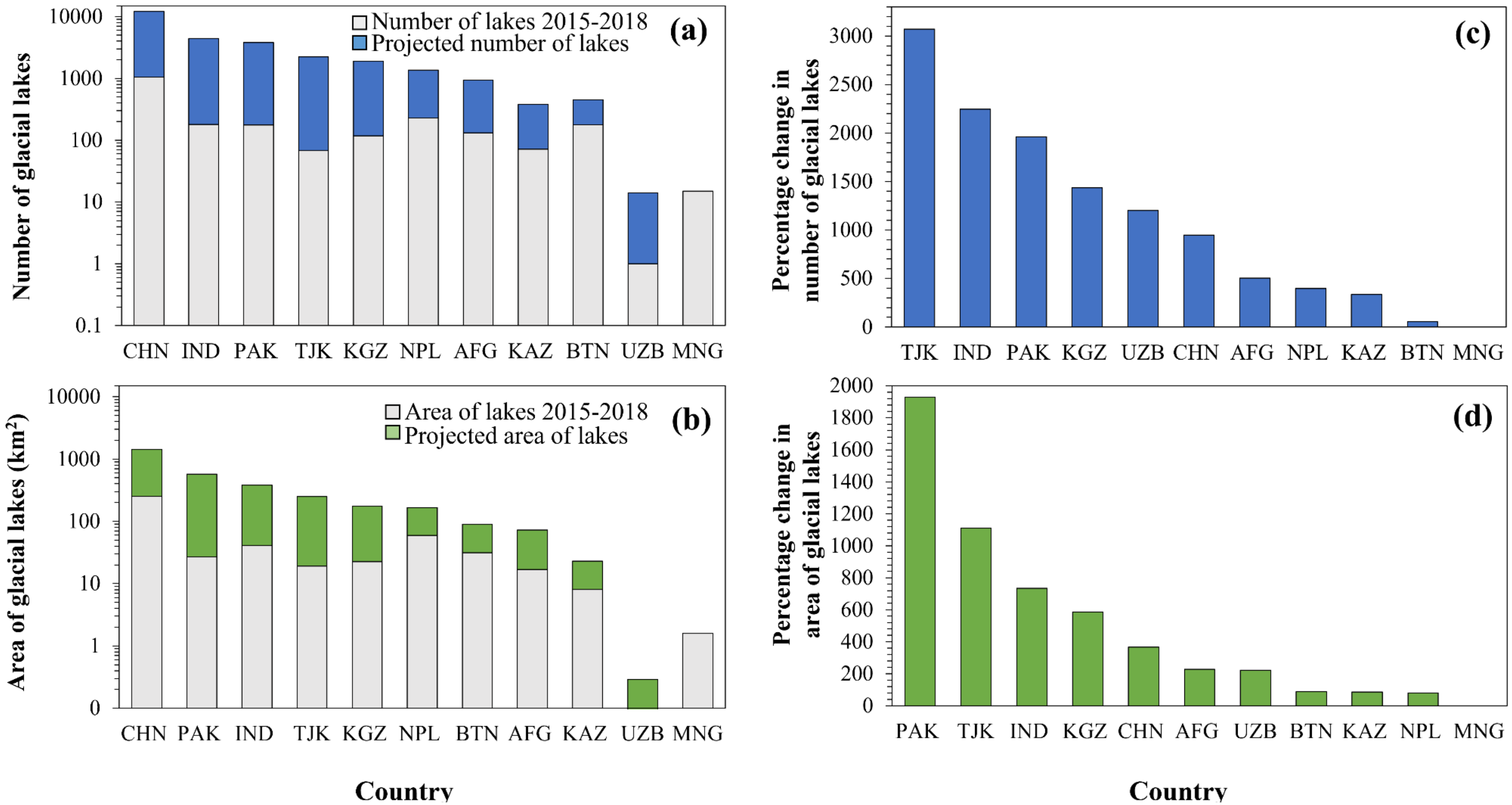

Figure 5.3: Projected glacial lake number and area change 2020 to 2060. Panels (a) and (b) show the change in number and area of glacial lakes across High Mountain Asia per country between 2020 and 2060 repectively, where nations are ordered highest-smallest according to the projected number/area of glacial lakes. Panels (c) and (d) show the percentage change in number and area of glacial lakes over the 40-year period respectively. Grey bars on (a) and (b) show the exisiting number and area of glacial lakes (from 2020, Shugar *et al.* (2020)), coloured bars show future number and area of glacial lakes (based on projected glacial bed overdeepenings, Furian *et al.*, (2021)). Note the y-axis on (a) and (b) is a logarithmic scale.

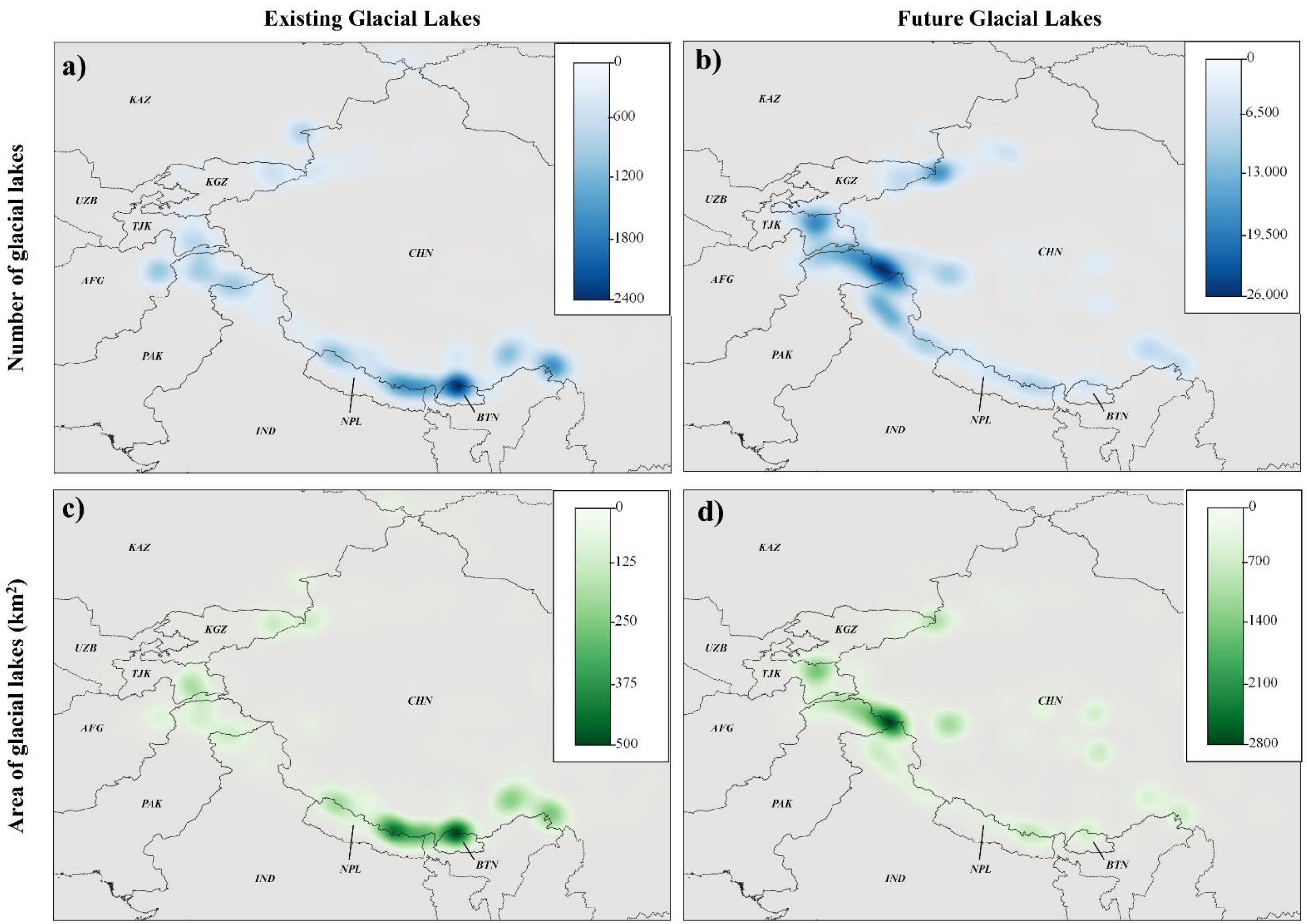

Figure 5.4: Spatial distribution of existing and future glacial lakes. Change in the spatial distribution of (a) number of existing glacial lakes in 2020 to (b) number of future overdeepenings in 2060 and (c) the area of existing glacial lakes in 2020 to (d) area of future overdeepenings in 2060. Density produced using moving window at $100m^2$.

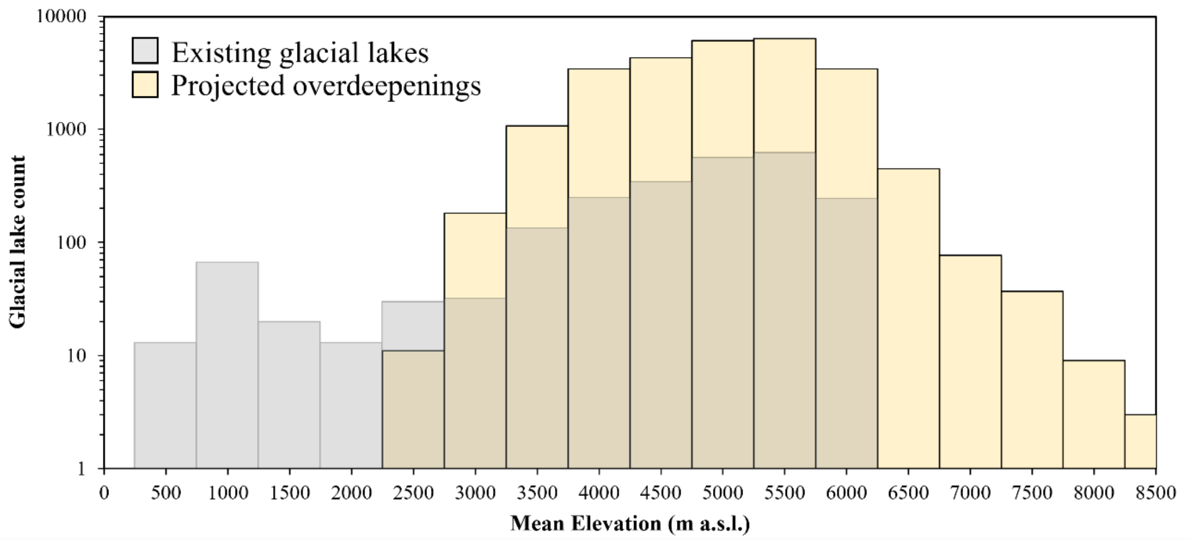

Figure 5.5: Elevation change of glacial lakes between 2020 and 2060. Projected change in the elevation distribution of glacial lakes across HMA, with existing lakes (2020) in grey and future lakes (2060) in yellow. No new lakes are projected to form below 2500m, thus only existing lakes will remain there, with the majority of change occurring between 4000m and 6000m.

5.3.2 Future GLOF exposure

5.3.2.1 Population

Over the next 40 years (2020-2060), under the assumption that all projected overdeepenings develop into glacial lakes across HMA, the number of people exposed to GLOFs may increase by 3.9 million (Figure 5.6). Within this, 650,00 are newly exposed, living along runout tracks of future glacial lakes. Of these, more than half (57%) are found in future glacial basins, with the remaining 43% found in existing glacial basins *with* additional lakes (Figure 5.6). Pakistan is expected to have the largest increase in exposure, of ~1.6 million (Figure 5.6) accounting for ~42% of the total population increase in HMA by 2060. Here, ~ 300,000 (22%) of these people are newly exposed (living along future runout tracks) (Figure 5.6, Figure 5.7). Of these, 89% (267,000) are in future glacial basins. Population exposed to glacial lakes in China is expected to decline, (by ~150,000) such that by 2060 the number of people exposed to potential GLOF impacts will be 1.7 million (Figure 5.6) despite an increase in the number and area of glacial lakes (Figure 5.3). Tajikistan has the largest percentage increase (135%) in exposure between 2020 and 2060 (Figure 5.7), where more than half (57%) of those exposed are found along future runout tracks and 94% in future glacial basins. There is a minor difference between the exposure to future glacial lakes and the exposure to existing glacial lakes in Kazakhstan, despite an increase in the number of glacial basins (by 5), with ~5,500 (3%) more people likely to be exposed to future glacial lakes than to just existing glacial lakes (Figure 5.7).

Within these national trends there are interesting basin-scale projected changes (Figure 5.8). Six basins are projected to see populations increases of >100,000 people, (accounting for exposure to both existing and future glacial lakes) (Figure 5.8). Two of these basins are existing basins *with* additional glacial lakes, and are found in Pakistan (PAK11411000000, Indus Basin and PAK11410040300, Swat Basin). Together, these two basins account for the majority of the total exposure increase in Pakistan, with exposure in the remaining 23 basins generally increasing by less than 20,000 persons each (Figure 5.8). Similarly, whilst population in Bhutan is projected to increase by a total of 19,667, the majority of this (53%) is accounted for by just one existing basin *with* additional lakes (Pa Chu), where the capital Thimphu, is located (Figure 5.8).

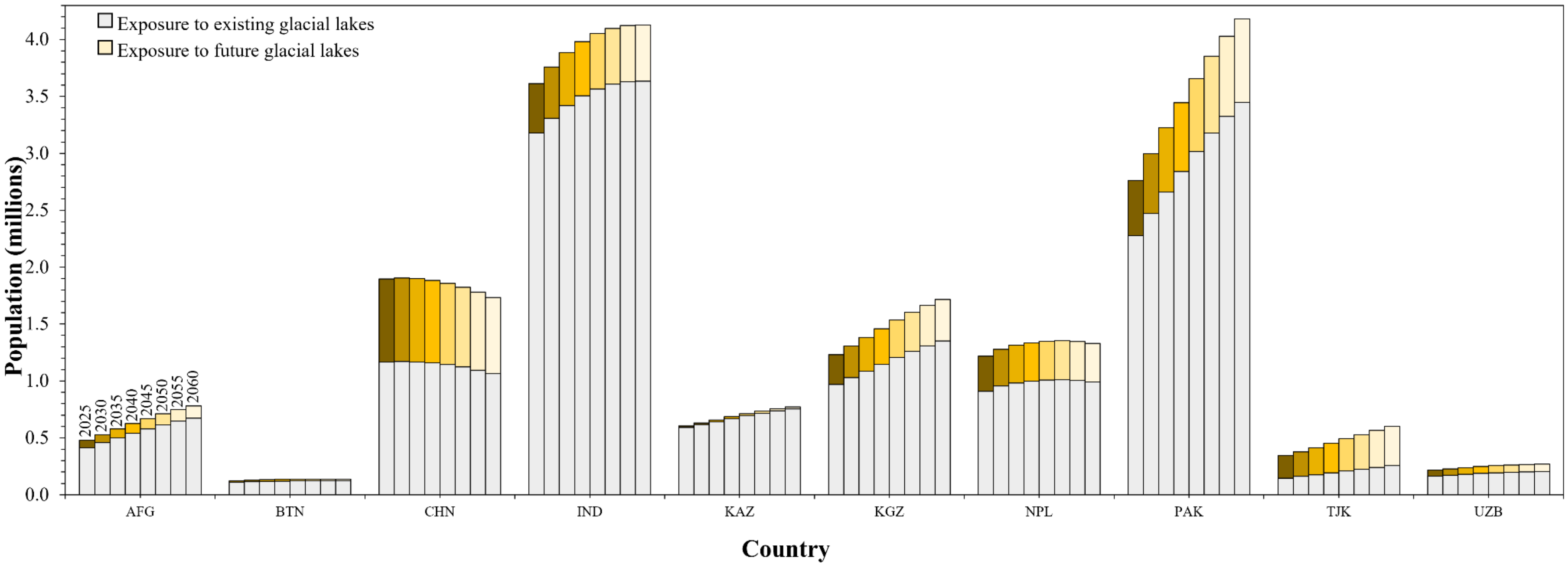

Figure 5.6: Projected national GLOF exposure change 2020 to 2060. Population living within 1 km of likely GLOF runout tracks up to 50 km from *existing* glacial lakes (grey) and *future* glacial lakes (yellow) for countries across HMA between 2020 to 2060 at 5-yearly intervals. Population is given in millions.

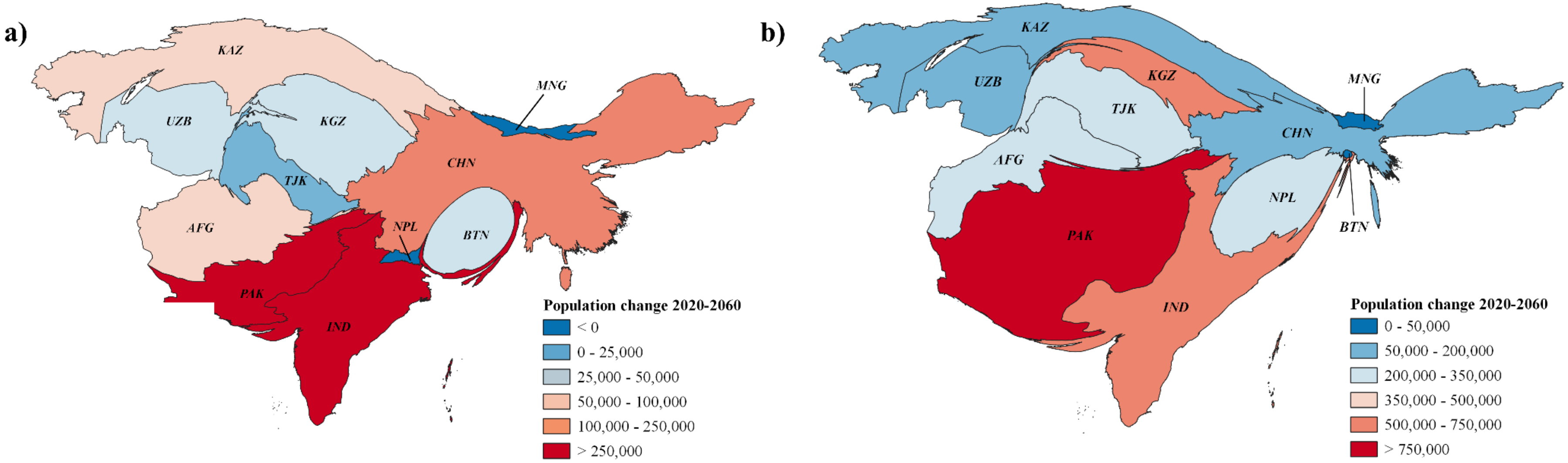

Figure 5.7: Projected population change across HMA between 2020 and 2060. Projected change in population living within 1 km of likely GLOF runout tracks up to 50 km from (a) *existing* glacial lakes (lakes static, population increased) and (b) *existing and future* glacial lakes (both lakes and population increased), between 2020 and 2060. Note the legends differ between panels.

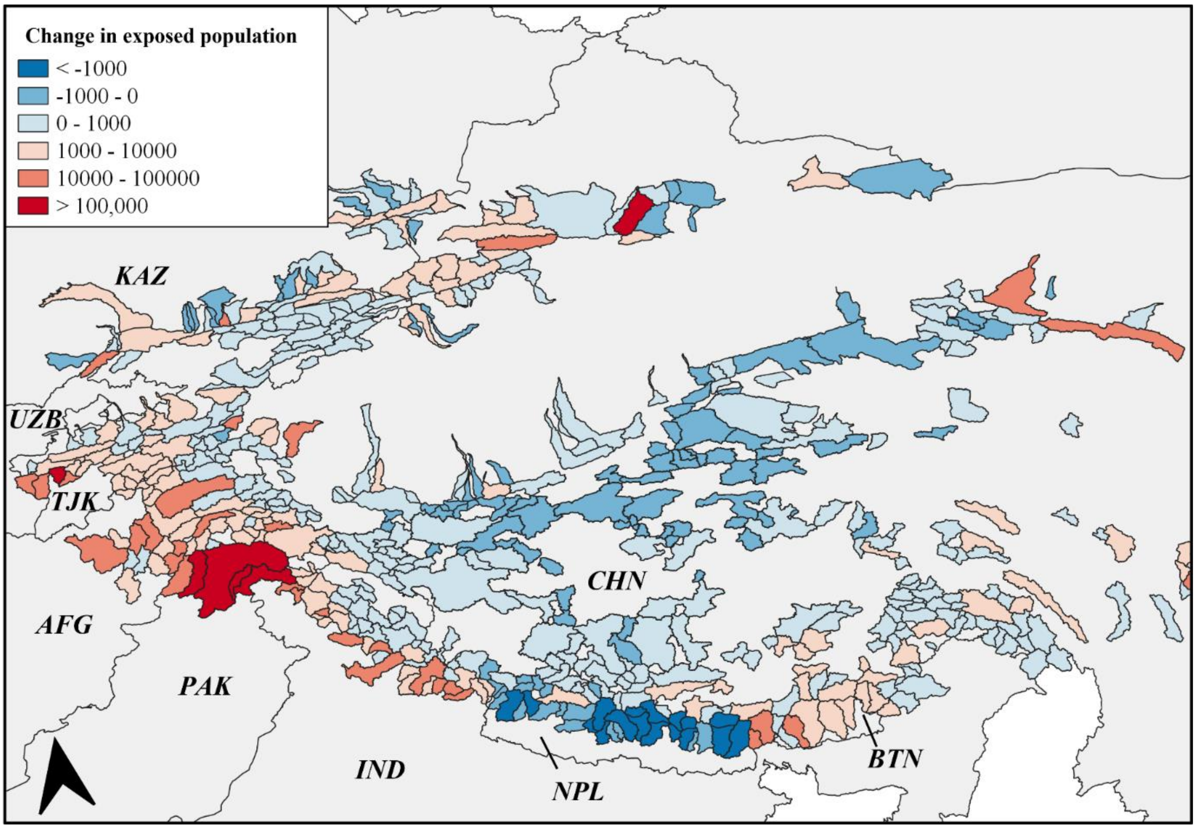

Figure 5.8: Basin scale change in exposure between 2020 and 2060. Projected change in exposure to glacial lakes between 2020 and 2060 for the 658 glacial basins that are projected to contain glacial lakes in the future.

5.3.2.2 Hydroelectric Power

Hydroelectric dams provide millions of people with power and contribute greatly to national economies. Whilst they can help modulate floods, more often than not dams are damaged by outburst floods, both during events, and, later by the influx of additional fine sediments disturbed by the event (Li et al., 2021, 2022), resulting in significant economic implications. As of 2018, there were 1240 operable hydroelectric power projects across HMA with a collective capacity of > 300,000 Mw (Figure 5.9). The majority of these (76%) are located in China (947), with the least number found in Kazakhstan (4) (Figure 5.9). China has the highest capacity at ~ 250,000 Mw, whilst Afghanistan has the least (239 Mw) (Figure 5.9). Of the total number of hydroelectric power projects across HMA, 182 (~ 10%) are within 50 km of an existing glacial lake, with this number rising to 173 (~ 14%) when future glacial lakes are considered (Figure 5.9). A further 809 hydroelectric power projects are planned across the region (Zarfl et al., 2015) of which 481 will be located in glacial lake basins, and near half (44%) will be found in Nepal (Figure 5.9). Of course, it remains to be seen if these planned projects will be completed, however the location of hydroelectric power projects is a vital consideration for GLOF danger.

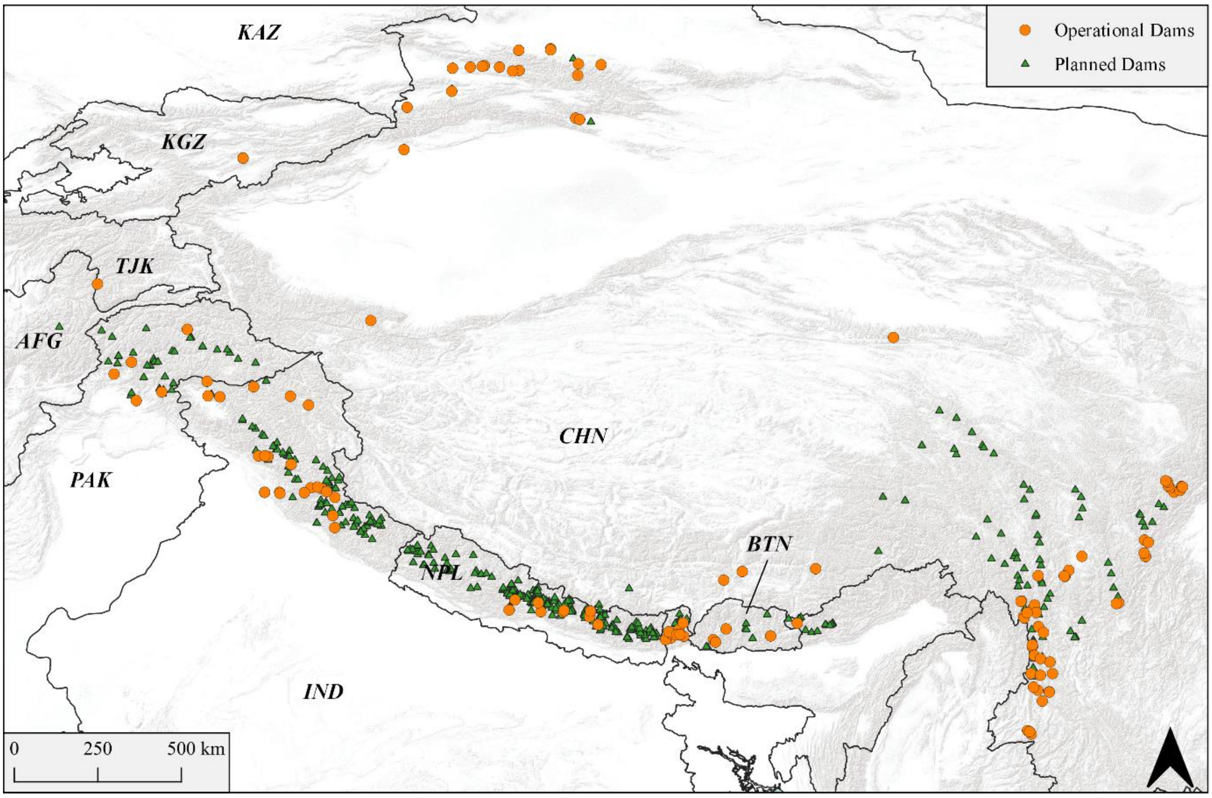

Figure 5.9: Location of hydroelectric power projects across High Mountain Asia. Completed dams and planned dams in glacial lake basins across HMA. (Data: (L. Byers et al., 2019; Zarfl et al., 2015)).

5.3.3 Potential GLOF danger

Future potential GLOF danger is projected to be highest in China (1.00) and Pakistan (0.318) (Figure 5.10) by the end of the 40-year study period. Mongolia will have the lowest potential GLOF danger as of 2060 (0.001) (Figure 5.10). Over the 40-year period, potential GLOF danger is expected to increase in four countries (India, Kyrgyzstan, Pakistan, and Tajikistan), and decrease in four countries (Afghanistan, Bhutan, Kazakhstan, and Nepal) (Figure 5.10). Danger scores in the remaining three countries (China, Mongolia, and Uzbekistan) show no change, with China remaining highest across the whole period. The largest increases in potential GLOF danger are forecast for Pakistan and projected to increase from 0.029 in 2020 to 0.318 by 2060, whilst potential GLOF danger in Nepal is projected to decline the most (by 0.077) (Figure 5.10). Thus, whilst Nepal had the 3rd highest danger score in 2020 (0.036) this is projected to reduce relative to the other nations by 85% to reach 0.005 by 2060 thus placing it 6th (Figure 5.10).

Applying three different forecasting scenarios for exposure and hazard demonstrated future danger could vary markedly if either or both were to be managed (Figure 5.11). Here, GLOF danger is projected by; **(a)** forecasting exposure whilst holding hazard static, **(b)** forecasting hazard whilst holding exposure static, and **(c)** forecasting change in both exposure and hazard (Figure 5.11). In six nations, future GLOF danger is highest when both exposure and hazard are changing, whilst in the remaining four, GLOF danger is highest when exposure changes and hazard is static (Figure 5.11). When exposure is kept static and hazard changes, there is very little difference in overall danger score.

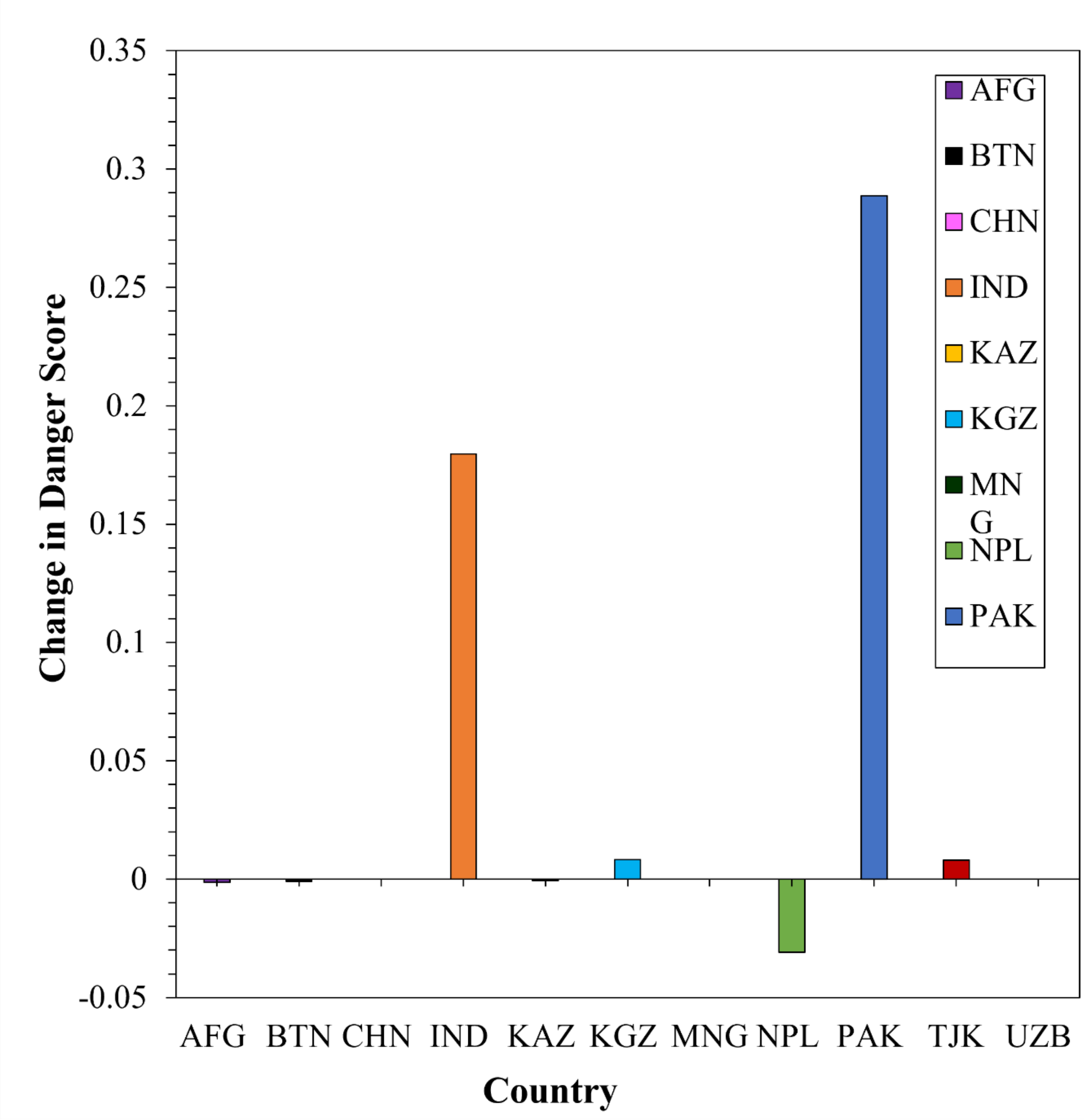

Figure 5.10: Change in potential GLOF danger 2020 to 2060. Projected change in potential GLOF danger for the period 2020-2060 for each country across HMA. Positive values indicate increase in danger and negative values indicate declines in danger. Note that some countries do not appear here as change in danger is relatively small or zero.

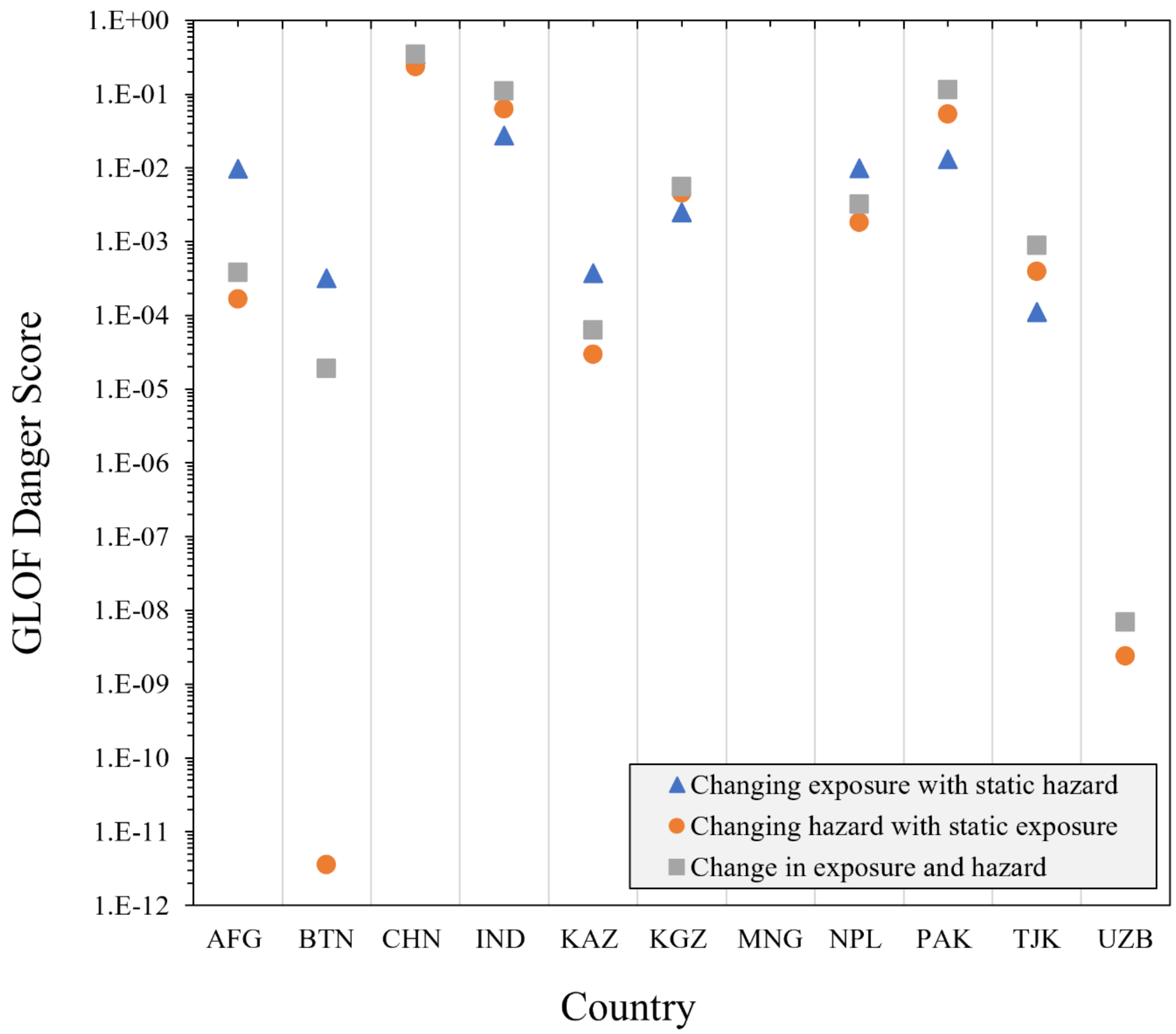

Figure 5.11: GLOF danger variation scenario testing. Difference in GLOF danger under three scenarios; Changing exposure with static hazard (blue), changing hazard with static exposure (orange), and changing both (grey).

5.4 Discussion

5.4.1 Spatial shift in potential GLOF danger

In 2020, GLOF danger is highest in the east of HMA (Zheng, Allen, et al., 2021), particularly in Bhutan and Nepal (Figure 5.10). Here, glacial lakes are primarily proglacial (~75% and 80% respectively) compared to the west where supraglacial lakes are the dominant type (>90%) (Gardelle et al., 2011; Veh et al., 2019). However, results indicate in a world with significantly reduced glacial ice mass, potential GLOF danger may shift west towards the Karakoram and Kunlun subregions (Figure S5. 1, p.250), with danger in Pakistan and Tajikistan increasing the most over the 40-year period (Figure 5.10). As shown in Figure 5.11, GLOF danger across the western nations (e.g. Pakistan, Tajikistan) remains high irrespective of change to exposure. Thus, this shift may be due primarily to the fact glaciers here have yet to experience large scale ice mass loss that, comparative to the east, has already led to the formation of large glacial lakes (Furian et al., 2021). Globally, rising temperatures have increased glacial melting in nearly all glaciated regions of the world (Hock et al., 2019) and the mountainous region of High Mountain Asia is no exception (Shean et al., 2020; Lee et al., 2021). However, the region is governed by different climatic regimes, with the mid-latitude cyclones of the Westerlies providing 60-70% of annual precipitation in the Tien Shan, Karakoram, and western Himalaya (Figure S5. 1, p.250), while areas in the eastern and central Himalaya receive ~80% from the East Asian and Indian summer monsoons (Bolch *et al.,* 2012; Mölg *et al.,* 2014). In recent years, the east has experienced a notable reduction in precipitation, leading to more rapid and pronounced glacier retreat and growth of glacial lakes (Mohanty & Maiti, 2021). As a result, a disproportionately larger number and area of glacial lakes is likely to form in the northwest regions of HMA by 2060 (e.g. the Pamir, Tien Shan, and Karakoram), owing to the higher availability of remaining glacial ice. Figure 5.11 exemplifies this point, whereby GLOF danger scores in countries to the east (e.g. Bhutan and Nepal) are lower when exposure is static and only hazard is changing. In particular, the difference in Bhutan is marked, with a much lower GLOF danger score where exposure does not change (Figure 5.11). This may suggest GLOF hazard in the east has passed its peak, whilst the west is yet to reach it, correlating with findings of Zheng *et al.* (2020). This observed spatial shift in GLOF hazard towards the west (Figure 5.4) is an important observation; knowing where glacial lakes are likely to form could allow communities and governments to prepare in advance of the emerging threat of outburst, where awareness and danger perception may be lacking, but mitigation and adaptation are still possible. In the east, these findings are also valuable, as they suggest a focus on reducing exposure could help manage future GLOF danger. Additionally, this gives scope for further research into refining GLOF probabilities and magnitude of existing glacial lakes to better define likely runout tracks, distances, inundations depths and more given the distribution of hazard is unlikely to see marked change.

Over the last few decades, the majority of GLOF research across HMA has been focussed on the Hindu-Kush-Himalaya, with 6x more research items (146) than the Karakoram (20) and almost 4x more than the Pamir and Tien Shan combined (37), despite the Hindu-Kush-Himalaya having the least number of recorded GLOF (47 events compared to 98 in the

Karakoram, and 69 in the Pamir/Tien Shan) (Emmer, 2018; Emmer, Allen, et al., 2022). Incomplete records of GLOF activity and fewer direct mass balance records across the Karakoram makes predicting future potential GLOF danger particularly difficult (Nie et al., 2021). With potential GLOF danger predicted to increase here, this data sparsity alongside lack of scientific understanding around the Karakorum anomaly and how it might evolve under climate change across the west urgently needs addressing if meaningful assessments of potential GLOF danger (including timings, extents etc.) are to be conducted. This is particularly crucial for areas such as Pakistan, where GLOF risk is already 2nd highest as of 2020 (Figure 3.10) and potential GLOF danger is projected to increase the most over the succeeding 40 years (Figure 5.10). Major ice-mass changes are likely to occur towards the end of the study period and beyond (e.g., 2060 and onwards). Thus, many areas across HMA that are forecast to have high potential GLOF danger in the future have a unique opportunity to prepare, and results presented here could be used to direct research to these areas.

Whilst potential GLOF danger is likely to shift west away from the likes of Bhutan and Nepal towards Pakistan and Tajikistan (Figure 5.4; Figure 5.10), the potential expansion of numerous, already large glacial lakes in the east is still a major concern. For example, outburst simulations in the Mo Chu River Basin, Bhutan from existing lakes shows that under the worst-case scenario (i.e. complete ice-loss and filling of all projected overdeepenings), existing infrastructure (bridges, roads etc.) and farmland (both arable and pastural) would already be significantly impacted by floodwaters (Hagg et al., 2021). Further, a shift can be expected towards Po Chu and the capital of Thimphu and away from current research hotspots of Wangdue and Punakha. With the area of glacial lakes in Bhutan potentially set to increase by 27.4 km^2 (Figure 5.3), future outbursts could be expected to have greater social and economic implications simply due to their larger magnitude outbursts. Recent modelling suggests future outburst from two existing dangerous lakes in Tibet, Galongco and Jialongco, could generate discharges more than 15x greater than previously observed (Allen et al., 2022). Thus, with continued changes in exposure, the impact of a GLOF could be much greater in the coming years. However, compared to the west of HMA, where most lakes will form in areas with no pre-existing lakes (Figure 5.1c), fewer new lakes will form in the east, with existing lakes likely to expand instead (Figure 5.1a). As a result, the east may be better prepared to mitigate future potential GLOF danger given GLOFs are an existing hazard, and in many communities living downstream from glacial lakes identified as being ‘potentially dangerous,’ mitigation strategies are already in place or glacial lakes subject to continued monitoring. For example, in 2008 a 5-year lake-lowering project was conducted at Thorthomi Tsho in Bhutan, successfully reducing lake water levels by 5m (NCHM, 2019), whilst a similar exercise was undertaken at Imja Lake in Nepal in early 2016 through the creation of an artificial channel opening (Thompson et al., 2020; Bajracharya et al., 2020). Thus, authorities and downstream communities are already aware of the dangers posed and are better prepared to handle the changing danger.

