# Progress and challenges in glacial lake outburst flood research (2017-2021): a research community perspective

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**Abstract.** Glacial lake outburst floods (GLOFs) are among the most concerning consequences of retreating glaciers in mountain ranges worldwide. GLOFs have attracted significant attention amongst scientists and practitioners in the past ~few~ two decades, with particular interests in the physical drivers and mechanisms of GLOF hazard, and socioeconomic and other human-related developments that affect vulnerabilit~ies~ies~y to GLOF events. This increased research focus on GLOFs is reflected in the gradually increasing number of papers published annually. This study offers an overview of recent GLOF research by analysing ~570~ 594 peer-reviewed GLOF studies published between 2017 and 2021 (Web of Science and Scopus databases), reviewing the content, geographical focus as well as other characteristics of GLOF studies. This review is complemented with perspectives from the first GLOF conference (7-9 July 2021, online) where a global GLOF research community from major mountain regions gathered to discuss the current state of the art of integrated GLOF research. Therefore, representatives from 17 countries identified and elaborated trends and challenges and proposed possible ways forward to navigate future GLOF research, in four thematic areas: (i) understanding GLOFs – timing and processes; (ii) modelling GLOFs and GLOF process chains; (iii) GLOF risk management, prevention and warning; (iv) human dimensions of GLOFs and GLOF attribution to climate change.

## 1 Introduction

60  Sudden releases of water from a glacial lake, commonly referred to as ~—~Glacial Lake Outburst Floods (GLOFs) ~–~, have become emblematic symptom~s~ of climate change in many mountain areas throughout the world (Clague et al., 2012; Harrison et al., 2018). GLOFs are described as 'low frequency, high magnitude events' with major geomorphic consequences (Costa and Schuster, 1988; Evans and Clague, 1994; Clague and Evans, 2000), extreme hydrological characteristics (Richardson and Reynolds, 2000; Cenderelli and Wohl, 2003; Cook et al., 2018) and possibly adverse impacts on societies (Carey, 2005; Huggel et al., 2015; Carrivick and Tweed, 2016). While more than 1,300 historical GLOFs have been catalogued throughout the world by Carrivick and Tweed (2016), recent studies show that this number is likely a lower bound for many regions (Emmer, 2017; Nie et al., 2018; Veh et al., 2019; Zheng et al., 2021a; Emmer et al., 2022). Recent~ly~ ~work by~ Veh et al. (2022) compiled a dataset of more than 2,800 GLOFs globally. These studies indicate that GLOFs may be more frequent than previously thought (Carrivick and Tweed, 2016; Emmer et al., 2022; Veh et al., 2022).

70    Research on GLOFs has been rapidly growing in recent ~~two~~ decades (Emmer, 2018), driven in part by the urgent need to improve understanding trends in GLOF occurrence under climate change, and its links to retreating glaciers and the formation of ~~hundreds to~~ thousands of new lakes globally (Clague and O'Connor, 2015; Harrison et al., 2018; Shugar et al., 2020). ~~These dynamics competee with~~At the same time increasing urbanization, land and water demand, migration, mountain tourism, and other socioeconomic and human-related forces ~~that increase~~exacerbate human exposure and raise vulnerabiliti~~es~~y to GLOFs,

75    especially in low income countries such as Peru or Nepal (Carey, 2010; Sherry et al., 2018; Motschmann et al., 2020a; Sherpa et al., 2020; Carey et al., 2021). However, possible synergies and trade-offs between climate change adaptation (Moulton et al., 2021; Aggarwal et al., 2021), sustainable water use and management (Drenkhan et al., 2019; Haeberli and Drenkhan, 2022), hydropower generation (Schwanghart et al., 2016; Li et al., 2022), glacier protection (Anacona et al., 2018) and GLOF hazard mitigation are still under discussion.

80    Our goal is to provide a state-of-the-art review of GLOF research for charting future research directions. We provide insights into current trends within the GLOF research community ~~and trends~~ gained from a bibliometrical analysis and the first conference on GLOFs (7-9th July 2021, online, convened by: University of Graz, Austria; the University of Potsdam, Germany; the University of Zurich, Switzerland; and the University of Oregon, USA). This paper addresses four key questions: (i) What are the characteristics of the GLOF research community and recently published (2017-2021) GLOF papers? (ii) What are

85    current trends in GLOF research and published GLOF papers? (iii) Where are the geographical and thematic research gaps, challenges and emerging directions in GLOF research? (iv) Where should GLOF research move next?