5.4.1.1 Role of exposure

Data show that the change in potential GLOF danger globally is generally caused by increasing exposure, with projected GLOF danger lower for four nations when exposure does not change and highest for five nations when exposure is the changing factor (Figure 5.6; Figure 5.7; Figure 5.11). This suggests changes in hazard do not have the biggest effect on driving changes in GLOF danger and reflects the trends observed over the last 20 years (2000-2020) (see Figure 4.14 , section 4.4.1.1; Taylor *et al.*, in review). Thus, whilst hazard still needs to be assessed as part of GLOF danger, the role of exposure requires more attention. Numerous GLOF hazard assessments have been undertaken across HMA (Ives et al., 2010; Mool et al., 2011; Ashraf et al., 2012; Worni et al., 2013; Rounce et al., 2016, 2017; Kougkoulos et al., 2018; Washakh et al., 2019; Rinzin et al., 2023), however, there are very few documented holistic studies that integrate exposure and vulnerability (Drenkhan et al., 2019; Motschmann, Huggel, Muñoz, et al., 2020; Taylor et al., 2023). With recent findings indicating the role of exposure for driving GLOF risk increases as well as the importance of vulnerability for offsetting increases in hazard and exposure (Chapter 3, Chapter 4) (Taylor *et al.*, 2023; Taylor *et al.*, in review), holistic assessments are vital.

UN probabilistic projections for population growth exemplify the role exposure could have on overall potential GLOF danger (Figure 5.12). If GLOF hazard and exposure continue to increase according to their current trajectories, by 2060 potential GLOF danger in Pakistan will still be the second highest in HMA (0.318, Figure 5.10). However, if areas earmarked as having high future potential GLOF danger, such as Pakistan, could begin to implement strategies now to effectively mitigate hazard or reduce exposure, ultimately the trajectory of potential GLOF danger could be changed (Figure 5.12). For instance, adopting land-use policies, educating and drilling populations in evacuation practises, and enforcing restrictions on the movement of people, goods, and services along likely GLOF runout tracks could successfully reduce future danger, whilst still promoting and enabling socioeconomic development through the likes of tourism and hydroelectric power projects. Further, future research may wish to perform cost-benefit analyses of such scenarios as shown in Figure 5.12; if GLOF danger is going to increase regardless of the level of intervention taken, it will be useful to determine at which point the benefits of mitigation are outstripped by the cost. In this example, glacial lakes are assumed to fill instantly, thus variance shown here is only variance of one parameter, population. In reality, the timeline of exposure, hazard, and danger is likely dynamic, with 'peak danger' perhaps found within the time-series, not the end (Figure 5.13). If for instance, the increase in GLOF hazard is not linear (Figure 5.13) or exposure grows exponentially (Figure 5.13) the point at which GLOF danger 'peaks,' will differ. Refining the timeline of glacial lake formation and filling as well as linking lake growth rates to inventories of known GLOFs could help constrain the results presented here and identify more accurate timings for the emergence of potential GLOF danger, as well as likely peak potential GLOF danger.

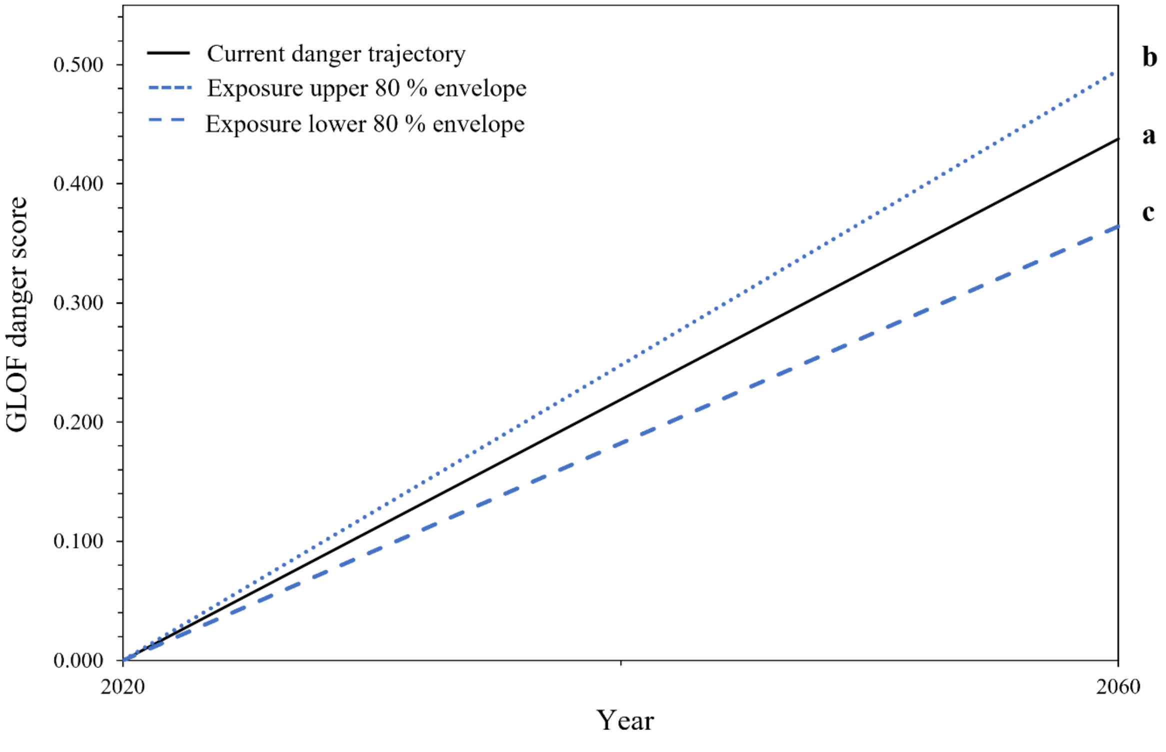

Figure 5.12: Danger scenario testing in Pakistan. Projections showing how future potential GLOF danger in Pakistan could evolve under varying exposure; (a) current trajectory, (b) Upper 80% exposure envelope and (c) Lower 80% exposure envelope.

Communities across HMA often struggle with effectively planning, managing, and funding of GLOF mitigation projects due to multiple institutional factors and barriers (Thompson et al., 2020). In Bhutan, the National Centre for Hydrology and Meteorology has prepared GLOF-specific hazard zoning maps for the Mangde Chhu and Chamkhar Chhu basins (Dorji, 2021) to prevent new buildings within 30 m of the river edge along any rivers that have been subject to glacial flooding, without first obtaining planning permission. Although still in their early phases, such strategies could remain effective in the future given fewer lakes will form in new locations. Often however, enforcing such strict land-use policy is not desirable given most settlements are located alongside river channels with glacial lakes in their upper reaches where land is fertile (Dorji, 2021) and given the high levels of corruption at multiple institutional levels that hinders compliance. A recent study (Bower et al., 2022) demonstrates the value of community involvement, where relocation processes of at-risk communities that were initiated and driven by community members themselves had better outcomes than government-driven processes. This highlights the importance of community autonomy for effective management of GLOF danger, and further promotes the need for inclusive engagement at all stages of GLOF mitigation. In the case of Bhutan, a long history of GLOFs and engagement of policy makers, scientists and locals (Watanabe & Rothacher, 1996; Komori et al., 2012; Gurung et al., 2017; Hagg et al., 2021) has resulted in high levels of risk perception within affected communities, making it possible to deploy such strategies here. In areas where the threat of GLOF has not been faced by downstream communities, such strategies may be harder to implement, and even harder to enforce. Whilst comparatively exposure is likely to increase less in the west given the mountainous terrain, the intensity of GLOFs could increase as lakes expand, thus, adaptation measures akin to those already in place or planned across the east urgently need to be considered and adopted by the west in the near future if GLOF disasters are to be avoided (Furian et al., 2021).

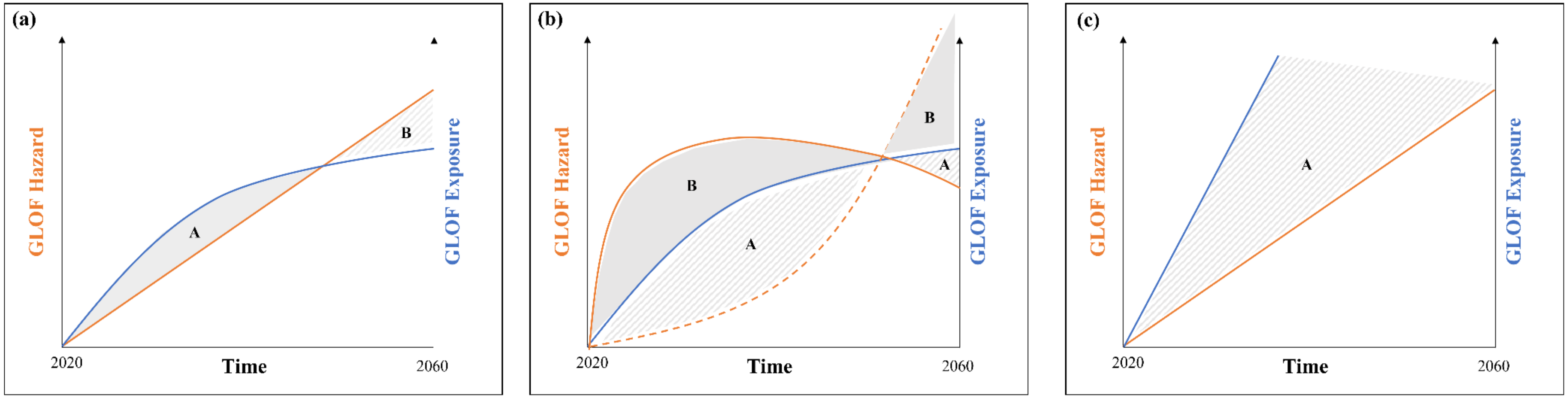

Figure 5.13: Conceptual curve of potential GLOF danger over time. Three potential scenarios for future GLOF danger trajectories caused by changes in exposure (blue) and hazard (orange). Here, A represent exposure driven danger and B represent hazard driven danger. (a) Increase of both GLOF hazard and GLOF exposure over time, shifting from exposure driven to hazard driven, (b) exponential increase in GLOF hazard OR gradual increase in GLOF hazard and (c) linear increase in GLOF exposure.

Over the coming decades across the entire HMA, and increasing focussing on risk knowledge, hazard monitoring and warning, dissemination and communication will be crucial for reducing the impact of future GLOFs (Huggel, Cochachin, et al., 2020). Using studies such as presented here to identify areas where potential GLOF danger may be high in the future presents an opportunity to alter danger trajectories. Regions in the northwest of HMA yet to experience rapid deglaciation and glacial lake growth (Mohanty & Maiti, 2021) (Figure 5.4) perhaps have a rare opportunity to proactively develop adaptation concepts and implement strategies before the threat of GLOFs fully arises. Through mitigating the hazard (e.g. construction of artificial spillways, creation of outlet channels, artificial lake lowering, moraine-dam reinforcing) and/or exposure (e.g. land-zone planning, infrastructure regulations), trajectories of future potential GLOF danger could be altered (Haeberli et al., 2017; Kattelmann & Watanabe, 1997). A move towards designing mitigation systems that not only protect life but also infrastructure, such as that in place for the Almaty Dam, Talgar, Kazakhstan, would enable populations to continue to develop in hazard-prone areas whilst ensuring socioeconomic stability.

5.4.1.2 Implications of surging glaciers

The projected shift in potential GLOF danger towards the west is particularly uncertain given the presence of surge-type glaciers, where the blocking and release of glacial meltwater as a result of glacier surge and retreat increases the probability of lake formation (Hewitt & Liu, 2010). Surging adds another dynamic to GLOF threat that is hard to monitor and predict given it is largely independent of climate change, and harder still to mitigate (Bhambri et al., 2019; Quincey et al., 2015). Across the Karakoram and Pamir, repeat, high-frequency outbursts from ice-dammed glacial lakes are the dominant GLOF threat (Zheng, Allen, et al., 2021; Ashraf et al., 2021); the recent surge cycle of Kyagar glacier in the Chinese Karakoram formed an ice-dammed lake on the Yarkant River which subsequently burst, generating a GLOF with volume exceeding 40 million m^3 (Round et al., 2017). Commonly used mitigation strategies such as lake-level lowering, or spillway creation are often not suitable for surge-type glaciers, thus it remains difficult to mitigate GLOFs resulting from surge activity. Eventually however, continued deglaciation in the west may result in a change in the landscape processes, with a shift from predominantly ice-dammed lakes to moraine or bedrock-dammed lakes (Zheng, Allen, et al., 2021). This shift will inevitably lead to frequency and predictability of outburst events. Identifying subregions and basins across the western HMA where numerous, large area moraine-dammed and ice-dammed glacial lakes will likely form, and more importantly where people are likely to be exposed to them, is therefore highly beneficial for planning and deploying long-term GLOF danger reduction. In the meantime, compiling a database of surge frequency and surge-induced GLOFs alongside creating a hazard assessment framework specifically for surge-type glaciers could be useful. Further, early education of communities living downstream from these surge-type glaciers, and those living where moraine-dammed glacial lakes are likely to form should be a priority, allowing people to prepare for future threats.

5.4.2 Role of risk perception

More than one third of future glacial lakes (36%) are likely to form in basins where currently no glacial lakes are present (Figure 5.2), particularly across the west of HMA (Figure 5.4) where glaciers are yet to experience rapid and pronounced deglaciation as has been observed in the east (Mohanty & Maiti, 2021). This poses significant concerns in terms of risk perception. People's perception of risk and therefore their response to natural hazards is influenced by a complex mix of social factors (e.g. livelihoods, exposure, spirituality, religion) that shape an individual's evaluation of their vulnerability to natural hazards (Thompson et al., 2020; IPCC, 2019; Lavell et al., 2012). In locations where glacial lakes are already numerous and large, such as Bhutan and Nepal, GLOFs are a well-known and accepted hazard (Sherpa et al., 2019; Aslam et al., 2022). However, even here there is evidence of a distance decay factor in risk perception, whereby people living further away from the hazard in question are significantly less concerned, having no first-hand experience of the potential implications (Dahal, 2008). Over the next 40 years (2020-2060) 650,000 people are likely to become newly exposed to the threat of GLOFs, with more than half of these (57%) found in new glacial basins thus likely to have no past experience of GLOFs. As these new, unmonitored lakes form in locations previously free from the threat of GLOFs, priority should be given to informing/educating downstream populations to establish an understanding of the potential danger, in efforts to reduce vulnerability to GLOF impacts.

While knowledge is generated and distributed within science and policy communities to inform and influence policymakers (Thompson et al., 2020), the dissemination of hazard and risk information to locals living downstream from glacial lakes is lacking in almost all developing regions globally (Ojha et al., 2017). Where efforts are made, information is largely distributed via static means, such as signposts, leaflets, or radio. Given the low levels of literacy, particularly female literacy, and access to media across HMA, particularly in the west (e.g. Pakistan, Afghanistan, (see Table 3.2)) communicating potential GLOF danger is challenging

(Byers et al., 2017). Previous attempts have led to distrust towards external institutions, reducing community compliance with risk reduction strategies (Dahal & Hagelman, 2011). In the case of Tsho Rolpa for instance, expert opinion suggested the lake to be potentially dangerous, with various studies indicating the need for urgent mitigation works (Ageta et al., 2000; Reynolds, 2000; Kattelmann, 2003; Khadka et al., 2019). Yet within downstream communities the risk is perceived to be low, given the disconnection between science and community (Dahal, 2008) as well as the infrequency of GLOFs. As a result, during an evacuation in 1997 sparked by expert assessments regarding the stability of Tsho Rolpa, many residents were reluctant to leave their homes, with some refusing to evacuate at all (Dahal, 2008). This was further exacerbated as on this occasion the evacuation turned out to be false (no outburst occurred), further cementing the local communities' views and distrust, highlighting the clear gap between experts and residents that needs bridging. Thus, communication of potential GLOF danger within communities likely to be impacted by outbursts will become increasingly more important in the coming decades as the number and area of glacial lakes and exposure to these lakes increases (UN, 2006; Shrestha et al., 2016; Dhungel & Ojha, 2012).

Evidence suggests in the absence of community involvement and education, installation of engineered remediation (e.g. spillways, lake lowering, artificial dams) often results in a false sense of security that can enhance rather than reduce vulnerability to GLOFs (Dahal, 2008; Dahal & Hagelman, 2011). This has been observed elsewhere globally such as in the Huaraz District, Peru where residents have moved back into high-risk areas following engineering interventions (Carey, 2008). Lack of community involvement is a longstanding issue; in many developing nations there is a tumultuous history of national governments pushing local communities to the periphery in favour of economic gains, particularly where corruption is present. In Pakistan, the number of glacial lakes is projected to increase by 3453 (518.41 km^2) (Figure 5.3) whilst at the same time the number of people exposed to GLOF impacts will increase by 0.5 million (Figure 5.6). Historically however, most funding for mitigation is dispersed via governmental bodies and with high levels of corruption prevalent at multiple levels of governance here (Transparency, 2019) the implementation of risk reduction projects for GLOFs faces a major economic barrier (Shaw, 2016). As such, installation of EWS, evacuation efforts and post-disaster relief is often largely community led (Ashraf et al., 2012; Iribarren Anacona et al., 2015). Thus, studies identifying locations where potential GLOF danger is likely to be high in the future as presented here could allow for immediate and targeted remediate actions within communities (Haeberli et al., 2016), but only if mitigative efforts are developed collaboratively between locals, experts, and government agencies by taking a bottom-up approach to prevent marginalisation of those most likely to be directly impacted by GLOF.

Hazard zoning is often considered a favourable mitigation strategy from a government standpoint (Carey, 2010), however, the livelihood, religious, spiritual, and geographical preferences of local residents are often strongly averse to such stringent measures (Thompson et al., 2020). The rebuilding of the Huaraz District in Peru following the 1941 outburst evidence as much (Hegglin & Huggel, 2008; Carey, 2008, 2010; Frey et al., 2018). Future adaptation strategies should aim to reduce risk related to the newly developing conditions while trying to balance the socioeconomic gains arising from new opportunities developing across the region (e.g. tourism, hydroelectric schemes). Further, strategies should aim to recognise and acknowledge traditional knowledge and narratives in part of a constructive narrative to finding solutions to the increasing danger (Huggel, Cochachin, et al., 2020). This will require a comprehensive approach and harmonisation of all stakeholders (Haeberli et al., 2016) to anticipate changes in what is a complex interconnected natural system, whilst also considering human expansion and economic dependency (Ritchie, 2008).

5.4.3 Future of hydroelectric power

The economic impacts of outbursts can be significant (Carrivick & Tweed, 2016), and as energy demands of nations across HMA rise (Schwanghart et al., 2016) the economic implications of future outbursts are likely to be even greater, due to the proliferation of hydroelectric power projects across the region. Given the abundant monsoonal river discharge along steep mountain rivers, the Himalayas offer an ideal setting for hydroelectric power projects, thus there has been marked expansion of hydroelectric capacity over the last 30 years. However, GLOFs can substantially exceed the designed flood capacity of hydroelectric dams, causing damage or rendering them inoperable (Richardson & Reynolds, 2000a; Hagg et al., 2021). There are numerous documented events of outbursts causing damage to hydro dams; in 1985 a GLOF from Langmoche Lake in the Khumbu Himal, Nepal, destroyed an almost completed hydro dam (Ives, 1986), whilst an outburst from Chorabari Lake, Uttarakhand, India, in June 2013 severely damaged at least two sites (Thakkar & Dandekar, 2013).

There are 1240 hydroelectric power projects across HMA (Figure 5.14), and damage to any one of these by a GLOF could cause significant economic implications. Bhutan has five hydroelectric power projects in operation with a capacity of ~ 1500 Mw (Figure 5.14). Whilst only one of these (Basochhu Hydroelectric Power Plant) currently lies along likely GLOF flood corridors, as a nation, Bhutan relies near 100% on hydropower for energy security, as well as being the primary source of income nationally (Tshering & Tamang, 2004). In 2017, this station alone generated 262 Gwh of electricity, 12% of the annual total energy consumption nationally, thus, damage to, or loss of, this station could have substantial implications across the nation both socially and economically. Further, three of the current hydroelectric power projects in Bhutan are located in the Wangchu basin, where population exposed to future glacial lakes is expected to increase by more than 15,000 (Figure 5.14) and a further seven glacial lakes may form in overdeepenings (Figure 5.4). Similarly, two basins in Pakistan, the Khyber Pakhtunkhwa basin and basin ID:11410040300 that are home to four hydroelectric power projects with a capacity of 3,682Mw are expected to see the largest increases in exposure between 2020 and 2060, with an increase of more than 100,000 each (Figure 5.14). With less than 20% of the hydroelectric potential currently being tapped across HMA (Vaidya, 2013), the rise in GLOF danger due to the proliferation of hydroelectric power projects alongside the expansion of large, numerous glacial lakes and increases in population exposure is a major concern (Nie et al., 2021). Hydropower dams could attenuate outburst discharges and reduce overall immediate impact to downstream communities (i.e. fatalities) if designed with GLOFs in mind (Reynolds, 2022). However, estimates of extreme flood magnitudes largely overlook GLOFs as a flood mechanism during design. Thus, most existing hydroelectric power projects do not have the capacity to cope with discharges generated from GLOFs (Schwanghart et al., 2016), which instead result in substantial structural damage to the dams themselves leading to widespread economic implications and energy security issues as well as exacerbating the risk further downstream due to cascade processes Clearly updates to design-flood estimates are required if hydroelectric power projects are to remain a viable method for generating energy across HMA. The results of this research on HMA could be used to inform on the location of potential hydroelectric power project in order to moderate future danger. Basins identified as containing future glacial lakes should be avoided or at least well-managed to ensure infrastructure is not constructed in unsuitable locations or if it is, that it is designed to cope with potential discharges of a GLOF.

GLOFs as a risk to hydroelectric power projects is a consideration that urgently needs to be integrated into planning and policy of future hydroelectric power projects; it remains unclear the extent to which increasing discharges from GLOFs may pose a threat to hydroelectric power projects further downstream. Further, it remains unclear how the loss of HEP interacts with national vulnerability. With glacial lakes forming at higher elevation above existing lakes (Figure 5.5), GLOFs are more likely to cause cascading damages for hydroelectric power projects and could result in large scale power-grid instability (Nie et al., 2021). Over the last few years, Integrated Geohazard Assessments (IGA) has gained the interest of some hydropower developers, enabling past GLOF events to be identified and the information used to develop Disaster Risk Management Action Plans as well as to refine a hydropower scheme's Risk Register. Not only can the results feed into engineering design of the scheme infrastructure, but it can also be used to ensure the proposed project is not vulnerable to future disasters, which in turn can benefit investors decision making and insurance policies. In Nepal, hydropower schemes with an IGA have been offered annual insurance discounts of up to 25%. (Reynolds, 2022). Knowing where glacial lakes are likely to form, as presented here, thus provides a high-level guide for planning future hydroelectric power project locations, allowing high hazard areas to be avoided, or designed with GLOF hazard in mind. Whilst here only the number of people is used as a proxy for exposure, further research may wish to also integrate hydroelectric power projects as done by Mal *et al.* (2021) given the potential economic implications GLOFs could have in these high-risk areas.

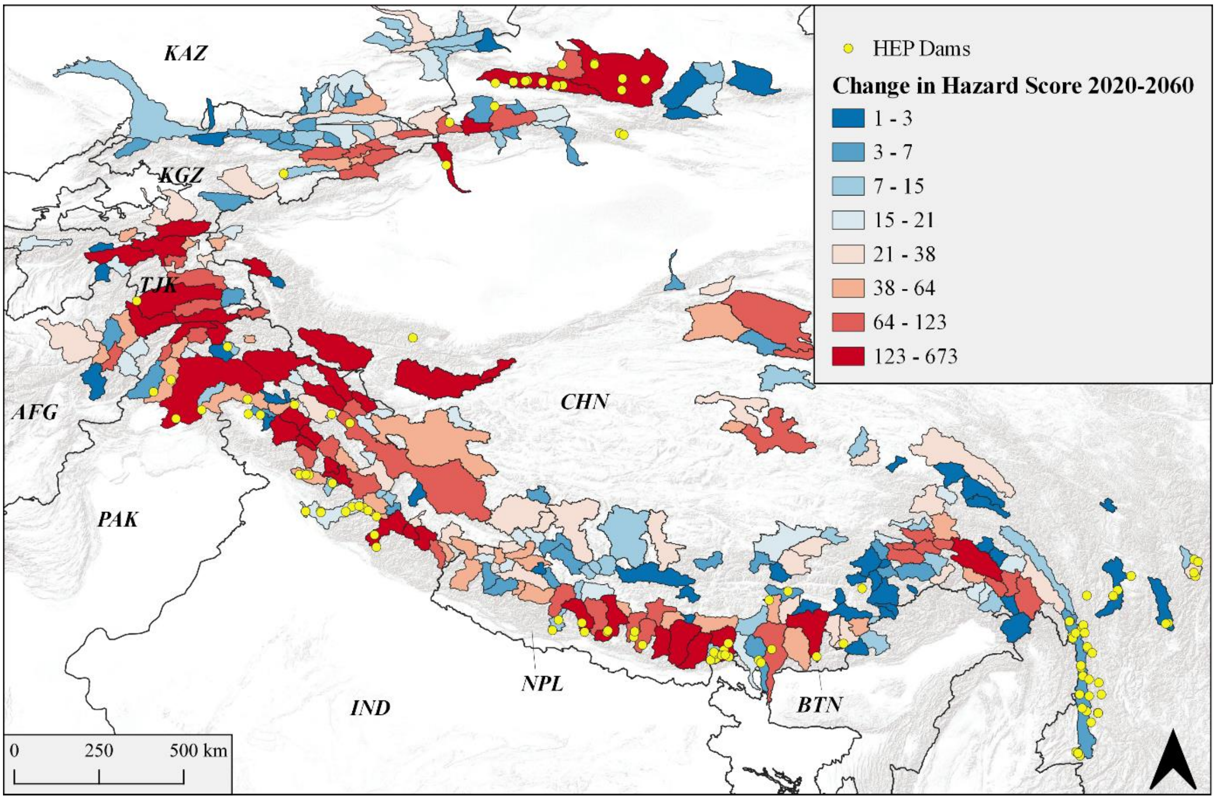

Figure 5.14: Spatial distribution of hydroelectric power projects and GLOF hazard across HMA. Completed hydropower dams in glacial lake basins only across HMA as of 2018, overlaying projected change in hazard per basin between 2020 and 2060. (Data from the World Resources Institute, 2018).

5.4.4 Higher elevation glacial lake formation

As glaciers continue to retreat, new glacial lakes are projected to form at higher elevations than in 2020 (Figure 5.5) (Wang et al., 2020; Furian et al., 2021); 65% of future glacial lakes (excluding existing lakes) across HMA will be located above 5000 m a.s.l. by 2060 compared to the 39% that exist above the same elevation as of 2020. The implications of this are two-fold. First, formation of glacial lakes at higher elevations above existing lakes presents a heightened risk of cascade events, whereby even a small release of volume from a higher elevation lake could trigger an outburst of a lower lying lake (Falátková et al., 2019) with catastrophic implications (Bajracharya *et al.,* 2007). Examples of such events have already been documented in the region; an outburst from Chongbaxia Tsho, in the eastern Himalaya cascaded into two lakes downstream (Chongbamang Tsho and Chongbayong Tsho) (Nie et al., 2020), whilst glacial retreat in the Adygine Valley, Tien Shan has resulted in the formation of a potential three-level cascade of glacial lakes (Falátková et al., 2019). Whilst in some cases (as observed in the GLOF from Chongbaxia Tsho) lower-lying glacial lakes can substantially attenuate GLOF discharges and thus reduce their overall impact downstream, others can increase GLOF impact by adding to initial breach volumes (Haeberli et al., 2001). However, given the complexity of GLOF modelling (Zhou et al., 2019; Westoby et al., 2014), few studies have considered the implications of cascade events; thus, our understanding remains limited. With the frequency of cascade events likely to increase in the future, this is a knowledge gap that should be addressed (Haeberli et al., 2016).

Second, given the retreat of glaciers into higher elevations surrounded by steep, mountainous terrain, almost every modelled future glacial lake (98.3%) is likely to be surrounded by potentially dangerous slopes (Furian et al., 2021), with many slope angles > 20° and recently debuttressed by the removal of ice, thus are typically predisposed for mass-movement events (Furian et al., 2021; Allen et al., 2011; Fischer et al., 2012). However, due to the presence of more rugged mountainous terrain where slopes often exceed 40°, glacial lakes forming in the west, particularly those in the Tien Shan, Pamir and Central Karakoram (Figure S5. 1) are likely to be more susceptible to mass movement impacts than those in the east (e.g. Hengduan Shan, Kunlun) (Furian et al., 2021) through low magnitude but high frequency rockfall and avalanche events (Blöthe et al., 2015). Thus, GLOFs initiated at higher elevations by mass-movement events can affect downstream areas over much larger distances, reaching previously unaffected settlements (Haeberli et al., 2016; Schaub et al., 2013). In addition to increasing hazard, as populations across HMA move to higher elevations for tourism, hydropower production and agriculture (GAPHAZ, 2017; Haeberli et al., 2016), more people will be in closer proximity to GLOF hazard than ever before (Figure 5.6; Figure 5.7). Thus, the future formation of glacial lakes in the vicinity of such steep slopes across the west of HMA is particularly concerning for future potential GLOF danger. Modelling future high-mountain landscapes under a warming climate with deglaciation needs further improvement to develop our understanding of complex GLOF cascade events as well as mass-movements from unstable slopes. This should go hand in hand with focused monitoring of changes in downstream populations. Urban planning and mitigation strategies will need to consider these spatial changes in GLOF hazard and exposure in detail, allowing changes to current strategies to be made early (e.g. moving monitoring stations for EWS to higher elevations in order to maximise warning times (Fischer et al., 2022)) and allow the most effective mitigation strategies to be deployed over the coming decades.

5.4.5 *Future research*

Knowing where and what to target to reduce GLOF danger will be crucial for the future, as glacial lakes continue to form and expand and development in high mountain regions heightens. A combined approach of hazard and exposure management could be most effective in reducing danger in the long-term, alongside the instigation of risk dissemination to communities downstream at the earliest opportunity. Specifically, data on GLOF frequency and magnitude, runout distances, rate of lake expansion, rate of increase in exposure and location of exposure could all aid this process. A special consideration of GLOF impacts on hydroelectric power projects is crucial, and urgently needs to be integrated into planning and policy if large-scale energy disasters are to be avoided. Further to this, an understanding of how the characteristics of future outbursts may vary between newly forming glacial lakes and expanding existing lakes is needed, to determine which posed a greater threat to communities. For instance, the magnitude of outburst from an expanding lake is likely to increase (thus increasing runout distances, inundation depths etc.), whilst the formation of new glacial lakes presents the added threat of cascade events should they form above existing lakes. This type of analysis could be conducted using ensemble models and would be invaluable for planners and policy makers in high mountain Asia.

As hydroelectric power continues to grow across HMA, a consideration for community and national reliance on it for power and income must be added to future assessments; a GLOF that damages a hydroelectric plant in a nation where dependency is high will have a larger impact socially and economically than in a nation where alternative energy supplies are available. This is particularly pertinent given the number of planned projects across HMA (Figure 5.9). Further, a measure of the reliance on glacial meltwater as source of water could be considered as an additional metric; as glaciers retreat the supply of meltwater will eventually diminish (Wang et al., 2021; Nie et al., 2021) leading to widespread water shortages. Considering this information in future GLOF assessments could help better prepare communities and reduce the overall impact of future GLOFs.

The abundance of readily available data for HMA allowed us to present one scenario of future potential GLOF danger across the region. Globally, this approach could be valuable for other regions where GLOF risk has been shown to be high or rapidly increasing, such as the Andes (see Chapter 3, Chapter 4) (Taylor et al., 2023). Comparative to HMA, data availability for glacial and glacial lakes changes, changes to the frequency and magnitude of triggering mechanisms, changes in exposure etc. across the Andes is lacking, significantly hindering our ability to forecast future GLOF scenarios. I suggest the Andes be targeted for more detailed hazard studies to facilitate forecasting of potential GLOF danger such as presented in this chapter to help avoid future catastrophes.

5.5 Conclusions

As deglaciation continues and accelerates over the coming decades, the formation of glacial lakes and the GLOF threat they pose to the growing communities downstream will only increase. Whilst large, moraine-dammed proglacial lakes already present in the east of HMA are expected to expand, it is the west of the region that will see the largest increase in the number and area of new, unmonitored glacial lakes. With the formation of glacial lakes at higher elevations closer to steep and unstable slopes, particularly in the west, the magnitude and frequency of future GLOF events as well as the possibility of lesser-studied cascade events is likely to increase, and urgently requires attention. With 80% of increasing potential GLOF danger attributed to exposure, over the coming decades across the entire HMA anticipatory action and cooperation will be crucial; by placing an early focus on risk knowledge, hazard monitoring and warning, dissemination and communication and response capability (Huggel, Cochachin, et al., 2020), regions in the west of HMA have a rare opportunity to develop adaptation concepts and implement strategies before the threat of GLOFs starts to fully evolve. This chapter provides a valuable contribution to GLOF understanding and could be used as a starting point for more detailed research into how the future danger of glacial lake outburst flood events could evolve.

Chapter 6 Discussion

6.1 Introduction

Overall, this thesis aimed to **1)** quantify contemporary (2020) glacial lake outburst flood risk and its spatial variability at a global scale (Chapter 3); **2)** determine how GLOF risk has changed, and evaluate the role of hazard, exposure, and vulnerability on driving these changes between 2000 and 2020 (Chapter 4); and **3)** appraise the future potential GLOF danger across High Mountain Asia (Chapter 5). Chapters 3, 4 and 5 successfully address these three objectives (outlined in Chapter 1), with the findings of this thesis therefore fulfilling the overall aim of the project. This chapter first summarises the core findings of the thesis (Table 6. 1) before identifying key directions for future research that arise from the key findings of Chapters 3-5 (Table 6.2).

6.3 Key findings

Key Finding	
1.	**Hazard is not the sole driver of GLOF risk** (Chapter 3). Catchments with the most numerous, or largest glacial lakes do not automatically have the highest GLOF risk, and risk changes do not directly follow hazard changes.
2.	**Exposure plays a key role in driving GLOF risk** (Chapter 3, Chapter 4), particularly in HMA. Catchments with few or comparatively small area glacial lakes can be high risk due to the presence of large populations downstream. Thus, a measure of exposure **must** be included in risk appraisals.
3.	**Vulnerability acts as a dampener of GLOF risk** (Chapter 3, Chapter 4), where increasing hazard and exposure could otherwise lead to increasing risk. Managing vulnerability thus remains important for GLOF risk management.
4.	**The Andes is an emerging hotspot of GLOF risk** (Chapter 4), driven by increasing hazard and exposure. Here, comparatively few studies have been undertaken and the region should be targeted for future research.

5.	The **spatial distribution of GLOF danger is likely to change** (Chapter 5) across HMA as glaciers recede, new lakes form and the spatial distribution of people changes. The west is likely to emerge as higher risk, and the role of cascade events likely to become more important.

Table 6. 1: Key findings of this thesis.

6.3.1 The role of Hazard and Exposure on GLOF risk

Three key findings of Chapter 3 and Chapter 4 concern the relative roles of hazard, exposure, and vulnerability in governing GLOF risk and current understanding in the field (Table 6. 1). Chapter 3 showed exposure and vulnerability play vital roles in determining GLOF risk, and it is not the basins with the largest number or area of glacial lakes with the highest GLOF risk, rather it is those with large numbers of vulnerable people living along likely GLOF runout tracks (Chapter 3, section 3.4.3). This finding is important, given the apparently common view in the GLOF literature that risk is directly proportional to hazard, with exposure and vulnerability often left out of the conversation with the majority of studies hazard-focussed. Further, Chapter 4 showed the primary driver of temporally variable GLOF risk varies between and within regions, due to differences in the number and area of glacial lakes, the number and location of people, and the socio-political situation of the countries. For instance, whilst exposure was found to be the key driver of GLOF risk increase across HMA, in Bhutan rapidly increasing hazard is the main driver (Figure 4.12). Not only is this useful for directing mitigation efforts (e.g. hazard reduction might be more pertinent over land zoning to reduce exposure for instance) but also clearly shows GLOF risk and GLOF hazard do not mirror one another. This reaffirms the results of Chapter 3**,** that showed exposure to be a key driver of GLOF risk and rebutting the current narrative that monitoring changes in GLOF hazard alone without considerations of exposure and/or vulnerability can be directly related to GLOF risk changes. These findings address the second objective of the project (section 1.3) and reiterates the need for holistic risk assessments; that whilst an integral part of GLOF risk, we need to move away from just quantifying changes in hazard and begin to integrate downstream information (exposure, vulnerability) if risk is to be accurately identified and managed moving forward. The distinct role increasing exposure has on driving GLOF risk is an important, if not the most important, finding of this thesis, because it questions previous assumptions on how GLOF risk may evolve as the number and area of glacial lakes increases; it is likely to be the basins with the highest number of people exposed alongside those with a reduced capacity to cope with disaster that will play a more central role in governing future risk. This finding raises questions for how future GLOF risk assessments and GLOF risk reduction strategies should be conducted, where a more holistic approach will be essential.

6.3.1.1 Exposure In HMA

Populations living in HMA were living the closest to glacial lakes globally in 2020 (Chapter 3 Section 3.4.2), with ~9 million people living within 1 km of likely GLOF runout tracks and within 50 km of a glacial lake (Figure 3.5, Figure 3.6). Of these, ~1 million people live within 10 km of a glacial lake. Chapter 4 showed populations in HMA have been moving closer to glacial lakes since 2000, and Chapter 5 demonstrates this trend is likely to continue in HMA over the next 40-years. Driven primarily by changes in economic sectors, with an increase in tourism and hydroelectric power projects, this movement of populations closer to glacial lakes could raise issues for mitigation of GLOF risk, particularly in areas reliant on EWS, where close proximity of populations to lakes may not provide sufficient warning times for evacuations. Having highlighted the importance of exposure for driving GLOF risk in Chapter 4, prioritising mitigation that reduces exposure, rather than hazard, may be more beneficial for GLOF risk management over the coming decades across HMA.

Chapter 5 showed the number and area of glacial lakes across HMA is expected to increase markedly over the coming decades, in response to glacial mass loss and retreat (Section 5.3.1). Consequently, the number of people living within 1 km of likely *future* GLOF runout tracks up to 50 km could increase by 3.9 million (Figure 5.6). Thus, coupled with the changes in hazard, if rates of population increase in HMA remain the highest globally (Figure 3.15), the region will remain the hotspot of GLOF risk over the coming decades. In light of this, and alongside better integration of exposure monitoring to GLOF studies across the region, a reconsideration of where GLOF research is being conducted is also needed. Studies currently dominate in the Himalaya (364 items) with ~ one third the number of studies found in Central Asia and the Karakoram (57 and 70 items respectively) (Figure 6.1). This is despite the Himalaya having nearly four times fewer recorded GLOFs (50 recorded GLOFs) compared to Central Asia and the Karakoram (182 recorded GLOFs) (Figure 6.1). It should be noted that GLOFs in central Asia and Karakorum often are associated with repeat events from the same lake, whereas in Himalaya they are unique events, thus the number of studies may not be proportional to the number of events, but rather the number of GLOF-producing lakes. Whilst this study does identify HMA as being very high risk (0.124, Figure 6.1) thus warranting the current high research interest, at a sub-regional level the majority of the risk is located in the west, towards the Karakoram (Figure 6.1). I therefore suggest that research interest in HMA should be redistributed west towards the basins most at-risk of GLOFs. Whilst Central Asia is also comparatively understudied (Figure 6.1), as of 2020 GLOF risk in Kazakhstan, Tajikistan, and Uzbekistan are 7th, 8th, and 10th out of all 10 nations in HMA (Figure 3.10), and future GLOF danger is predicted to decrease or remain the same here (Figure 5.10). As such, whilst research should continue here, comparatively the risk and potential future danger of other regions warrants greater attention at present.

6.3.2 Andes as a hotspot of risk

Chapter 4 demonstrated that over the past 20-years the Andes has experienced the second most rapid increase in risk globally as well as a percentage increase in risk nearly 1.5 times that of HMA (Figure 4.14, Table 4.1), which since 2005 can be attributed to increasing exposure (Figure 4.14b). Further, results show the region houses the second and third most at-risk basins as of 2020 (Santa basin in Peru, and Beni basin in Bolivia) (Figure 3.11). This fourth key finding (Table 6. 1) is important, given the lack of attention GLOFs in the region have received compared to elsewhere, and further highlights the disparity between where GLOF research is commonly being published on and where GLOF risk is highest. The Himalayas remains a clear hotspot of GLOF research (Figure 6.1) with 346 research items (30% of the global total) since 1979, despite only 3% of the total number of recorded GLOFs occurring there (50). Similarly, Iceland has high levels of research interest, with 206 items (17% global total). Whilst the number of GLOFs in Iceland is high (295, 19%) in this study Iceland is classified as being at very low risk of GLOF impacts due to its low exposure and vulnerability (Figure 6.1) and thus may be a lower priority for risk research. Outside of Scandinavia, the Andes has the least number of research items globally, with less than 8% of the total number of research items focussing on the region (101). Whilst there are comparatively fewer recorded GLOFs in the region (145, <10% global total) the lack of long-term monitoring, data and funding may be masking historical outbursts, thus the actual number of GLOFs is likely much greater (Veh et al., 2022).

Additionally, despite the few recorded GLOFs in the Andes, the impact of GLOFs historically has been great (Lliboutry et al., 1977; Carey, 2005; Emmer et al., 2020). As a severely data-poor region where only a few, small scale studies have been undertaken in English

(Colonia et al., 2017), there is a high degree of uncertainty as to how GLOF risk may evolve (Vuille & Bradley, 2000; Salzmann et al., 2013; Wilson et al., 2018; Harrison 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). Thus, the contemporary risk of GLOFs across the Andes identified in this thesis should motivate greater research in the region, and the results of this work could help redirect research efforts to the basins where GLOF risk is highest (Figure 3.10).

Chapter 5 revealed the value of forecasting GLOF danger for identifying potential future hotspots. Unlike in HMA, where future ice coverage and glacial overdeepenings have been modelled for the entire region, (Linsbauer et al., 2016; Furian et al., 2021, 2022) there is no regionally complete database of overdeepenings and very few glacier-specific ice thickness information across the Andes, thus it remains unclear how future glacial lakes could evolve. The lack of existing glacial bed data and few direct measurements of glacier mass balance makes it difficult to model dynamic changes in activity, thus glacier ice loss and glacier interactions with new and future lakes is hard to model. Having shown vulnerability to GLOFs in the region is particularly high (section 3.3.3) primarily due to high Corruption Perception Index scores (Figure 4.8) reflective of longstanding, deep rooted corruption, and lack of trust between locals and governments, the findings of this thesis for the Andes highlights the urgent need for more detailed study of GLOF risk parameters across the region, particularly in view of the social aspects of the risk nexus.

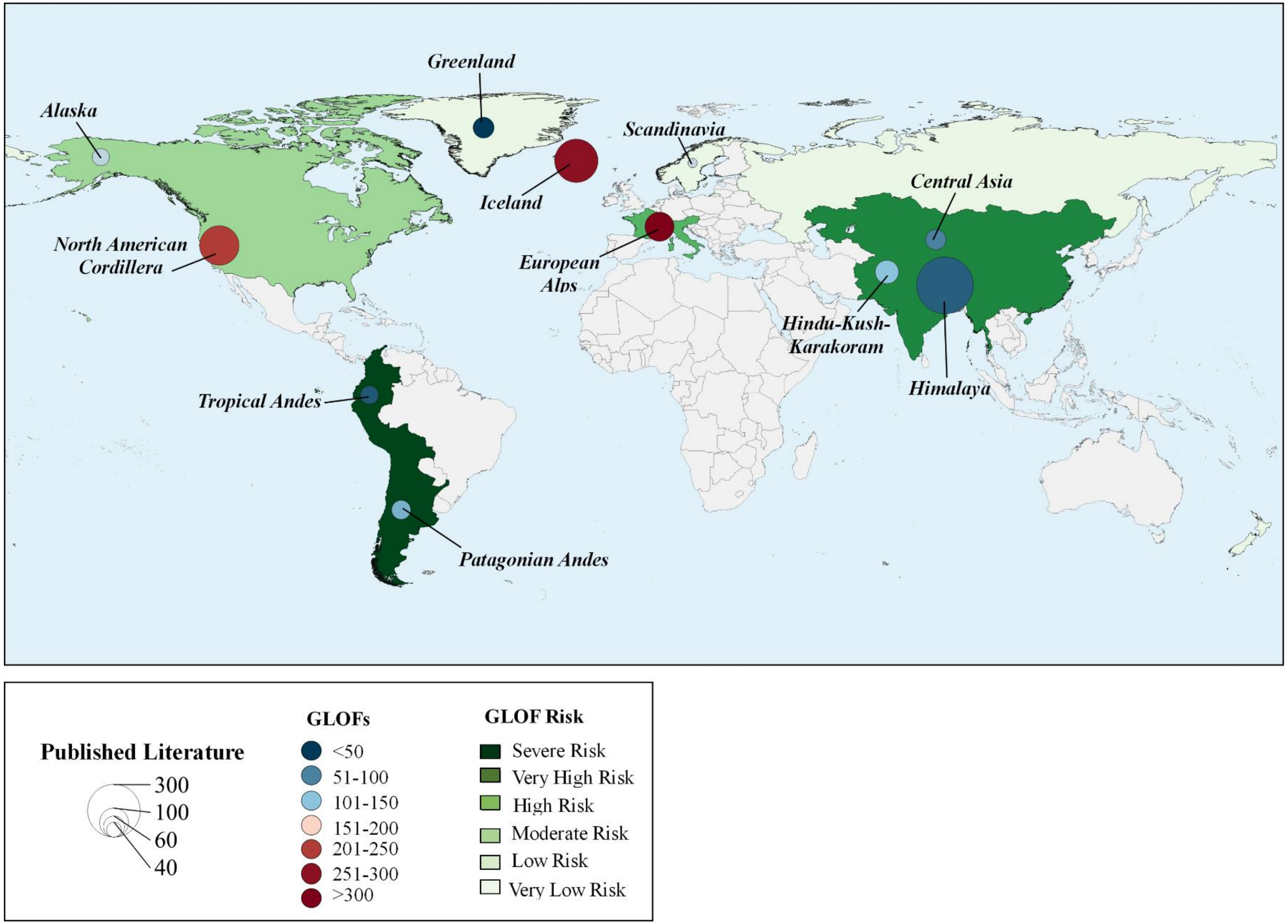

Figure 6.1: Comparison of GLOF research, GLOF occurrence and GLOF risk calculated in this study. Number of published GLOF research items per region compared to the number of recorded GLOFs and the GLOF risk score calculated in this study. Countries where no glacial lakes are found are shown in grey. Data on GLOF occurrence and GLOF research: (Emmer, 2018; Emmer, Allen, et al., 2022)

6.3.3 New risk versus increasing risk

The fifth key finding of this thesis resulting from Chapter 5 is that the spatial distribution of GLOF danger (here used to infer GLOF risk) in HMA is likely to change over the coming decades, shifting westwards towards the Karakoram region and away from the east (section 5.3.3). Specifically, Chapter 5 shows that 20% more people in the west of HMA could be exposed to GLOFs in the future, compared to exposure in 2020. Thus, the social and economic impacts of potential future GLOFs in western HMA urgently requires attention whilst this can be considered a tractable problem. Further, most new lakes are likely to form in locations where no glacial lakes yet exist (Section 5.3.1). Here, formation of glacial lakes upstream of highly populated areas, where GLOFs are yet to emerge as a prominent natural hazard is concerning, as peoples capacity to respond to and recover from disaster is expected to be comparatively low due to lack of awareness. I therefore suggest the research interest in HMA should be better balanced between the east and west, with a focus on the basins most at-risk of GLOFs. I note however there are multiple factors that determine where research is focused, including local research capacities, political and security limitations. Although Chapter 4 showed vulnerability has declined almost everywhere over the last 20 years (section 4.3.1.3), it remains comparatively high across the Andes and HMA, where the percentage of dependants and levels of literacy are particularly low (Figure 4.9). This could hinder mitigative efforts given the difficulties in communicating risk and reaching the most vulnerable members of the communities. Studies such as this provide an opportunity for action before the threat of GLOFs fully emerge. By identifying high risk basins where implementation of mitigative strategies could alter the trajectories of risk, sustainable development can be maintained across the region.

6.4 Directions for future research

This thesis shows that GLOF risk is strongly driven by exposure and vulnerability changes and thus focussing on hazard alone is not enough, with the result of this thesis clearly showing the impact changing exposure and vulnerability can have on driving risk changes, with very different resulting scenarios if even one metric is excluded from analysis (Figure 4.15). Clearly then, we need to move away from purely climate and process driven GLOF risk assessments to more holistic assessments with a strong interdisciplinary focus, allowing all elements to be evaluated together. The outcomes of this thesis motivate some key directions for research at the interface of GLOF risk knowledge and management (Table 6.2) and are discussed in the following section.

Future research recommendations	
1.	**Place a greater focus on understanding, monitoring, and managing exposure as the main driver of increasing GLOF risk**. Including the implementation of mitigation strategies such as EWS designed to allow communities to live alongside GLOF hazard whilst reducing risk.
2.	**Begin exploring the roles of transient populations and how their unique vulnerability may impact GLOF risk.**
3.	**Begin to fill gaps in dataset of GLOF hazard.** Specifically for the Andes and select nations such as Pakistan where lack of data prevents future GLOF risk from being assessed.
4.	**Promote interdisciplinary research**

Table 6. 2: Recommendations for future research motivated by the results of this study.

6.4.1 Exposure

Over the past few decades, anthropogenic activity in high mountain regions has grown vastly, as nations explore new pathways for socioeconomic development such as tourism, agricultural practises, and hydroelectric power (Bajracharya *et al.*, 2007; Schwanghart *et al.*, 2016; Allen *et al.*, 2019; Zheng, Allen, *et al.*, 2021). Thus, exposure to GLOFs has risen substantially (Figure 4.7). This thesis has shown that this movement of people, infrastructure, and services into higher elevations and closer to glacial lakes is the primary driver of increasing GLOF risk, particularly across HMA and the Andes (Figure 4.15). The result of these spatial changes has major implications for GLOF risk management, with continued adaptation required across all stakeholder groups to manage risks and enable sustainable development across these high-risk nations.

6.4.1.1 Role of Early Warning Systems

Historically, EWS have been installed to limit the impact of GLOFs on human lives (Nie et al., 2018), with the aim of detecting impending GLOFs in sufficient time to warn people who might be affected so they might move to safer ground (Bajracharya *et al.*, 2007). As populations continue to move closer to glacial lakes (Figure 4.5) it is possible that EWS may become less effective in their current state (Maurer et al., 2020). For instance, outburst simulations for two previously identified dangerous glacial lakes (Galongco and Jialongco) upstream of the town of Nyalam, Tibet indicate a warning time of between five and 11 minutes, which is unlikely to be sufficient for evacuations downstream (Allen et al., 2022). However, if EWS are coproduced with communities at risk of GLOFs, they could be key for enabling people to live alongside GLOF hazard. The design, organisation and operation of GLOF EWS are generally comprised of four key stages (Figure 6.2): (i) *Risk Knowledge* through the collection and analysis of data concerning hazards, exposure, and vulnerabilities (e.g. this thesis); (ii) *Monitoring and Warning Service* for predicting and forecasting hazards, and for continuously monitoring hazard parameters, which is essential to the generation of accurate warnings in a timely fashion; (iii) *Dissemination and Communication*, enabling warnings to reach those at risk; and (iv) *Response Capability*, where education and preparedness programs play a key role in translating warnings into effective action (Fluixá-Sanmartín et al., 2018; Huggel, Cochachin, et al., 2020). Adaptation at each stage could enhance the effectiveness of EWS as GLOF risk management strategies.

6.4.1.1.1 Risk knowledge

Understanding GLOF risk is fundamental for the design of an effective EWS (Figure 6.2a) (Huggel, Cochachin, et al., 2020). Risk is established through analysing the physical hazards (moraine stability, magnitude and frequency of potential triggers, runout pathways and inundation depths etc.), exposure of people and their assets (e.g. infrastructure, land-use type) and the vulnerability (e.g. social, economic) of the elements at risk (Huggel, Carey, et al., 2020). Comprehensive risk assessments for GLOFs are rare (Allen, *et al.*, 2016) and only recently has downstream impact and socioeconomic vulnerability been recognised as a fundamental component of GLOF risk assessments (Mool et al., 2011). This thesis begins to fill this research gap by providing the first comprehensive global dataset of GLOF risk that integrates hazard, exposure, and vulnerability. However, how we begin to quantify, monitor, and compare all three metrics and integrate these effectively into risk appraisals requires further research.

Developing a framework for assessing GLOF risk that can be deployed for any glacial lake using mostly remotely sensed data would fill large gaps in knowledge, save time and money and allow the implementation of risk reduction strategies to be made site-specific (Nie et al., 2018). In recent years, advances in the capability of remote sensing has enabled accurate monitoring of glacier retreat, lake growth, rates of glacial calving and other hazard- related metrics (Huggel et al., 2002; Quincey et al., 2007; Worni et al., 2012; Khanal et al., 2015; Rounce et al., 2016; Schaub et al., 2016; Rounce et al., 2017; Begam & Sen, 2019). At the most fundamental level, this thesis provides a basic method for quantifying GLOF risk at a large scale, using freely available remotely sensed and open-access census data. However, improvements could be made to better refine this, such as including a measure of hazard probability for GLOF hazard (e.g. frequency of mass movement events, surrounding slope angles), whilst integrating other metrics of exposure present along likely GLOF runout tracks such as infrastructure, hydroelectric power projects or land-use type, which could be achieved using earth observation data. I acknowledge that remote sensing may not be able to fill all gaps. For instance, remote sensing can be, and is, widely used to map buildings to determine exposure; however determining how they are constructed, and with which materials for instance remains difficult, and may not be possible using remote sensing alone, but could add valuable insight into vulnerability. Similarly, whilst it may be possible to determine moraine-dam lowering rates, determining internal dam structure remotely is not. However, there are still advances that could be made in order to develop a robust GLOF risk framework that substantially reduces the need for in-situ study.

Given exposure was shown to be a key driver of increasing GLOF risk (Chapter 4) there is a pressing need to add granularity to the spatial and temporal variations in exposure, in relation to GLOFs in order to better refine risk outcomes. Obtaining population data at higher resolutions than used here (1 km^2) could help reduce over- or under-estimations along likely runout tracks. Further, integrating data on temporal movements of populations over both the short-term (hourly, daily) and long-term (months, years) would provide greater insight into how GLOF exposure varies, allowing mitigation strategies to be more targeted. Many existing studies assume static populations, given the difficulties in determining such information remotely (e.g. Rounce *et al.*, 2016), however this does not reflect reality, and should be a consideration of future studies. Similarly, integrating more metrics into the social vulnerability index would be beneficial, including those relating to physical vulnerability e.g. building material type or number of roads. Such metrics could be obtained through national census data, or databases such as OpenStreetMap and would not necessarily require field studies, making it more widely applicable, yet when combined with exposure and hazard data could add greater granularity to our understanding of GLOF risk.

6.4.1.1.2 Monitoring and warning

This thesis identifies hotspots of GLOF risk, however, once risk has been determined, hazard monitoring and warning are the next central elements to an EWS. By nature, GLOFs have short lead times (< 5-6 hrs) (UNDP, 2015). Thus, a key challenge as exposure increases is how to reduce the lag time between outburst detection and raising of alarms, particularly where moving monitoring stations to higher elevations is no longer viable, if they are already stationed at or near the lakes themselves (Fischer et al., 2022). Monitoring hazard parameters and having a wealth of data does not automatically translate to successful management; data collected must be accurately measurable by sensors, site-specific, and readily translatable to warnings (Huggel, Cochachin, et al., 2020). I suggest gaining an adequate understanding of the local physical environment and interplay of processes and variables within it that can result in varying GLOF scenarios (both natural and anthropogenic) for each individual lake would be beneficial. From this, a global assessment of likely GLOF triggers could be conducted allowing the most appropriate monitoring type to be identified and deployed, whether that be using geophones to record mass movements or hydrometeorological sensors to monitor water levels, air temperatures, humidity, precipitations, wind speeds etc. to enable timely detection and warning. Better contextualisation of the hazard is key, for instance in HMA, moraine self-destruction is the second most common trigger of outburst (Emmer & Cochachin, 2013) primarily due to the large volumes of buried ice within moraines (Yamada, 1998; Bajracharya *et al.*, 2007). In comparison, in the North America Cordillera, intense rainfall/snowmelt is the secondary trigger (Emmer & Cochachin, 2013). Thus, priority might be given to monitoring and recording dam stability in HMA whilst in the North America Cordillera it might be more pertinent to focus on meteorological monitoring. Integrating such local risk knowledge with accurate and actionable data is the key to enabling timely warnings.

Following detection, warning messages must be relayed in the most direct manner; at present the process of activating GLOF warnings are defined by individual site-specific protocols (Huggel, Cochachin, et al., 2020), with messages travelling through a series of responsible personnel identified in each warning protocol before an official warning can be deployed. In most cases, warnings cannot be automatically generated by the EWS nor deployed by wardens manning the system. This lag whilst messages are relayed could be fundamental as populations move closer to glacial lakes, thus simplification and/or automation of warning pathways will be crucial; with people moving closer to glacial lakes (Figure 4.5) any delay in relaying the warning to communities downstream means less time for evacuation and greater potential impact. For example, under Peruvian law, only the mayor can authorize an evacuation (Huggel, Cochachin, *et al.*, 2020) and even then, the authorities have the discretion to reject the warning as they see fit (Carey, 2005; Carey et al., 2012). A review of this law across Peru could shorten the message pathway and reduce the lag time between detection and warning, increasing the time for evacuation of exposed communities downstream. Percentage of population with internet access was included in the social vulnerability index in this study as a means of measuring access to information and found less than half (42%) of the exposed population across HMA have access (Figure 4.9). Efforts could be made to improve access to internet, as well as smartphones and radios, through which warning messages can be sent quickly and easily. Alternatively, the use of simple sirens, such as those used for fire and tsunami warnings, could be considered. This would be particularly beneficial for marginalised members of the community (women, elderly, disabled), who would otherwise miss information displayed within the wider community or at focus groups.

6.4.1.1.3 Dissemination and communication

Chapter 4 showed that whilst vulnerability to GLOF impacts has reduced globally since 2000 (section 4.3.1.3) many of the factors that impact an individual's vulnerability remain high across HMA and the Andes (Figure 4.8). In particular, levels of literacy and particularly female literacy, remain low (Figure 4.9). Given exposure in HMA is increasing at higher elevations as populations move closer to glacial lakes (Figure 4.5, Figure 4.6) making improvements to these vulnerability factors will be vital if EWSs are to be effective. In many communities, information dissemination between authorities and locals is disconnected or complex as a result of the low levels of literacy and local response to outbursts remains largely *reactive* (Figure 6.2c). For example, within communities downstream of Imja Lake, Nepal, only 16.7% of people responded to hearing early warning sirens having understood the signs installed, with 30.4% still reliant on physically witnessing (through sight and sound) to know when flooding is occurring due to their inability to read (Thompson et al., 2020). This questions the benefit of implementing such a costly mitigative strategy if it is not going to be supported by appropriate communication. There is a pressing need to move towards a more *proactive* dissemination of risk (Figure 6.2c); communities must first be made aware of the risk posed and second be able to act on this knowledge when needed and could be tackled through increasing literacy rates first and foremost.

Co-produced early warning systems could play an important role here, whereby local communities are active participants in the design, implementation, and running of EWSs (Aslam et al., 2022; UNDP, 2015). Co-produced systems have been shown to be effective not only for increasing compliance with policies by providing communities with a sense of ownership, but also increasing understanding of the hazard in question and thus improving the overall perception of risk (Abon et al., 2012). However, community engagement across the four EWS elements (Figure 6.2) is still inadequate, with a tendency for involvement to be limited to the 'response' (Figure 6.2d) element (Sufri et al., 2020). Engaging the community in EWS's plays an essential role in reducing the impact of potential GLOFs, and greater efforts should be made to improve community involvement in all EWS elements.

Land in mountain valleys, particularly flat land, is scarce, and thus highly sought after (UNDP, 2015). Over the past few decades, land within likely GLOF runout tracks has been developed, and this thesis shows population here has increased (Figure 4.5). Thus, more people than ever before are exposed to hazards they may not be aware of. This is particularly true in areas where glacial lakes as a hazard are beginning to emerge, such as the Karakoram. Thus, in addition to increasing overall literacy within communities, active GLOF education must be introduced. For instance, installing basic markers to indicate where water levels could reach during a flooding event, or which buildings will be most vulnerable and which will be safe for evacuation purposes under different GLOF scenarios, and which routes should be followed during an evacuation would be a good start. Further, making these visible on maps within community buildings where everyone can see it on a regular basis (e.g. town halls, places of worship) would help start the conversations needed to raise awareness. Whilst tackling national literacy is key, in the interim providing alternative visual communications (e.g. artwork, photographs, basic maps) could be helpful, given visuals are easier for locals to comprehend than scientific models, pamphlets, or aerial plans (Haynes et al., 2007; Shrestha et al., 2016). In Bhutan, the Department of Disaster Management (DDM) organises annual GLOF evacuation drills for communities living downstream from dangerous glacial lakes where EWSs are in place (Shrestha et al., 2016). I acknowledge that spatial literacy (i.e. the ability to read and interpret maps) is generally poor outside of the field of geography, thus the use of even basic maps would still require some education and guidance. Clear authoritative involvement is crucial for ensuring long-term success of EWSs and whilst moves are being made elsewhere, such as in Northern India where the District Disaster Management Authority (DDMA) has been fully integrated into their risk framework (Allen et al., 2018) other regions should look to obtain such support.

6.4.1.1.4 Response capacity

Chapter 4 explored how improving vulnerability to GLOFs impacts may dampen the increases in GLOF risk driven up by exposure and hazard, given the overall increase in GLOF risk has mostly been slower than increasing exposure and/or hazard in each mountain range between 2000 and 2020 (Figure 4.10). Given the change in spatial distribution of glacial lakes predicted across HMA (Figure 5.4) the concept of risk perceptions within vulnerability will become increasingly important, particularly for the western nations where glacial lakes are likely to form upstream of communities that have not yet been exposed to GLOF hazards (Figure 5.2). I therefore suggest it would be valuable to include a measure of risk perception within future vulnerability assessments. People's perception of risk, and therefore, their response to adaptation measures is influenced by a complex mix of social factors such as livelihood, exposure, spirituality, and religious beliefs, that all shape an individual's evaluation of their vulnerability to glacial hazards (Thompson et al., 2020). Some mountain communities will have adopted strategies to live with the natural hazards and risks that are endemic to the region (Dahal & Hagelman, 2011), and thus, may be wary of new strategies proposed by external sources. Previous exposure (or not) to GLOFs, absence of outbursts and 'cry-wolf' effect from failed EWSs can all reduce risk perceptions. For EWSs, the ability of people at risk to appropriately respond to warnings issued is perhaps the most critical element (Figure 6.2), but also the most susceptible to failure as the last element in the chain that is highly influenced by risk perceptions (Huggel, Cochachin, et al., 2020). Gaining a better understanding of how GLOF risk is perceived within communities at risk would help make mitigation more effective and could be achieved through questionnaires/surveys or focus groups in areas identified as having high GLOF hazard.

In areas where risk perception is identified as being low in the initial vulnerability assessments, taking a community-focused approach would be most valuable; it has been shown that engaging even a handful of community members with the monitoring and mitigation of GLOFs increases the overall community compliance with evacuations and other remedial policies such as land-zoning (Bower et al., 2022), as residents are more likely to trust one another than outsiders (e.g. scientists, NGOs, government members). As such, exposing locals to GLOF hazard and educating them on the potential impacts an outburst could have on their livelihoods would provide a basic starting point, whilst increasing involvement with mitigation planning and implementation would give residents a sense of authority that could help reduce vulnerability, and lessen the reluctance to evacuation seen so often in high mountain areas (Khanal & Koirala., 2009; Thompson et al., 2020). Making GLOF risk more visible in addition to exposing and educating more vulnerable, younger generations who perhaps have never experienced GLOFs could help promote a safer and more resilient culture within the community, reduce fear, whilst also ensuring the success and longevity of socioeconomic development in high mountain regions.

In basins where GLOFs have not yet emerged as a prominent hazard but are projected to over the coming decades (see Chapter 5), communities will be faced with a unique situation of raising perceptions of risk from zero; globally this type of scenario is rare, as often there is a starting point to work from, with already known hazards shifting spatially or in magnitude. In the case of emerging GLOF hazard, communities will be preparing for an event they cannot begin to imagine, similar in theory to the concept of 'Black Swan events' (Dindarian, 2023); in short, preparing for the unexpected. Within this framework, a focus on increasing resilience is key, and the first step is often suggested as identifying potential emerging risks and assessing them – of which this thesis provides – before embedding these findings within decision making processes to reduce or neutralise the impact of Black Swan event. In the contexts of GLOFs, knowledge bases already exist elsewhere, so work must look to share this with those yet to be exposed to GLOF hazard if future disasters are to be avoided in future glacial lake basins.

6.4.1.1.5 Future of EWS

With Chapter 4 showing GLOF risk has increased over the last 20 years and Chapter 5 indicating this trajectory is likely to continue at least for HMA, moving forward the design and implementation of EWS will require adaptation if they are to remain a viable and effective mitigative tool. When designing and implementing future EWS, protocols should look at all four stages of the system (Risk Knowledge, Monitoring and Warning, Dissemination and Comunication and Response Capacity), and seek to achieve the following:

1. Make risk **VISIBLE AND RELEVANT** (E.g. through monitoring, data sharing, knowledge dissemination across all stakeholder levels, media).
2. Make warnings **EARLY AND ACCURATE** (E.g. through identifying appropriate sensors, reducing communication pathways, automating systems).
3. Make knowledge **ACTIONABLE** (E.g. through education, practise evacuations).

It is critical that both local authorities and residents understand that an EWS cannot reduce risks to zero – the main objective is to avoid harm to human lives. There is a danger with the installation of hard engineering such as EWSs for complacency, where installation often results in a false sense of security that increases vulnerability rather than reducing it (Dahal, 2008; Dahal & Hagelman, 2011). As an example of an accommodation strategy - allowing communities to 'live with the hazard' (IPCC, 2019), achieving the three steps outlined above would significantly enhance the effectiveness of EWS, and guarantee the longevity of EWS as a risk reduction strategy.

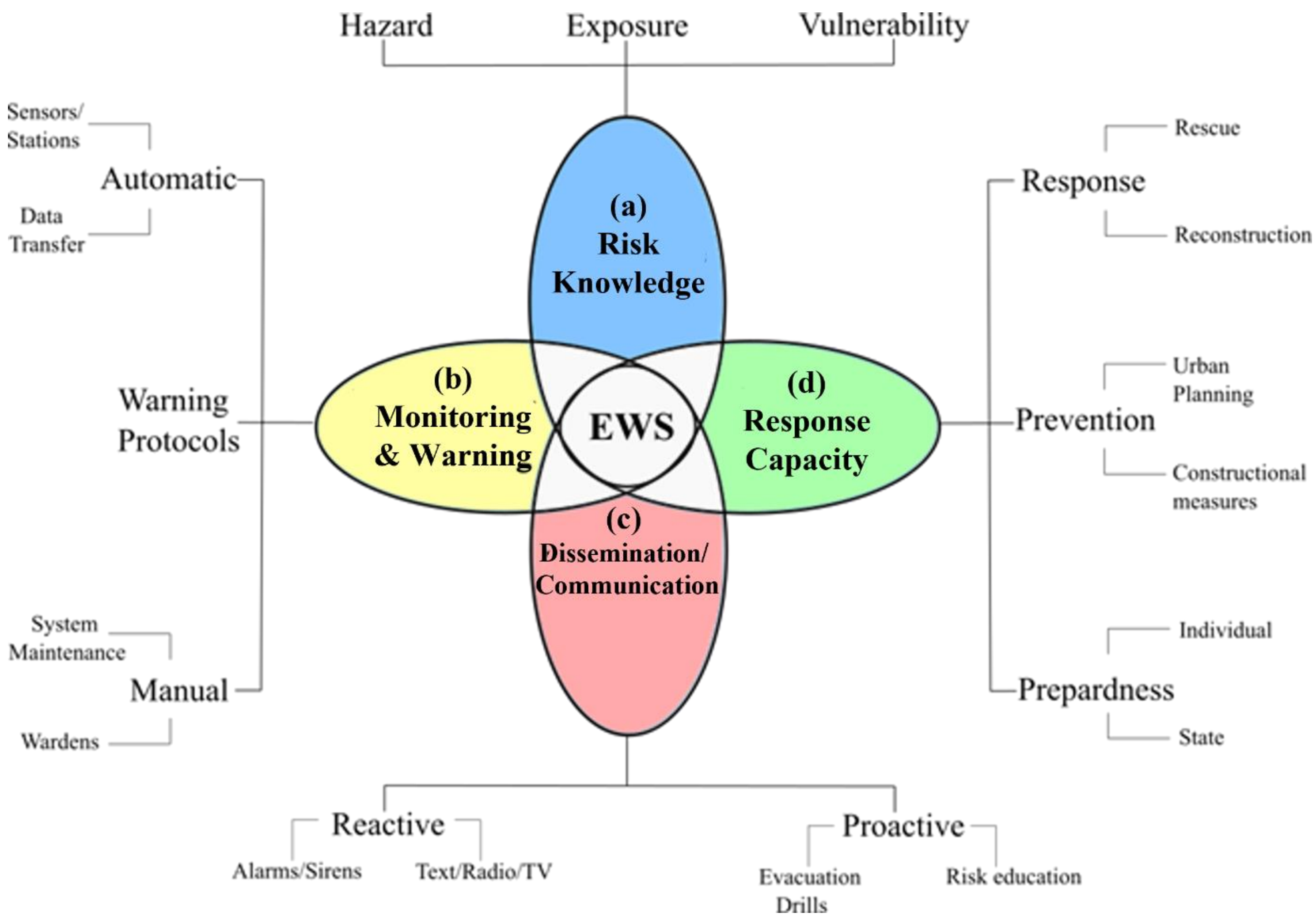

Figure 6.2: Elements of an effective early warning system. Design, organisation, and operation of an EWS comprised of four key elements; a) Risk Knowledge, b) Monitoring and Warning, c) Dissemination and Comunication and d) Response Capacity. Adapted from Huggel, *et al.* (2020).

6.4.1.2 Sustainable development in mountain regions

Until recently, mitigating the impacts of GLOFs has primarily been 'structural' – deploying technical or engineered solutions to reduce risk through managing the hazard (Frey et al., 2018). Meanwhile, the development of community-based mitigation strategies has been largely overlooked. Under continued climate warming, and as glacial lakes continue to expand and proliferate across mountainous regions in response to glacial retreat (Carrivick & Tweed, 2013; Allen, Linsbauer, et al., 2016; Lei et al., 2018) GLOF risk and the frequency of outbursts may increase (Zheng, Allen, et al., 2021). This is exacerbated by increasing population exposure and the expansion of communities, hydropower, and other critical infrastructure in downstream valleys (Dimri et al., 2021); the results of this thesis show that over the last 20 years (2000-2020), exposure to GLOF in HMA increased by 2.2 million, with 13% of this increase occurring along likely GLOF runout tracks within 10 km of a glacial lake (see section 4.3.1.2). Thus, implementing structural mitigation at all potentially dangerous lakes will become increasingly costly and, given the spatial scale of the issue, impractical. Arguably, communities living downstream of potentially dangerous glacial lakes are the most important stakeholders in risk reduction strategies, and yet risk knowledge is rarely shared with them. A shift towards more community-based, or bottom-up, risk reduction approaches that are easy to implement, low cost and feasibly understood and adoptable by local people could offer a more practical, and sustainable option that could be as effective in reducing the impact of GLOFs. If residents can feel the necessity, understand the functionality, and implement the strategies into their day-to-day lives' communities living with the threat of GLOF can begin to move towards long-term, sustainable GLOF risk mitigation. This approach can be challenging however, given the scale of the issue; a single glacial lake runout track can have multiple different 'communities' that all need to be integrated into mitigation plans, with this repeated across all the basins identified as being high risk. Further, this approach requires full community buy-in and the development of trust, which are both hard and time consuming to obtain. Thus, whilst a valuable approach that should be encouraged, consideration must be given to the time and commitment needed for this approach to be effective.

Across HMA, this thesis found populations are moving closer to glacial lakes than elsewhere globally; of the total 2.2 million increase in GLOF exposure between 2000 and 2020, more than half (57%) was within 25 km of a glacial lake and near 300,000 (13%) within 10 km (Figure 4.5). Although it may not be ideal for populations, in an ideal risk reduction plan, exposed populations and infrastructure here would be moved outside of flood pathways (Carey et al., 2012) and future habitation and development prevented. In mountainous regions across the globe, flat land suitable for development is scarce, thus communities, and infrastructure tend to be concentrated in river valleys, highlighted by the spatial distribution of exposure in Chapter 4. Thus, the impact of GLOFs can be severe, with national scale implications (Dorji, 2021). Land-use planning of settlements and infrastructure distribution management if well planned should not only be able to respond well to disaster, but also have the capacity to adapt to it (Dorji, 2021), leading to long-term resilience and sustainability to the threat of existing and future GLOF. GLOF hazard zonation mapping should be made a compulsory prerequisite for land use planning in all areas along river basins of potentially dangerous glacial lakes, as is being implemented across Bhutan (Dorji, 2021). Denoting zones of susceptibility to GLOF impacts, zonation maps classify the area into high, medium, and low risks which then guides planners in assigning appropriate land use (Dorji, 2021). For example, in Khuruthang, Bhutan, high, medium, and low risk denotes zones where development is prohibited, regulated or informative, respectively. Such strict enforcement may not be possible in all regions, particularly where high levels of corruption exist (Figure 4.8). Further, a multi-hazard assessment approach should be taken, where the movement of people away from GLOFs is viewed in the context other surrounding hazards.

Further, a measure of GLOF frequency here would be needed, with consideration given to the likelihood of repeat outbursts compared to once in a lifetime events, which would inform on potential policies deployed. Thus, whilst an ideal risk reduction strategy, basin-scale situations must be fully considered. In basins where glacial lakes have not yet emerged but are projected to as shown in Chapter 5, land zonation could be used as a powerful planning tool, allowing development in these basins to be managed to prevent exposure from increasing further. Implementing policy for a hazard not yet present would be difficult, thus we need more constrained timelines for when these glacial lakes are likely to form, through the likes of targeted modelling, to better understand when to implement these strategies in these future glacial basins.

To mitigate GLOF risk over the coming decades, ideal risk reduction strategies should aim to base future settlement planning on a detailed risk and vulnerability assessments of the planning area and its context, with no construction of habitable structures allowed in areas falling in identified ‘red zones,’ whilst appropriate structural and precautionary measures should be put in place in the areas falling in 'yellow zones.' Studies such as the one presented here, where high-risk basins are identified, could help to direct this hazard zonation, providing a basic indication of where the impact of GLOFs would be severe and where should be prioritised. However, implementing and enforcing strict land policy where habitable land is limited will have substantial barriers, and is by no means sustainable if people are unable to move elsewhere or unable to support themselves economically if forced to do so (Dorji, 2021). In fact, this can present new risks within communities (e.g. economic and material losses, decreased social standing, abandonment of homeland, (Carey et al., 2012)). As such, community involvement in the hazard mapping process will be critical to ensure their social and economic needs are fully understood and integrated into plans.

This thesis highlights GLOF hazard may play a key role in driving GLOF risk across the European Alps, most nations included in the High Arctic and Outlying Countries Mountain range and a handful of others globally such as Nepal and Bhutan (Figure 4.12, Figure 4.14). Therefore, should the number and area of glacial lakes across these regions continue to increase (Figure 3.4, Figure 4.2) hazard mitigation will be needed for risk reduction. Implementing hard-engineering measures to mitigate the hazard for all high-risk lakes would entail significant costs; the cost of artificially lowering Thorthormi Lake in Bhutan and the Tsho Rolpa Lake in Nepal ranged from $1 million to $3.2 million per lake (Asian Developement Bank (ADB), 2014). As of 2020, there are 153 glacial lakes in Nepal (Figure 4.2). If all these lakes needed to be mitigated structurally, like at Tsho Rolpa, the cost is likely to be in excess of what is feasible nationally. Moving towards more sustainable GLOF risk management we need to undertake careful cost-benefit analysis; if the costs of the structural mitigation far outweigh the cost of the losses and damage the GLOF may inflict, then alternative measures may be more appropriate. For example, there are three potentially dangerous glacial lakes in the Mangde Chhu Basin (basin ID:11501110201 in this study) in Bhutan (NCHM, 2019), however, exposure here is relatively low (~10,000 people living >25 km along glacial runout tracks) and another study shows there are not a substantial number of settlements or large infrastructural developments that could be impacted by a potential outburst (Dorji, 2021). Thus here, engineered mitigative strategies may not be needed, allowing funding to be directed elsewhere. However, it is only by detailed risk assessments where hazard, exposure and vulnerability are assessed in conjunction, as presented in this thesis, that we can begin to implement appropriate and sustainable solutions that are also economically sustainable. I suggest future studies look to integrate other measures of exposure, including building number and type, hydroelectric power projects, number of livestock etc. to better refine exposure to likely GLOFs that can be used to refine cost-benefit analyses for hazard mitigation.

6.4.1.2.1 Mountain infrastructure

Many high mountain regions have begun extensive hydroelectric schemes, with the growth of hydroelectric power projects proliferating over the last decade (Schwanghart et al., 2016). Situated at high elevations close to glacial lakes, and with future lakes projected to form at even higher elevations in HMA (Figure 5.5) the threat from GLOFs will continue to evolve, and the potential social and economic disruption could be catastrophic; in Bhutan near 100% of national electricity is generated through hydroelectric means, with many stations paid for in loans from India, thus damage to just one hydroelectric power project could have wide-reaching implications beyond just the immediate downstream. Development of infrastructure in mountain regions (e.g. HEP, roads, airports, railway) thus urgently requires both better regulations as to where they can be built, but also evaluation of existing facilities to determine which are at high risk of GLOF impact and how they could be protected to avoid major implications. The approach taken in this thesis could be used to identify high risk basins, from which future work could be focussed; whilst this thesis used population only as a proxy for exposure, there is potential for expanding this approach to include other downstream metrics, such as number of bridges, buildings, land-use etc. This could be conducted at national or basin scale to gain a more granular picture of critical infrastructure and potential downstream impacts and could integrate tracking methods e.g. smart phones to identify most used infrastructure.

6.4.2 Vulnerability

Over the past few decades, tourism has proliferated across high mountain regions (Gardner et al., 2002; Uniyal, 2013), resulting in increased exposure and vulnerability in many high-risk regions (Motschmann, Huggel, Carey, et al., 2020; Hock et al., 2019; Schwanghart et al., 2018). Emerging glacial lakes offer desirable benefits for alpine tourism (Drenkhan et al., 2019; Haeberli et al., 2017), generating revenue for both local and regional economies (Masiokas et al., 2020). With lakes existing in regions where development of infrastructure for tourist purposes (e.g. roads, trails, hotels) may be less well regulated, infrastructure is often not adapted to GLOF hazard. For instance, the removal of vegetation along river channels for development has significantly reduced the natural flood buffer, further increasing the risk of GLOF impacts (Ziegler et al., 2014; Sattar et al., 2021). Tourism is now the primary source of income in many mountain regions; since the creation of the Sagarmatha National Park in Nepal in the 1950s, tourism has emerged as the primary source of both local and national income (Thompson et al., 2020). For example, in the town of Khuruthan, located in western Bhutan, revenue generated from shops, hotels and taxi services from tourists near-entirely supports the local economy (Shrestha et al., 2016). High mountain tourism now acts as a major source of income, providing direct and indirect employment across many regions globally (Palomo, 2017); in 2018, mountain-specific tourism in Nepal accounted for 8% of the country's Gross Domestic Product (GDP) and supported >1.05 million jobs (Sah et al., 2021). As a result, many locals continue to live in, or move specifically to, areas known to be dangerous, due to relying on tourism as their permanent income, where incomes are often higher than previous locations or occupation. Whilst tourists represent a temporary increase in vulnerability, their exposure is generally short-lived, whereas the increase due to permanent exposure of locals supporting the industry is a greater concern, with infrastructure not designed with hazards in mind and risk management schemes often not implemented to protect them from hazards. Here, a greater importance on sustainable development in mountain regions is needed, to allow continued economic development in the face of GLOF hazard.

As a transient population, tourists themselves are generally considered more vulnerable to natural disasters due to their lack of awareness and familiarity with **a)** the hazard in the environment, **b)** the available risk reduction strategies and/or resources and **c)** EWS and evacuation plans, instead relying heavily on tourist operators and local residents to translate information (Ritchie, 2008; Ziegler et al., 2021). There are several documented examples of where GLOFs have had major impacts due to unusually high exposure and vulnerability of tourists (Allen, Linsbauer, et al., 2016); several thousand religious pilgrims were killed during the 2013 Kedarnath glacier flood (Uttarakhan, India) due to lack of awareness and inability to understand warnings (Kala, 2014). Thus, sustainable development of tourism in high mountain regions at-risk of GLOFs not only requires more stringent planning protocols for infrastructure, but also a consideration of increased vulnerability of these transient folk. Tourism also presents both a time-variable and spatially variable role on risk, with seasons differing globally (e.g. ski season in the Alps will be different to South America), as well as locally (trekking season different to ski season) and with certain 'hotspot zones' attracting higher footfall than others. As the number and area of glacial lakes and the exposure to them continues to increase, it will be critical that risk reduction strategies integrate tourism into protocols, allowing for dissemination of information to these more vulnerable transient as well as ensuring mitigation strategies are temporally considerate. Substantial risk reduction and adaptation strategies will be required to avoid future disaster (Zheng, Allen, et al., 2021) and could begin to be implemented now, before the threat of GLOF fully emerges.

6.4.3 Hazard

While hazard assessments typically dominate GLOF risk studies (Kougkoulos et al., 2018), vulnerability assessment and adaptation in the broader context of retreating glaciers and natural hazards remain relatively new topics. Having shown the importance of vulnerability and exposure for driving GLOF risk in Chapter 4, this needs to be further addressed in most regions; especially those located in developing countries where datasets are lacking or incomplete (Vuille et al., 2018). Effective and sustainable GLOF risk management must be based on detailed assessments of societal impact and response that requires long-term, local-scale data (Huss et al., 2017). Such data is often missing, be it for climate, glaciologic, hydrologic or socioeconomic aspects, presenting a major obstacle for developing sustainable mitigative measures (Vuille et al., 2018). This data scarcity, particularly across western HMA and the Andes remains a significant issue that urgently needs addressing. In many cases, records are not long, or detailed enough to determine trends, frequency, or magnitude of GLOFs themselves or the triggers that cause them (Salzmann et al., 2013). Records of glacial lake growth are incomplete, thus how lakes have evolved over time, or how they might be expected to evolve in the future is difficult to determine (Zemp et al., 2019). Moving forward, there needs to be a prioritisation of long-term monitoring and a widespread collation of data to open-access sharing platforms (Salzmann et al., 2013) to enable forward planning and proactive- rather than reactive- risk mitigation. This thesis begins to bridge a gap in this knowledge by identifying high risk basins which I suggest could be targeted for more detailed, long-term monitoring and highlights a significant gap in glaciological data across the Andes and Pakistan.

6.4.3.1 Data scarcity in the Andes

This thesis identified the Andes as having the second most rapidly increasing, GLOF risk globally (section 4.4.2). With a long history of GLOFs (Lliboutry et al., 1977; Carey, 2005; Emmer et al., 2020) the observed increase in GLOF risk over the last 20-years is concerning, particularly given data on hazard, exposure and vulnerably is sparse across the region (Vuille & Bradley, 2000; Salzmann et al., 2013; Wilson et al., 2018; Harrison et al., 2018). The first major uncertainty in GLOF risk in the Andes relates to glacier retreat and lake formation and growth. Research has documented twentieth-century glacier retreat and glacial lake formation across key regions such as the Cordillera Blanca, especially for the last three decades, but there remains relatively little information on previous periods (Georges, 2004; Mark & Seltzer, 2005; Racoviteanu et al., 2008; Silverio & Jaquet, 2005) or projections of future glacier retreat. In the Alps and HMA, methods have been developed to project sites of future glacial lakes using techniques of different complexity to assess ice thickness and detect glacially over deepened areas (Frey et al., 2010; Furian et al., 2021, 2022; Magnin et al., 2020). Whilst clearly subject to uncertainty as to the timing and actual formation of glacial lakes, it is useful for expanding scientific knowledge and forecasting trends, as demonstrated in Chapter 5 of this thesis. With the exception of work by Emmer *et al.* (2020), this type of data on future glacial retreat and lake formation is lacking in the Andes (Carey et al., 2012), yet well-developed techniques could be applied to the region to indicate approximate timing and dimensions of future glacier retreat and allow for more relevant mitigative strategies to be implemented early. For instance, radar surveys could be used to obtain ice geometry data required for the numerical modelling of future glacier change as well as to identify and quantify overdeepenings as possible locations of future lake area and volume (Furian et al., 2021).