## 2 Data and Methods

### 2.1 WOS and Scopus databases analysis

As a first step, we conducted a scoping review to identify most relevant GLOF studies in Clarivate Analytics' Web of Science

90    (WOS) Core collection database (www.webofscience.com), and Elsevier's Scopus database (www.scopus.com). These databases cover selected peer-reviewed scholarly journals, books and proceedings in the fields of natural sciences, social sciences, arts and humanities (WOS, 2022), and present themselves as the most reliable, relevant and up-to-date research databases (Scopus, 2022) that are broadly used. Both WOS and Scopus databases are among the largest available databases and are broadly used for bibliometric analysis, and studying research and publishing trends across research fields (Sandstrom

95    and van den Besselaar, 2016; Thelwall and Sud, 2016; Da Silva and Dobranszki, 2018; Martín-Martín et al., 2018; Fire and Guestrin, 2019). Yet, these databases have several limitations: (i) they do not capture technical reports, white papers, gray literature and local and indigenous knowledge; (ii) they are strongly oriented towards English-language literature while many journals published in other languages are not indexed; (iii) they do not necessarily capture books which are the standard form of publishing in many disciplines (for instance in humanities and social sciences); and (iv) the representation of authors from

100    different geographic regions is uneven (Mongeon and Paul-Hus, 2016).

To ensure the consistency with the analysis of ~~GLOF data previously analysed by Emmer (2018) for~~ the ~~previous~~ period 1970-2016 ~~(Emmer, 2018)~~, we used an identical search string:

TOPIC: (glaci* AND outburst* AND flood* OR jökulhlaup*)

The period of interest was limited to publication date 2017-2021, returning ~~495~~ 516 results in the WOS database and 427~~1~~ in the Scopus database (search performed in ~~March~~ August 2022). In the next step, we combined the outcomes of these databases and removed duplicates. The resulting dataset of ~~570~~ 594 GLOF papers is further considered in the analytical part of this study. Each GLOF paper in the database is described by several qualitative and quantitative characteristics ~~(see~~ which are summarized in Tab~~-le~~ 1~~),~~. ~~sS~~ome of ~~which~~ those were derived automatically from the databases (e.g. document type, access mode), while some had to be assigned manually in the second step of the dataset building procedure (e.g. geographical focus, international cooperation).

**Tab. 1: Characteristics of GLOF papers analysed in this study.**

| Characteristics | Description | Values |
|---|---|---|
| Characteristics derived from the database: | | |
| Title | Title of the paper | ~~570~~ 594 titles |
| Abstract | Published abstracts summarizing the work | ~~569~~ 593 abstracts |
| Author(s) | List of authors | 2,~~107~~ 173 unique authors |
| Year published | Year of publication in the journal | 2017 to 2021 |
| Publication title | Name of the journal, proceeding, book | ~~213~~ 217 journal titles, proceeding titles and book titles |
| Subject area / category | Scopus subject area / Web of Science category in which the publication is indexed | 15 subject areas / 35 WOS categories |
| Document type | Classification of studies according to the structure of the content | 4 document types (article, review, proceedings paper, other) |
| WOS research domain | The WOS All databases classification of indexed papers; each paper is assigned to one or more research domains | 6 research domains (Science Technology, Physical Sciences, Life Sciences Biomedicine, Social Sciences, Technology, Arts Humanities) |

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| Language | Language of the paper | 5 languages (English, Chinese, Russian, Spanish, French) |
|---|---|---|
| ~~Open~~ Access mode | Access mode by which a paper was published | GLOF paper published in any kind of open access mode (gold, green, hybrid) or not |
| Manually assigned characteristics: | | |
| No. of authors | Number of authors that co-authored a GLOF paper | Single-author or co-authored GLOF paper (1 author to 21 co-authors) |
| International cooperation | Paper is written by author(s) from one country, or by authors from several countries | National or international GLOF paper |
| Geographical focus | Regional focus of a GLOF paper assigned to one, more than one, or none of 11 GLOF hotspots (Emmer, 2018) based on the titles and abstracts | One, more than one, or none of 11 GLOF hotspots (Alaska, North-American Cordillera, Tropical Andes, Southern Andes, Iceland, Greenland, Scandinavia, European Alps, Hindu Kush-Karakoram, Himalaya, Central Asia) |

Titles and abstracts of individual papers (all papers included a title and ~~569~~ 593 out of ~~570~~ 594 papers included an abstract) were used for qualitative content analysis. We used a free word cloud generator (www.wordclouds.com) in order to identify frequently occurring words ~~(and so enhanced focus)~~ among the abstracts and titles of GLOF papers. After automatic removal of general verbs, pronouns and prepositions we manually removed other irrelevant words and clustered words with identical roots. Word clouds of the 50 most frequently occurring words were visualized separately for titles and abstracts. This method has been successfully employed in characterizing and visualizing the content of large textual data sets across other scientific fields (McGee and Craig, 2012; Atenstaedt, 2017), including ~~the~~ geosciences (Li and Zhou, 2017; Emmer et al., 2019). Clearly, word clouds can only illustrate priorities and the choice of wording of the group under study. ~~Science~~ Scientific paper word clouds (including those presented in this study) can thus differ substantially from those of local communities (e.g. Gearheard et al., 2013).