Across the Andes, data related to GLOF triggers (e.g. rock slope failures, ice avalanches, moraine failures) are rare, due to scarce climatic, glaciological, and geological data, coupled with a limited understanding of how the stability of steep ice and bedrock will respond to climatic warming and glacial retreat (Carey et al., 2012). It is well known that long-term warming and climatic extremes (both temperature and precipitation related) can impact slope stability in glacier and permafrost environments (Gruber & Haeberli, 2007; Huggel, 2009). However, prediction of the exact location and timing of slope failures is virtually impossible. Consequently, forecasting mass movement events that could trigger a GLOF is difficult (Hegglin & Huggel, 2008; McKillop & Clague, 2007) limiting our ability to accurately identify locations and timings of potential GLOF events. To accommodate this uncertainty, within the adaptation and risk reduction framework improving the long-term monitoring of environmental changes around glacial lakes should be prioritised.

6.4.3.2 Data scarcity in Pakistan

Outside of the Andes, this thesis has also highlighted Pakistan as an emerging hotspot for GLOF risk (Chapter 3: Figure 3.10). Driven primarily by rapidly increasing exposure close to existing glacial lakes (Figure 4.6), projections suggest GLOF danger here could be highest globally by 2060 (Figure 5.10). Nationally, Pakistan faces special challenges for GLOF hazard mitigation given the high altitude, isolated nature of glacial lakes and communities exposed to them (Ashraf et al., 2012). In addition, glacial lakes here are predominantly ice-dammed (Bhambri et al., 2019) thus, mitigative strategies will differ from neighbouring regions and requires a locally focussed approach. Between 2007 and 2008, five GLOFs were recorded in the Hunza valley alone, causing severe social and economic damage (UNDP, 2015; Ashraf et al., 2012). Such high return frequencies demand better hazard assessments, risk reduction strategies and mitigation, yet with no formally recognised governmental support, community response is generally still one of 'self-help' – with many communities using traditional methods such as torch lighting to warn of impending floods (Ives et al., 2010). This lack of resources, coordination and specialist knowhow severely limits effective community response to GLOFs, thus there is a need to create awareness of flood hazard preparedness and risk reduction among targeted communities and key stakeholders, to impart specialized training and capacity building for hazard mitigation and risk management (Ashraf et al., 2012). Given the lack of long-term data across Pakistan regarding glacier retreat, lake development and expansion, GLOF triggers (Hock et al., 2019) and with Chapter 5 showing a projected shift in GLOF danger towards the region (section 5.4.1: Figure 5.10), we need more targeted hazard studies here to manage future GLOFs.

6.4.3.3 Simplification of hazard

Within natural hazard research and practise, hazard is defined as a function of the *intensity* and *probability* of an event, i.e., the overall magnitude of the event combined with the likelihood that an event will occur from a given site based on intrinsic properties and dynamic characteristics of that site (GAPHAZ, 2017). Assessing hazard of glacial lakes for such a vast number of lakes that exist at differing elevations and in different environmental settings thus requires a strong simplification, and here was done so in two parts. First, the 'intensity' metric is simplified by using the area of glacial lakes as a proxy under the assumption that larger area lakes would lead to a higher intensity outburst flood. Whilst other studies favour the use of glacial lake volume over area, that approach requires either detailed bathymetric data or the application of an area-volume relationship equation to convert area to volume (e.g. Zheng *et al.,* 2021). The former is simply not available at the global scale whilst the latter often utilises estimations and is thus subject to a high degree of error. Lake area is an often-used proxy for lake depth (and volume) and thereby a suitable representation of potential flood magnitude at the global scale (Huggel et al., 2004).

Here a 50 km runout distance from the source was designated as the maximum impact zone, following a previous approach in a study on GLOF risk in the Indian Himalayas by Dubey and Goyal (2020). The maximum downstream travel distance for each GLOF path is commonly determined using an empirically derived worst-case scenario defined by the angle of reach from the source lake, often chosen to be 2° or 3° (Huggel et al., 2004). Beyond these worst- case run-out distances, severe damages are not expected. At a global scale, defining the worse-case scenario for each glacial lake is unfeasible, with the range of reach angles too great to warrant the use of one common value. I appreciate the 50 km runout chosen is a strong simplification, and one which potentially overestimates, or underestimates runout distances given literature for the Cordillera Blanca and HMA indicate much shorter distances (12 km and 22 km, respectively). However, I argue that for an analysis such as ours, some consistently applicable value needs to be defined. Further, as the study focusses on the impacts of GLOFs on downstream communities, it is better to be conservative than to miss areas that could be at risk. Future work could then be undertaken to determine more accurate runout distances if the area is identified as being at-risk. I also note that taking a larger distance than previous averages accounts for increasing hazard from GLOF due to increasing lake area, which suggests future GLOFs could be expected to have longer runout distances comparative to previous events. This is particularly noteworthy given Chapter 5 focusses specifically on future GLOF risk.

Second, the probability of a GLOF occurring at a given point in time is dependent on specific local conditions, including topographic triggers (ice/rock/snow avalanche etc), lake-dam geometries, lake area/volume etc. (Allen, Linsbauer, et al., 2016; Allen et al., 2019; Dubey & Goyal, 2020; Zheng, Allen, et al., 2021). Thus, accounting for all parameters for each of the 1089 identified glacial lake basins globally goes far beyond the scope of this study. Previous works (e.g. Zheng *et al.*, 2021) used inputs from landslides and ice avalanches to estimate outburst frequency. However, this approach is reliant on high resolution DEMs that are well known to suffer artefacts at higher elevations where glacial lakes are found (Bolch & Loibl, 2017). Further, whilst mass movement events are the primary trigger for outbursts globally, this method does not account for other causes of failure (e.g. moraine degradation, meteorological) and is therefore not applicable at the global scale. Considering this, I assume all glacial lakes have the potential to fail at some time in the future, using the area as a proxy for intensity, and focus on quantifying the impact of this failure on downstream communities. I therefore accept the approach here is a simplification, however at the global scale allows GLOF hazard to be quantified in relation to exposure and vulnerability, of which remain relatively understudied within GLOF literature. I suggest the findings of this study could now be used to target more detailed assessments, where lake-specific parameters for intensity and probability are assessed in order to build a more granular picture of risk.

6.4.4 Risk

6.4.4.1 Temporal variations in risk

Hazard, exposure, and vulnerability all change over a range of timescales; thus, risk also varies temporally. In existing risk assessments, exposure is often taken as static (e.g., Rounce *et al.* (2016) assumed mapped buildings had permanent occupants) and vulnerability often not quantified (Mal *et al.,* 2021; Zheng *et al.,* 2021). Whilst Chapter 4 and Chapter 5 do evaluate change over time, the data used do not consider short-term temporal changes and thus present a static version of risk at a particular point in time. In reality, risk is likely more transient, changing over finer temporal resolutions, such that the degree of awareness and mitigation needed at different points in time likely varies on a range of temporal scales. For instance, in Huaraz, Peru, ~22,500 people reside in zones exposed to potential GLOFs, however because this zone includes the central business district and marketplace the number of people present during the day is much higher, with estimates indicating as much as 50,000 (Huggel *et al.*, 2020). Seasonal tourism for trekking, mountaineering, skiing etc. also increases the number of people exposed to GLOFs each year: in 2014 more than 100,000 tourists visited Nepal, with 30,000 of these visiting the Khumbu region in the Dudhkoshi Basin, Nepal (Khanal *et al.*, 2015); the Huascaran National Park in Peru annually receives over 180,000 visitors; whilst in Norway glacial related tourism attracts up to 30,000 visitors per year (Palomo, 2017). Not only does this increase the number of people exposed to a potential GLOF, but inevitably elevates the vulnerability of the community as visitors may not speak the language, are unlikely to be aware of GLOF risk or be familiar with response protocols (Drabek, 1999; Cutter *et al.,* 2003).

Vulnerability to GLOFs likely varies temporally too, for instance communities reliant on glacial meltwater as a source of clean drinking water are likely more vulnerable during dry seasons where availability is reduced, however as yet no study has explored the impact of this on overall risk. Efforts need to be made to better quantify spatial and temporal variations of exposure and vulnerability to GLOFs. The use of mobile phones for tracking exposure could be an option whilst increasing the detail and frequency of census reports could be beneficial. In Bhutan for instance, it is a requirement that all mobile phones be registered with the government, thus the number can be monitored closely, and in 2014 official figures list 568,527 phones, the equivalent of one phone for every inhabitant above the age of twelve (Orlove, 2016). Whilst not exact, it does provide a good indication of exposure, and could be used in other locations for monitoring purposes, however I acknowledge this type of monitoring would raise vast ethical and privacy issues.

Seasonal to daily variations in GLOF hazard, exposure, vulnerability, and risk are difficult to quantify at a global scale and to date, no such study has investigated the impact of this temporal variability on GLOF risk. However, understanding these temporal changes in hazard, exposure and vulnerability could be fundamental for sustainable risk mitigation; knowing when monitoring and intervention might be more pertinent or placed on 'higher-alert' versus when community-based awareness and knowledge dissemination may suffice would allow for more targeted and appropriate resource deployment. This will be particularly important in regions where resources are limited (Carrivick & Tweed, 2016). Several studies have highlighted an apparent temporal pattern in GLOF occurrence globally, with outbursts generally occurring during warmer, wetter periods characteristics of the ablation season (Harrison et al., 2018; Veh et al., 2019; Nie et al., 2018; Falátková, 2016). Many GLOF triggers undergo seasonal trends; a recent study (Taylor et al., 2021) showed supraglacial lake drainage is higher during the monsoon and post-monsoon season in HMA, whilst the frequency of mass movement events has been seen to increase during the ablation season (Richardson & Reynolds, 2000a). However, few studies have looked at temporal variations in exposure or vulnerability in detail due to the difficulties in obtaining accurate datasets, thus the ability to determine temporal variations in risk is poor. This issue could be tackled through integrating the likes of high-resolution hazard monitoring alongside smart phone data, with basins identified in this thesis as being at high risk suggested as starting points for implementing this type of monitoring.

6.4.4.2 Promoting interdisciplinarity

As a relatively new addition to GLOF studies (ICIMOD, 2011), the human dimensions of GLOF risk are generally underrepresented in natural science literature (Emmer, 2018). If future GLOF risk mitigation strategies are to be sustainable as the exposure of people, infrastructure and services continues to increase at high elevations close to glacial lakes, a better consideration of the cultural, spiritual, and religious values the local people associate with glacial lakes and high mountain environments, alongside local and indigenous knowledge will be needed (Haeberli and Drenkhan, 2022). Here, empowering local and indigenous communities will be crucial. Further, more detailed work is required to understand vulnerability as a driver, or potential dampener, of GLOF risk, to reveal how social variables that make populations more (or less) vulnerable can be equated to GLOF risk. Although the recent increased focus on GLOFs by natural scientists is moving some way to develop understanding, social science or humanities researchers are rarely involved (Harrison et al., 2018; Huggel, Cochachin, et al., 2020). Moving forward, an interdisciplinary approach must be adopted to include these overlooked, yet important, dimensions of GLOF risk, particularly given the results of this thesis highlight how important exposure and vulnerability are for driving GLOF risk changes.

6.4.4.3 Recognising GLOF risk

Although GLOFs as hazards are more widely recognised within the science community, so far GLOFs have not received adequate attention of many governments globally, with the risks posed not factored into development policies and plans (UNDP, 2015). Whilst some national governments, such as Norway and Bhutan, have begun to recognise the importance of GLOFs as a hazard and provide funding for specific policies, elsewhere most funding for GLOF risk reduction projects is dispersed to national government from international organisations (e.g. NGOs) and then distributed via government agencies (Fakhruddin & Basnet, 2018). However, governmental response to GLOF disaster tends to be reactive by nature; unless the threat of GLOF is imminent, funding, and general interest for mitigation or preparation is lacking (Ritchie, 2008). Thus, funding designated for disaster reduction strategies is often not received, with many projects remaining unfunded (Peniston, 2013; Shaw, 2016). For example, in the case of Lake 513, Peru, the relabelling of the lake from ‘potentially dangerous’ to an ‘imminent threat’ by scientists was finally incentive enough for governments to devote funding and resources to the mitigation project despite very little physical differences reported (Carey et al., 2012). This lack of governmental interest, alongside corruption within governmental systems remains a key barrier in many high mountain regions (Thompson et al., 2020), leaving local people to use their own lived experiences, knowledge, and resources to reduce risk (Ashraf et al., 2012). As the risk posed by GLOFs increases over the coming decades, improving the response capacity of governments both pre- and post-disaster will be crucial for sustainable risk management. Here, a focus on four key stages of disaster management could be beneficial (Figure 6.3a): **(a)** Preparedness, **(b)** Response, **(c)** Recovery and **(d)** Review.

Improving preparedness at the national scale (Figure 6.3a), through the likes of emergency planning, drills, training would reduce vulnerability of citizens and thus risk. Here, governmental involvement in hazard knowledge and communication with scientists and engineers to identify high risk areas will be paramount for implementing effective hazard mitigation strategies. In areas where the number of people living close to glacial lakes continues to increase (e.g. Pakistan, India), land-use planning could offer an effective mitigative strategy but will require an in-depth understanding of the local environment, as well as acknowledgement of the socioeconomic needs of citizens. By providing incentives, financial or otherwise, such as tax breaks, grants/loans to cover relocation costs alongside better insurance policies, governments could encourage compliancy with zoning regulations, making communities more prepared for GLOF disaster. In regions where stakeholders could be negatively impacted by strict zoning, such as agricultural or tourist dependent economies, governmental help to diversify to new sectors could be beneficial. By improving preparedness at the national- not just individual- scale, vulnerability of communities can be successfully reduced and the impacts of GLOFs managed.

GLOF risk can never be removed entirely, however having an efficient post-disaster governmental response (Figure 6.3b) and recovery (Figure 6.3c) could significantly reduce overall GLOF impact. With adequate funding for first responder training, search and rescue can be deployed immediately post-disaster, significantly enhancing survival rates (UNDP, 2015), whilst aid can be distributed to most affected communities within hours, enhancing the individual’s ability to recover. With many GLOFs occurring in remote locations (B. Bajracharya et al., 2007; Dubey & Goyal, 2020) reconnecting water and electricity, and repairing roads and bridges is critical for social and economic recovery. Following the Lemthang Tsho GLOF in 2015, Bhutan, the army was deployed as part of the response plan, reconnecting lost power within 24 hours, and rebuilding six bridges that were destroyed during the outburst within two weeks (Orlove, 2016). Had the government response not been as efficient, communities could have been left isolated and without power reducing their ability to recover. Moving forward, ensuring nations have clearly defined response and recovery plans specifically for GLOF disaster will be critical for the long-term sustainability of mountain communities and the economic activities being carried out there.

For sustainable risk management, the final stage is the review post-disaster (Figure 6.3d), learning from the event itself, including how effective the emergency plan was and identifying areas for improvements to ensure GLOF risk is managed appropriately as the threat of GLOF grows. Here, involvement of stakeholders at all levels, from national to local, will be important for understanding how best to evolve risk mitigation.

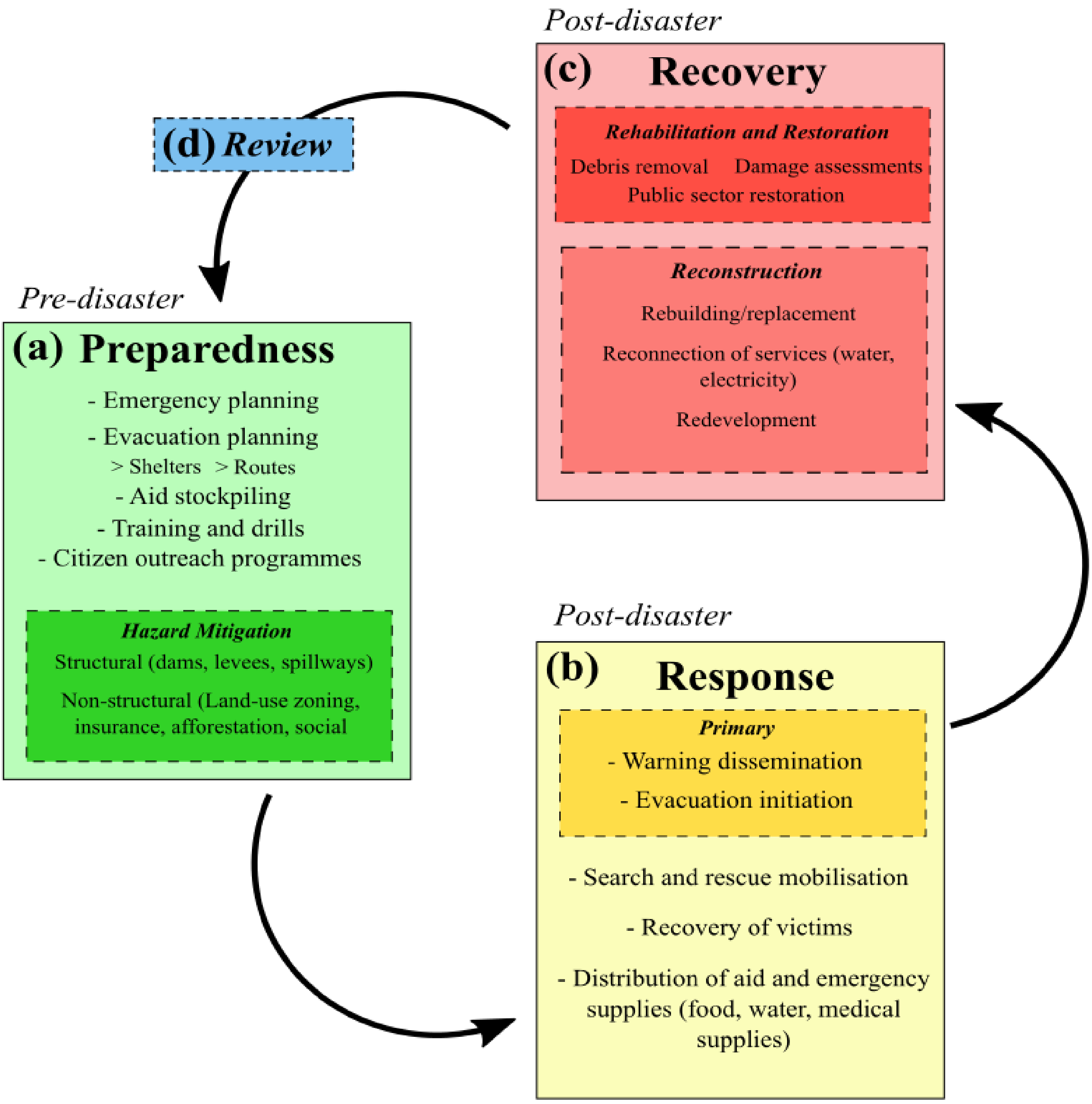

Figure 6.3: Risk management cycle. Cycle of GLOF risk management at the national scale, including (a) Preparation, (b) Response, (c) Recovery and (d) Review. Adapted from (Dahal, 2008).

6.4.4.4 Data sharing and transboundary cooperation

Implementing effective GLOF monitoring, and mitigation must involve the collaboration of a wide range of actors and institutions, including local communities, national governments, regional organisations, Non-governmental Organisations (NGOs), the private sector, and science community (UN, 2006; IPCC, 2012). Despite being a transboundary natural hazard with potential for outbursts to cross international borders, at present there is a tendency for GLOF risk to be managed by individual nations; an EWS installed in the Upper Bhote Koshi valley, Nepal, stretches to the border of China and no further, giving a warning time of just six minutes to the hydroelectric station it was primarily installed to protect (UNDP, 2015). Extending the system into China would make the system more effective but requires a level of national cooperation that has not yet been achieved. As the proximity of people and infrastructure to glacial lakes increases (Chapter 4), and the economic reliance on this infrastructure grows, particularly 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 GLOFs (Zhang et al., 2021), particularly where GLOF runout tracks knowingly cross international borders (Kougkoulos et al., 2018; Nie et al., 2018). One potential way to achieve this would be through the creation of an independently functioning GLOF-focussed disaster reduction team within broader regions (e.g. ‘HMA GLOF Risk Reduction Team’) that could be deployed to effected areas and would not be constrained by national boundaries or economic limits of individual countries. Similar working groups exist for other natural hazards, for instance the International Platform for Reducing Earthquake Disasters (IPRED) is an organisation dedicated to training researchers and engineers in developing countries in the field of seismology and earthquake engineering, producing specific guidelines for mitigating the impacts of earthquakes (UNESCO, 2014).

Over the coming decades, anticipatory action and cooperation will be crucial. Placing a focus on shared risk knowledge, hazard monitoring and warning, dissemination and communication and response capability (Huggel, Carey, et al., 2020) will be fundamental to successful GLOF risk management. Valuable experiences have been learnt through previous GLOFs and the implementation of a variety of mitigation strategies across the likes of the Alps and Andes (UNDP, 2015), and yet little effort has been made to share these experiences internationally. Further, knowledge gained through field and remote studies is rarely transformed into workable strategies to address the risks, primarily due to political, economic, and social barriers. Thus, a wealth of actionable knowledge remains dispersed across individual institutions and organisations. It is imperative this knowledge is collated and synthesised to make it readily available to disaster risk management practitioners, administrators, civil society actors and other key stakeholders to promote actionable reduction strategies across all levels (UNDP, 2015). There are examples of where such collaboration has been successful. For instance, in the Cordillera Blanca, continued monitoring by scientists first identified Lake 513 as potentially dangerous in 1985 and enabled accurate detection of impending outburst risk in 1988 (Carey et al., 2012). Communicating their findings with engineers initiated the immediate installation of several mitigation measures, whilst also motivated the national government to devote resources to the project. The threat posed by Lake 513 was only recognized because of a collation of environmental knowledge and engineering experience from other glacial lakes throughout Cordillera Blanca; without which the Lake 513 mitigation project might have proceeded differently, possibly with catastrophic consequences (Carey et al., 2012). Sharing of relevant engineering practices, appropriate technologies, and specific local knowledge with all stakeholders thus facilitates glacier hazard management and should be a key focus in the future. A GLOF-specific data sharing platform could facilitate this exchange of information, allowing a collation of research findings and learnt-experiences and vastly enhance the ability of individual nations to reduce the impact of GLOFs in the most cost-effective, and appropriate manner. This type of cross-learning and cooperation will be fundamental as we move towards more sustainable risk reduction strategies that will withstand the changes in hazard, exposure and vulnerability that are inevitable in the future.

6.5 Summary

This thesis has successfully quantified the spatial and temporal changes in global GLOF risk over the last 20 years, from regional to basin scale. The key findings (Table. 6.1) findings show hazard, exposure, and vulnerability all play a key role in governing overall GLOF risk, but the relative importance of each varies across spatial and temporal scales, with exposure highlighted as a key driver. Crucially, this thesis shows all three metrics must be included in assessments in order to accurately determine risk, and a move away from hazard focussed research would be beneficial for managing GLOF risk. Results show the Andes to be an emerging hotspot of GLOF risk, and I strongly suggest it be targeted for detailed research. The findings of this thesis contribute to literature through filling an important data gap in GLOF risk understanding and provide a comprehensive platform from which to launch future research projects (Table. 6.2) and better direct future mitigative efforts.

Chapter 7 Conclusions and future research questions

This thesis provides the first global inventory of GLOF risk between 2000 and 2020 that integrates hazard, exposure, and vulnerability. Motivated by a lack of holistic, interdisciplinary risk assessments and understanding of risk drivers, this research contributes to the field by identifying primary drivers of risk growth at the regional and basin scale and highlighting hotspots of high risk. The results of this thesis thus provide the platform for more detailed, high-resolution studies of GLOF hazard and risk.

Results show GLOF risk has varied globally, regionally, and at the basin scale over the last 20 years, with the respective roles of hazard, exposure, and vulnerability varying markedly. Importantly, these findings show that ***increasing hazard is not the sole driver of risk anywhere globally***, and the most at-risk basins do not always host the most, or the largest, glacial lakes. This demonstrates that whilst understanding and monitoring glacial lake hazard is important, for GLOF risk management hazard should not be the primary focus of research. ***Exposure was identified as a key driver of risk worldwide over the period 2000 to 2020***, particularly in HMA, where populations in 2020 are living the closest to glacial lakes than elsewhere globally. Thus, managing exposure increases would be effective in managing risk. Furthermore, in regions where populations are exposed to multiple hazards (e.g. landslides, flooding), managing exposure increases could have wider reaching benefits. Alongside the role of exposure, the global ***decrease in vulnerability was seen to act as a dampener of increasing risk.*** These finding together exemplify the importance of analysing the human aspects of risk, alongside the natural aspects, for GLOF risk management. Thus, future GLOF risk assessments need to integrate hazard, exposure, and vulnerability metrics if GLOF risk is to be accurately understood, and a move towards interdisciplinary cooperation would be the most valuable approach for successful future GLOF risk assessments.

Across HMA, projections indicate under an ice-free scenario, ***3.9 million people could be exposed to glacial lake outburst floods in HMA in the future***, driven primarily by increasing exposure. These results indicate that if left unchecked, increasing exposure of populations close to glacial lakes is likely to have serious implications for future GLOF risk. This research provides useful insight into the potential future of GLOF risk in HMA by identifying areas where drivers are causing rapid GLOF risk increases and could be used to prioritise mitigation in order to manage future GLOF risk. Another key finding is that the area of highest GLOF danger may migrate from the eastern to the western Himalaya, which may have important implications for GLOF management. Comparative to the east, we currently lack sufficient research and databases in these regions to enable targeted management or the identification of trends. GLOF risk needs to be brought to the attention of policy makers and stakeholders across all levels so that communities where GLOF is not currently a threat can continue to develop socially and economically whilst managing the growing risk of outbursts.

The Andes was identified as a hotspot of high- and rapidly increasing-risk, and as of 2020 the second and third most at risk basins were found in Peru and Bolivia, respectively. Here, high vulnerability, increasing hazard and exposure, and a lack of data, knowledge and understanding across the region comparative to elsewhere globally relating to GLOFs prevents meaningful assessments of past, current, and future GLOF risk trends and is a key limitation of GLOF risk management in the region. ***The Andes is recommended as being a priority for future research***, to developing long-term, continuous glaciologic, meteorologic, and social datasets if future GLOF disasters are to be mitigated.

Under a warming climate research suggest we can expect the number and area of glacial lakes in mountainous regions is likely to increase. As glaciers retreat, existing glacial lakes will expand whilst the exposure of topographic overdeepenings will facilitate the formation of new glacial lakes, as demonstrated in Chapter 5 across HMA. In addition, the susceptibility of glacial lakes to GLOF triggers is likely to increase. Exposure of steep, unstable slopes could increase the magnitude and frequency of mass movement events (rock, snow, ice avalanche etc.), whilst the proliferation of lake growth at higher elevations above existing glacial lakes could increase both the likelihood of outburst due to mass movement events as well as cascade events. Thus, irrespective of changes to exposure and vulnerability downstream, outbursts are likely to become more frequent as triggers increase. Finally, the increase in exposure to glacial lakes as shown in this thesis during the period 2000 to 2020 at higher elevations is likely to continue, driven by regional economic development for the likes of tourism and hydroelectric power projects. Together, this could lead to a future of significantly higher GLOF risk. Considering this, and the findings of this thesis, I suggest the following as next steps for GLOF research:

1. **Encouraging collaborative learning and sharing across all stakeholders**
2. **Filling gaps in hazard knowledge, particularly for high-risk regions such as the Andes, with a particular focus on timings of GLOF events**

3. **Promoting holistic risk assessment that integrate exposure and vulnerability metrics alongside hazard to enable continued sustainable development in mountain regions**
4. **Developing more effective, accurate, and actionable early warning systems**

To conclude, this thesis mapped GLOF risk at the global scale for the first time and identified HMA and the Andes as key hotspots of risk. Results show that GLOF risk, and its evolution over the past 20 years, is heterogenous, at the global, regional and basin scale. The findings show that hazard, exposure, and vulnerability all play a key role in governing overall GLOF risk, but subject to a high degree of variation; in HMA exposure is the key driver whilst in the PNW hazard is. Critically, only when all three metrics are included in assessments can risk be accurately determined, with vastly different risk scenarios when one or more metrics are not included. This work is important as it contributes to our understanding of risk drivers, that can help to better direct mitigative efforts. Projections for future GLOF danger in HMA suggest a shift in danger away from the east where it is currently highest, towards the west, where GLOFs have yet to emerge as a well-known risk to communities as new glacial lakes form and the spatial distribution of exposure changes. Overall, this global analysis of GLOF risk provides an essential guide for future studies, so that research can be focused on the highest risk areas and target the key factors driving GLOF risk at those sites, with an emphasis on the role of exposure going forward.

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Appendix A: Supplementary Materials

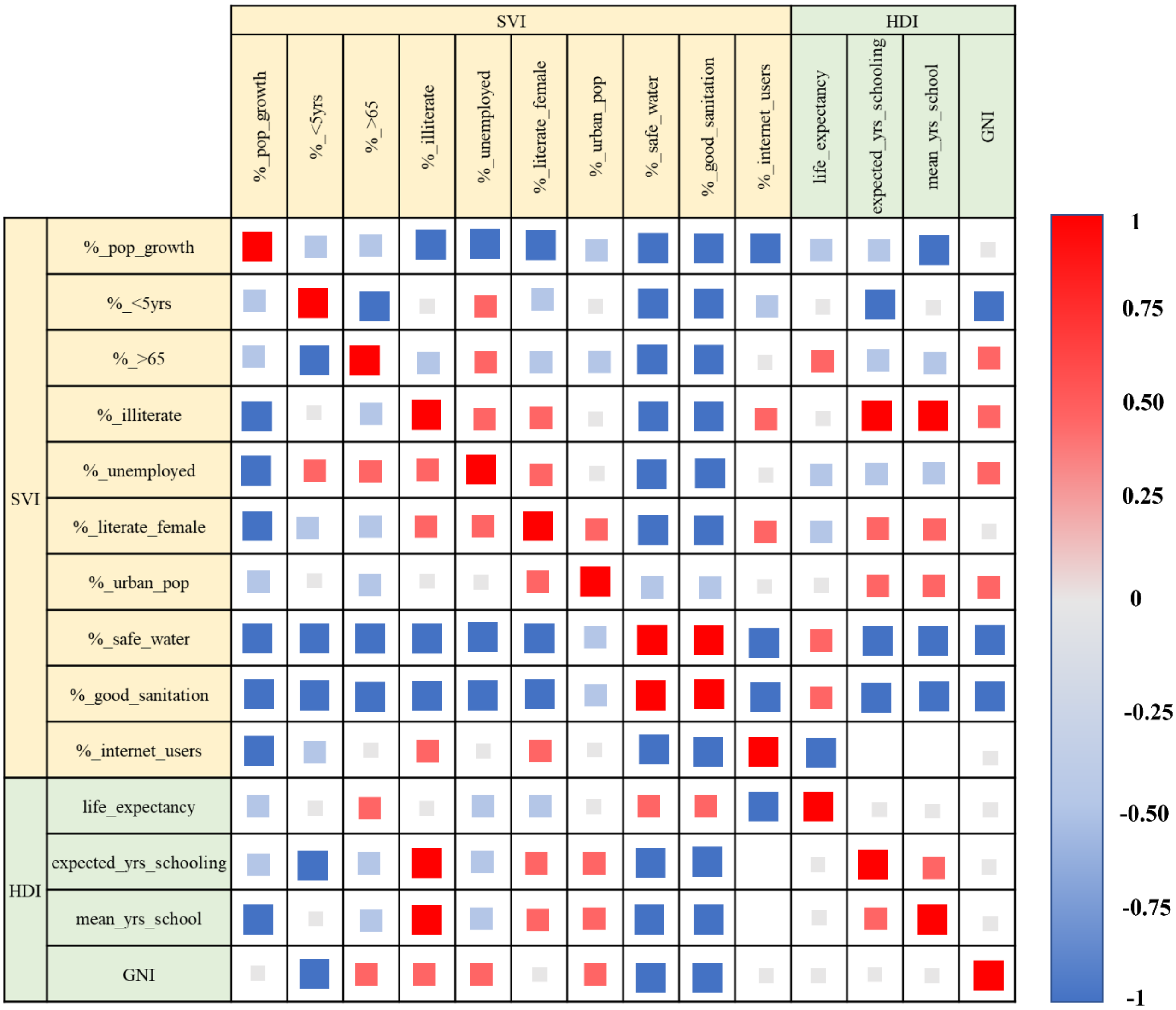

Figure S3. 1: Correlation matrix plot used to select social vulnerability index variables. Correlation plot demonstrating the relationship between variables used to determine social vulnerability index and the human development index. Variables with absolute correlation were discarded from analysis to avoid double-counting.

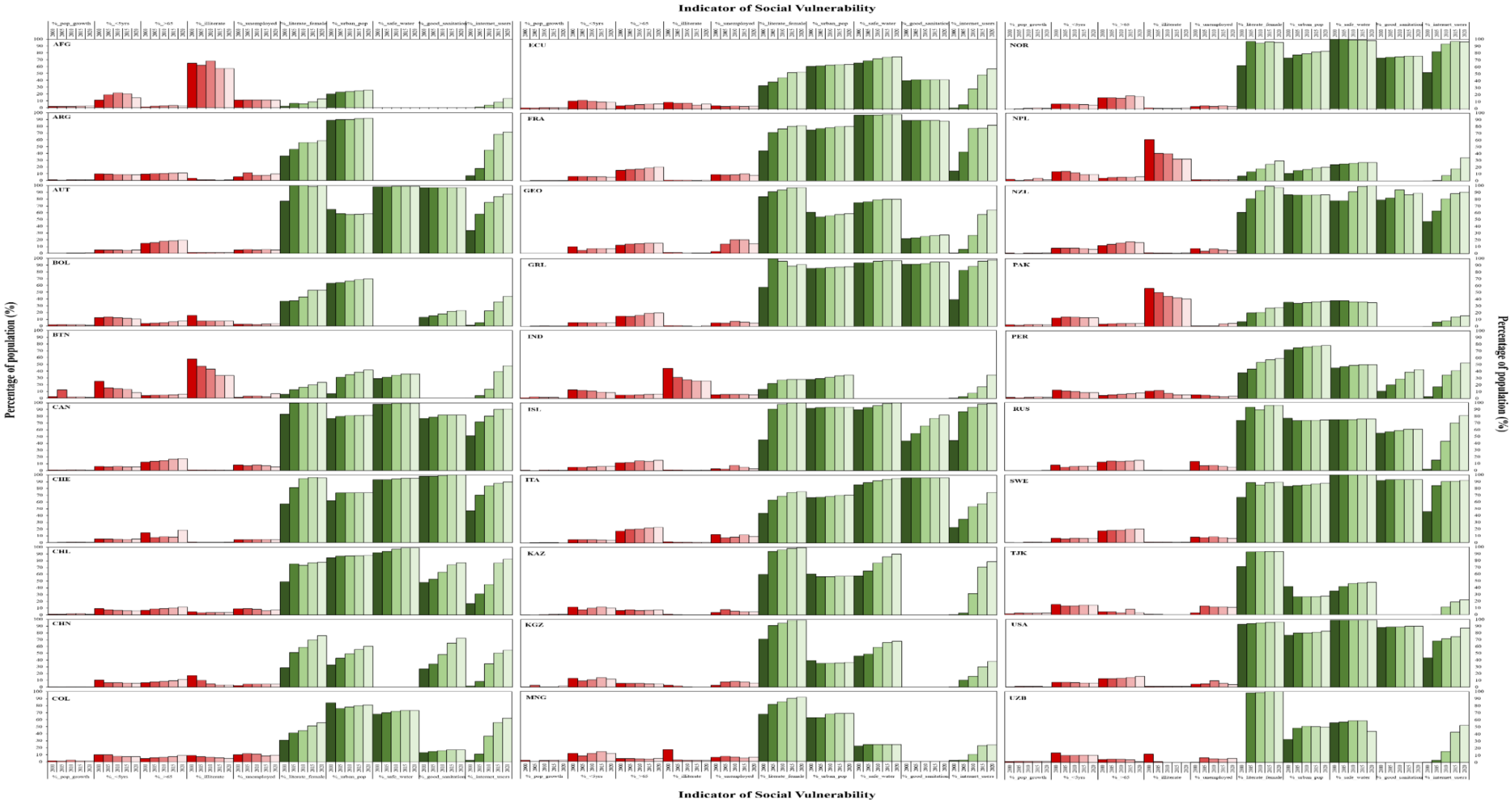

Figure S4. 1: Indicators of the GLOF Social Vulnerability Index. Changes in all 10 indicators used to calculate SVI between 2000 and 2020 in this study per nation. Countries are shown in alphabetical order. Indicators are listed as follows: rate of population change; percentage of population under 5 years; percentage of population over 65 years; percentage of population that are illiterate; percentage of population unemployed; percentage of the female population over 25 that have some formal education to secondary standard; percentage of urban population; percentage of population with access to safe drinking water; percentage of population with access to good sanitation; percentage of the population that use the internet. Data in red represents factors that increase social vulnerability to GLOFs, while data in green represents factors that decrease social vulnerability to GLOFs.

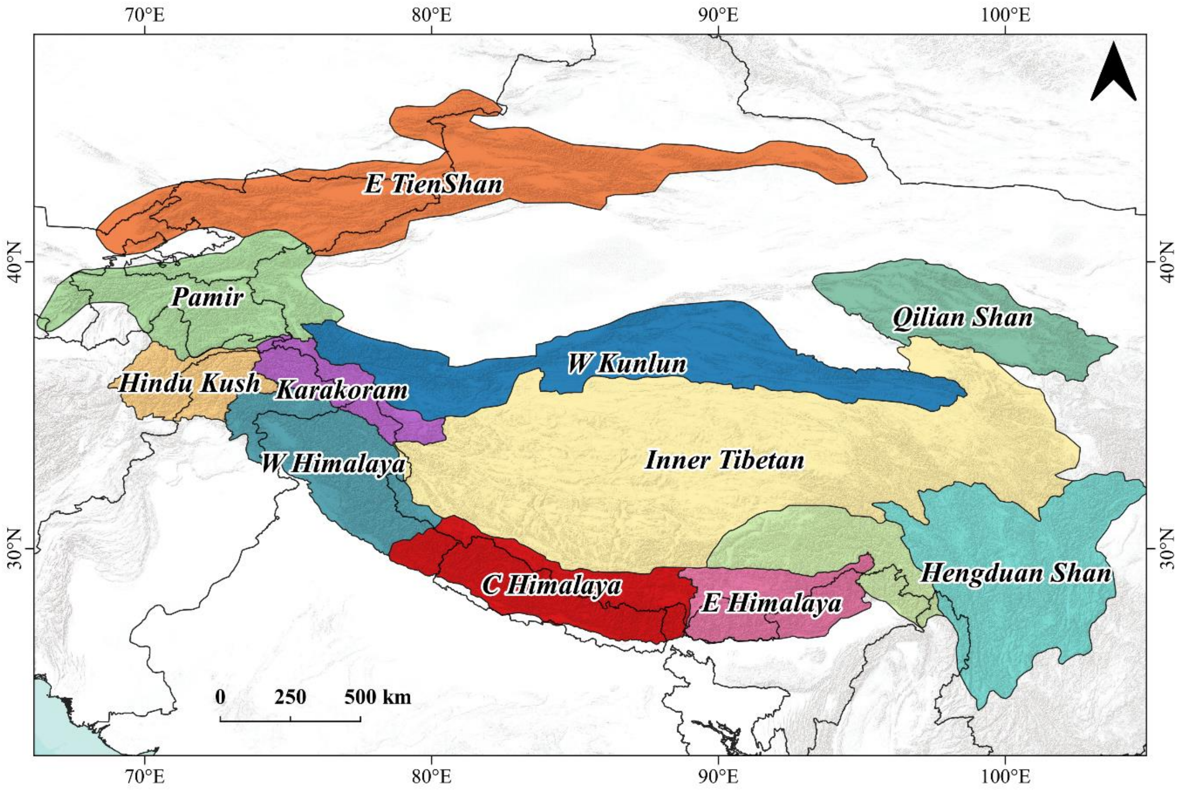

Figure S5. 1: Subregions of High Mountain Asia. Selected subregions within HMA mentioned in text.

Basin	ID	Risk
1.141E+10	PAK	1.47E-03
5.043E+10	PER	3.43E-04
5.041E+10	BOL	3.40E-04
1.15E+10	BTN	2.61E-04
1.15E+10	IND	1.75E-04
5.12E+10	CHL	1.69E-04
1.141E+10	PAK	1.60E-04
5.12E+10	ARG	1.40E-04
3.01E+10	USA	1.39E-04
3.04E+10	USA	1.31E-04
4.1E+10	NOR	1.10E-04
5.15E+10	PER	9.47E-05
1.141E+10	PAK	9.40E-05
1.141E+10	PAK	7.95E-05
1.15E+10	CHN	7.78E-05
4.1E+10	NOR	7.33E-05
1.141E+10	IND	7.17E-05
1.15E+10	NPL	6.83E-05
1.15E+10	NPL	6.55E-05
1.151E+10	NPL	5.37E-05
4.021E+10	CHE	5.07E-05
4.021E+10	ITA	4.44E-05
5.12E+10	CHL	4.39E-05
1.151E+10	NPL	4.07E-05
1.15E+10	NPL	3.95E-05
1.091E+10	AFG	3.92E-05
1.091E+10	TJK	2.89E-05
1.141E+10	IND	2.83E-05
5.13E+10	CHL	2.80E-05
1.15E+10	NPL	2.75E-05
4.1E+10	NOR	2.49E-05
5.043E+10	PER	2.25E-05
5.13E+10	ARG	2.23E-05
1.141E+10	IND	2.16E-05
5.043E+10	PER	2.12E-05
1.1E+10	CHN	1.80E-05
3.04E+10	CAN	1.73E-05
5.15E+10	PER	1.70E-05
5.041E+10	PER	1.68E-05
1.15E+10	BTN	1.65E-05
1.252E+10	CHN	1.65E-05
1.1E+10	CHN	1.52E-05
1.15E+10	BTN	1.48E-05
4.1E+10	NOR	1.38E-05
1.15E+10	IND	1.29E-05
5.14E+10	PER	1.26E-05
5.14E+10	PER	1.25E-05
4.052E+10	AUT	1.21E-05
4.021E+10	ITA	1.19E-05
1.15E+10	BTN	1.11E-05
4.021E+10	CHE	1.08E-05
3.04E+10	USA	1.07E-05
1.15E+10	CHN	1.01E-05
4.1E+10	NOR	9.96E-06
3.04E+10	USA	9.58E-06
4.1E+10	NOR	9.50E-06
3.04E+10	CAN	9.46E-06
3.05E+10	CAN	9.06E-06
4.1E+10	NOR	9.03E-06
1.09E+10	KGZ	8.97E-06
1.151E+10	NPL	8.91E-06
5.043E+10	PER	8.26E-06
4.15E+10	RUS	7.56E-06
1.141E+10	AFG	7.55E-06
1.171E+10	CHN	7.49E-06
3.101E+10	USA	7.19E-06
1.1E+10	CHN	7.07E-06
3.01E+10	USA	7.01E-06
4.021E+10	CHE	6.32E-06
1.142E+10	CHN	6.23E-06
4.021E+10	ITA	6.05E-06
4.11E+10	NOR	6.02E-06
1.141E+10	AFG	5.92E-06
5.011E+10	COL	5.85E-06
4.1E+10	NOR	5.47E-06
3.04E+10	CAN	5.39E-06
3.04E+10	CAN	5.23E-06
5.14E+10	BOL	5.19E-06
4.1E+10	NOR	5.17E-06
1.091E+10	KGZ	5.13E-06
4.04E+10	ITA	4.63E-06
1.091E+10	KGZ	4.63E-06
4.021E+10	ITA	4.38E-06
1.15E+10	CHN	4.25E-06
5.02E+10	COL	4.15E-06
1.15E+10	BTN	4.10E-06
3.101E+10	USA	3.66E-06
1.151E+10	NPL	3.65E-06
3.04E+10	CAN	3.64E-06
1.141E+10	IND	3.61E-06
5.043E+10	PER	3.53E-06
1.1E+10	KAZ	3.43E-06
1.141E+10	AFG	3.37E-06
3.101E+10	USA	3.35E-06
3.04E+10	CAN	3.28E-06
5.13E+10	CHL	3.24E-06
4.11E+10	NOR	3.11E-06
5.15E+10	PER	3.08E-06
1.141E+10	PAK	3.05E-06
4.081E+10	RUS	2.98E-06
1.15E+10	CHN	2.92E-06
1.151E+10	NPL	2.88E-06
1.15E+10	CHN	2.84E-06
1.141E+10	PAK	2.82E-06
3.01E+10	USA	2.80E-06
1.091E+10	AFG	2.75E-06
4.021E+10	FRA	2.75E-06
5.13E+10	CHL	2.70E-06
1.302E+10	CHN	2.68E-06
1.172E+10	CHN	2.66E-06
4.1E+10	NOR	2.61E-06
4.021E+10	CHE	2.53E-06
4.1E+10	NOR	2.51E-06
1.141E+10	PAK	2.50E-06
4.16E+10	ISL	2.49E-06
3.04E+10	CAN	2.44E-06
1.14E+10	IND	2.39E-06
5.15E+10	PER	2.38E-06
1.1E+10	KAZ	2.21E-06
1.15E+10	CHN	2.20E-06
1.141E+10	PAK	2.16E-06
1.14E+10	IND	2.14E-06
1.15E+10	CHN	2.08E-06
5.13E+10	CHL	2.07E-06
4.1E+10	NOR	2.06E-06
4.052E+10	AUT	2.00E-06
5.043E+10	PER	2.00E-06
1.09E+10	KGZ	1.99E-06
1.113E+10	CHN	1.98E-06
1.15E+10	CHN	1.95E-06
1.151E+10	NPL	1.92E-06
5.13E+10	CHL	1.89E-06
1.141E+10	IND	1.88E-06
1.15E+10	CHN	1.86E-06
1.151E+10	NPL	1.84E-06
5.043E+10	ECU	1.79E-06
1.1E+10	KAZ	1.79E-06
4.1E+10	NOR	1.73E-06
1.091E+10	UZB	1.71E-06
1.391E+10	RUS	1.70E-06
1.172E+10	CHN	1.67E-06
4.021E+10	ITA	1.66E-06
1.091E+10	KGZ	1.65E-06
5.13E+10	ARG	1.58E-06
1.141E+10	IND	1.57E-06
5.043E+10	PER	1.53E-06
4.021E+10	ITA	1.52E-06
1.141E+10	AFG	1.51E-06
1.1E+10	CHN	1.51E-06
1.15E+10	CHN	1.50E-06
1.1E+10	CHN	1.50E-06
1.15E+10	CHN	1.48E-06
1.141E+10	IND	1.47E-06
1.182E+10	CHN	1.45E-06
1.151E+10	NPL	1.44E-06
5.12E+10	CHL	1.40E-06
3.04E+10	USA	1.40E-06
1.1E+10	CHN	1.39E-06
5.043E+10	PER	1.35E-06
4.15E+10	RUS	1.35E-06
1.171E+10	CHN	1.26E-06
5.14E+10	BOL	1.25E-06
1.09E+10	KGZ	1.19E-06
4.16E+10	ISL	1.18E-06
5.14E+10	BOL	1.16E-06
5.043E+10	PER	1.16E-06
3.04E+10	CAN	1.14E-06
5.13E+10	CHL	1.12E-06
1.37E+10	GEO	1.12E-06
1.171E+10	CHN	1.11E-06
1.301E+10	CHN	1.10E-06
1.09E+10	KGZ	1.10E-06
1.301E+10	CHN	1.09E-06
1.151E+10	NPL	1.08E-06
1.151E+10	CHN	1.07E-06
5.13E+10	CHL	1.03E-06
3.022E+10	CAN	1.02E-06
1.15E+10	CHN	1.02E-06
1.15E+10	CHN	1.02E-06
5.14E+10	BOL	1.00E-06
1.091E+10	AFG	9.60E-07
1.141E+10	PAK	9.39E-07
1.091E+10	AFG	9.13E-07
4.052E+10	AUT	8.90E-07
1.1E+10	CHN	8.85E-07
1.091E+10	AFG	8.78E-07
1.1E+10	KAZ	8.56E-07
1.301E+10	CHN	8.42E-07
1.1E+10	CHN	8.42E-07
4.021E+10	FRA	8.24E-07
1.302E+10	CHN	8.22E-07
1.1E+10	KAZ	8.16E-07
1.15E+10	CHN	7.80E-07
1.141E+10	PAK	7.79E-07
1.091E+10	KGZ	7.61E-07
1.141E+10	IND	7.54E-07
5.011E+10	COL	7.32E-07
3.04E+10	CAN	7.25E-07
1.141E+10	PAK	7.17E-07
3.04E+10	USA	7.13E-07
4.1E+10	NOR	7.06E-07
5.011E+10	COL	6.99E-07
1.15E+10	CHN	6.94E-07
3.04E+10	USA	6.94E-07
4.1E+10	NOR	6.77E-07
1.1E+10	KAZ	6.57E-07
5.043E+10	PER	6.40E-07
1.141E+10	PAK	6.37E-07
3.04E+10	CAN	6.09E-07
1.304E+10	CHN	6.00E-07
5.12E+10	CHL	5.83E-07
5.15E+10	PER	5.75E-07
1.091E+10	TJK	5.75E-07
3.133E+10	USA	5.54E-07
5.12E+10	CHL	5.53E-07
5.13E+10	CHL	5.51E-07
4.11E+10	NOR	5.39E-07
1.091E+10	AFG	5.34E-07
3.04E+10	USA	5.27E-07
5.13E+10	CHL	5.17E-07
4.1E+10	NOR	5.14E-07
3.101E+10	USA	5.10E-07
1.151E+10	NPL	5.09E-07
1.141E+10	PAK	5.07E-07
5.13E+10	CHL	5.00E-07
1.172E+10	CHN	4.94E-07
5.043E+10	PER	4.93E-07
4.11E+10	NOR	4.89E-07
1.141E+10	PAK	4.89E-07
4.051E+10	AUT	4.88E-07
4.04E+10	ITA	4.85E-07
1.301E+10	CHN	4.77E-07
4.16E+10	ISL	4.70E-07
5.043E+10	PER	4.67E-07
1.021E+10	RUS	4.65E-07
1.091E+10	AFG	4.64E-07
1.091E+10	TJK	4.57E-07
1.15E+10	CHN	4.55E-07
4.1E+10	NOR	4.55E-07
1.303E+10	CHN	4.49E-07
1.151E+10	CHN	4.41E-07
1.151E+10	IND	4.36E-07
1.1E+10	CHN	3.98E-07
1.1E+10	CHN	3.96E-07
3.01E+10	CAN	3.92E-07

1.15E+10	CHN	3.87E-07
3.133E+10	USA	3.87E-07
1.061E+10	RUS	3.79E-07
1.1E+10	KAZ	3.70E-07
5.15E+10	PER	3.67E-07
1.151E+10	NPL	3.65E-07
5.13E+10	CHL	3.60E-07
5.011E+10	COL	3.49E-07
4.15E+10	RUS	3.47E-07
1.141E+10	PAK	3.44E-07
1.15E+10	CHN	3.37E-07
1.1E+10	CHN	3.34E-07
5.043E+10	PER	3.29E-07
1.304E+10	CHN	3.23E-07
3.01E+10	USA	3.22E-07
1.301E+10	KGZ	3.15E-07
3.101E+10	USA	3.11E-07
1.15E+10	CHN	3.09E-07
4.021E+10	CHE	3.08E-07
1.141E+10	PAK	3.08E-07
1.141E+10	PAK	3.02E-07
1.141E+10	PAK	3.00E-07
5.13E+10	CHL	2.98E-07
1.14E+10	IND	2.98E-07
1.15E+10	CHN	2.97E-07
1.141E+10	PAK	2.96E-07
1.091E+10	TJK	2.94E-07
5.12E+10	CHL	2.91E-07
1.1E+10	KAZ	2.89E-07
1.141E+10	IND	2.88E-07
1.15E+10	IND	2.86E-07
5.13E+10	CHL	2.84E-07
3.133E+10	USA	2.83E-07
1.091E+10	TJK	2.82E-07
5.12E+10	CHL	2.79E-07
1.15E+10	CHN	2.79E-07
1.251E+10	CHN	2.76E-07
1.301E+10	KGZ	2.75E-07
5.15E+10	PER	2.74E-07
1.151E+10	NPL	2.71E-07
1.091E+10	AFG	2.65E-07

1.304E+10	CHN	2.58E-07
4.1E+10	NOR	2.53E-07
5.15E+10	PER	2.50E-07
4.11E+10	SWE	2.49E-07
1.251E+10	CHN	2.48E-07
1.141E+10	PAK	2.47E-07
1.15E+10	CHN	2.45E-07
1.251E+10	CHN	2.44E-07
5.15E+10	PER	2.44E-07
5.01E+10	ECU	2.43E-07
1.091E+10	AFG	2.42E-07
1.15E+10	CHN	2.41E-07
4.15E+10	RUS	2.41E-07
3.101E+10	USA	2.40E-07
1.15E+10	CHN	2.39E-07
1.15E+10	CHN	2.39E-07
1.091E+10	KGZ	2.38E-07
1.1E+10	KAZ	2.37E-07
1.1E+10	CHN	2.33E-07
4.1E+10	SWE	2.33E-07
1.15E+10	CHN	2.32E-07
1.141E+10	IND	2.31E-07
4.1E+10	SWE	2.30E-07
5.043E+10	PER	2.27E-07
3.031E+10	CAN	2.25E-07
3.01E+10	CAN	2.24E-07
4.11E+10	NOR	2.24E-07
1.15E+10	CHN	2.22E-07
1.15E+10	CHN	2.22E-07
1.151E+10	NPL	2.20E-07
5.13E+10	ARG	2.19E-07
1.172E+10	CHN	2.19E-07
1.14E+10	IND	2.19E-07
5.12E+10	CHL	2.14E-07
1.09E+10	KGZ	2.11E-07
1.15E+10	IND	2.07E-07
1.304E+10	CHN	2.06E-07
3.05E+10	USA	2.05E-07
4.021E+10	FRA	2.04E-07
5.12E+10	CHL	2.03E-07
1.091E+10	KGZ	2.01E-07

1.091E+10	TJK	1.99E-07
1.1E+10	CHN	1.97E-07
3.04E+10	USA	1.97E-07
1.301E+10	KGZ	1.94E-07
1.091E+10	KGZ	1.88E-07
1.1E+10	KAZ	1.85E-07
3.01E+10	CAN	1.82E-07
3.04E+10	CAN	1.81E-07
1.061E+10	RUS	1.81E-07
1.15E+10	CHN	1.80E-07
1.141E+10	IND	1.80E-07
4.1E+10	NOR	1.79E-07
4.15E+10	RUS	1.79E-07
1.182E+10	CHN	1.77E-07
1.141E+10	IND	1.73E-07
5.13E+10	CHL	1.70E-07
1.141E+10	IND	1.70E-07
1.301E+10	CHN	1.69E-07
6.09E+10	NZL	1.69E-07
4.081E+10	RUS	1.68E-07
5.13E+10	CHL	1.67E-07
4.021E+10	FRA	1.67E-07
1.15E+10	IND	1.67E-07
1.15E+10	CHN	1.64E-07
1.091E+10	TJK	1.60E-07
4.11E+10	NOR	1.59E-07
1.061E+10	RUS	1.59E-07
1.391E+10	RUS	1.59E-07
1.091E+10	TJK	1.58E-07
1.182E+10	CHN	1.55E-07
1.15E+10	CHN	1.53E-07
1.301E+10	KGZ	1.50E-07
4.051E+10	AUT	1.48E-07
1.09E+10	KGZ	1.47E-07
4.021E+10	CHE	1.45E-07
1.171E+10	CHN	1.45E-07
1.141E+10	IND	1.45E-07
5.12E+10	CHL	1.44E-07
5.14E+10	PER	1.44E-07
1.15E+10	IND	1.42E-07
1.141E+10	PAK	1.42E-07

3.04E+10	USA	1.42E-07
5.13E+10	CHL	1.41E-07
1.141E+10	IND	1.41E-07
1.09E+10	KGZ	1.40E-07
1.091E+10	KGZ	1.36E-07
4.1E+10	NOR	1.35E-07
3.101E+10	USA	1.33E-07
4.15E+10	RUS	1.29E-07
4.1E+10	NOR	1.24E-07
5.15E+10	PER	1.24E-07
1.301E+10	KGZ	1.23E-07
1.141E+10	PAK	1.23E-07
3.101E+10	USA	1.23E-07
1.301E+10	CHN	1.22E-07
3.04E+10	USA	1.22E-07
1.251E+10	CHN	1.21E-07
1.15E+10	CHN	1.20E-07
3.04E+10	CAN	1.19E-07
1.091E+10	KGZ	1.19E-07
1.151E+10	IND	1.18E-07
1.1E+10	KAZ	1.18E-07
1.091E+10	TJK	1.18E-07
1.15E+10	CHN	1.17E-07
3.04E+10	CAN	1.09E-07
1.091E+10	TJK	1.09E-07
3.04E+10	CAN	1.08E-07
1.09E+10	KGZ	1.08E-07
4.15E+10	RUS	1.07E-07
1.091E+10	KGZ	1.06E-07
3.101E+10	USA	1.06E-07
1.15E+10	CHN	1.05E-07
1.251E+10	CHN	1.02E-07
5.15E+10	PER	9.87E-08
4.11E+10	SWE	9.83E-08
3.1E+10	USA	9.82E-08
5.13E+10	CHL	9.81E-08
1.252E+10	CHN	9.81E-08
1.301E+10	KGZ	9.70E-08
1.141E+10	IND	9.69E-08
5.13E+10	CHL	9.65E-08
3.133E+10	USA	9.62E-08

3.133E+10	USA	9.53E-08
5.13E+10	CHL	9.49E-08
5.12E+10	CHL	9.43E-08
5.12E+10	ARG	9.36E-08
1.091E+10	AFG	9.23E-08
1.302E+10	CHN	9.14E-08
5.12E+10	CHL	9.07E-08
1.151E+10	IND	9.03E-08
4.1E+10	NOR	8.95E-08
1.151E+10	NPL	8.94E-08
4.1E+10	NOR	8.91E-08
1.091E+10	TJK	8.90E-08
1.303E+10	CHN	8.80E-08
3.04E+10	CAN	8.71E-08
4.11E+10	NOR	8.64E-08
4.081E+10	RUS	8.51E-08
5.15E+10	PER	8.34E-08
1.15E+10	CHN	8.13E-08
3.04E+10	USA	8.07E-08
3.021E+10	CAN	8.03E-08
3.101E+10	USA	7.92E-08
1.09E+10	KGZ	7.81E-08
1.15E+10	CHN	7.80E-08
1.151E+10	IND	7.75E-08
1.15E+10	CHN	7.63E-08
1.091E+10	KGZ	7.44E-08
3.04E+10	CAN	7.36E-08
5.13E+10	CHL	7.36E-08
3.05E+10	USA	7.30E-08
3.133E+10	USA	7.24E-08
5.13E+10	CHL	7.20E-08
1.141E+10	PAK	7.07E-08
3.05E+10	CAN	6.94E-08
1.15E+10	CHN	6.93E-08
3.01E+10	USA	6.88E-08
3.04E+10	CAN	6.67E-08
6.09E+10	NZL	6.66E-08
1.15E+10	CHN	6.61E-08
1.1E+10	CHN	6.59E-08
1.15E+10	CHN	6.46E-08
1.304E+10	CHN	6.44E-08

3.131E+10	USA	6.44E-08
1.14E+10	IND	6.18E-08
1.171E+10	CHN	6.08E-08
1.251E+10	CHN	6.07E-08
3.133E+10	USA	5.99E-08
3.101E+10	USA	5.96E-08
1.15E+10	BTN	5.93E-08
4.15E+10	RUS	5.86E-08
1.301E+10	CHN	5.82E-08
4.16E+10	ISL	5.77E-08
5.13E+10	CHL	5.70E-08
1.141E+10	IND	5.70E-08
1.09E+10	KGZ	5.64E-08
3.04E+10	CAN	5.57E-08
1.182E+10	CHN	5.57E-08
1.09E+10	KGZ	5.55E-08
3.101E+10	USA	5.53E-08
1.15E+10	IND	5.48E-08
3.04E+10	USA	5.43E-08
1.084E+10	RUS	5.37E-08
1.172E+10	CHN	5.29E-08
4.16E+10	ISL	5.22E-08
3.04E+10	USA	5.21E-08
1.09E+10	KGZ	5.00E-08
4.1E+10	NOR	4.97E-08
3.101E+10	USA	4.93E-08
1.101E+10	MNG	4.91E-08
5.043E+10	PER	4.91E-08
3.022E+10	CAN	4.89E-08
1.15E+10	IND	4.88E-08
1.151E+10	NPL	4.88E-08
3.01E+10	USA	4.88E-08
1.172E+10	CHN	4.86E-08
3.04E+10	USA	4.83E-08
5.13E+10	CHL	4.80E-08
1.15E+10	CHN	4.77E-08
5.13E+10	CHL	4.74E-08
1.09E+10	KGZ	4.73E-08
3.04E+10	USA	4.73E-08
4.11E+10	SWE	4.65E-08
1.1E+10	KAZ	4.61E-08

1.091E+10	KGZ	4.60E-08
1.15E+10	CHN	4.54E-08
1.304E+10	CHN	4.48E-08
4.081E+10	RUS	4.46E-08
3.01E+10	CAN	4.33E-08
1.15E+10	CHN	4.33E-08
1.15E+10	CHN	4.31E-08
1.14E+10	CHN	4.28E-08
1.091E+10	AFG	4.24E-08
4.1E+10	SWE	4.23E-08
1.301E+10	KGZ	4.19E-08
3.04E+10	CAN	4.18E-08
1.091E+10	KGZ	4.16E-08
3.04E+10	CAN	3.99E-08
3.04E+10	CAN	3.98E-08
1.091E+10	KGZ	3.95E-08
1.141E+10	IND	3.94E-08
1.091E+10	KGZ	3.94E-08
4.1E+10	NOR	3.90E-08
5.12E+10	CHL	3.89E-08
1.15E+10	CHN	3.89E-08
1.14E+10	IND	3.84E-08
1.09E+10	KGZ	3.82E-08
4.1E+10	SWE	3.78E-08
4.15E+10	RUS	3.73E-08
4.1E+10	SWE	3.72E-08
3.04E+10	CAN	3.66E-08
1.141E+10	PAK	3.65E-08
4.1E+10	NOR	3.63E-08
1.15E+10	CHN	3.58E-08
1.15E+10	CHN	3.58E-08
3.133E+10	USA	3.57E-08
1.302E+10	CHN	3.52E-08
1.15E+10	CHN	3.49E-08
4.16E+10	ISL	3.49E-08
1.061E+10	RUS	3.48E-08
1.301E+10	KGZ	3.47E-08
5.13E+10	CHL	3.45E-08
1.1E+10	CHN	3.41E-08
3.04E+10	CAN	3.40E-08
1.302E+10	CHN	3.39E-08

1.061E+10	RUS	3.38E-08
1.091E+10	KGZ	3.36E-08
1.06E+10	RUS	3.33E-08
5.043E+10	ECU	3.30E-08
3.04E+10	CAN	3.27E-08
1.15E+10	CHN	3.26E-08
4.16E+10	ISL	3.24E-08
3.101E+10	USA	3.23E-08
5.13E+10	CHL	3.21E-08
1.251E+10	CHN	3.21E-08
5.1E+10	ARG	3.18E-08
1.14E+10	IND	3.18E-08
1.15E+10	CHN	3.16E-08
1.15E+10	CHN	3.14E-08
6.09E+10	NZL	3.13E-08
1.302E+10	CHN	3.12E-08
1.251E+10	CHN	3.08E-08
1.15E+10	CHN	2.93E-08
4.021E+10	CHE	2.91E-08
5.13E+10	CHL	2.88E-08
1.15E+10	IND	2.87E-08
1.303E+10	CHN	2.86E-08
1.15E+10	CHN	2.85E-08
1.301E+10	CHN	2.85E-08
1.09E+10	KAZ	2.85E-08
1.15E+10	CHN	2.84E-08
4.11E+10	NOR	2.81E-08
1.15E+10	CHN	2.74E-08
3.031E+10	CAN	2.72E-08
1.172E+10	CHN	2.72E-08
4.16E+10	ISL	2.61E-08
1.091E+10	KGZ	2.59E-08
1.141E+10	IND	2.57E-08
4.11E+10	NOR	2.57E-08
3.04E+10	CAN	2.54E-08
1.06E+10	RUS	2.53E-08
1.37E+10	GEO	2.47E-08
1.182E+10	CHN	2.46E-08
1.14E+10	CHN	2.45E-08
1.09E+10	KGZ	2.44E-08
4.15E+10	RUS	2.43E-08

1.303E+10	CHN	2.42E-08
3.101E+10	USA	2.33E-08
1.15E+10	CHN	2.29E-08
3.01E+10	USA	2.26E-08
4.16E+10	ISL	2.20E-08
1.162E+10	CHN	2.18E-08
3.01E+10	USA	2.09E-08
1.061E+10	RUS	2.06E-08
3.05E+10	USA	2.01E-08
5.13E+10	CHL	2.00E-08
1.15E+10	CHN	2.00E-08
1.064E+10	CHN	2.00E-08
6.09E+10	NZL	2.00E-08
3.04E+10	USA	2.00E-08
3.01E+10	USA	1.96E-08
1.141E+10	IND	1.93E-08
3.05E+10	CAN	1.91E-08
6.09E+10	NZL	1.88E-08
1.14E+10	CHN	1.86E-08
3.133E+10	USA	1.85E-08
1.15E+10	CHN	1.84E-08
4.11E+10	NOR	1.84E-08
1.304E+10	CHN	1.83E-08
3.022E+10	CAN	1.82E-08
1.09E+10	KGZ	1.77E-08
3.05E+10	CAN	1.76E-08
1.011E+10	RUS	1.76E-08
4.021E+10	FRA	1.74E-08
4.15E+10	RUS	1.74E-08
1.1E+10	KAZ	1.71E-08
1.06E+10	RUS	1.70E-08
5.13E+10	CHL	1.67E-08
4.15E+10	RUS	1.67E-08
1.302E+10	CHN	1.66E-08
1.141E+10	PAK	1.65E-08
5.11E+10	ARG	1.64E-08
1.011E+10	RUS	1.64E-08
5.13E+10	CHL	1.63E-08
1.141E+10	IND	1.63E-08
4.1E+10	SWE	1.62E-08
3.04E+10	CAN	1.59E-08

1.301E+10	CHN	1.55E-08
3.04E+10	USA	1.55E-08
4.11E+10	NOR	1.54E-08
1.061E+10	RUS	1.50E-08
1.063E+10	KAZ	1.48E-08
5.13E+10	CHL	1.47E-08
1.171E+10	CHN	1.46E-08
1.071E+10	RUS	1.46E-08
5.12E+10	ARG	1.44E-08
3.04E+10	CAN	1.43E-08
1.303E+10	CHN	1.40E-08
1.063E+10	KAZ	1.39E-08
1.14E+10	CHN	1.38E-08
3.04E+10	USA	1.36E-08
3.133E+10	USA	1.29E-08
1.061E+10	RUS	1.28E-08
3.022E+10	CAN	1.27E-08
1.171E+10	CHN	1.27E-08
3.04E+10	CAN	1.24E-08
1.304E+10	CHN	1.23E-08
1.101E+10	MNG	1.19E-08
3.031E+10	CAN	1.16E-08
5.13E+10	CHL	1.16E-08
4.16E+10	ISL	1.16E-08
4.1E+10	NOR	1.16E-08
5.13E+10	CHL	1.14E-08
3.01E+10	USA	1.14E-08
3.031E+10	CAN	1.13E-08
1.15E+10	CHN	1.13E-08
3.01E+10	USA	1.12E-08
1.302E+10	CHN	1.11E-08
1.061E+10	RUS	1.10E-08
3.133E+10	USA	1.09E-08
1.1E+10	KAZ	1.08E-08
1.301E+10	CHN	1.00E-08
1.021E+10	RUS	1.00E-08
1.064E+10	CHN	9.53E-09
5.13E+10	CHL	9.48E-09
6.09E+10	NZL	9.47E-09
3.04E+10	CAN	9.41E-09
1.301E+10	CHN	9.32E-09

1.15E+10	CHN	9.31E-09
3.01E+10	USA	9.15E-09
1.071E+10	RUS	9.06E-09
3.04E+10	CAN	9.05E-09
1.101E+10	MNG	9.04E-09
3.04E+10	CAN	8.93E-09
1.15E+10	CHN	8.80E-09
3.04E+10	CAN	8.73E-09
1.09E+10	KGZ	8.62E-09
4.1E+10	NOR	8.57E-09
1.15E+10	CHN	8.39E-09
3.04E+10	CAN	8.23E-09
1.072E+10	RUS	8.15E-09
3.04E+10	CAN	7.75E-09
1.101E+10	MNG	7.47E-09
1.071E+10	RUS	7.45E-09
1.301E+10	CHN	7.41E-09
5.12E+10	ARG	7.40E-09
1.141E+10	PAK	6.99E-09
1.05E+10	RUS	6.86E-09
4.1E+10	NOR	6.83E-09
3.04E+10	CAN	6.82E-09
3.01E+10	USA	6.79E-09
1.15E+10	CHN	6.77E-09
1.15E+10	CHN	6.70E-09
6.09E+10	NZL	6.66E-09
1.301E+10	CHN	6.64E-09
4.1E+10	NOR	6.49E-09
1.302E+10	CHN	6.31E-09
6.09E+10	NZL	5.94E-09
1.1E+10	MNG	5.86E-09
1.14E+10	IND	5.79E-09
1.301E+10	CHN	5.50E-09
3.04E+10	CAN	5.35E-09
5.13E+10	CHL	5.08E-09
1.182E+10	CHN	5.02E-09
1.1E+10	CHN	4.96E-09
4.1E+10	NOR	4.95E-09
3.04E+10	CAN	4.76E-09
1.083E+10	RUS	4.76E-09
1.064E+10	CHN	4.68E-09

1.15E+10	CHN	4.66E-09
1.061E+10	RUS	4.65E-09
1.101E+10	MNG	4.45E-09
1.06E+10	RUS	4.45E-09
5.13E+10	CHL	4.31E-09
5.13E+10	ARG	4.23E-09
1.061E+10	RUS	4.22E-09
1.14E+10	CHN	4.20E-09
3.023E+10	CAN	4.17E-09
1.15E+10	CHN	4.11E-09
1.071E+10	RUS	4.11E-09
3.04E+10	USA	4.06E-09
1.1E+10	KAZ	4.05E-09
1.15E+10	CHN	4.04E-09
3.01E+10	USA	3.97E-09
3.04E+10	USA	3.94E-09
1.15E+10	CHN	3.87E-09
3.04E+10	CAN	3.85E-09
3.01E+10	USA	3.85E-09
3.04E+10	USA	3.77E-09
1.101E+10	MNG	3.73E-09
3.04E+10	CAN	3.72E-09
1.304E+10	CHN	3.68E-09
1.021E+10	RUS	3.63E-09
4.1E+10	SWE	3.58E-09
4.16E+10	ISL	3.49E-09
6.09E+10	NZL	3.49E-09
3.04E+10	CAN	3.42E-09
1.091E+10	TJK	3.37E-09
1.302E+10	CHN	3.18E-09
3.04E+10	CAN	3.16E-09
3.04E+10	CAN	3.02E-09
5.1E+10	ARG	2.92E-09
1.15E+10	CHN	2.90E-09
3.04E+10	CAN	2.84E-09
5.12E+10	CHL	2.69E-09
1.061E+10	RUS	2.65E-09
1.304E+10	CHN	2.63E-09
1.14E+10	CHN	2.62E-09
3.01E+10	USA	2.61E-09
1.302E+10	CHN	2.53E-09

3.01E+10	CAN	2.48E-09
1.304E+10	CHN	2.36E-09
3.04E+10	CAN	2.35E-09
1.101E+10	MNG	2.28E-09
5.1E+10	ARG	2.27E-09
3.05E+10	CAN	2.27E-09
3.04E+10	CAN	2.26E-09
4.16E+10	ISL	2.26E-09
1.061E+10	RUS	2.08E-09
1.15E+10	CHN	2.07E-09
3.04E+10	USA	2.07E-09
1.091E+10	TJK	2.04E-09
3.01E+10	CAN	1.97E-09
3.04E+10	CAN	1.96E-09
3.04E+10	CAN	1.89E-09
3.133E+10	USA	1.80E-09
3.04E+10	USA	1.77E-09
3.04E+10	USA	1.74E-09
1.14E+10	CHN	1.73E-09
4.16E+10	ISL	1.72E-09
3.04E+10	CAN	1.70E-09
3.031E+10	CAN	1.69E-09
1.05E+10	RUS	1.66E-09
1.3E+10	CHN	1.64E-09
3.133E+10	USA	1.63E-09
1.091E+10	TJK	1.61E-09
3.04E+10	CAN	1.60E-09
1.252E+10	CHN	1.53E-09
1.301E+10	CHN	1.47E-09
3.04E+10	CAN	1.44E-09
5.13E+10	CHL	1.43E-09
1.15E+10	CHN	1.28E-09
5.13E+10	CHL	1.27E-09
5.1E+10	ARG	1.24E-09
3.01E+10	USA	1.22E-09
3.01E+10	USA	1.19E-09
3.01E+10	CAN	1.18E-09
3.01E+10	CAN	1.17E-09
4.16E+10	ISL	1.14E-09
1.303E+10	CHN	1.13E-09
1.021E+10	RUS	1.04E-09

1.02E+10	RUS	1.01E-09
3.01E+10	USA	9.93E-10
1.021E+10	RUS	9.81E-10
1.252E+10	CHN	9.79E-10
3.01E+10	CAN	9.43E-10
1.021E+10	RUS	9.33E-10
3.01E+10	CAN	9.08E-10
1.021E+10	RUS	8.94E-10
5.1E+10	ARG	8.87E-10
3.01E+10	USA	8.79E-10
1.091E+10	TJK	8.70E-10
3.04E+10	CAN	8.68E-10
1.252E+10	CHN	8.47E-10
3.01E+10	USA	8.43E-10
1.071E+10	RUS	8.17E-10
1.252E+10	CHN	7.96E-10
3.04E+10	CAN	7.89E-10
3.04E+10	CAN	7.79E-10
3.04E+10	CAN	7.58E-10
5.12E+10	ARG	7.47E-10
3.04E+10	CAN	7.00E-10
1.302E+10	CHN	6.74E-10
3.04E+10	CAN	6.72E-10
3.04E+10	CAN	6.59E-10
6.09E+10	NZL	6.32E-10
1.021E+10	RUS	6.27E-10
1.252E+10	CHN	6.24E-10
3.04E+10	CAN	5.90E-10
1.303E+10	CHN	5.79E-10
1.252E+10	CHN	5.75E-10
1.3E+10	CHN	5.58E-10
4.1E+10	SWE	5.25E-10
1.021E+10	RUS	4.99E-10
1.021E+10	RUS	4.86E-10
1.021E+10	RUS	4.85E-10
1.021E+10	RUS	4.81E-10
3.04E+10	CAN	4.76E-10
1.303E+10	CHN	4.55E-10
3.04E+10	CAN	4.48E-10
1.083E+10	RUS	4.32E-10
3.01E+10	USA	4.30E-10

1.304E+10	CHN	4.27E-10
3.101E+10	USA	4.27E-10
1.05E+10	RUS	4.06E-10
3.01E+10	CAN	3.95E-10
3.04E+10	CAN	3.82E-10
3.01E+10	USA	3.81E-10
1.14E+10	CHN	3.70E-10
3.04E+10	CAN	3.64E-10
1.021E+10	RUS	3.61E-10
3.01E+10	USA	3.44E-10
1.071E+10	RUS	3.28E-10
1.303E+10	CHN	3.13E-10
3.01E+10	CAN	3.10E-10
1.304E+10	CHN	2.94E-10
1.072E+10	RUS	2.86E-10
1.021E+10	RUS	2.75E-10
4.16E+10	ISL	2.70E-10
6.09E+10	NZL	2.65E-10
3.01E+10	USA	2.42E-10
5.12E+10	CHL	2.23E-10
3.04E+10	CAN	2.22E-10
3.04E+10	CAN	2.12E-10
1.021E+10	RUS	2.12E-10
1.15E+10	CHN	1.98E-10
3.01E+10	CAN	1.89E-10
3.01E+10	USA	1.88E-10
3.01E+10	CAN	1.76E-10
1.021E+10	RUS	1.47E-10
4.16E+10	ISL	1.44E-10
3.01E+10	USA	1.44E-10
3.01E+10	USA	1.42E-10
1.05E+10	RUS	1.41E-10
3.01E+10	CAN	1.40E-10
1.021E+10	RUS	1.36E-10
1.021E+10	RUS	1.35E-10
3.01E+10	USA	1.23E-10
1.302E+10	CHN	1.22E-10
3.04E+10	CAN	1.16E-10
1.303E+10	CHN	1.09E-10
4.1E+10	SWE	1.09E-10
1.051E+10	RUS	9.71E-11

1.021E+10	RUS	8.68E-11
3.01E+10	USA	8.59E-11
6.09E+10	NZL	7.97E-11
3.01E+10	CAN	7.52E-11
3.04E+10	CAN	7.49E-11
3.04E+10	CAN	6.96E-11
1.021E+10	RUS	6.69E-11
3.04E+10	CAN	6.56E-11
3.04E+10	CAN	5.22E-11
1.021E+10	RUS	5.12E-11
3.01E+10	USA	4.29E-11
1.021E+10	RUS	4.23E-11
1.021E+10	RUS	3.79E-11
3.04E+10	CAN	3.71E-11
3.04E+10	CAN	3.44E-11
3.04E+10	CAN	3.24E-11
3.04E+10	USA	3.21E-11
3.01E+10	USA	3.14E-11
3.01E+10	CAN	3.09E-11
3.01E+10	CAN	3.02E-11
3.01E+10	CAN	2.83E-11
3.04E+10	CAN	2.78E-11
3.04E+10	CAN	2.71E-11
1.021E+10	RUS	2.51E-11
3.04E+10	CAN	2.32E-11
3.04E+10	CAN	2.32E-11
1.021E+10	RUS	2.29E-11
3.01E+10	CAN	2.27E-11
3.01E+10	USA	2.07E-11
3.01E+10	USA	2.03E-11
3.01E+10	USA	1.83E-11
3.04E+10	CAN	1.71E-11
3.04E+10	CAN	1.65E-11
1.021E+10	RUS	1.62E-11
3.022E+10	CAN	1.61E-11
3.021E+10	CAN	1.60E-11
1.021E+10	RUS	1.56E-11
3.01E+10	USA	1.55E-11
3.031E+10	CAN	1.22E-11
3.01E+10	USA	1.22E-11
3.04E+10	CAN	1.20E-11

3.01E+10	USA	1.20E-11
3.022E+10	CAN	1.10E-11
3.02E+10	CAN	1.05E-11
3.01E+10	USA	8.61E-12
3.031E+10	CAN	8.33E-12
3.01E+10	CAN	8.25E-12
3.01E+10	USA	7.13E-12
3.031E+10	CAN	6.83E-12
3.01E+10	USA	5.98E-12
3.01E+10	USA	4.98E-12
3.021E+10	CAN	4.91E-12
3.01E+10	CAN	4.91E-12
3.04E+10	CAN	4.55E-12
3.031E+10	CAN	4.40E-12
3.04E+10	CAN	4.37E-12
3.021E+10	CAN	3.40E-12
3.04E+10	CAN	3.37E-12
3.031E+10	CAN	3.15E-12
3.01E+10	USA	2.83E-12
3.031E+10	CAN	2.73E-12
3.01E+10	USA	2.72E-12
3.031E+10	CAN	2.65E-12
3.031E+10	CAN	2.45E-12
3.031E+10	CAN	2.00E-12
3.031E+10	CAN	1.95E-12
3.01E+10	USA	1.54E-12
3.021E+10	CAN	1.52E-12
3.04E+10	CAN	1.18E-12
3.04E+10	CAN	1.07E-12
3.031E+10	CAN	1.04E-12
3.021E+10	CAN	9.85E-13
3.04E+10	CAN	9.16E-13
1.021E+10	RUS	6.25E-13
3.031E+10	CAN	4.84E-13
3.031E+10	CAN	4.66E-13
3.022E+10	CAN	4.47E-13
1.021E+10	RUS	4.36E-13
3.04E+10	CAN	3.97E-13
3.01E+10	CAN	3.96E-13
3.031E+10	CAN	3.60E-13
3.01E+10	CAN	2.65E-13

3.021E+10	CAN	2.47E-13
3.031E+10	CAN	2.27E-13
3.04E+10	CAN	2.13E-13
3.01E+10	USA	2.12E-13
3.031E+10	CAN	2.08E-13
3.031E+10	CAN	2.02E-13
3.021E+10	CAN	1.67E-13
3.031E+10	CAN	1.65E-13
3.01E+10	CAN	1.53E-13
3.021E+10	CAN	1.46E-13
3.021E+10	CAN	1.42E-13
3.021E+10	CAN	1.37E-13
3.022E+10	CAN	7.69E-14
3.021E+10	CAN	5.80E-14
3.031E+10	CAN	4.24E-14
3.022E+10	CAN	3.52E-14
3.031E+10	CAN	2.66E-14
3.031E+10	CAN	2.14E-14
3.031E+10	CAN	2.06E-14
3.021E+10	CAN	1.79E-14
3.031E+10	CAN	7.69E-15
3.01E+10	USA	6.61E-15
3.031E+10	CAN	5.96E-15
3.031E+10	CAN	3.77E-15
3.031E+10	CAN	2.26E-15
3.031E+10	CAN	2.22E-15
3.031E+10	CAN	4.52E-16
3.021E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.081E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.021E+10	CAN	0.00E+00

3.031E+10	CAN	0.00E+00
3.04E+10	CAN	0.00E+00
3.04E+10	CAN	0.00E+00
3.081E+10	CAN	0.00E+00
3.04E+10	CAN	0.00E+00
3.04E+10	CAN	0.00E+00
3.04E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.022E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00

3.021E+10	CAN	0.00E+00
3.01E+10	CAN	0.00E+00
3.01E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
3.031E+10	CAN	0.00E+00
1.3E+10	CHN	0.00E+00
1.303E+10	CHN	0.00E+00
1.303E+10	CHN	0.00E+00
1.303E+10	CHN	0.00E+00
1.303E+10	CHN	0.00E+00
1.303E+10	CHN	0.00E+00
1.303E+10	CHN	0.00E+00

.301E+10	CHN	0.00E+00
1.301E+10	CHN	0.00E+00
1.303E+10	CHN	0.00E+00
3.031E+10	GRL	0.00E+00
3.01E+10	USA	0.00E+00
3.01E+10	USA	0.00E+00
3.01E+10	USA	0.00E+00
3.01E+10	USA	0.00E+00
3.01E+10	USA	0.00E+00
3.01E+10	USA	0.00E+00
3.01E+10	USA	0.00E+00
3.01E+10	USA	0.00E+00
3.01E+10	USA	0.00E+00
3.01E+10	USA	0.00E+00
3.01E+10	USA	0.00E+00
3.01E+10	USA	0.00E+00
3.01E+10	USA	0.00E+00
3.01E+10	USA	0.00E+00
3.01E+10	USA	0.00E+00
3.01E+10	USA	0.00E+00
3.01E+10	USA	0.00E+00
3.01E+10	USA	0.00E+00
3.01E+10	USA	0.00E+00
3.01E+10	USA	0.00E+00

Table S3.1: Global GLOF risk ranking. All 1089 basins ranked from most to least at risk of GLOF impacts as of 2020. Basins are coloured according to mountain range where; Andes = Blue, Alps = red, HMA = green, PNW = purple and HAOC = orange.