## 2.2 The GLOF conference and workshop

The GLOF conference & workshop took place from 7 to 9 July 2021 (online) and was completely open access upon pre-registration and co-organized by the University of Graz (Austria), the University of Potsdam (Germany), the University of

125 Zurich (Switzerland) and the University of Oregon (USA). The main objective was to gather researchers dealing with GLOFs to exchange recent knowledge and progress in GLOF research as well as to identify gaps, challenges, emerging directions and ways forward in GLOF research. This conference was organized under the patronage of the scientific standing group on Glacier and Permafrost Hazards in Mountains (GAPHAZ; www.gaphaz.org) and has been disseminated primarily via the GAPHAZ webpage, GAPHAZ ~~mailing list~~community consisting of about 150 contacts and through ResearchGate

130 (www.researchgate.net/project/GLOF-conference-workshop-7-9-July-online; about 400 reads at the time of the conference).

The conference programme consisted of four conference sessions (7 and 8 July 2021), and two discussion sessions (9 July 2021). These sessions focused on the following topics: (i) understanding GLOFs – timing and processes; (ii) modelling GLOFs and GLOF process chains; (iii) GLOF risk management, prevention and warning; and (iv) human dimensions of GLOFs and GLOF attribution to climate change. These topics were previously identified based on the analysis of published GLOF papers

135 (see Section 2.1).

The timing of individual sessions facilitated access for diverse time zones, thereby allowing organizers to engage with colleagues from across the globe and across diverse disciplines such as the geosciences, environmental sciences, engineering, social sciences, and humanities. Individual conference sessions had between 45 to 65 attendees and consisted of five presentations each (see the conference programme: www.gaphaz.org/files/GLOF_conference_programme.pdf). A total of 37

140 participants from 17 countries across the globe, different scientific backgrounds and career stages, took part in two moderated sessions, during which a research community perspective on trends and challenges in GLOF research were discussed.

**3 GLOF papers published in 2017-2021: results from WOS and Scopus databases analysis**
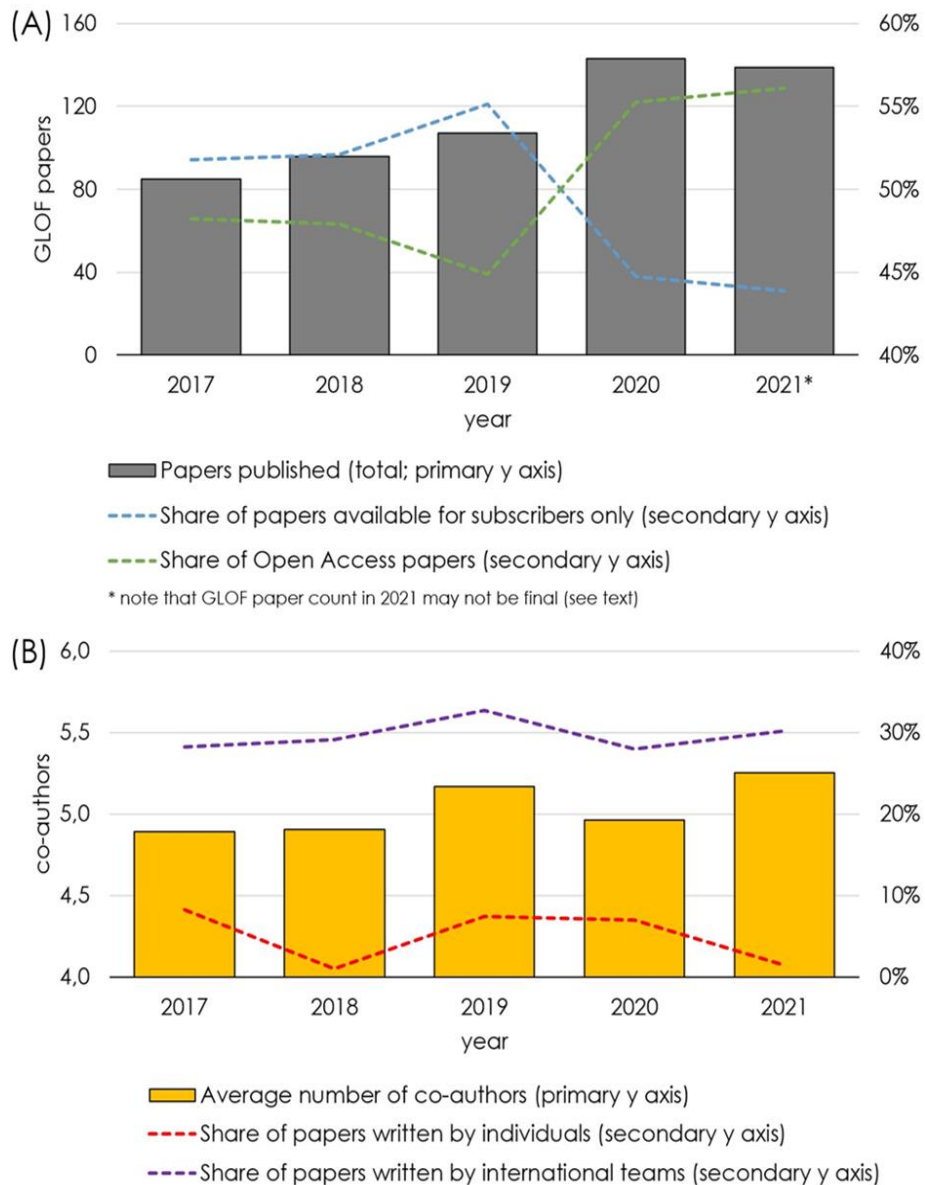
**3.1 General characteristics**