ID	(a) SVI					(b) HDI					(c) CPI				
	2000	2005	2010	2015	2020	2000	2005	2010	2015	2020	2000	2005	2010	2015	2020
AFG	0.59	0.68	0.68	0.78	0.83	0.35	0.42	0.47	0.50	0.51	0.06	0.06	0.08	0.11	0.19
ARG	0.98	0.98	0.98	0.99	0.99	0.78	0.79	0.83	0.84	0.85	0.34	0.34	0.35	0.32	0.42
AUT	0.99	0.99	0.99	0.99	0.99	0.85	0.86	0.90	0.92	0.92	0.63	0.64	0.69	0.76	0.76
BOL	0.97	0.97	0.98	0.98	0.98	0.63	0.64	0.67	0.70	0.72	0.34	0.35	0.34	0.34	0.31
BTN	0.78	0.89	0.93	0.96	0.96	/	0.52	0.57	0.63	0.65	0.61	0.61	0.63	0.65	0.68
CAN	0.99	0.99	0.99	0.99	0.99	0.87	0.89	0.90	0.92	0.93	0.86	0.86	0.84	0.83	0.77
CHE	0.99	1.00	1.00	1.00	0.99	0.90	0.91	0.94	0.95	0.96	0.86	0.86	0.86	0.86	0.85
CHL	0.99	0.99	0.99	0.99	0.99	0.76	0.79	0.80	0.84	0.85	0.77	0.78	0.72	0.70	0.67
CHN	0.96	0.98	0.99	0.99	0.99	0.59	0.64	0.70	0.74	0.76	0.38	0.38	0.39	0.37	0.42
COL	0.98	0.98	0.99	0.99	0.99	0.67	0.69	0.73	0.76	0.77	0.35	0.35	0.36	0.37	0.39
ECU	0.98	0.99	0.99	0.99	0.99	0.68	0.70	0.73	0.76	0.76	0.32	0.33	0.32	0.32	0.39
FRA	0.99	0.99	0.99	0.99	0.99	0.85	0.87	0.88	0.90	0.90	0.74	0.73	0.71	0.70	0.69
GEO	0.99	0.99	0.99	0.99	0.99	0.69	0.73	0.75	0.79	0.81	0.47	0.47	0.52	0.52	0.56
GRL	0.99	0.99	0.99	0.99	0.99	0.87	0.91	0.92	0.93	0.94	0.89	0.90	0.90	0.91	0.88
IND	0.84	0.90	0.92	0.94	0.95	0.50	0.54	0.58	0.62	0.65	0.32	0.32	0.36	0.38	0.40
ISL	1.00	1.00	0.99	1.00	0.99	0.87	0.90	0.90	0.93	0.95	0.86	0.86	0.82	0.79	0.75
ITA	0.99	0.99	0.99	0.99	0.99	0.84	0.87	0.88	0.88	0.89	0.37	0.38	0.42	0.44	0.53
KAZ	0.99	0.99	0.99	0.99	0.99	0.69	0.75	0.76	0.81	0.83	0.27	0.27	0.28	0.28	0.38
KGZ	0.98	0.98	0.99	0.99	0.99	0.62	0.64	0.66	0.69	0.70	0.21	0.20	0.24	0.28	0.31
MNG	0.97	0.99	0.99	0.99	0.99	0.59	0.65	0.70	0.74	0.74	0.34	0.34	0.36	0.39	0.35
NOR	0.99	0.99	0.99	0.99	0.99	0.92	0.93	0.94	0.95	0.96	0.85	0.85	0.85	0.88	0.84
NPL	0.81	0.89	0.91	0.94	0.95	0.45	0.48	0.54	0.58	0.60	0.25	0.25	0.27	0.27	0.33
NZL	0.99	0.99	0.99	0.99	0.99	0.88	0.90	0.91	0.92	0.93	0.90	0.90	0.90	0.91	0.88
PAK	0.92	0.93	0.93	0.94	0.94	0.45	0.49	0.51	0.54	0.56	0.24	0.25	0.27	0.30	0.31
PER	0.98	0.98	0.99	0.99	0.99	0.68	0.70	0.72	0.76	0.78	0.38	0.39	0.38	0.36	0.38
RUS	0.99	0.99	0.99	0.99	0.99	0.72	0.75	0.78	0.81	0.82	0.27	0.27	0.28	0.29	0.30
SWE	0.99	0.99	0.99	0.99	0.99	0.90	0.90	0.91	0.94	0.95	0.88	0.88	0.88	0.89	0.85
TJK	0.98	0.98	0.98	0.98	0.98	0.56	0.61	0.64	0.65	0.67	0.19	0.19	0.22	0.26	0.25
USA	0.99	0.99	0.99	0.99	0.99	0.89	0.90	0.92	0.92	0.93	0.72	0.72	0.73	0.76	0.67
UZB	0.96	0.99	0.99	0.99	0.99	0.60	0.63	0.67	0.70	0.72	0.15	0.15	0.17	0.19	0.26

ALPS	0.99	0.99	0.99	0.99	0.99	0.86	0.88	0.90	0.91	0.92	0.65	0.65	0.67	0.69	0.71
ANDES	0.98	0.98	0.99	0.99	0.99	0.70	0.72	0.75	0.78	0.79	0.42	0.42	0.41	0.40	0.43
HMA	0.89	0.93	0.94	0.95	0.96	0.49	0.58	0.62	0.65	0.67	0.27	0.27	0.30	0.32	0.35
PNW	0.99	0.99	0.99	0.99	0.99	0.88	0.90	0.91	0.92	0.93	0.79	0.79	0.79	0.80	0.72
HOAC	0.99	0.99	0.99	0.99	0.99	0.84	0.86	0.88	0.90	0.91	0.73	0.73	0.74	0.74	0.72
*HDI not available for Bhutan in 2000															

Table S4.1: GLOF Vulnerability metrics 2000 to 2020. Normalised values of SVI, HDI, and CPI between 2000 and 2020.

Appendix A: Supplementary Information

Country	%_pop growth					%_<5yrs					%_>65					%_illiterate					%_unemployed				
	2000	2005	2010	2015	2020	2000	2005	2010	2015	2020	2000	2005	2010	2015	2020	2000	2005	2010	2015	2020	2000	2005	2010	2015	2020
AFG	2.0	2.0	2.1	2.2	2.5	11.3	19.0	21.7	20.3	14.8	1.3	2.3	2.9	3.3	2.6	65.0	62.0	68.3	57.0	57.0	11.2	11.4	11.5	11.4	11.1
ARG	1.1	0.7	1.2	1.2	1.0	9.7	9.6	9.1	8.8	8.4	9.6	10.2	10.6	11.0	11.2	3.3	1.0	1.0	0.8	1.0	5.4	11.5	7.7	7.8	9.8
AUT	0.1	0.3	0.5	0.5	0.7	4.9	4.9	4.8	4.6	4.9	14.7	15.8	17.9	18.6	19.4	1.0	1.0	1.0	1.0	1.0	4.7	5.6	4.8	5.7	4.7
BOL	2.0	2.1	1.9	2.0	1.4	12.5	13.5	12.4	11.2	10.3	3.9	4.5	5.2	6.6	7.3	15.6	7.6	7.5	7.5	7.5	2.7	2.8	2.6	3.1	3.5
BTN	2.6	12.5	1.9	1.9	1.2	25.0	15.4	14.1	12.9	8.3	4.0	4.5	4.7	5.3	6.1	58.0	47.2	43.0	33.4	33.5	1.3	3.1	3.3	2.5	6.8
CAN	0.9	1.0	1.2	1.2	0.9	6.2	5.6	5.9	5.5	5.3	12.5	13.7	14.8	16.8	17.6	1.0	1.0	1.0	1.0	1.0	8.3	6.8	8.1	6.9	5.6
CHL	1.1	1.2	1.7	1.9	1.2	9.5	7.6	7.1	6.4	6.2	6.9	8.9	9.4	10.2	11.9	4.6	3.3	3.7	3.6	3.6	9.0	9.3	8.4	6.5	7.1
CHN	0.7	0.4	0.7	0.8	0.5	10.6	6.5	6.4	6.3	5.4	6.5	7.8	8.3	9.5	11.5	17.2	10.0	4.9	3.2	3.2	2.4	4.5	4.5	4.6	4.3
COL	1.6	1.0	2.6	1.1	1.4	10.3	9.8	7.9	7.3	7.4	4.6	5.8	6.2	7.3	8.8	8.8	7.2	6.6	5.8	4.9	10.1	11.9	11.0	8.3	9.7
ECU	1.6	1.3	2.1	2.1	1.7	11.5	12.3	11.2	10.1	9.6	4.6	5.4	6.3	7.0	7.4	9.4	8.1	8.4	5.5	7.2	4.6	3.8	4.1	3.6	4.0
FRA	0.2	0.5	0.7	0.8	0.3	6.5	6.3	6.3	6.0	5.6	15.6	16.8	17.0	18.9	20.4	1.0	1.0	0.9	0.7	1.0	9.1	8.5	8.9	10.4	8.4
GEO	0.0	-2.8	-1.2	-0.6	-0.2	9.8	4.6	7.3	7.5	6.9	12.2	13.7	14.6	15.0	15.1	1.0	1.0	0.4	0.6	0.6	2.7	13.8	20.2	20.3	14.4
GRL	0.0	0.4	0.7	0.4	0.4	5.7	5.6	5.4	5.3	5.2	15.2	14.8	16.1	19.3	20.0	1.0	1.0	0.5	0.2	1.0	5.1	4.8	7.5	6.2	4.9
IND	1.2	2.3	1.7	1.7	1.0	12.4	11.8	10.8	9.2	8.5	4.8	5.0	5.3	5.7	6.4	44.3	30.7	27.4	25.6	25.8	5.5	5.6	5.6	5.6	5.4
ISL	0.7	-0.6	1.0	1.0	0.7	0.0	0.0	0.0	0.0	6.1	11.4	12.0	14.3	13.6	15.2	1.0	1.0	0.8	0.6	1.0	2.7	2.5	7.6	4.9	2.8
ITA	-0.3	0.0	0.4	0.5	0.0	4.9	4.9	4.8	4.3	3.9	17.6	20.0	20.6	22.1	23.0	1.7	1.2	1.0	0.8	0.8	12.2	7.7	8.4	11.9	9.9
KAZ	0.2	-1.3	0.8	1.1	1.3	11.7	7.9	10.1	12.0	10.5	6.9	7.9	6.9	7.2	7.7	1.0	0.4	0.2	0.2	0.2	3.7	8.1	5.8	4.9	4.6
KGZ	1.0	3.1	0.5	0.5	1.8	13.0	9.4	11.0	14.3	12.0	5.9	5.6	5.5	5.4	4.6	3.0	2.0	0.8	0.4	0.4	3.1	8.1	8.6	7.6	6.3
MNG	1.5	-0.9	1.3	1.7	1.8	11.5	8.0	11.3	13.9	11.6	3.9	4.0	3.8	3.5	4.2	17.0	2.2	1.7	1.6	1.6	5.9	7.1	6.5	4.9	6.0
NOR	0.4	-0.1	0.9	1.0	0.8	6.8	6.9	6.5	6.2	5.2	15.7	16.0	15.3	18.7	17.3	1.0	0.7	0.6	0.6	1.0	3.3	4.4	3.5	4.3	3.3
NPL	2.1	0.4	1.9	3.8	1.5	13.6	14.2	11.8	9.2	9.5	3.6	4.7	5.5	5.0	5.8	60.8	40.4	40.0	32.1	32.1	1.7	1.6	1.5	1.5	1.4
NZL	0.8	-0.4	0.7	0.8	0.9	7.9	8.1	7.8	7.5	6.3	11.6	13.4	15.6	17.5	16.0	1.0	0.6	0.6	0.4	1.0	7.5	3.8	6.6	5.4	4.1
PAK	2.4	1.7	2.6	2.6	2.0	12.4	14.1	13.2	12.7	12.8	3.1	4.1	4.4	4.2	4.3	56.0	50.1	44.6	42.0	40.3	0.6	0.6	0.7	3.6	4.5
PER	1.5	1.1	1.9	2.1	1.6	12.5	11.1	10.5	8.8	8.6	4.6	5.7	6.3	6.9	8.4	10.8	12.1	7.6	5.8	5.6	5.5	4.9	3.5	3.0	3.3
RUS	-0.2	-0.5	-0.2	-0.2	0.1	7.8	4.8	5.7	6.6	6.4	12.3	13.8	13.2	14.0	15.1	0.5	0.5	0.3	0.3	0.3	13.3	7.1	7.4	5.6	4.6
SWE	0.1	-0.2	0.8	0.8	0.7	6.7	5.7	6.5	6.3	6.0	17.4	18.1	18.5	19.9	20.2	1.0	1.0	0.8	0.6	1.0	8.2	7.5	8.6	7.4	6.5
CHE	0.3	0.7	0.9	1.0	0.8	5.5	5.3	5.1	4.8	5.2	14.5	7.9	8.8	8.4	18.8	1.0	0.8	0.8	0.7	1.0	4.4	4.4	4.8	4.8	4.6

TJK	1.5	2.6	2.2	2.3	2.4	15.0	13.3	13.2	14.3	14.4	4.5	4.4	2.6	8.3	3.1	1.0	0.5	0.2	0.2	0.2	2.9	13.0	11.6	11.5	11.0
USA	0.7	1.3	1.0	1.1	0.6	7.0	6.9	6.8	6.2	6.0	12.5	12.4	13.1	14.6	16.2	1.0	1.0	1.0	1.0	1.0	4.5	5.1	9.6	5.3	3.7
UZB	1.4	1.8	1.7	1.7	1.6	13.6	9.8	10.1	10.6	10.4	4.4	4.9	4.5	4.2	1.3	12.0	1.4	0.0	0.0	0.0	0.4	6.9	5.4	5.2	5.9
ALPS	0.4	-0.7	0.4	0.7	0.8	9.0	6.2	7.3	7.6	7.1	10.2	11.6	12.2	12.8	13.5	1.9	1.4	1.3	1.4	1.4	5.0	9.2	9.8	9.4	7.7
ANDES	0.9	0.8	1.1	1.1	0.8	9.8	8.9	8.5	8.2	7.6	8.8	9.7	10.1	11.1	12.2	7.8	4.7	3.8	3.0	3.0	3.3	5.1	5.8	5.4	4.8
HMA	1.4	2.0	1.5	1.5	1.5	11.5	10.1	10.4	10.5	9.6	6.5	7.2	7.4	8.5	8.0	16.2	12.4	11.8	9.6	16.5	5.7	6.9	6.6	5.3	7.0
PNW	0.8	1.2	1.1	1.1	0.8	6.6	6.2	6.3	5.8	5.7	12.5	13.1	13.9	15.7	16.9	1.0	1.0	1.0	1.0	2.6	4.7	4.4	5.8	4.9	3.9
OTHER	0.8	0.8	1.3	1.5	0.9	8.7	8.8	8.2	7.4	7.3	10.9	10.7	11.3	12.1	14.1	23.7	17.9	16.4	14.6	9.4	8.0	6.8	6.8	7.6	6.7
GLOBAL	1.0	1.1	1.2	1.3	1.1	9.9	8.8	8.8	8.6	8.1	8.9	9.5	9.9	10.9	11.6	13.4	9.9	9.2	7.8	1.3	4.1	7.6	9.3	8.8	6.9

Table S4.2: GLOF Social Vulnerability Indicators used in this study. Raw values of the indicators used to calculate SVI for each country in the study. Data in red represents factors that increase social vulnerability to GLOF, while data in green represents factors that decrease social vulnerability to GLOF. Dash indicates where no data was available. Countries are coloured according to mountain range where; Andes = blue, Alps = red, HMA = green, PNW = purple and HAOC = orange. Whole mountain range totals are also given.

Appendix A: Supplementary Information

Country	%_literate female					%_urban_pop					%_safe_water					%_good_sanitation					%_internet_users				
	2000	**2005**	**2010**	**2015**	**2020**	**2000**	**2005**	**2010**	**2015**	**2020**	**2000**	**2005**	**2010**	**2015**	**2020**	**2000**	**2005**	**2010**	**2015**	**2020**	**2000**	**2005**	**2010**	**2015**	**2020**
AFG	2.3	6.3	5.9	8.8	13.2	20.0	22.7	23.7	24.8	25.8	/	/	/	/	/	/	/	/	/	/	/	1.2	4.0	8.3	13.5
ARG	36.3	46.1	56.1	56.2	59.2	88.9	90.0	90.1	91.5	92.0	/	/	/	/	/	/	/	/	/	/	7.0	17.7	45.0	68.0	71.8
AUT	77.0	100.0	100.0	98.7	100.0	64.7	58.8	57.4	57.7	58.5	98.0	98.0	99.0	99.0	99.0	97.0	97.0	97.0	97.0	97.0	33.7	58.0	75.2	83.9	87.7
BOL	37.0	37.5	42.9	52.8	53.1	63.2	64.2	66.4	68.4	69.8	/	/	/	/	/	13.0	15.0	18.0	22.0	23.0	1.4	5.2	22.4	35.6	43.8
BTN	5.8	12.8	16.3	19.8	23.3	6.7	31.0	34.8	38.7	41.6	29.0	31.0	34.0	36.0	36.0	/	/	/	/	/	0.4	3.8	13.6	39.8	48.1
CAN	83.3	99.8	100.0	100.0	100.0	76.9	80.1	80.9	81.3	81.5	98.0	98.0	99.0	99.0	99.0	77.0	79.0	82.0	82.0	82.0	51.3	71.7	80.3	90.0	91.0
CHL	49.0	75.4	73.3	76.9	77.8	84.3	86.8	87.1	87.4	87.6	92.0	94.0	97.0	99.0	99.0	48.0	53.0	63.0	74.0	77.0	16.6	31.2	45.0	76.6	82.3
CHN	28.5	51.0	58.7	69.8	76.0	32.7	42.5	49.2	55.5	60.3	/	/	/	/	/	27.0	34.0	48.0	65.0	72.0	1.8	8.5	34.3	50.3	54.3
COL	31.0	41.1	44.4	51.1	55.7	84.1	76.0	78.0	79.8	81.1	68.0	70.0	72.0	73.0	73.0	13.0	15.0	16.0	17.0	17.0	2.2	11.0	36.7	55.9	62.3
ECU	33.3	38.6	44.5	52.1	52.5	61.1	61.7	62.7	63.4	64.0	66.0	69.0	72.0	74.0	75.0	41.0	42.0	42.0	42.0	42.0	1.5	6.0	29.0	48.9	57.3
FRA	44.4	71.3	76.4	80.6	81.7	75.2	77.1	78.4	79.7	80.7	97.0	97.0	97.0	98.0	98.0	89.0	89.0	89.0	89.0	88.0	14.3	42.9	77.3	78.0	82.0
GEO	83.9	91.2	93.7	96.8	97.2	60.7	53.6	55.5	57.4	59.0	75.0	76.0	79.0	80.0	80.0	22.0	23.0	25.0	26.0	27.0	0.5	6.1	26.9	57.6	64.0
GRL	58.0	100.0	96.1	89.2	91.2	85.5	85.9	86.8	87.5	88.0	94.0	94.0	96.0	97.0	97.0	92.0	92.0	93.0	95.0	95.0	39.2	82.7	88.7	96.3	97.6
IND	13.4	21.8	27.0	27.7	27.7	27.7	29.2	30.9	33.2	34.5	/	/	/	/	/	/	/	/	/	/	0.5	2.4	7.5	17.0	34.5
ISL	45.6	91.0	98.0	100.0	100.0	92.0	93.0	93.6	93.7	93.9	90.0	93.0	96.0	99.0	100.0	44.0	55.0	66.0	77.0	82.0	44.5	87.0	93.4	98.2	99.0
ITA	44.1	63.5	69.1	74.3	75.9	66.8	67.7	68.3	69.9	70.7	86.0	89.0	92.0	94.0	95.0	96.0	96.0	96.0	96.0	96.0	23.1	35.0	53.7	58.1	74.7
KAZ	59.8	94.2	96.1	98.1	99.3	60.8	56.6	56.8	57.3	57.5	58.0	65.0	77.0	86.0	90.0	/	/	/	/	/	0.7	3.0	31.6	70.8	78.9
KGZ	71.1	91.1	94.5	98.7	99.1	39.5	35.3	35.3	35.8	36.6	46.0	49.0	59.0	66.0	68.0	/	/	/	/	/	1.0	10.5	16.3	30.2	38.0
MNG	67.6	81.5	85.3	89.7	91.5	62.4	62.5	67.6	68.2	68.5	22.0	24.0	24.0	24.0	24.0	/	/	/	/	/	1.3	2.0	10.2	22.5	23.7
NOR	62.5	96.9	94.5	96.3	95.4	73.2	77.7	79.1	81.5	82.6	100.0	100.0	99.0	99.0	98.0	73.0	74.0	75.0	76.0	76.0	52.0	82.0	93.4	96.8	96.5
NPL	7.0	13.3	17.7	24.1	29.3	11.2	15.1	16.8	18.9	20.2	24.0	25.0	26.0	27.0	27.0	/	/	/	/	/	0.2	0.8	7.9	17.6	34.0
NZL	60.5	81.0	92.6	99.2	97.4	86.5	86.3	86.2	86.4	86.6	78.0	78.0	91.0	99.0	100.0	79.0	82.0	94.0	87.0	89.0	47.5	62.7	80.5	88.2	90.8
PAK	6.9	19.9	20.7	26.9	27.6	35.6	34.0	35.0	36.2	36.9	38.0	38.0	36.0	36.0	35.0	/	/	/	/	/	0.1	6.3	8.0	14.0	15.5
PER	37.9	43.6	53.2	57.1	58.9	72.0	75.0	76.4	77.4	78.1	45.0	47.0	49.0	50.0	50.0	11.0	20.0	29.0	39.0	43.0	3.1	17.1	34.8	40.9	52.5
RUS	74.2	93.6	89.6	95.9	96.3	77.0	73.5	73.7	74.2	74.6	75.0	75.0	75.0	76.0	76.0	55.0	57.0	59.0	61.0	61.0	2.0	15.2	43.0	70.1	80.9
SWE	67.2	88.7	85.1	88.4	89.3	83.2	84.3	85.1	86.6	87.7	100.0	100.0	100.0	100.0	100.0	92.0	93.0	93.0	93.0	93.0	45.7	84.4	90.0	90.6	92.1
CHE	57.4	81.5	94.6	96.4	95.6	61.9	73.5	73.6	73.7	73.8	93.0	93.0	94.0	95.0	95.0	98.0	98.0	99.0	100.0	100.0	47.1	70.1	83.9	87.5	89.7

TJK	71.2	92.7	93.2	93.3	93.3	41.8	26.5	26.5	26.9	27.3	35.0	42.0	46.0	47.0	48.0	/	/	/	/	/	0.0	0.3	11.6	19.0	22.0
USA	92.8	93.9	94.9	95.7	96.1	76.8	79.9	80.2	81.2	82.5	99.0	99.0	99.0	99.0	99.0	88.0	89.0	89.0	90.0	90.0	43.1	68.0	71.7	74.6	87.3
UZB		98.2	98.7	99.9	99.9	32.5	48.5	51.0	50.6	50.4	56.0	57.0	59.0	59.0	44.0	/	/	/	/	/	0.5	3.3	15.9	42.8	52.3

ALPS	67.4	90.2	90.8	92.6	93.6	67.6	64.0	64.2	65.0	65.7	80.8	83.3	88.0	91.0	92.0	41.8	43.3	46.3	49.3	50.3	12.9	24.6	44.7	72.2	78.2
ANDES	42.3	56.4	61.4	67.9	69.8	55.2	57.0	59.4	61.8	63.7	35.0	35.8	38.8	40.8	41.3	33.0	35.3	39.8	45.5	47.5	10.9	26.7	40.4	53.1	58.4
HMA	41.4	66.9	70.6	74.0	75.2	45.2	49.7	52.8	55.0	56.4	29.8	31.3	32.5	33.3	33.3	3.3	3.8	4.0	4.3	4.3	1.1	4.8	17.0	33.8	42.2
PNW	88.1	96.9	97.5	97.9	98.1	75.8	78.1	79.1	80.0	80.5	88.5	90.0	91.5	92.8	93.0	58.8	62.5	66.3	69.3	70.5	37.3	61.7	74.0	83.5	86.0
OTHER	36.3	55.5	58.6	61.0	62.4	59.4	61.7	62.7	64.0	64.8	74.8	76.3	78.0	79.5	79.8	58.3	59.5	62.0	64.8	65.3	13.6	27.5	46.0	57.6	68.3
GLOBAL	47.0	67.3	111.2	73.8	75.1	60.2	59.8	61.9	64.2	65.9	52.8	54.8	61.8	66.3	67.5	32.0	34.8	41.8	44.5	47.0	12.6	20.1	43.3	66.7	72.0

Table S4.2: Continued.

Location	Hazard		Exposure		Vulnerability		Risk	
	Actual Change	**Percentage change**	**Actual Change**	**Percentage change**	**Actual Change**	**Percentage change**	**Actual Change**	**Percentage change**
Alps	0.002	33.68%	0.019	15.42%	-0.091	-20.40%	0.002	28.70%
Andes	0.008	19.03%	0.036	27.86%	-0.058	-7.55%	0.034	39.34%
HMA	0.006	16.95%	0.071	31.56%	-0.092	-10.66%	0.040	37.85%
PNW	0.018	3.90%	0.025	33.53%	0.023	7.45%	0.019	44.88%
HAOC	0.027	15.69%	-0.001	-4.39%	-0.039	-10.23%	0.003	1.07%

Table S4.3: Actual and percentage change in GLOF risk drivers. Actual and percentage change in hazard, exposure, vulnerability, and risk between 2000 and 2020 for each mountain region in this study.

Country	Basin ID	Normalised Risk
PAK	11411000000	1.47E-03
PER	50432000000	3.43E-04
BOL	50411230301	3.40E-04
BTN	11501060201	2.61E-04
IND	11501050200	1.75E-04
CHL	51203030111	1.69E-04
PAK	11410040300	1.60E-04
ARG	51202010101	1.40E-04
USA	30101130110	1.39E-04
USA	30403131201	1.31E-04
NOR	41001010201	1.10E-04
PER	51502040200	9.47E-05
PAK	11410040201	9.40E-05
PAK	11406150100	7.95E-05
CHN	11504090000	7.78E-05
NOR	41001010211	7.33E-05
IND	11406190000	7.17E-05
NPL	11504080301	6.83E-05
NPL	11504080500	6.55E-05
NPL	11506070000	5.37E-05
CHE	40210100400	5.07E-05
ITA	40208060200	4.44E-05
CHL	51202050211	4.39E-05
NPL	11506050100	4.07E-05
NPL	11504080101	3.95E-05
AFG	10907220101	3.92E-05
TJK	10907330101	2.89E-05
IND	11406190100	2.83E-05
CHL	51301020211	2.80E-05
NPL	11504070100	2.75E-05
NOR	41001050911	2.49E-05
PER	50426270600	2.25E-05
ARG	51301060200	2.23E-05
IND	11406180100	2.16E-05
PER	50426221300	2.12E-05
CHN	11002030201	1.80E-05
CAN	30401070401	1.73E-05

PER	51502030101	1.70E-05
PER	50411231301	1.68E-05
BTN	11501110301	1.65E-05
CHN	12517000000	1.65E-05
CHN	11002031101	1.52E-05
BTN	11501110201	1.48E-05
NOR	41001051211	1.38E-05
IND	11501050101	1.29E-05
PER	51401160500	1.26E-05
PER	51401160101	1.25E-05
AUT	40515060000	1.21E-05
ITA	40208140000	1.19E-05
BTN	11501060500	1.11E-05

Table S4.4: Highest GLOF risk basins. The 50 basins most at risk of GLOFs as of 2020. Countries are coloured according to range; Andes = blue, Alps = red, HMA = green, PNW = purple and HAOC = orange.

Appendix A: Supplementary Information

Basin	ID	Risk				
		2000	2005	2010	2015	2020
10907220101	AFG	3.20E-05	3.61E-05	3.22E-05	3.69E-05	3.92E-05
11410080101	AFG	6.51E-06	7.06E-06	5.98E-06	7.24E-06	7.55E-06
11410070200	AFG	3.52E-06	4.43E-06	4.13E-06	5.25E-06	5.92E-06
11410050101	AFG	1.96E-06	2.34E-06	3.75E-07	1.96E-06	3.37E-06
10907240101	AFG	1.42E-06	1.68E-06	1.98E-06	2.60E-06	2.75E-06
11410050201	AFG	9.65E-07	1.18E-06	1.19E-06	1.32E-06	1.51E-06
10907220401	AFG	2.41E-07	8.24E-07	7.41E-07	1.23E-06	9.60E-07
10907330300	AFG	4.51E-07	5.35E-07	6.72E-07	8.29E-07	9.13E-07
10907330201	AFG	6.02E-07	6.49E-07	7.60E-07	8.34E-07	8.78E-07
10907240400	AFG	2.43E-07	2.92E-07	3.01E-07	4.11E-07	5.34E-07
10907240201	AFG	2.11E-07	1.02E-07	1.50E-07	3.67E-07	4.64E-07
10907240301	AFG	1.33E-07	1.56E-07	1.86E-07	2.23E-07	2.65E-07
10907240300	AFG	0.00E+00	0.00E+00	1.73E-07	0.00E+00	2.42E-07
10907330200	AFG	6.55E-08	7.58E-08	7.73E-08	8.71E-08	9.23E-08
10907220501	AFG	4.66E-08	2.22E-07	9.82E-08	2.65E-07	4.24E-08
51202010101	ARG	2.42E-05	1.35E-05	5.54E-05	3.29E-05	1.40E-04
51301060200	ARG	1.77E-05	1.95E-05	2.01E-05	2.23E-05	2.23E-05
51301070101	ARG	4.99E-07	9.40E-07	7.10E-07	1.49E-06	1.58E-06
51301070201	ARG	1.47E-07	2.05E-07	1.44E-07	1.98E-07	2.19E-07
51202080400	ARG	1.93E-08	3.78E-08	3.87E-08	7.15E-08	9.36E-08
51003040600	ARG	0.00E+00	0.00E+00	0.00E+00	3.34E-08	3.18E-08
51101050601	ARG	1.64E-08	1.70E-08	1.63E-08	1.64E-08	1.64E-08
51202080201	ARG	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.44E-08
51202011000	ARG	0.00E+00	2.22E-09	0.00E+00	0.00E+00	7.40E-09
51301070300	ARG	0.00E+00	0.00E+00	1.10E-08	3.05E-08	4.23E-09
51003320200	ARG	1.70E-09	1.99E-09	2.26E-09	0.00E+00	2.92E-09
51003310200	ARG	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.27E-09
51003290600	ARG	0.00E+00	1.13E-09	0.00E+00	1.69E-09	1.24E-09
51003340100	ARG	1.60E-09	3.82E-09	1.29E-09	1.94E-09	8.87E-10
51202010901	ARG	0.00E+00	5.01E-10	0.00E+00	0.00E+00	7.47E-10
40515060000	AUT	1.49E-05	1.63E-05	1.48E-05	1.25E-05	1.21E-05
40515020200	AUT	2.82E-06	2.95E-06	2.39E-06	2.23E-06	2.00E-06
40515050100	AUT	1.51E-06	1.44E-06	1.30E-06	1.09E-06	8.90E-07
40510040400	AUT	2.16E-07	6.33E-07	3.38E-07	5.69E-07	4.88E-07
40510080100	AUT	3.51E-07	3.09E-07	2.42E-07	1.72E-07	1.48E-07
11501060201	BTN	5.75E-05	2.23E-04	2.29E-04	2.40E-04	2.61E-04
11501110301	BTN	3.60E-06	1.61E-05	1.57E-05	1.56E-05	1.65E-05
11501110201	BTN	0.00E+00	1.40E-05	1.38E-05	1.37E-05	1.48E-05
11501060500	BTN	8.79E-06	1.88E-05	1.23E-05	1.14E-05	1.11E-05
11501060301	BTN	0.00E+00	2.19E-06	3.12E-06	3.56E-06	4.10E-06
11501110401	BTN	0.00E+00	2.53E-08	8.86E-08	3.41E-08	5.93E-08
50411230301	BOL	2.22E-04	2.67E-04	2.83E-04	3.06E-04	3.40E-04
51401170100	BOL	2.09E-06	2.73E-06	3.37E-06	3.90E-06	5.19E-06
51401180301	BOL	1.01E-06	1.21E-06	1.25E-06	1.24E-06	1.25E-06
51401180100	BOL	8.11E-07	7.88E-07	8.49E-07	1.18E-06	1.16E-06
51401180101	BOL	8.20E-07	9.70E-07	1.01E-06	9.65E-07	1.00E-06
30401070401	CAN	1.46E-05	1.34E-05	1.42E-05	1.41E-05	1.73E-05
30402050601	CAN	3.74E-06	5.71E-06	2.94E-06	9.39E-06	9.46E-06
30503240500	CAN	3.20E-06	2.71E-06	3.62E-06	5.14E-06	9.06E-06
30403131601	CAN	2.44E-06	2.96E-06	2.14E-06	3.65E-06	5.39E-06
30402050101	CAN	3.10E-06	3.45E-06	3.71E-06	4.09E-06	5.23E-06
30402030115	CAN	0.00E+00	2.53E-06	0.00E+00	1.91E-06	3.64E-06
30401010311	CAN	8.25E-07	1.65E-06	1.64E-06	2.05E-06	3.28E-06
30402040301	CAN	1.34E-06	1.58E-06	1.72E-06	1.94E-06	2.44E-06
30402050401	CAN	4.86E-07	5.92E-07	6.68E-07	7.72E-07	1.14E-06
30218240000	CAN	7.29E-07	8.16E-07	8.08E-07	1.06E-06	1.02E-06
30402051801	CAN	4.16E-07	4.76E-07	3.60E-07	6.76E-07	7.25E-07
30402020611	CAN	1.68E-07	4.21E-07	3.34E-07	6.10E-07	6.09E-07
30101090110	CAN	2.56E-07	2.96E-07	2.91E-07	2.83E-07	3.92E-07
30307080111	CAN	1.54E-07	1.73E-07	1.73E-07	1.78E-07	2.25E-07
30101100111	CAN	1.42E-07	1.77E-07	1.62E-07	1.65E-07	2.24E-07
30101090114	CAN	1.26E-07	2.02E-07	3.49E-08	9.17E-08	1.82E-07
30403132601	CAN	3.19E-08	1.50E-07	1.68E-07	1.39E-07	1.81E-07
30402010301	CAN	8.64E-08	9.18E-08	9.21E-08	9.61E-08	1.19E-07
30402020619	CAN	0.00E+00	0.00E+00	6.96E-08	0.00E+00	1.09E-07
30402020618	CAN	5.16E-08	7.06E-08	6.76E-08	7.49E-08	1.08E-07
30402050201	CAN	1.84E-08	3.17E-08	4.99E-08	6.59E-08	8.71E-08
30212090401	CAN	8.14E-08	8.14E-08	7.85E-08	6.57E-08	8.03E-08
30402051401	CAN	1.60E-08	2.82E-08	1.55E-08	5.65E-08	7.36E-08
30503211400	CAN	2.41E-08	1.12E-08	4.13E-09	3.85E-08	6.94E-08
30401010111	CAN	5.66E-08	5.89E-08	9.21E-08	7.09E-08	6.67E-08
30402040201	CAN	2.61E-08	3.90E-08	3.39E-08	4.14E-08	5.57E-08
30220030400	CAN	6.63E-09	2.71E-08	5.97E-09	4.13E-08	4.89E-08
30102470501	CAN	2.50E-08	2.76E-08	3.22E-08	3.05E-08	4.33E-08
30402050901	CAN	1.00E-08	1.49E-08	1.54E-08	2.88E-08	4.18E-08
30401080201	CAN	3.89E-08	3.94E-08	3.25E-08	3.53E-08	3.99E-08
30402052001	CAN	2.67E-08	3.52E-08	3.09E-08	2.40E-08	3.98E-08
30403131801	CAN	1.82E-08	2.45E-08	1.79E-08	2.36E-08	3.66E-08
30402030401	CAN	2.10E-08	1.45E-08	2.06E-08	1.57E-08	3.40E-08
30402051101	CAN	2.19E-08	2.64E-08	2.70E-08	2.66E-08	3.27E-08
30308030911	CAN	7.77E-09	7.92E-09	1.82E-08	1.44E-08	2.72E-08
30401040101	CAN	7.27E-09	1.75E-08	1.03E-08	2.80E-08	2.54E-08
30503102301	CAN	1.46E-08	7.69E-09	3.55E-09	1.23E-08	1.91E-08
30222020000	CAN	1.10E-08	1.18E-08	8.61E-09	2.07E-08	1.82E-08
30503102500	CAN	1.03E-08	9.76E-09	9.53E-09	1.19E-08	1.76E-08
30402030501	CAN	1.27E-08	1.63E-08	1.27E-08	2.19E-08	1.59E-08
30401050112	CAN	1.60E-08	1.08E-08	1.13E-08	3.11E-08	1.43E-08
30223000000	CAN	0.00E+00	0.00E+00	2.79E-08	0.00E+00	1.27E-08
30401070100	CAN	4.92E-09	1.42E-08	3.20E-09	1.40E-08	1.24E-08
30307020411	CAN	1.57E-09	3.03E-09	4.81E-09	4.37E-09	1.16E-08
30307050511	CAN	1.54E-09	6.17E-09	1.10E-08	4.99E-09	1.13E-08
30401010101	CAN	1.53E-09	3.37E-09	6.51E-09	7.60E-09	9.41E-09
30401080111	CAN	8.21E-09	8.28E-09	6.95E-09	7.56E-09	9.05E-09
30402052101	CAN	7.40E-09	1.11E-08	7.27E-09	7.21E-09	8.93E-09
30402020301	CAN	3.78E-09	4.56E-09	4.91E-09	6.71E-09	8.73E-09
30402020501	CAN	4.13E-09	5.20E-09	5.70E-09	6.45E-09	8.23E-09
30403131701	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.75E-09
30402010201	CAN	4.52E-09	5.72E-09	3.31E-09	4.93E-09	6.82E-09
30401070201	CAN	3.41E-09	4.78E-09	3.87E-09	4.57E-09	5.35E-09
30401070101	CAN	1.52E-09	1.35E-09	1.84E-09	3.65E-09	4.76E-09
30225000000	CAN	0.00E+00	2.72E-09	8.72E-10	2.23E-09	4.17E-09
30402050600	CAN	2.83E-09	2.67E-09	2.95E-09	3.06E-09	3.85E-09
30401070601	CAN	1.10E-09	3.29E-09	1.80E-09	1.25E-09	3.72E-09
30402020411	CAN	9.25E-10	9.55E-10	1.05E-09	1.73E-09	3.42E-09
30401070300	CAN	2.36E-09	1.89E-09	7.51E-10	2.52E-09	3.16E-09
30402020401	CAN	1.43E-09	1.56E-09	1.79E-09	2.34E-09	3.02E-09
30402052201	CAN	1.97E-09	2.23E-09	1.88E-09	2.21E-09	2.84E-09
30101090101	CAN	1.07E-09	1.51E-09	1.71E-09	1.89E-09	2.48E-09
30402020601	CAN	1.01E-09	1.03E-09	1.51E-09	1.63E-09	2.35E-09
30503102101	CAN	5.26E-10	9.60E-10	5.45E-10	9.99E-10	2.27E-09
30401040200	CAN	1.54E-09	1.59E-09	1.67E-09	1.79E-09	2.26E-09
30101090400	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.97E-09
30402010211	CAN	1.23E-09	1.26E-09	1.06E-09	1.26E-09	1.96E-09
30401020110	CAN	1.22E-09	1.28E-09	1.28E-09	1.06E-09	1.89E-09
30401060100	CAN	1.12E-07	0.00E+00	2.18E-08	9.92E-08	1.70E-09
30308030411	CAN	1.23E-09	5.14E-10	1.04E-09	8.63E-10	1.69E-09
30402030101	CAN	4.90E-10	8.45E-10	7.31E-10	9.56E-10	1.60E-09
30403132700	CAN	1.17E-09	1.09E-09	0.00E+00	1.12E-09	1.44E-09
30101090401	CAN	0.00E+00	6.79E-10	3.13E-10	8.68E-10	1.18E-09
30101090300	CAN	2.62E-10	4.01E-10	5.26E-10	5.64E-10	1.17E-09
30102400700	CAN	2.04E-11	2.75E-10	6.42E-10	1.50E-09	9.43E-10
30101090301	CAN	1.33E-10	3.59E-10	2.59E-10	4.71E-10	9.08E-10
30402020211	CAN	2.19E-10	6.12E-10	2.78E-10	7.79E-10	8.68E-10
30402050701	CAN	3.68E-10	4.20E-10	4.50E-10	6.05E-10	7.89E-10
30401030111	CAN	3.66E-10	4.41E-10	3.53E-10	6.09E-10	7.79E-10
30402040101	CAN	3.20E-10	5.46E-10	4.72E-10	6.07E-10	7.58E-10
30401020100	CAN	3.50E-10	3.88E-10	4.12E-10	4.13E-10	7.00E-10
30403132800	CAN	3.26E-10	2.05E-10	9.33E-10	3.23E-10	6.72E-10
30402050801	CAN	4.32E-10	8.90E-10	4.89E-10	9.88E-10	6.59E-10
30402010311	CAN	3.52E-10	4.41E-10	3.48E-10	4.72E-10	5.90E-10
30401080411	CAN	2.69E-10	2.98E-10	1.22E-10	2.71E-10	4.76E-10
30401030211	CAN	1.47E-10	3.86E-10	2.28E-10	3.72E-10	4.48E-10
30102400201	CAN	3.40E-11	9.01E-11	7.57E-11	1.62E-10	3.95E-10
30401040100	CAN	2.73E-10	2.85E-10	9.78E-11	3.15E-10	3.82E-10
30401030101	CAN	3.08E-10	3.03E-10	2.94E-10	2.99E-10	3.64E-10
30101090200	CAN	1.72E-11	5.89E-11	1.05E-10	1.87E-10	3.10E-10
30402050501	CAN	3.21E-11	3.19E-11	1.17E-10	1.29E-10	2.22E-10
30401060201	CAN	3.03E-11	8.14E-11	9.40E-11	3.71E-10	2.12E-10
30102400501	CAN	1.25E-11	5.39E-11	1.09E-11	1.98E-10	1.89E-10

30101090500	CAN	0.00E+00	0.00E+00	0.00E+00	1.03E-10	1.76E-10
30102410301	CAN	8.18E-11	8.10E-11	9.61E-11	1.01E-10	1.40E-10
30402020416	CAN	3.33E-11	8.71E-11	9.32E-11	9.16E-11	1.16E-10
30101090100	CAN	4.21E-11	4.95E-11	5.16E-11	6.07E-11	7.52E-11
30401080101	CAN	4.32E-11	5.53E-11	3.55E-11	5.00E-11	7.49E-11
30401040301	CAN	8.88E-11	2.08E-10	1.57E-11	2.06E-10	6.96E-11
30402010101	CAN	5.29E-11	5.37E-11	4.33E-11	5.24E-11	6.56E-11
30401040110	CAN	7.86E-12	9.81E-12	0.00E+00	3.26E-11	5.22E-11
30402020201	CAN	2.26E-11	2.18E-11	1.79E-11	3.04E-11	3.71E-11
30401080401	CAN	2.78E-11	3.10E-11	2.49E-11	2.52E-11	3.44E-11
30401010301	CAN	4.31E-12	5.33E-12	5.53E-12	1.48E-11	3.24E-11
30101090201	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.09E-11
30102410701	CAN	1.80E-11	1.77E-11	2.12E-11	2.26E-11	3.02E-11
30102470500	CAN	0.00E+00	1.22E-11	0.00E+00	1.96E-11	2.83E-11
30401050201	CAN	6.59E-12	1.03E-11	1.24E-11	2.19E-11	2.78E-11
30401040401	CAN	1.97E-11	1.80E-11	1.84E-11	3.50E-11	2.71E-11
30401050101	CAN	9.81E-12	1.27E-11	1.35E-11	2.57E-11	2.32E-11
30401060200	CAN	2.47E-11	1.05E-11	1.97E-11	7.80E-11	2.32E-11
30101100201	CAN	7.92E-12	9.35E-12	8.23E-12	1.75E-11	2.27E-11
30401010201	CAN	0.00E+00	1.86E-12	3.22E-12	3.41E-12	1.71E-11
30402020101	CAN	5.31E-12	8.48E-12	5.92E-12	1.68E-11	1.65E-11
30224030000	CAN	0.00E+00	5.77E-12	5.81E-12	7.16E-12	1.61E-11
30212120101	CAN	2.09E-11	2.96E-11	1.80E-12	1.65E-11	1.60E-11
30308030211	CAN	8.99E-12	1.56E-11	8.47E-12	4.24E-12	1.22E-11
30401080211	CAN	1.91E-12	6.08E-12	0.00E+00	3.40E-12	1.20E-11
30218220100	CAN	8.65E-13	6.81E-12	2.67E-12	1.28E-11	1.10E-11
30201080200	CAN	7.56E-12	7.30E-12	0.00E+00	7.68E-12	1.05E-11
30308031411	CAN	3.25E-12	1.06E-12	3.57E-12	8.54E-12	8.33E-12
30102391100	CAN	4.58E-12	4.97E-12	5.28E-12	4.77E-12	8.25E-12
30308031111	CAN	5.35E-13	4.72E-14	1.33E-12	1.05E-12	6.83E-12
30212091100	CAN	0.00E+00	0.00E+00	3.14E-12	0.00E+00	4.91E-12
30102390901	CAN	1.79E-12	1.68E-12	2.16E-12	2.44E-12	4.91E-12
30401070110	CAN	0.00E+00	4.20E-12	0.00E+00	4.37E-12	4.55E-12
30308030111	CAN	4.34E-13	0.00E+00	2.38E-12	1.55E-12	4.40E-12
30402020417	CAN	0.00E+00	0.00E+00	0.00E+00	2.12E-12	4.37E-12
30212190301	CAN	1.85E-12	1.63E-12	0.00E+00	9.47E-13	3.40E-12
30401070700	CAN	2.44E-12	4.36E-12	1.00E-12	1.87E-12	3.37E-12
30308031212	CAN	1.63E-12	0.00E+00	1.72E-12	4.82E-12	3.15E-12
30308020211	CAN	1.21E-12	1.04E-12	1.63E-12	2.04E-12	2.73E-12
30308030401	CAN	6.47E-13	8.74E-13	1.65E-12	1.95E-12	2.65E-12
30308030312	CAN	8.99E-13	4.32E-14	1.30E-12	1.64E-12	2.45E-12
30308031301	CAN	1.27E-13	4.98E-13	9.83E-13	1.24E-12	2.00E-12
30308030511	CAN	1.06E-12	5.30E-13	4.74E-13	6.31E-13	1.95E-12
30212030301	CAN	1.53E-12	9.15E-13	1.57E-12	1.35E-12	1.52E-12
30401030201	CAN	0.00E+00	4.12E-13	0.00E+00	1.51E-13	1.18E-12
30403132701	CAN	9.48E-13	3.33E-13	1.03E-12	8.70E-13	1.07E-12
30308031401	CAN	5.91E-13	1.64E-13	4.95E-13	8.53E-13	1.04E-12

30212200100	CAN	6.05E-13	6.27E-13	6.97E-13	7.56E-13	9.85E-13
30402052500	CAN	7.04E-13	7.37E-13	7.17E-13	7.56E-13	9.16E-13
30308030212	CAN	1.07E-12	6.84E-13	3.20E-13	3.31E-14	4.84E-13
30220090000	CAN	0.00E+00	0.00E+00	0.00E+00	1.18E-12	4.47E-13
30401010211	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.97E-13
30102391000	CAN	0.00E+00	0.00E+00	2.87E-13	0.00E+00	3.96E-13
30308030311	CAN	5.76E-13	1.79E-13	1.62E-13	2.34E-13	3.60E-13
30101100101	CAN	0.00E+00	1.27E-12	0.00E+00	0.00E+00	2.65E-13
30212030700	CAN	2.94E-13	2.52E-13	2.43E-13	2.45E-13	2.47E-13
30308030711	CAN	3.75E-13	2.03E-13	2.26E-13	1.87E-13	2.27E-13
30401080301	CAN	1.19E-13	1.40E-13	1.15E-13	1.58E-13	2.13E-13
30308031501	CAN	3.35E-14	0.00E+00	2.74E-14	2.12E-13	2.08E-13
30308030611	CAN	7.80E-14	9.31E-14	1.49E-13	1.87E-13	2.02E-13
30212030800	CAN	1.99E-13	1.73E-13	1.74E-13	1.60E-13	1.67E-13
30308030801	CAN	1.08E-13	4.45E-14	4.92E-14	1.11E-13	1.65E-13
30101100211	CAN	1.27E-14	3.49E-14	4.38E-14	1.09E-13	1.53E-13
30212030701	CAN	1.62E-13	1.07E-13	1.39E-13	1.06E-13	1.46E-13
30212030601	CAN	1.56E-13	1.30E-13	1.61E-13	1.24E-13	1.42E-13
30212190500	CAN	0.00E+00	1.83E-13	0.00E+00	2.67E-13	1.37E-13
30220080100	CAN	0.00E+00	2.83E-14	0.00E+00	5.43E-14	7.69E-14
30208040000	CAN	5.63E-14	5.01E-14	5.22E-14	5.01E-14	5.80E-14
30308030601	CAN	1.77E-14	2.84E-15	1.96E-14	3.17E-14	4.24E-14
30224020100	CAN	3.02E-14	3.62E-14	2.70E-14	1.61E-14	3.52E-14
30308030701	CAN	1.30E-15	2.00E-15	1.83E-15	5.31E-15	2.66E-14
30308010618	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.14E-14
30308030101	CAN	1.15E-14	0.00E+00	5.83E-15	0.00E+00	2.06E-14
30208030100	CAN	1.51E-14	1.79E-14	1.80E-14	1.42E-14	1.79E-14
30308030901	CAN	1.17E-15	1.89E-15	2.82E-15	5.35E-15	7.69E-15
30308030811	CAN	2.49E-15	4.77E-15	3.44E-15	3.75E-15	5.96E-15
30308031011	CAN	1.60E-16	2.32E-16	4.80E-16	1.66E-16	3.77E-15
30308031101	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.26E-15
30308030712	CAN	0.00E+00	0.00E+00	1.05E-15	1.92E-15	2.22E-15
30308031001	CAN	1.59E-15	2.01E-15	7.86E-16	1.61E-15	4.52E-16
30212250101	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307180301	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30308020501	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307060301	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307150101	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307030411	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307080201	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307080401	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30308020401	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307051011	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307040413	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30806060111	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307180400	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30212030900	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

30307070101	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30401080311	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30401070701	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30806060101	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30401020200	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30401020101	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30401041001	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30308020601	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307050801	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307050601	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307190101	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307050901	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307170501	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307170601	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307050701	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307060201	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307060401	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307060101	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307070201	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307070301	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307030101	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307040201	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307040101	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30308020701	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307030201	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307040401	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307040301	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307020401	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307050101	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307050501	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307200400	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307200301	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307050401	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307050301	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307050201	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30224010100	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307080101	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307080301	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307100101	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307090400	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307140201	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30212250200	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30102410901	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30102470401	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307070111	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307050212	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307091112	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

30307100511	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30308020511	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307070311	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307040111	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30308031012	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307040311	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307040411	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307050411	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307050211	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307040414	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307040112	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307040211	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307030111	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307010411	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307050811	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307050711	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307050611	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307050311	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307070211	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307060211	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307060111	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307050911	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307091111	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30307080211	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30308020111	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30308020611	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30308020512	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30308010317	CAN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30308030501	CAN	3.43E-13	1.56E-13	2.14E-13	2.91E-13	4.66E-13
51203030111	CHL	2.43E-05	4.84E-05	8.50E-05	4.17E-05	1.69E-04
51202050211	CHL	1.04E-05	1.50E-05	1.65E-05	2.86E-05	4.39E-05
51301020211	CHL	3.10E-06	9.15E-06	1.32E-05	1.53E-05	2.80E-05
51301010600	CHL	2.01E-06	2.07E-06	2.37E-06	2.67E-06	3.24E-06
51302120400	CHL	1.92E-06	1.57E-06	2.12E-06	2.34E-06	2.70E-06
51302090101	CHL	1.48E-06	1.54E-06	1.77E-06	1.85E-06	2.07E-06
51301030101	CHL	5.80E-07	1.16E-06	1.25E-06	1.11E-06	1.89E-06
51202070101	CHL	1.15E-07	6.41E-07	1.13E-06	1.20E-06	1.40E-06
51301060110	CHL	8.79E-07	8.25E-07	1.03E-06	9.15E-07	1.12E-06
51302120301	CHL	6.30E-07	0.00E+00	7.51E-07	9.66E-07	1.03E-06
51202070111	CHL	1.66E-07	1.94E-07	2.17E-07	3.52E-07	5.83E-07
51202060100	CHL	1.21E-07	2.23E-07	3.14E-07	3.93E-07	5.53E-07
51301050200	CHL	4.29E-07	4.00E-07	4.82E-07	4.78E-07	5.51E-07
51301060100	CHL	4.26E-07	4.56E-07	5.13E-07	4.70E-07	5.17E-07
51302120201	CHL	2.02E-07	1.94E-07	3.86E-07	4.18E-07	5.00E-07
51302030201	CHL	2.56E-07	2.62E-07	2.99E-07	3.02E-07	3.60E-07
51302140200	CHL	0.00E+00	0.00E+00	0.00E+00	1.42E-07	2.98E-07
51202080300	CHL	5.21E-08	6.99E-08	1.01E-07	2.47E-08	2.91E-07

51301080101	CHL	1.34E-07	1.40E-07	2.57E-07	1.81E-07	2.84E-07
51202080301	CHL	7.27E-08	1.01E-07	1.33E-07	1.74E-07	2.79E-07
51202060101	CHL	6.45E-08	7.35E-08	1.15E-07	1.22E-07	2.14E-07
51203010111	CHL	2.45E-08	0.00E+00	3.54E-07	2.34E-08	2.03E-07
51301020301	CHL	3.29E-08	6.88E-08	1.17E-07	1.16E-07	1.70E-07
51301010201	CHL	1.01E-07	5.24E-08	5.59E-08	6.47E-08	1.67E-07
51202080100	CHL	5.40E-08	5.81E-08	7.64E-08	9.14E-08	1.44E-07
51301030300	CHL	2.28E-08	1.05E-07	4.75E-08	1.60E-07	1.41E-07
51301010100	CHL	7.24E-08	7.60E-08	6.63E-08	7.67E-08	9.81E-08
51302080400	CHL	1.28E-07	1.10E-07	9.57E-08	9.46E-08	9.65E-08
51302040200	CHL	9.29E-07	1.00E-06	1.37E-06	2.54E-07	9.49E-08
51202050112	CHL	4.61E-08	6.29E-09	5.86E-08	6.85E-08	9.43E-08
51202080101	CHL	3.21E-08	3.57E-08	4.82E-08	6.57E-08	9.07E-08
51301070200	CHL	5.36E-08	6.12E-08	6.33E-08	6.58E-08	7.36E-08
51301050101	CHL	5.47E-08	5.55E-08	5.83E-08	6.08E-08	7.20E-08
51301010701	CHL	2.84E-08	4.58E-08	4.46E-08	3.90E-08	5.70E-08
51301020201	CHL	2.10E-08	2.68E-08	3.11E-08	3.03E-08	4.80E-08
51301010601	CHL	2.06E-08	3.73E-08	3.87E-08	2.52E-08	4.74E-08
51202090101	CHL	1.03E-08	1.37E-08	8.73E-09	1.56E-08	3.89E-08
51302100101	CHL	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.45E-08
51301010700	CHL	5.79E-09	1.71E-08	1.93E-08	2.14E-08	3.21E-08
51301010801	CHL	1.20E-08	2.01E-08	2.11E-08	2.29E-08	2.88E-08
51301050110	CHL	3.63E-08	2.90E-08	1.85E-08	1.93E-08	2.00E-08
51301010101	CHL	6.41E-09	1.51E-08	9.68E-09	1.21E-08	1.67E-08
51301010401	CHL	3.40E-09	8.33E-09	8.48E-09	1.09E-08	1.63E-08
51302130401	CHL	6.66E-09	6.50E-09	7.34E-09	1.33E-08	1.47E-08
51301040200	CHL	1.10E-08	1.21E-08	1.09E-08	6.89E-09	1.16E-08
51301010301	CHL	1.78E-09	1.02E-08	7.83E-09	8.74E-09	1.14E-08
51301020101	CHL	2.81E-09	3.80E-09	4.55E-09	5.47E-09	9.48E-09
51301030100	CHL	1.51E-09	2.06E-09	5.24E-09	4.78E-09	5.08E-09
51301010501	CHL	7.90E-10	4.38E-09	3.19E-09	3.11E-09	4.31E-09
51202060201	CHL	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.69E-09
51301040101	CHL	0.00E+00	1.16E-09	1.32E-09	1.34E-09	1.43E-09
51301010200	CHL	1.43E-09	1.03E-09	9.78E-10	1.04E-09	1.27E-09
51202080200	CHL	4.54E-11	0.00E+00	0.00E+00	0.00E+00	2.23E-10
11504090000	CHN	3.35E-05	7.66E-05	7.61E-05	8.10E-05	7.78E-05
11002030201	CHN	1.40E-05	1.48E-05	1.91E-05	1.65E-05	1.80E-05
12517000000	CHN	1.32E-05	1.44E-05	1.28E-05	1.52E-05	1.65E-05
11002031101	CHN	1.03E-05	1.51E-05	1.17E-05	1.34E-05	1.52E-05
11501320201	CHN	4.98E-06	5.59E-06	1.04E-05	9.17E-06	1.01E-05
11712000000	CHN	0.00E+00	0.00E+00	1.65E-06	0.00E+00	7.49E-06
11001251301	CHN	6.49E-06	6.56E-06	7.16E-06	7.95E-06	7.07E-06
11415000000	CHN	3.13E-06	3.04E-06	4.91E-06	5.25E-06	6.23E-06
11504100200	CHN	2.55E-06	3.53E-06	3.80E-06	4.20E-06	4.25E-06
11501330100	CHN	2.53E-06	2.76E-06	3.28E-06	3.50E-06	2.92E-06
11501460201	CHN	2.29E-06	2.49E-06	2.57E-06	2.76E-06	2.84E-06
13024040501	CHN	2.37E-06	2.43E-06	2.50E-06	2.70E-06	2.68E-06

11717000000	CHN	7.13E-07	8.40E-07	1.52E-06	2.10E-06	2.66E-06
11504120000	CHN	1.45E-06	1.99E-06	2.00E-06	2.22E-06	2.20E-06
11501320401	CHN	9.78E-07	1.35E-06	1.31E-06	1.91E-06	2.08E-06
11125130301	CHN	2.26E-06	2.26E-06	2.02E-06	2.03E-06	1.98E-06
11501330101	CHN	1.71E-06	1.54E-06	1.73E-06	1.96E-06	1.95E-06
11501110600	CHN	7.09E-08	7.94E-07	1.30E-06	1.50E-06	1.86E-06
11718000000	CHN	1.03E-06	1.34E-06	1.23E-06	2.29E-06	1.67E-06
11001251800	CHN	1.10E-06	1.24E-06	1.35E-06	1.56E-06	1.51E-06
11501460400	CHN	1.06E-06	1.52E-06	1.54E-06	1.56E-06	1.50E-06
11002031301	CHN	1.51E-06	1.55E-06	1.86E-06	1.54E-06	1.50E-06
11501250401	CHN	6.80E-07	9.59E-07	1.07E-06	1.17E-06	1.48E-06
11817000000	CHN	1.23E-06	1.47E-06	1.43E-06	1.45E-06	1.45E-06
11002031200	CHN	1.14E-06	1.55E-06	1.74E-06	1.59E-06	1.39E-06
11713000000	CHN	8.81E-07	1.02E-06	1.08E-06	1.13E-06	1.26E-06
11713010000	CHN	7.12E-07	9.57E-07	9.54E-07	9.70E-07	1.11E-06
13009020000	CHN	5.42E-08	1.18E-06	5.47E-07	1.09E-06	1.10E-06
13007080000	CHN	3.43E-08	1.04E-06	3.57E-07	8.84E-07	1.09E-06
11511140200	CHN	0.00E+00	0.00E+00	5.37E-07	6.89E-07	1.07E-06
11501250600	CHN	5.99E-07	7.28E-07	9.61E-07	8.24E-07	1.02E-06
11501410501	CHN	9.60E-07	7.96E-07	9.94E-07	6.00E-07	1.02E-06
11002010400	CHN	8.43E-07	8.58E-07	8.10E-07	7.86E-07	8.85E-07
13005020201	CHN	6.71E-07	6.81E-07	6.77E-07	7.60E-07	8.42E-07
11001251901	CHN	6.37E-07	8.88E-07	8.95E-07	7.53E-07	8.42E-07
13024010901	CHN	4.22E-07	5.26E-07	5.75E-07	7.14E-07	8.22E-07
11504130100	CHN	3.93E-07	6.04E-07	6.44E-07	6.63E-07	7.80E-07
11501110501	CHN	0.00E+00	5.07E-07	6.55E-07	6.95E-07	6.94E-07
13036020501	CHN	1.32E-07	0.00E+00	0.00E+00	3.18E-07	6.00E-07
11716020000	CHN	1.64E-07	2.40E-07	3.32E-07	4.81E-07	4.94E-07
13005010601	CHN	3.36E-07	2.78E-07	3.64E-07	4.65E-07	4.77E-07
11501420100	CHN	4.13E-07	4.50E-07	3.67E-07	4.51E-07	4.55E-07
13033030401	CHN	3.24E-07	2.94E-07	3.46E-07	3.62E-07	4.49E-07
11508200000	CHN	2.13E-07	2.62E-07	2.49E-07	3.01E-07	4.41E-07
11001251801	CHN	3.41E-07	7.09E-07	3.28E-07	3.90E-07	3.98E-07
11002030101	CHN	9.81E-08	2.28E-07	2.51E-07	4.60E-07	3.96E-07
11501410101	CHN	2.01E-07	3.52E-07	3.02E-07	4.67E-07	3.87E-07
11501430100	CHN	3.78E-07	4.24E-07	3.73E-07	3.88E-07	3.37E-07
11002010300	CHN	2.49E-07	2.42E-07	2.52E-07	2.57E-07	3.34E-07
13035030101	CHN	2.98E-07	2.84E-07	3.02E-07	3.15E-07	3.23E-07
11501430101	CHN	3.60E-07	3.83E-07	3.56E-07	3.37E-07	3.09E-07
11501320601	CHN	1.76E-07	2.31E-07	2.35E-07	2.95E-07	2.97E-07
11501330201	CHN	1.36E-07	2.47E-07	2.74E-07	2.84E-07	2.79E-07
12514040200	CHN	2.11E-07	2.03E-07	2.37E-07	2.43E-07	2.76E-07
13035030201	CHN	1.49E-07	1.74E-07	1.91E-07	1.17E-07	2.58E-07
12511120100	CHN	1.56E-07	1.82E-07	2.02E-07	1.95E-07	2.48E-07
11501330400	CHN	2.05E-07	0.00E+00	2.06E-07	2.48E-07	2.45E-07
12511040501	CHN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.44E-07
11501520000	CHN	2.21E-07	2.64E-07	2.35E-07	2.71E-07	2.41E-07

11501320101	CHN	1.71E-07	1.83E-07	1.92E-07	2.61E-07	2.39E-07
11504090100	CHN	9.98E-08	1.58E-07	1.83E-07	2.24E-07	2.39E-07
11002010301	CHN	2.26E-07	2.24E-07	1.94E-07	2.20E-07	2.33E-07
11501320501	CHN	6.54E-08	1.17E-07	2.27E-07	1.75E-07	2.32E-07
11501380000	CHN	1.84E-07	2.88E-08	1.88E-07	1.54E-07	2.22E-07
11501310100	CHN	8.74E-08	1.26E-07	1.66E-07	2.17E-07	2.22E-07
11717020100	CHN	1.54E-07	2.03E-07	1.72E-07	3.59E-07	2.19E-07
13036010101	CHN	8.50E-08	1.61E-07	1.70E-07	1.83E-07	2.06E-07
11001251701	CHN	2.06E-07	2.42E-07	2.28E-07	2.89E-07	1.97E-07
11501190801	CHN	1.31E-07	1.69E-07	1.77E-07	1.91E-07	1.80E-07
11818020000	CHN	9.53E-08	0.00E+00	5.64E-08	1.22E-07	1.77E-07
13005050000	CHN	1.18E-07	1.00E-07	1.73E-07	1.98E-07	1.69E-07
11501570101	CHN	1.26E-07	1.46E-07	1.65E-07	1.23E-07	1.64E-07
11820000000	CHN	1.79E-07	0.00E+00	0.00E+00	2.63E-07	1.55E-07
11504100000	CHN	4.36E-08	1.38E-07	1.32E-07	1.53E-07	1.53E-07
11714010100	CHN	2.68E-08	1.32E-08	7.27E-08	1.18E-07	1.45E-07
13005040101	CHN	2.44E-08	0.00E+00	6.30E-08	8.04E-08	1.22E-07
12511120000	CHN	0.00E+00	9.82E-08	1.13E-07	0.00E+00	1.21E-07
11501430201	CHN	1.25E-07	1.33E-07	1.23E-07	1.22E-07	1.20E-07
11501600000	CHN	8.55E-08	8.51E-08	1.06E-07	8.46E-09	1.17E-07
11501370000	CHN	4.33E-08	2.12E-08	6.71E-08	6.34E-08	1.05E-07
12514050000	CHN	1.02E-07	8.79E-08	8.87E-08	9.67E-08	1.02E-07
12516020000	CHN	7.50E-08	8.86E-08	8.65E-08	9.68E-08	9.81E-08
13017080100	CHN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.14E-08
13026020400	CHN	2.39E-08	2.22E-08	5.31E-08	8.31E-08	8.80E-08
11501560100	CHN	6.43E-08	5.71E-08	8.44E-08	8.31E-08	8.13E-08
11501490100	CHN	7.19E-08	8.19E-08	7.50E-08	8.41E-08	7.80E-08
11501380100	CHN	7.82E-08	4.62E-08	7.24E-08	7.55E-08	7.63E-08
11501250501	CHN	5.45E-08	6.27E-08	6.68E-08	6.92E-08	6.93E-08
11501340000	CHN	3.49E-08	0.00E+00	5.44E-08	5.26E-08	6.61E-08
11002032701	CHN	5.37E-08	5.61E-08	5.77E-08	0.00E+00	6.59E-08
11501400200	CHN	6.73E-08	7.02E-08	6.46E-08	6.38E-08	6.46E-08
13035010601	CHN	4.38E-08	5.58E-08	5.72E-08	6.23E-08	6.44E-08
11712010000	CHN	0.00E+00	0.00E+00	0.00E+00	5.34E-08	6.08E-08
12514110100	CHN	4.87E-08	8.09E-08	7.59E-08	6.56E-08	6.07E-08
13011050000	CHN	0.00E+00	1.68E-08	1.91E-08	3.32E-08	5.82E-08
11817020000	CHN	1.35E-07	1.45E-07	1.97E-07	2.17E-07	5.57E-08
11716000000	CHN	0.00E+00	0.00E+00	0.00E+00	5.18E-08	5.29E-08
11716010000	CHN	1.77E-08	0.00E+00	4.30E-08	1.93E-08	4.86E-08
11501190900	CHN	5.55E-08	6.06E-08	5.10E-08	5.56E-08	4.77E-08
11501410601	CHN	3.72E-08	0.00E+00	2.06E-08	2.15E-08	4.54E-08
13035011801	CHN	3.62E-08	3.83E-08	3.87E-08	4.30E-08	4.48E-08
11501250500	CHN	3.51E-08	3.55E-08	4.80E-08	1.96E-08	4.33E-08
11501540000	CHN	1.85E-08	2.77E-08	2.20E-08	4.22E-08	4.31E-08
11404210200	CHN	0.00E+00	1.67E-08	4.08E-08	0.00E+00	4.28E-08
11501450101	CHN	6.68E-08	7.07E-08	3.21E-08	3.88E-08	3.89E-08
11501500101	CHN	0.00E+00	0.00E+00	0.00E+00	3.61E-08	3.58E-08

11501330000	CHN	0.00E+00	0.00E+00	1.90E-08	3.37E-08	3.58E-08
13024011100	CHN	2.62E-08	2.74E-08	2.76E-08	3.04E-08	3.52E-08
11501530101	CHN	3.62E-08	3.48E-08	3.47E-08	3.60E-08	3.49E-08
11002010101	CHN	0.00E+00	0.00E+00	0.00E+00	3.43E-08	3.41E-08
13020040000	CHN	0.00E+00	2.86E-08	2.91E-08	0.00E+00	3.39E-08
11501320301	CHN	1.15E-08	1.60E-08	2.13E-08	2.89E-08	3.26E-08
12514100100	CHN	1.98E-08	1.76E-08	1.05E-08	2.32E-08	3.21E-08
11501530200	CHN	2.57E-08	2.62E-08	2.86E-08	3.04E-08	3.16E-08
11501370100	CHN	3.53E-08	1.11E-08	3.78E-08	2.00E-08	3.14E-08
13024010801	CHN	2.36E-08	2.43E-08	2.59E-08	2.70E-08	3.12E-08
12511040401	CHN	0.00E+00	1.29E-08	2.43E-08	3.77E-08	3.08E-08
11501500301	CHN	3.09E-08	3.05E-08	2.90E-08	3.14E-08	2.93E-08
13027010401	CHN	1.52E-08	1.65E-08	1.16E-08	2.34E-08	2.86E-08
11501580100	CHN	2.71E-08	2.89E-08	2.69E-08	2.86E-08	2.85E-08
13007040100	CHN	2.94E-08	2.95E-08	3.13E-08	2.99E-08	2.85E-08
11501350100	CHN	4.11E-09	3.91E-09	1.27E-08	4.99E-09	2.84E-08
11501430000	CHN	2.65E-08	2.76E-08	2.76E-08	2.85E-08	2.74E-08
11717010100	CHN	0.00E+00	9.99E-09	0.00E+00	4.05E-08	2.72E-08
11818030000	CHN	0.00E+00	0.00E+00	4.10E-08	2.39E-08	2.46E-08
11404270100	CHN	1.34E-08	1.68E-08	1.70E-08	2.01E-08	2.45E-08
13027040500	CHN	4.63E-09	5.11E-09	1.69E-08	1.98E-08	2.42E-08
11501410701	CHN	1.57E-08	0.00E+00	2.00E-08	2.17E-08	2.29E-08
11616000000	CHN	1.43E-08	1.87E-08	2.01E-08	0.00E+00	2.18E-08
11501190800	CHN	1.15E-08	1.05E-08	1.81E-08	1.98E-08	2.00E-08
10635010100	CHN	2.97E-08	7.88E-09	1.28E-08	7.60E-09	2.00E-08
11404230100	CHN	9.32E-09	7.42E-09	1.55E-08	1.27E-08	1.86E-08
11504110100	CHN	0.00E+00	2.42E-08	0.00E+00	3.37E-08	1.84E-08
13035030701	CHN	2.25E-08	1.42E-08	2.04E-08	0.00E+00	1.83E-08
13017020501	CHN	2.75E-08	6.63E-09	1.52E-08	2.40E-08	1.66E-08
13005060100	CHN	9.93E-09	7.04E-09	1.18E-08	1.33E-08	1.55E-08
11714000000	CHN	9.01E-09	0.00E+00	0.00E+00	1.67E-08	1.46E-08
13033020101	CHN	1.29E-08	0.00E+00	1.31E-08	0.00E+00	1.40E-08
11404280000	CHN	1.25E-09	9.04E-09	5.23E-09	1.20E-08	1.38E-08
11714020000	CHN	3.23E-09	1.50E-08	9.47E-09	8.03E-09	1.27E-08
13035030601	CHN	1.10E-08	1.20E-08	1.20E-08	1.14E-08	1.23E-08
11501570201	CHN	1.63E-08	1.63E-08	1.68E-08	3.49E-09	1.13E-08
13022000000	CHN	8.94E-09	9.05E-09	5.55E-09	1.02E-08	1.11E-08
13011010101	CHN	0.00E+00	2.61E-08	0.00E+00	1.77E-09	1.00E-08
10635030000	CHN	2.37E-08	1.37E-08	3.20E-08	0.00E+00	9.53E-09
13007030200	CHN	8.27E-09	8.85E-09	8.95E-09	9.39E-09	9.32E-09
11501550100	CHN	1.10E-08	1.10E-08	1.07E-08	1.16E-08	9.31E-09
11501190601	CHN	5.98E-09	5.90E-09	8.79E-09	4.63E-09	8.80E-09
11501330300	CHN	3.76E-09	1.35E-08	0.00E+00	1.29E-08	8.39E-09
13005080000	CHN	5.93E-09	6.23E-09	6.57E-09	7.08E-09	7.41E-09
11501330301	CHN	1.42E-08	1.40E-08	1.51E-08	1.12E-08	6.77E-09
11501590100	CHN	1.13E-08	1.08E-08	1.54E-08	5.87E-09	6.70E-09
13005050100	CHN	3.79E-09	5.73E-09	5.53E-09	5.83E-09	6.64E-09

13017080101	CHN	4.89E-09	5.03E-09	5.56E-09	6.11E-09	6.31E-09
13005070000	CHN	0.00E+00	2.41E-09	3.25E-09	3.72E-09	5.50E-09
11818020100	CHN	0.00E+00	3.71E-09	4.05E-09	4.38E-09	5.02E-09
11001251601	CHN	5.26E-09	5.19E-09	5.18E-09	5.34E-09	4.96E-09
10635020100	CHN	1.27E-08	5.06E-09	1.34E-08	0.00E+00	4.68E-09
11501350000	CHN	7.28E-09	0.00E+00	9.92E-09	1.34E-08	4.66E-09
11404220000	CHN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.20E-09
11501570300	CHN	5.25E-09	3.46E-09	2.06E-09	2.54E-09	4.11E-09
11501540100	CHN	2.40E-09	3.26E-09	3.09E-09	3.18E-09	4.04E-09
11501320400	CHN	0.00E+00	0.00E+00	0.00E+00	2.49E-09	3.87E-09
13035030501	CHN	4.98E-09	3.84E-09	3.75E-09	2.70E-09	3.68E-09
13020010100	CHN	2.84E-09	2.68E-09	2.94E-09	3.16E-09	3.18E-09
11501610000	CHN	2.66E-09	3.04E-09	3.26E-09	1.17E-09	2.90E-09
13035011301	CHN	2.53E-09	2.66E-09	2.50E-09	2.64E-09	2.63E-09
11404220100	CHN	0.00E+00	0.00E+00	2.52E-09	2.72E-09	2.62E-09
13020050000	CHN	2.58E-09	2.58E-09	2.65E-09	2.65E-09	2.53E-09
13035020501	CHN	2.04E-09	2.26E-09	2.28E-09	0.00E+00	2.36E-09
11501190700	CHN	0.00E+00	0.00E+00	1.94E-09	1.94E-09	2.07E-09
11404240100	CHN	2.88E-09	1.08E-09	0.00E+00	1.26E-09	1.73E-09
13001300000	CHN	1.03E-09	1.20E-09	1.36E-09	1.62E-09	1.64E-09
12518050100	CHN	8.52E-10	6.96E-10	9.40E-10	1.32E-09	1.53E-09
13012120000	CHN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.47E-09
11501320500	CHN	0.00E+00	0.00E+00	0.00E+00	5.17E-10	1.28E-09
13031020201	CHN	0.00E+00	3.51E-10	3.47E-10	3.88E-10	1.13E-09
12518010300	CHN	1.02E-09	0.00E+00	6.99E-10	0.00E+00	9.79E-10
12518030100	CHN	5.05E-10	0.00E+00	0.00E+00	0.00E+00	8.47E-10
12518040100	CHN	4.57E-10	0.00E+00	0.00E+00	0.00E+00	7.96E-10
13023010201	CHN	5.39E-10	5.34E-10	6.27E-10	6.57E-10	6.74E-10
12518020100	CHN	3.95E-10	0.00E+00	1.40E-10	1.69E-10	6.24E-10
13025030301	CHN	1.46E-10	2.05E-10	2.62E-10	4.19E-10	5.79E-10
12518010101	CHN	4.26E-10	4.73E-10	4.20E-10	6.34E-10	5.75E-10
13001290100	CHN	1.61E-10	2.75E-10	3.80E-10	5.04E-10	5.58E-10
13032012201	CHN	2.78E-10	3.12E-10	3.27E-10	4.19E-10	4.55E-10
13036020201	CHN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.27E-10
11404260100	CHN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.70E-10
13025030401	CHN	3.68E-11	1.02E-10	4.45E-11	0.00E+00	3.13E-10
13036011101	CHN	2.74E-10	0.00E+00	0.00E+00	9.41E-10	2.94E-10
11501600100	CHN	7.39E-10	6.71E-10	7.25E-10	1.01E-10	1.98E-10
13023011001	CHN	9.74E-11	0.00E+00	0.00E+00	8.83E-11	1.22E-10
13025011400	CHN	3.29E-11	0.00E+00	0.00E+00	0.00E+00	1.09E-10
13001190400	CHN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13031020401	CHN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13031020101	CHN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13031010201	CHN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13032020901	CHN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13032010301	CHN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13031040801	CHN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

13012150000	CHN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13006290000	CHN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13026020410	CHN	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
50105100101	COL	7.93E-06	1.19E-05	1.07E-05	9.27E-06	5.85E-06
50202310301	COL	2.10E-06	2.82E-06	3.30E-06	3.67E-06	4.15E-06
50105041201	COL	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.32E-07
50105180000	COL	0.00E+00	0.00E+00	6.64E-07	5.83E-07	6.99E-07
50106010201	COL	4.00E-07	1.55E-07	3.54E-07	0.00E+00	3.49E-07
50429090100	ECU	0.00E+00	1.68E-06	1.64E-06	1.56E-06	1.79E-06
50103060400	ECU	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.43E-07
50429080100	ECU	3.82E-08	2.73E-08	0.00E+00	0.00E+00	3.30E-08
40210090101	FRA	2.14E-06	2.74E-06	3.22E-06	2.59E-06	2.75E-06
40210090200	FRA	8.18E-07	8.37E-07	8.85E-07	8.93E-07	8.24E-07
40210090201	FRA	1.85E-07	2.11E-07	1.52E-07	4.15E-07	2.04E-07
40210030500	FRA	2.49E-07	2.82E-07	1.53E-07	1.74E-07	1.67E-07
40210030401	FRA	1.59E-08	1.73E-08	1.75E-08	1.95E-08	1.74E-08
13701050501	GEO	2.09E-06	2.09E-06	1.67E-06	9.87E-07	1.12E-06
13701050401	GEO	4.74E-08	4.20E-08	0.00E+00	4.28E-08	2.47E-08
30308030412	GRL	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
41601010201	ISL	1.31E-06	1.40E-06	1.82E-06	2.06E-06	2.49E-06
41601011201	ISL	0.00E+00	6.81E-09	7.96E-08	1.70E-08	1.18E-06
41601011211	ISL	7.49E-08	2.89E-07	4.40E-07	2.33E-08	4.70E-07
41601010101	ISL	2.91E-08	3.44E-08	3.88E-08	4.03E-08	5.77E-08
41601010301	ISL	1.24E-08	2.40E-08	3.06E-08	1.57E-08	5.22E-08
41601011111	ISL	8.66E-09	1.34E-08	2.63E-08	1.10E-08	3.49E-08
41601010111	ISL	7.84E-09	8.11E-08	6.62E-08	9.69E-07	3.24E-08
41601011101	ISL	2.57E-09	1.11E-08	1.09E-08	1.37E-08	2.61E-08
41601011401	ISL	4.04E-09	6.97E-09	1.07E-08	1.12E-08	2.20E-08
41601011912	ISL	0.00E+00	4.16E-08	4.35E-07	4.80E-07	1.16E-08
41601011001	ISL	0.00E+00	9.75E-10	4.73E-10	1.56E-10	3.49E-09
41601011901	ISL	2.51E-09	2.50E-09	2.30E-08	3.63E-08	2.26E-09
41601010601	ISL	4.70E-10	6.25E-10	1.60E-09	1.88E-09	1.72E-09
41601010901	ISL	3.58E-09	0.00E+00	3.08E-09	6.96E-10	1.14E-09
41601010801	ISL	8.91E-11	5.06E-11	4.22E-11	2.65E-10	2.70E-10
41601012001	ISL	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.44E-10
11501050200	IND	8.23E-05	1.52E-04	1.66E-04	1.63E-04	1.75E-04
11406190000	IND	7.45E-05	8.45E-05	8.01E-05	7.84E-05	7.17E-05
11406190100	IND	2.44E-05	2.50E-05	2.63E-05	2.72E-05	2.83E-05
11406180100	IND	1.44E-05	1.69E-05	1.85E-05	2.01E-05	2.16E-05
11501050101	IND	3.79E-06	1.14E-05	1.02E-05	1.06E-05	1.29E-05
11406210000	IND	1.47E-06	2.64E-06	2.70E-06	2.61E-06	3.61E-06
11404200000	IND	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.39E-06
11404101400	IND	3.81E-07	2.01E-06	1.56E-06	2.07E-06	2.14E-06
11413010200	IND	1.13E-06	1.97E-06	2.22E-06	2.00E-06	1.88E-06
11406170100	IND	3.43E-06	1.37E-06	1.25E-06	1.42E-06	1.57E-06
11406071101	IND	5.80E-07	9.96E-07	1.55E-06	1.24E-06	1.47E-06
11414000000	IND	1.77E-07	6.81E-07	6.26E-07	6.66E-07	7.54E-07

11511180000	IND	0.00E+00	2.24E-07	3.39E-07	4.41E-07	4.36E-07
11404210000	IND	8.19E-08	2.06E-07	2.23E-07	2.03E-07	2.98E-07
11406071500	IND	1.81E-07	2.57E-07	2.57E-07	2.69E-07	2.88E-07
11501170101	IND	0.00E+00	2.92E-07	0.00E+00	0.00E+00	2.86E-07
11406071300	IND	0.00E+00	5.32E-08	1.17E-07	5.04E-08	2.31E-07
11404170301	IND	0.00E+00	1.82E-07	0.00E+00	1.59E-07	2.19E-07
11501260501	IND	2.08E-07	2.76E-07	1.76E-07	1.82E-07	2.07E-07
11412050000	IND	9.03E-08	1.06E-07	9.68E-08	1.53E-07	1.80E-07
11412020100	IND	7.31E-08	8.76E-08	6.20E-08	1.19E-07	1.73E-07
11413020100	IND	1.44E-07	2.00E-07	1.53E-07	1.63E-07	1.70E-07
11501250400	IND	1.40E-07	1.87E-07	1.24E-07	1.13E-07	1.67E-07
11412040100	IND	8.02E-08	5.42E-08	6.59E-08	1.02E-07	1.45E-07
11501170300	IND	0.00E+00	1.58E-07	1.36E-07	1.37E-07	1.42E-07
11414030000	IND	7.02E-08	8.72E-08	9.49E-08	1.17E-07	1.41E-07
11508100401	IND	0.00E+00	2.26E-07	0.00E+00	0.00E+00	1.18E-07
11406071201	IND	6.71E-08	1.30E-07	1.25E-07	1.26E-07	9.69E-08
11508100501	IND	0.00E+00	4.56E-08	4.77E-08	8.20E-08	9.03E-08
11511170100	IND	2.52E-08	7.26E-08	5.46E-08	5.59E-08	7.75E-08
11404210101	IND	2.16E-08	2.08E-08	1.93E-08	1.88E-08	6.18E-08
11414020100	IND	0.00E+00	0.00E+00	9.56E-09	1.49E-08	5.70E-08
11501250301	IND	0.00E+00	4.59E-08	4.32E-08	4.78E-08	5.48E-08
11501260401	IND	1.34E-08	4.03E-08	1.62E-08	1.30E-08	4.88E-08
11406071401	IND	0.00E+00	3.71E-08	9.80E-09	1.56E-08	3.94E-08
11404200100	IND	1.92E-08	0.00E+00	0.00E+00	2.58E-08	3.84E-08
11404210201	IND	3.03E-08	1.52E-08	2.81E-08	2.67E-08	3.18E-08
11501260600	IND	2.93E-08	2.74E-08	2.89E-08	1.75E-08	2.87E-08
11412030000	IND	8.48E-09	8.62E-09	0.00E+00	1.29E-08	2.57E-08
11414030100	IND	0.00E+00	1.94E-08	1.23E-08	1.71E-08	1.93E-08
11412030100	IND	0.00E+00	7.45E-09	7.50E-09	7.97E-09	1.63E-08
11404210100	IND	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.79E-09
40208060200	ITA	5.26E-05	5.52E-05	5.33E-05	5.28E-05	4.44E-05
40208140000	ITA	1.40E-05	1.22E-05	1.33E-05	1.50E-05	1.19E-05
40208040300	ITA	6.72E-06	6.71E-06	7.00E-06	7.05E-06	6.05E-06
40401010101	ITA	3.78E-06	5.53E-06	5.32E-06	5.26E-06	4.63E-06
40208090201	ITA	5.57E-06	5.18E-06	4.65E-06	4.97E-06	4.38E-06
40208130100	ITA	1.85E-06	1.67E-06	2.00E-06	2.65E-06	1.66E-06
40208090300	ITA	1.17E-06	5.19E-06	9.14E-07	1.57E-06	1.52E-06
40401010301	ITA	6.98E-07	6.74E-07	6.57E-07	6.43E-07	4.85E-07
11001260101	KAZ	1.21E-06	1.95E-06	1.90E-06	2.56E-06	3.43E-06
11001270200	KAZ	0.00E+00	1.39E-06	9.48E-07	1.40E-06	2.21E-06
11001250701	KAZ	2.08E-06	2.22E-06	2.03E-06	2.02E-06	1.79E-06
11001250901	KAZ	9.70E-07	9.80E-07	9.08E-07	8.81E-07	8.56E-07
11001170301	KAZ	4.49E-07	8.05E-07	7.34E-07	8.38E-07	8.16E-07
11001170500	KAZ	5.26E-07	6.00E-07	6.40E-07	7.09E-07	6.57E-07
11001160101	KAZ	4.63E-07	5.67E-07	4.47E-07	4.14E-07	3.70E-07
11001240111	KAZ	2.00E-07	3.14E-07	2.65E-07	2.40E-07	2.89E-07
11001260201	KAZ	0.00E+00	1.98E-07	2.29E-07	3.24E-07	2.37E-07

11001260301	KAZ	1.34E-07	1.42E-07	1.60E-07	1.80E-07	1.85E-07
11001220401	KAZ	6.27E-08	8.35E-08	8.51E-08	1.03E-07	1.18E-07
11001252000	KAZ	6.14E-08	5.26E-08	5.08E-08	4.86E-08	4.61E-08
10903310501	KAZ	3.13E-08	2.95E-08	2.86E-08	3.04E-08	2.85E-08
11001160500	KAZ	1.41E-08	2.39E-08	2.20E-08	2.11E-08	1.71E-08
10633070000	KAZ	1.38E-07	9.01E-08	3.85E-08	1.45E-08	1.48E-08
10633060100	KAZ	4.51E-08	3.24E-08	2.68E-08	1.80E-08	1.39E-08
11001140101	KAZ	1.56E-08	1.63E-08	1.25E-08	1.40E-08	1.08E-08
11001140200	KAZ	6.25E-09	5.98E-09	0.00E+00	4.56E-09	4.05E-09
10903160701	KGZ	6.80E-06	5.74E-06	7.88E-06	9.03E-06	8.97E-06
10905400201	KGZ	4.50E-06	4.66E-06	4.92E-06	5.10E-06	5.13E-06
10905370400	KGZ	4.73E-06	4.76E-06	4.30E-06	4.53E-06	4.63E-06
10903350100	KGZ	0.00E+00	0.00E+00	1.57E-06	2.69E-06	1.99E-06
10905550000	KGZ	1.46E-06	1.80E-06	1.68E-06	1.69E-06	1.65E-06
10903410100	KGZ	7.62E-07	7.58E-07	7.35E-07	1.16E-06	1.19E-06
10903420100	KGZ	1.05E-06	1.13E-06	1.06E-06	1.02E-06	1.10E-06
10907230900	KGZ	4.88E-07	6.47E-07	6.29E-07	7.44E-07	7.61E-07
13011010301	KGZ	1.37E-07	2.56E-07	1.78E-07	3.03E-07	3.15E-07
13011010401	KGZ	7.21E-07	2.46E-07	3.92E-07	1.98E-07	2.75E-07
10905220500	KGZ	2.17E-07	2.38E-07	2.32E-07	2.24E-07	2.38E-07
10903390200	KGZ	2.29E-07	2.33E-07	2.21E-07	2.03E-07	2.11E-07
10905440100	KGZ	1.83E-07	1.95E-07	1.82E-07	1.96E-07	2.01E-07
13011010201	KGZ	6.64E-08	1.57E-07	1.29E-07	1.52E-07	1.94E-07
10905400900	KGZ	2.01E-07	1.99E-07	1.88E-07	1.87E-07	1.88E-07
13011070100	KGZ	1.25E-07	1.32E-07	1.47E-07	1.53E-07	1.50E-07
10903430000	KGZ	1.63E-07	1.78E-07	1.60E-07	1.59E-07	1.47E-07
10903380100	KGZ	0.00E+00	6.68E-08	7.76E-08	0.00E+00	1.40E-07
10905540100	KGZ	6.31E-08	8.73E-08	1.20E-07	1.33E-07	1.36E-07
13011010200	KGZ	5.65E-08	1.87E-07	1.12E-07	1.21E-07	1.23E-07
10905460300	KGZ	1.36E-07	6.30E-08	1.15E-07	1.23E-07	1.19E-07
10903430100	KGZ	1.18E-07	1.13E-07	1.01E-07	9.87E-08	1.08E-07
10905460100	KGZ	8.84E-08	6.42E-08	1.14E-07	8.51E-08	1.06E-07
13011040100	KGZ	0.00E+00	3.31E-08	6.62E-08	9.27E-08	9.70E-08
10903410000	KGZ	8.56E-08	9.05E-08	8.66E-08	8.19E-08	7.81E-08
10905480100	KGZ	0.00E+00	0.00E+00	0.00E+00	1.42E-07	7.44E-08
10903390100	KGZ	3.91E-08	6.13E-08	5.78E-08	5.72E-08	5.64E-08
10903330101	KGZ	5.98E-08	6.04E-08	5.88E-08	5.72E-08	5.55E-08
10903440000	KGZ	3.91E-08	5.46E-08	5.71E-08	5.57E-08	5.00E-08
10903390101	KGZ	4.85E-08	5.49E-08	5.05E-08	4.69E-08	4.73E-08
10905500200	KGZ	5.57E-08	6.18E-08	5.72E-08	5.17E-08	4.60E-08
13011010600	KGZ	1.75E-08	1.77E-08	3.74E-08	6.06E-08	4.19E-08
10905460201	KGZ	4.54E-08	0.00E+00	4.11E-08	3.37E-08	4.16E-08
10905450100	KGZ	3.85E-08	0.00E+00	0.00E+00	0.00E+00	3.95E-08
10905540000	KGZ	0.00E+00	0.00E+00	0.00E+00	2.96E-08	3.94E-08
10903310101	KGZ	3.67E-08	6.81E-08	4.37E-08	4.05E-08	3.82E-08
13011080000	KGZ	0.00E+00	0.00E+00	2.13E-08	2.77E-08	3.47E-08
10905530100	KGZ	3.57E-08	0.00E+00	0.00E+00	3.56E-08	3.36E-08

10905460200	KGZ	2.91E-08	0.00E+00	2.79E-08	2.70E-08	2.59E-08
10903400100	KGZ	4.91E-08	2.48E-08	2.45E-08	0.00E+00	2.44E-08
10903400101	KGZ	1.07E-08	1.08E-08	1.01E-08	9.86E-09	1.77E-08
10903400200	KGZ	0.00E+00	8.39E-09	8.24E-09	8.70E-09	8.62E-09
11011000000	MNG	1.40E-07	7.64E-09	7.81E-08	1.04E-08	4.91E-08
11006010000	MNG	1.52E-08	0.00E+00	6.84E-09	0.00E+00	1.19E-08
11009010000	MNG	1.33E-08	1.21E-08	8.92E-09	3.89E-09	9.04E-09
11007010000	MNG	1.56E-08	1.39E-08	1.24E-08	6.74E-09	7.47E-09
11001010100	MNG	7.94E-09	7.34E-09	6.71E-09	6.14E-09	5.86E-09
11007010100	MNG	6.49E-09	8.43E-09	5.20E-09	0.00E+00	4.45E-09
11010000000	MNG	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.73E-09
11007020000	MNG	2.10E-09	0.00E+00	2.00E-09	1.89E-09	2.28E-09
11504080301	NPL	3.27E-05	6.71E-05	7.11E-05	7.23E-05	6.83E-05
11504080500	NPL	4.09E-05	5.71E-05	6.26E-05	6.69E-05	6.55E-05
11506070000	NPL	3.50E-05	4.78E-05	4.61E-05	5.48E-05	5.37E-05
11506050100	NPL	4.61E-05	4.59E-05	4.47E-05	4.32E-05	4.07E-05
11504080101	NPL	1.95E-04	1.21E-04	7.17E-05	5.19E-05	3.95E-05
11504070100	NPL	1.87E-05	2.97E-05	3.14E-05	3.19E-05	2.75E-05
11508130200	NPL	2.28E-06	4.99E-06	6.11E-06	9.68E-06	8.91E-06
11506060100	NPL	1.52E-06	3.96E-06	3.68E-06	3.58E-06	3.65E-06
11506030300	NPL	2.53E-06	2.62E-06	2.12E-06	2.50E-06	2.88E-06
11508150100	NPL	4.94E-06	3.11E-06	2.19E-06	1.81E-06	1.92E-06
11508160100	NPL	8.72E-07	9.46E-07	1.19E-06	1.09E-06	1.84E-06
11508120400	NPL	8.59E-07	9.40E-07	1.07E-06	1.10E-06	1.44E-06
11508160000	NPL	1.03E-06	1.94E-06	1.44E-06	1.18E-06	1.08E-06
11506030200	NPL	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.09E-07
11508190000	NPL	2.68E-07	2.92E-07	3.38E-07	3.51E-07	3.65E-07
11508180100	NPL	1.99E-07	2.47E-07	2.46E-07	2.38E-07	2.71E-07
11508170100	NPL	1.49E-07	1.81E-07	1.80E-07	1.64E-07	2.20E-07
11508120301	NPL	5.06E-08	5.56E-08	7.62E-08	7.85E-08	8.94E-08
11508190100	NPL	2.36E-08	3.31E-08	2.92E-08	2.86E-08	4.88E-08
41001010201	NOR	6.29E-05	1.01E-04	8.82E-05	7.01E-05	1.10E-04
41001010211	NOR	9.77E-06	5.78E-05	7.91E-05	4.93E-05	7.33E-05
41001050911	NOR	5.08E-06	2.39E-05	1.99E-05	2.01E-05	2.49E-05
41001051211	NOR	5.51E-06	1.25E-05	1.25E-05	1.10E-05	1.38E-05
41002020510	NOR	4.00E-06	8.29E-06	8.78E-06	5.41E-06	9.96E-06
41001051011	NOR	4.68E-06	6.00E-06	6.63E-06	8.39E-06	9.50E-06
41001051012	NOR	1.67E-06	7.77E-06	6.02E-06	6.93E-06	9.03E-06
41102010210	NOR	2.43E-06	6.54E-06	5.63E-06	6.63E-06	6.02E-06
41002010611	NOR	4.60E-06	6.13E-06	5.86E-06	4.90E-06	5.47E-06
41001051411	NOR	1.51E-06	7.39E-06	7.67E-06	3.43E-06	5.17E-06
41101040510	NOR	2.65E-06	3.91E-06	3.02E-06	2.41E-06	3.11E-06
41001020101	NOR	2.43E-07	2.68E-06	2.30E-06	8.05E-07	2.61E-06
41002010801	NOR	2.51E-06	2.52E-06	2.34E-06	2.12E-06	2.51E-06
41001040200	NOR	6.65E-07	2.53E-06	5.37E-06	1.00E-06	2.06E-06
41002010601	NOR	1.56E-06	1.89E-06	1.32E-06	1.71E-06	1.73E-06
41001020300	NOR	5.41E-07	7.49E-07	7.24E-07	5.59E-07	7.06E-07

41001051501	NOR	3.38E-07	5.25E-07	6.86E-07	4.05E-07	6.77E-07
41102010111	NOR	1.65E-08	5.60E-07	1.03E-06	1.97E-07	5.39E-07
41001051201	NOR	7.02E-08	3.95E-07	5.33E-07	3.13E-07	5.14E-07
41102010112	NOR	1.04E-07	6.73E-07	6.48E-07	5.43E-07	4.89E-07
41001051301	NOR	1.27E-07	3.90E-07	4.91E-07	2.92E-07	4.55E-07
41002010401	NOR	2.59E-08	1.62E-07	2.54E-08	1.94E-07	2.53E-07
41102030111	NOR	8.58E-08	2.32E-07	2.07E-07	1.99E-07	2.24E-07
41001050801	NOR	5.34E-08	2.14E-07	6.13E-08	1.36E-07	1.79E-07
41102010211	NOR	0.00E+00	4.99E-07	2.68E-07	2.41E-07	1.59E-07
41002010411	NOR	0.00E+00	0.00E+00	0.00E+00	2.04E-07	1.35E-07
41002010501	NOR	3.59E-08	6.43E-08	1.47E-08	9.88E-08	1.24E-07
41001051401	NOR	3.74E-08	1.21E-07	9.66E-08	6.27E-08	8.95E-08
41002010301	NOR	0.00E+00	5.80E-08	1.30E-08	7.73E-08	8.91E-08
41102010200	NOR	2.99E-08	9.40E-08	1.38E-07	6.83E-08	8.64E-08
41001051001	NOR	0.00E+00	2.27E-08	4.43E-08	1.74E-08	4.97E-08
41002010701	NOR	6.51E-09	2.99E-08	3.16E-08	3.65E-08	3.90E-08
41001051601	NOR	5.43E-09	1.65E-08	6.19E-08	8.60E-09	3.63E-08
41102010101	NOR	1.78E-08	2.73E-08	8.64E-08	1.10E-08	2.81E-08
41102040112	NOR	1.75E-08	1.76E-08	2.25E-08	4.31E-08	2.57E-08
41102010212	NOR	8.20E-09	3.11E-08	2.25E-08	2.35E-08	1.84E-08
41102020101	NOR	4.06E-09	1.65E-08	9.09E-09	1.78E-08	1.54E-08
41002020411	NOR	1.38E-08	1.62E-08	2.23E-08	4.96E-09	1.16E-08
41001051101	NOR	0.00E+00	9.26E-09	0.00E+00	3.18E-09	8.57E-09
41002010511	NOR	0.00E+00	0.00E+00	0.00E+00	7.67E-09	6.83E-09
41001050901	NOR	3.56E-09	6.95E-09	4.72E-09	5.54E-09	6.49E-09
41002010612	NOR	3.54E-09	1.65E-09	3.34E-09	2.20E-09	4.95E-09
60901040301	NZL	1.03E-07	1.27E-07	1.09E-07	1.23E-07	1.69E-07
60901010211	NZL	7.58E-08	7.35E-08	7.36E-08	6.00E-08	6.66E-08
60901040500	NZL	2.08E-08	2.07E-08	2.13E-08	2.19E-08	3.13E-08
60901020301	NZL	8.44E-09	1.03E-08	1.38E-08	1.51E-08	2.00E-08
60901020400	NZL	1.53E-08	1.57E-08	1.67E-08	1.56E-08	1.88E-08
60901011401	NZL	5.15E-09	5.94E-09	7.06E-09	7.10E-09	9.47E-09
60901010111	NZL	5.17E-09	6.34E-09	6.44E-09	6.14E-09	6.66E-09
60902031601	NZL	0.00E+00	0.00E+00	2.63E-09	5.75E-09	5.94E-09
60901060300	NZL	3.28E-09	1.84E-09	7.95E-10	1.24E-09	3.49E-09
60901040401	NZL	0.00E+00	0.00E+00	0.00E+00	4.66E-10	6.32E-10
60901011701	NZL	0.00E+00	0.00E+00	0.00E+00	1.74E-10	2.65E-10
60901010101	NZL	7.38E-11	3.84E-11	9.94E-11	2.61E-11	7.97E-11
11411000000	PAK	7.31E-04	1.04E-03	1.16E-03	1.25E-03	1.47E-03
11410040300	PAK	9.68E-05	1.21E-04	1.14E-04	1.51E-04	1.60E-04
11410040201	PAK	4.59E-05	8.26E-05	6.39E-05	7.83E-05	9.40E-05
11406150100	PAK	5.93E-05	7.80E-05	6.67E-05	6.31E-05	7.95E-05
11406140100	PAK	2.42E-06	4.57E-06	3.03E-06	0.00E+00	3.05E-06
11411010101	PAK	2.28E-06	2.38E-06	2.45E-06	2.64E-06	2.82E-06
11413040000	PAK	1.99E-06	2.27E-06	2.30E-06	2.33E-06	2.50E-06
11412000000	PAK	2.05E-06	2.13E-06	2.51E-06	2.32E-06	2.16E-06
11412020000	PAK	8.34E-07	9.50E-07	1.01E-06	1.15E-06	9.39E-07

11411010301	PAK	5.32E-07	5.13E-07	5.72E-07	8.12E-07	7.79E-07
11410050501	PAK	3.66E-07	4.63E-07	5.57E-07	6.25E-07	7.17E-07
11411010100	PAK	9.58E-08	2.80E-07	3.35E-07	5.15E-07	6.37E-07
11412010000	PAK	4.26E-07	4.82E-07	4.81E-07	6.53E-07	5.07E-07
11410050301	PAK	0.00E+00	0.00E+00	1.73E-07	2.53E-07	4.89E-07
11410050600	PAK	1.49E-07	2.03E-07	2.65E-07	2.95E-07	3.44E-07
11411010401	PAK	2.31E-07	2.35E-07	2.60E-07	2.87E-07	3.08E-07
11413030100	PAK	2.73E-07	3.72E-07	3.53E-07	3.42E-07	3.02E-07
11413000000	PAK	5.90E-07	8.19E-07	8.42E-07	8.45E-07	3.00E-07
11411010201	PAK	1.61E-07	1.73E-07	2.50E-07	2.89E-07	2.96E-07
11411010200	PAK	2.13E-07	2.14E-07	2.54E-07	2.86E-07	2.47E-07
11411020000	PAK	1.10E-07	1.29E-07	1.25E-07	1.35E-07	1.42E-07
11411010500	PAK	7.00E-08	8.31E-08	9.71E-08	1.11E-07	1.23E-07
11413030000	PAK	8.05E-08	7.20E-08	7.72E-08	8.39E-08	7.07E-08
11411010400	PAK	3.09E-08	3.24E-08	3.24E-08	3.72E-08	3.65E-08
11411040000	PAK	1.62E-08	2.55E-08	0.00E+00	1.86E-08	1.65E-08
11411010300	PAK	4.45E-09	4.10E-09	5.68E-09	6.78E-09	6.99E-09
50432000000	PER	1.84E-04	2.66E-04	2.86E-04	3.19E-04	3.43E-04
51502040200	PER	6.47E-05	8.22E-05	8.54E-05	8.38E-05	9.47E-05
50426270600	PER	5.80E-06	1.23E-05	2.85E-05	1.78E-05	2.25E-05
50426221300	PER	7.70E-06	8.78E-06	1.17E-05	1.95E-05	2.12E-05
51502030101	PER	8.24E-06	9.34E-06	1.15E-05	1.56E-05	1.70E-05
50411231301	PER	6.70E-06	8.88E-06	1.10E-05	1.32E-05	1.68E-05
51401160500	PER	7.75E-06	8.45E-06	9.20E-06	1.03E-05	1.26E-05
51401160101	PER	8.24E-06	8.90E-06	9.53E-06	1.04E-05	1.25E-05
50426220901	PER	4.31E-06	5.07E-06	5.91E-06	7.02E-06	8.26E-06
50426270500	PER	2.85E-06	2.82E-06	2.88E-06	2.70E-06	3.53E-06
51502030401	PER	1.79E-06	2.23E-06	2.21E-06	2.45E-06	3.08E-06
51502010401	PER	1.96E-06	2.06E-06	2.27E-06	2.21E-06	2.38E-06
50426270200	PER	1.94E-06	1.32E-06	1.52E-06	1.48E-06	2.00E-06
50426221400	PER	9.94E-07	1.36E-06	1.47E-06	1.51E-06	1.53E-06
50428210000	PER	1.01E-06	1.20E-06	1.14E-06	1.08E-06	1.35E-06
50426270201	PER	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.16E-06
50426330100	PER	4.94E-07	5.41E-07	5.81E-07	5.93E-07	6.40E-07
51502020101	PER	1.94E-07	2.35E-07	2.98E-07	4.08E-07	5.75E-07
50426300000	PER	5.36E-08	1.53E-07	6.17E-08	1.33E-07	4.93E-07
50426230301	PER	3.14E-07	4.38E-07	3.61E-07	2.70E-07	4.67E-07
51502030301	PER	2.81E-07	3.08E-07	3.50E-07	1.99E-07	3.67E-07
50426230201	PER	1.02E-07	1.48E-06	5.00E-07	3.19E-07	3.29E-07
51502020200	PER	2.07E-07	2.37E-07	2.34E-07	2.50E-07	2.74E-07
51502030201	PER	1.87E-07	1.96E-07	2.05E-07	2.30E-07	2.50E-07
51502010601	PER	1.77E-07	2.72E-07	3.11E-07	3.15E-07	2.44E-07
50426280000	PER	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.27E-07
51401160301	PER	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.44E-07
51502040101	PER	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.24E-07
51501100400	PER	2.61E-08	5.06E-08	5.33E-08	7.00E-08	9.87E-08
51501100201	PER	7.61E-08	7.73E-08	7.36E-08	7.81E-08	8.34E-08

50426270101	PER	0.00E+00	0.00E+00	4.13E-08	0.00E+00	4.91E-08
41502010512	RUS	4.14E-06	6.91E-06	4.60E-06	5.69E-06	7.56E-06
40807040601	RUS	4.22E-06	3.63E-06	3.81E-06	3.74E-06	2.98E-06
13905060700	RUS	4.25E-06	3.00E-06	3.91E-06	3.87E-06	1.70E-06
41504190601	RUS	1.48E-06	1.69E-06	1.46E-06	1.28E-06	1.35E-06
10205140301	RUS	2.47E-07	8.32E-07	2.51E-07	2.11E-07	4.65E-07
10611010000	RUS	5.49E-07	5.83E-07	5.34E-07	5.03E-07	3.79E-07
41502010511	RUS	9.67E-08	2.17E-07	5.76E-08	1.24E-07	3.47E-07
41503020400	RUS	2.15E-07	2.39E-07	1.68E-07	1.72E-07	2.41E-07
10609120401	RUS	1.32E-07	1.51E-07	1.35E-07	1.18E-07	1.81E-07
41504190201	RUS	8.20E-08	1.82E-07	1.82E-07	1.46E-07	1.79E-07
40807041201	RUS	1.59E-07	1.48E-07	1.11E-07	1.61E-07	1.68E-07
10610521700	RUS	1.73E-07	1.58E-07	1.75E-07	1.63E-07	1.59E-07
13905060501	RUS	1.11E-06	1.74E-07	3.43E-07	3.09E-07	1.59E-07
41504230200	RUS	1.09E-07	1.18E-07	1.20E-07	1.10E-07	1.29E-07
41504191501	RUS	1.34E-07	1.28E-07	1.15E-07	1.06E-07	1.07E-07
40807041101	RUS	9.59E-08	1.72E-07	7.58E-08	1.83E-07	8.51E-08
41504230101	RUS	3.74E-08	6.25E-08	5.81E-08	4.92E-08	5.86E-08
10836000000	RUS	0.00E+00	4.81E-08	0.00E+00	0.00E+00	5.37E-08
40807041300	RUS	5.50E-08	3.99E-08	0.00E+00	1.26E-07	4.46E-08
41504191001	RUS	5.59E-08	4.79E-08	4.72E-08	4.29E-08	3.73E-08
10610521401	RUS	9.25E-08	3.58E-08	3.51E-08	7.22E-08	3.48E-08
10610571301	RUS	5.01E-08	4.39E-08	2.99E-08	4.01E-08	3.38E-08
10604050000	RUS	3.23E-08	3.93E-08	2.52E-08	3.71E-08	3.33E-08
10603040000	RUS	2.13E-08	2.57E-08	2.13E-08	2.49E-08	2.53E-08
41504191600	RUS	3.88E-08	4.96E-08	1.67E-08	2.23E-08	2.43E-08
10610990200	RUS	1.58E-08	1.01E-08	2.34E-08	2.74E-08	2.06E-08
10105310701	RUS	1.50E-08	1.49E-08	1.66E-08	1.76E-08	1.76E-08
41503020301	RUS	1.48E-08	1.47E-08	1.64E-08	1.73E-08	1.74E-08
10601050100	RUS	5.73E-09	9.26E-09	1.20E-08	1.42E-08	1.70E-08
41504191401	RUS	2.30E-08	2.17E-08	2.08E-08	1.85E-08	1.67E-08
10105310801	RUS	1.60E-08	1.51E-08	1.59E-08	1.57E-08	1.64E-08
10610521601	RUS	1.53E-08	1.60E-08	1.61E-08	1.51E-08	1.50E-08
10713180701	RUS	0.00E+00	1.92E-08	1.82E-08	1.77E-08	1.46E-08
10609120900	RUS	1.30E-08	1.33E-08	1.47E-08	1.28E-08	1.28E-08
10610572201	RUS	0.00E+00	1.40E-08	1.13E-08	1.25E-08	1.10E-08
10209191001	RUS	1.70E-09	1.96E-10	1.44E-09	7.74E-09	1.00E-08
10714140000	RUS	1.65E-08	4.06E-08	1.21E-08	0.00E+00	9.06E-09
10721090100	RUS	0.00E+00	2.01E-08	2.98E-08	1.52E-08	8.15E-09
10713240701	RUS	0.00E+00	4.38E-08	0.00E+00	4.33E-08	7.45E-09
10504040110	RUS	8.98E-09	1.59E-08	0.00E+00	9.77E-09	6.86E-09
10830111001	RUS	0.00E+00	0.00E+00	0.00E+00	1.89E-09	4.76E-09
10611000200	RUS	4.92E-09	0.00E+00	0.00E+00	0.00E+00	4.65E-09
10604040200	RUS	2.93E-09	5.25E-09	4.33E-09	5.17E-09	4.45E-09
10610990101	RUS	2.67E-09	2.78E-09	6.65E-09	1.49E-09	4.22E-09
10713060800	RUS	4.91E-09	0.00E+00	4.23E-09	0.00E+00	4.11E-09
10209190301	RUS	8.30E-10	8.15E-10	5.88E-10	5.29E-10	3.63E-09

10611000201	RUS	3.65E-09	3.59E-09	1.93E-09	0.00E+00	2.65E-09
10611000101	RUS	0.00E+00	1.24E-09	2.17E-09	1.21E-09	2.08E-09
10503100211	RUS	0.00E+00	0.00E+00	4.41E-09	0.00E+00	1.66E-09
10209191101	RUS	6.47E-10	2.24E-09	5.71E-10	3.99E-10	1.04E-09
10204082501	RUS	0.00E+00	1.12E-09	0.00E+00	5.32E-10	1.01E-09
10209190111	RUS	4.61E-10	5.03E-10	0.00E+00	2.54E-09	9.81E-10
10209190711	RUS	4.91E-10	4.61E-09	3.37E-10	1.86E-08	9.33E-10
10209183011	RUS	7.68E-10	2.89E-09	8.26E-10	1.40E-09	8.94E-10
10713281500	RUS	0.00E+00	2.27E-09	2.45E-09	2.93E-09	8.17E-10
10209180601	RUS	2.04E-09	8.02E-09	9.90E-10	8.55E-10	6.27E-10
10209180101	RUS	0.00E+00	4.66E-10	0.00E+00	1.18E-10	4.99E-10
10209190201	RUS	4.72E-10	0.00E+00	3.24E-11	0.00E+00	4.86E-10
10209181111	RUS	6.44E-10	0.00E+00	0.00E+00	7.54E-10	4.85E-10
10209190211	RUS	3.29E-10	0.00E+00	3.27E-10	3.65E-10	4.81E-10
10830111601	RUS	0.00E+00	0.00E+00	0.00E+00	2.28E-10	4.32E-10
10504050101	RUS	1.46E-09	2.15E-09	0.00E+00	1.63E-10	4.06E-10
10209180211	RUS	3.34E-10	1.25E-09	3.59E-11	4.21E-10	3.61E-10
10713281401	RUS	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.28E-10
10721080100	RUS	0.00E+00	0.00E+00	4.16E-10	7.39E-10	2.86E-10
10209180612	RUS	5.93E-11	0.00E+00	0.00E+00	3.90E-10	2.75E-10
10209190512	RUS	1.17E-09	0.00E+00	2.28E-10	0.00E+00	2.12E-10
10209180701	RUS	3.34E-10	4.12E-11	0.00E+00	2.67E-10	1.47E-10
10503100201	RUS	0.00E+00	3.19E-10	2.01E-10	2.47E-10	1.41E-10
10209180901	RUS	1.75E-10	0.00E+00	2.55E-10	8.57E-11	1.36E-10
10209190401	RUS	5.93E-11	1.62E-11	7.14E-11	2.62E-10	1.35E-10
10505030101	RUS	0.00E+00	4.89E-10	0.00E+00	0.00E+00	9.71E-11
10209190411	RUS	6.29E-12	5.44E-12	3.48E-12	5.33E-11	8.68E-11
10209180611	RUS	5.53E-11	2.47E-11	4.52E-11	7.53E-11	6.69E-11
10209190801	RUS	1.68E-10	0.00E+00	1.71E-11	0.00E+00	5.12E-11
10209191011	RUS	7.84E-11	0.00E+00	0.00E+00	6.52E-09	4.23E-11
10209180501	RUS	2.28E-11	0.00E+00	5.22E-11	0.00E+00	3.79E-11
10209183001	RUS	2.48E-11	7.81E-11	2.20E-11	2.04E-11	2.51E-11
10209190601	RUS	0.00E+00	0.00E+00	0.00E+00	1.79E-10	2.29E-11
10209180801	RUS	6.30E-11	0.00E+00	2.81E-11	2.33E-11	1.62E-11
10209190501	RUS	8.28E-11	0.00E+00	1.58E-10	0.00E+00	1.56E-11
10209180401	RUS	1.50E-12	0.00E+00	1.20E-11	1.65E-11	6.25E-13
10209190101	RUS	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.36E-13
41101040201	SWE	9.76E-08	2.25E-07	2.18E-07	1.56E-07	2.49E-07
41002020500	SWE	2.00E-07	1.56E-07	1.58E-07	1.88E-07	2.33E-07
41002020301	SWE	3.06E-07	2.83E-07	3.60E-07	4.09E-08	2.30E-07
41101040500	SWE	4.26E-08	1.30E-07	1.40E-07	5.61E-08	9.83E-08
41101040401	SWE	3.96E-08	6.26E-08	6.94E-08	3.27E-08	4.65E-08
41002050101	SWE	3.80E-08	5.69E-08	7.43E-09	5.35E-08	4.23E-08
41002020201	SWE	1.57E-08	5.81E-08	2.47E-08	3.25E-08	3.78E-08
41002070201	SWE	4.45E-09	3.97E-08	0.00E+00	3.14E-08	3.72E-08
41002020401	SWE	0.00E+00	1.88E-08	2.11E-08	2.10E-09	1.62E-08
41002070900	SWE	0.00E+00	0.00E+00	6.26E-09	3.74E-09	3.58E-09

41002030300	SWE	0.00E+00	6.20E-10	0.00E+00	0.00E+00	5.25E-10
41002020400	SWE	0.00E+00	1.52E-10	1.02E-10	8.00E-11	1.09E-10
40210100400	CHE	4.86E-05	5.70E-05	4.52E-05	4.78E-05	5.07E-05
40205150100	CHE	9.34E-06	9.97E-06	8.92E-06	8.20E-06	1.08E-05
40205160100	CHE	5.79E-06	5.37E-06	6.14E-06	4.86E-06	6.32E-06
40205200000	CHE	2.39E-06	2.59E-06	2.42E-06	2.43E-06	2.53E-06
40205190100	CHE	3.55E-07	3.26E-07	3.00E-07	2.89E-07	3.08E-07
40205140401	CHE	1.80E-07	1.31E-07	1.53E-07	1.56E-07	1.45E-07
40205140500	CHE	3.30E-08	4.73E-08	2.42E-08	2.60E-08	2.91E-08
10907330101	TJK	3.13E-05	3.14E-05	2.95E-05	2.93E-05	2.89E-05
10907230701	TJK	3.22E-07	3.20E-07	3.66E-07	4.25E-07	5.75E-07
10907021001	TJK	3.96E-07	5.53E-07	4.62E-07	5.15E-07	4.57E-07
10907230500	TJK	1.83E-07	2.08E-07	2.08E-07	2.50E-07	2.94E-07
10907350000	TJK	3.68E-07	3.84E-07	2.97E-07	2.97E-07	2.82E-07
10907290000	TJK	0.00E+00	2.02E-07	1.52E-07	1.80E-07	1.99E-07
10907230301	TJK	7.86E-08	1.21E-07	0.00E+00	0.00E+00	1.60E-07
10907021201	TJK	0.00E+00	0.00E+00	1.38E-07	1.44E-07	1.58E-07
10907300000	TJK	0.00E+00	9.91E-08	1.07E-07	1.12E-07	1.18E-07
10907340100	TJK	1.22E-07	1.19E-07	1.16E-07	1.08E-07	1.09E-07
10907230601	TJK	7.67E-08	1.40E-07	1.71E-07	1.67E-07	8.90E-08
10907340201	TJK	4.54E-09	4.02E-09	3.78E-09	3.62E-09	3.37E-09
10907340101	TJK	2.64E-09	2.75E-09	2.32E-09	2.15E-09	2.04E-09
10907360100	TJK	3.08E-09	2.99E-09	2.75E-09	2.43E-09	1.61E-09
10907340301	TJK	1.16E-09	9.86E-10	9.92E-10	9.08E-10	8.70E-10
30101130110	USA	8.11E-05	9.60E-05	8.58E-05	9.50E-05	1.39E-04
30403131201	USA	8.21E-05	1.00E-04	9.77E-05	9.64E-05	1.31E-04
30402070201	USA	3.93E-06	7.42E-06	7.48E-06	6.36E-06	1.07E-05
30402080411	USA	1.51E-06	6.12E-06	7.67E-07	3.10E-06	9.58E-06
31007120200	USA	4.39E-06	5.31E-06	5.71E-06	5.13E-06	7.19E-06
30101120411	USA	1.79E-06	3.95E-06	3.84E-06	4.89E-06	7.01E-06
31007060100	USA	2.26E-06	3.08E-06	3.11E-06	2.86E-06	3.66E-06
31007140100	USA	2.25E-06	3.02E-06	3.29E-06	2.41E-06	3.35E-06
30101120301	USA	1.60E-07	1.54E-06	3.89E-07	2.06E-06	2.80E-06
30403130101	USA	2.79E-07	3.95E-07	7.63E-07	1.97E-07	1.40E-06
30402060501	USA	2.56E-07	3.82E-07	3.57E-07	4.65E-07	7.13E-07
30403070501	USA	4.34E-07	5.17E-07	5.74E-07	4.82E-07	6.94E-07
31325300000	USA	4.10E-07	4.52E-07	4.36E-07	3.84E-07	5.54E-07
30402050301	USA	0.00E+00	2.16E-07	9.78E-08	4.43E-07	5.27E-07
31005470000	USA	1.53E-07	2.01E-07	2.60E-07	2.86E-07	5.10E-07
31325130401	USA	3.19E-07	3.32E-07	3.29E-07	2.51E-07	3.87E-07
30101120111	USA	1.20E-07	1.52E-07	1.39E-07	1.41E-07	3.22E-07
31007200000	USA	1.53E-07	2.24E-07	2.68E-07	2.29E-07	3.11E-07
31325290201	USA	2.07E-07	2.12E-07	2.15E-07	2.31E-07	2.83E-07
31005080900	USA	2.00E-07	2.71E-07	2.33E-07	2.01E-07	2.40E-07
30503280100	USA	1.77E-07	1.74E-07	2.09E-07	1.57E-07	2.05E-07
30402070501	USA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.97E-07
30403130501	USA	9.49E-08	9.74E-08	9.35E-08	9.19E-08	1.42E-07

31007050100	USA	8.27E-08	9.36E-08	1.01E-07	8.93E-08	1.33E-07
31005301001	USA	6.76E-08	8.32E-08	8.18E-08	8.72E-08	1.23E-07
30403130701	USA	8.63E-08	9.91E-08	9.66E-08	8.92E-08	1.22E-07
31007080100	USA	7.07E-08	7.60E-08	8.49E-08	8.22E-08	1.06E-07
31001030201	USA	5.77E-08	7.19E-08	7.83E-08	8.24E-08	9.82E-08
31325290300	USA	7.98E-08	8.33E-08	8.30E-08	8.05E-08	9.62E-08
31325130501	USA	6.30E-08	6.83E-08	7.51E-08	6.43E-08	9.53E-08
30403132200	USA	0.00E+00	5.65E-08	0.00E+00	5.47E-08	8.07E-08
31007090400	USA	5.34E-08	6.00E-08	7.31E-08	6.02E-08	7.92E-08
30503290101	USA	5.98E-08	6.83E-08	6.61E-08	5.97E-08	7.30E-08
31325050301	USA	4.99E-08	5.56E-08	5.23E-08	6.44E-08	7.24E-08
30101010138	USA	1.03E-08	0.00E+00	6.40E-10	4.13E-09	6.88E-08
31314170400	USA	0.00E+00	4.51E-08	4.57E-08	4.00E-08	6.44E-08
31325310000	USA	4.59E-08	4.72E-08	4.73E-08	4.70E-08	5.99E-08
31005080901	USA	4.38E-08	4.52E-08	4.75E-08	4.32E-08	5.96E-08
31005301101	USA	3.24E-08	3.73E-08	3.56E-08	3.87E-08	5.53E-08
30403170201	USA	5.46E-08	5.42E-08	5.13E-08	4.68E-08	5.43E-08
30402060200	USA	2.67E-08	3.81E-08	3.75E-08	2.55E-08	5.21E-08
31008040101	USA	0.00E+00	2.33E-08	2.38E-08	5.42E-08	4.93E-08
30101120211	USA	4.30E-08	5.75E-08	4.53E-08	3.81E-08	4.88E-08
30403030701	USA	0.00E+00	2.77E-08	3.68E-08	0.00E+00	4.83E-08
30402060100	USA	4.02E-08	4.17E-08	3.94E-08	4.09E-08	4.73E-08
31329070100	USA	2.75E-08	3.03E-08	2.13E-08	2.89E-08	3.57E-08
31005460100	USA	1.07E-08	1.67E-08	1.64E-08	9.50E-09	3.23E-08
31005081000	USA	1.29E-08	2.14E-08	1.72E-08	1.70E-08	2.33E-08
30102141901	USA	4.00E-09	0.00E+00	6.47E-09	1.07E-08	2.26E-08
30101150201	USA	1.50E-08	1.56E-08	1.62E-08	1.58E-08	2.09E-08
30503290200	USA	1.74E-08	1.77E-08	1.67E-08	1.57E-08	2.01E-08
30402060101	USA	3.07E-09	7.64E-09	8.57E-09	4.78E-09	2.00E-08
30101120101	USA	0.00E+00	0.00E+00	4.99E-09	6.79E-09	1.96E-08
31325130900	USA	1.42E-08	1.57E-08	1.50E-08	1.40E-08	1.85E-08
30403230200	USA	1.26E-08	1.26E-08	1.23E-08	1.15E-08	1.55E-08
30403380800	USA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.36E-08
31329090000	USA	2.34E-09	1.12E-08	7.57E-09	1.05E-08	1.29E-08
30101130101	USA	6.97E-09	8.32E-09	7.27E-09	7.63E-09	1.14E-08
30101010129	USA	0.00E+00	0.00E+00	2.33E-08	2.24E-09	1.12E-08
31325200100	USA	9.58E-09	9.39E-09	1.07E-08	8.62E-09	1.09E-08
30101120401	USA	5.47E-09	9.26E-09	8.33E-09	1.23E-08	9.15E-09
30102142601	USA	9.17E-10	1.58E-09	2.28E-09	5.29E-09	6.79E-09
30403130801	USA	0.00E+00	3.96E-09	0.00E+00	3.44E-09	4.06E-09
30101010716	USA	3.45E-09	0.00E+00	0.00E+00	0.00E+00	3.97E-09
30403180800	USA	3.28E-09	3.24E-09	3.08E-09	2.82E-09	3.94E-09
30101110401	USA	8.10E-10	2.00E-09	1.38E-09	1.78E-09	3.85E-09
30403380900	USA	2.46E-09	2.80E-09	2.56E-09	2.34E-09	3.77E-09
30101020112	USA	1.58E-09	1.52E-09	1.48E-09	1.78E-09	2.61E-09
30403380801	USA	1.39E-09	1.48E-09	1.53E-09	1.55E-09	2.07E-09
31325130801	USA	4.46E-09	1.49E-09	1.50E-09	1.33E-09	1.80E-09

30403130601	USA	9.44E-10	2.33E-09	2.62E-09	5.70E-10	1.77E-09
30402080201	USA	6.28E-10	0.00E+00	0.00E+00	0.00E+00	1.74E-09
31325130800	USA	1.53E-09	1.50E-09	1.45E-09	1.36E-09	1.63E-09
30101010139	USA	0.00E+00	0.00E+00	0.00E+00	1.22E-10	1.22E-09
30101010100	USA	2.03E-09	0.00E+00	0.00E+00	1.05E-09	1.19E-09
30102141001	USA	0.00E+00	1.56E-09	2.02E-09	7.97E-10	9.93E-10
30101150301	USA	2.97E-10	3.43E-10	3.49E-10	5.12E-10	8.79E-10
30101110801	USA	8.14E-11	4.99E-11	7.83E-11	1.20E-10	8.43E-10
30101110100	USA	4.03E-11	2.11E-10	1.92E-10	3.29E-10	4.30E-10
31005440200	USA	4.67E-10	7.81E-10	4.43E-10	6.86E-10	4.27E-10
30101150101	USA	4.35E-10	2.49E-10	4.36E-10	2.22E-10	3.81E-10
30102142300	USA	0.00E+00	1.23E-10	1.13E-10	1.27E-10	3.44E-10
30101110201	USA	8.72E-11	1.17E-10	0.00E+00	3.42E-11	2.42E-10
30102140501	USA	5.30E-11	2.24E-11	2.68E-10	1.62E-10	1.88E-10
30101020101	USA	1.35E-09	1.29E-10	3.17E-10	4.91E-10	1.44E-10
30102142301	USA	2.92E-11	3.14E-11	8.90E-11	9.54E-11	1.42E-10
30101130112	USA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.23E-10
30101110701	USA	9.37E-12	6.40E-11	6.10E-11	4.18E-11	8.59E-11
30101040401	USA	3.51E-11	3.44E-11	3.53E-11	4.19E-11	4.29E-11
30403250301	USA	3.72E-11	3.27E-11	3.08E-11	2.89E-11	3.21E-11
30101051401	USA	5.73E-12	2.21E-11	2.64E-11	2.66E-11	3.14E-11
30101110101	USA	1.60E-12	6.63E-12	5.28E-12	2.41E-12	2.07E-11
30101110601	USA	1.06E-11	1.37E-11	9.08E-12	8.42E-12	2.03E-11
0103130401	USA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.83E-11
30101140101	USA	6.91E-12	5.92E-12	6.86E-12	1.25E-11	1.55E-11
30101020600	USA	2.82E-12	0.00E+00	6.76E-12	8.94E-12	1.22E-11
30101110301	USA	0.00E+00	1.13E-11	1.06E-11	0.00E+00	1.20E-11
30101110300	USA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.61E-12
30101011001	USA	1.67E-11	0.00E+00	0.00E+00	6.49E-12	7.13E-12
30101051001	USA	1.90E-11	7.00E-12	7.68E-12	7.86E-12	5.98E-12
30101110501	USA	2.17E-12	2.70E-12	3.46E-12	4.23E-12	4.98E-12
30101110200	USA	0.00E+00	0.00E+00	6.54E-13	1.79E-12	2.83E-12
30101110400	USA	1.51E-12	1.43E-12	1.32E-12	6.53E-13	2.72E-12
30101030301	USA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.54E-12
30101111001	USA	0.00E+00	2.55E-14	2.58E-14	6.07E-14	2.12E-13
30101100311	USA	0.00E+00	0.00E+00	0.00E+00	3.60E-15	6.61E-15
30101140300	USA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30101140301	USA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30101111201	USA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30101111300	USA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30101130200	USA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30103130801	USA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30101140401	USA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30101052000	USA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30101140900	USA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30101100401	USA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30101100501	USA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

30101100601	USA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30101100301	USA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30101120201	USA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30101111400	USA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30101100411	USA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30101100611	USA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30101110110	USA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30101130114	USA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30101010512	USA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
10905240200	UZB	1.53E-06	1.53E-06	1.63E-06	1.73E-06	1.71E-06

Table S4.5: Basin change in GLOF risk. All 1098 glacial basins ordered alphabetically showing GLOF risk from 2000 to 2020. Countries are coloured according to mountain range where; Andes = blue, Alps = red, HMA = green, PNW = purple and HAOC = orange.