Our dataset consists of ~~570~~ 594 GLOF papers ~~(see Fig. 1)~~ of which the vast majority are classified as articles (n = ~~481~~503;

145 84.~~4~~7%), ~~39~~41 (6.~~9~~8%) as reviews, 28 (4.~~9~~7%) as conference papers, 16 (2.~~8~~7%) as book chapters and the remaining 6 papers (1.0~~1~~%) are classified as others (corrections, editorials). Considering WOS research domains (unavailable for papers indexed in Scopus database), the majority of papers are assigned under the Physical Sciences domain (95.~~2~~9%; Earth and Planetary ~~S~~sciences, Geosciences ~~M~~multidisciplinary, Physical Geography and Environmental Sciences), while fewer than half (~~45.6~~47.0%) of all published papers are assigned to the Social Sciences domain, suggesting that GLOF research is currently

150 dominated by physical science, rather than social science, research.

The journals that published GLOF research most frequently were Geomorphology (n = 3~~2~~1), Remote Sensing (n = 2~~1~~2), Quaternary Science Reviews (n = ~~19~~20), Frontiers in Earth Science (n = 19), Earth-Science Reviews (n = 17)~~, Frontiers in Earth Science (n = 17)~~ and The Cryosphere (n = 16). Six other journals published 10 or more GLOF papers (Natural Hazards, Science of the Total Environment, Earth Surface Processes and Landforms, Journal of Glaciology, Water, Global and Planetary

155 Change). While some of these journals are well-established in publishing GLOF research (e.g. Geomorphology, Quaternary
Science Reviews), others experienced a recent growth in publishing GLOF papers, especially MDPI journals (Remote Sensing,
Water) and Frontiers publishing house (Frontiers in Earth Science).
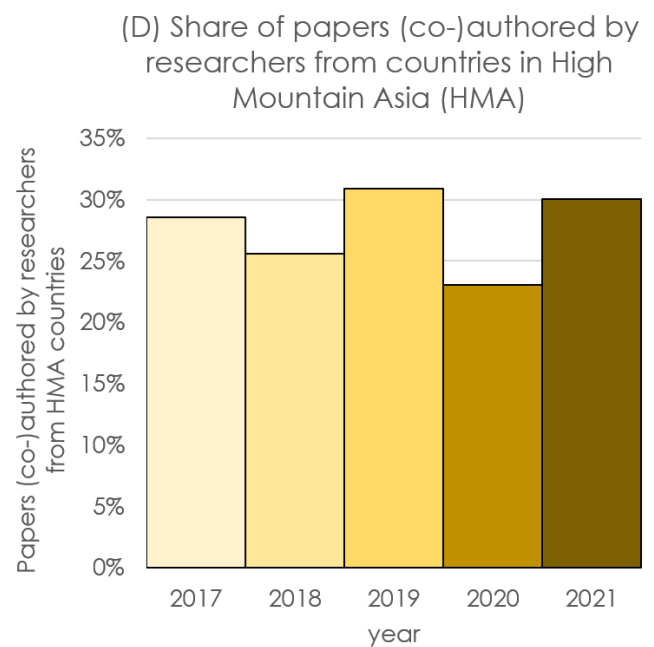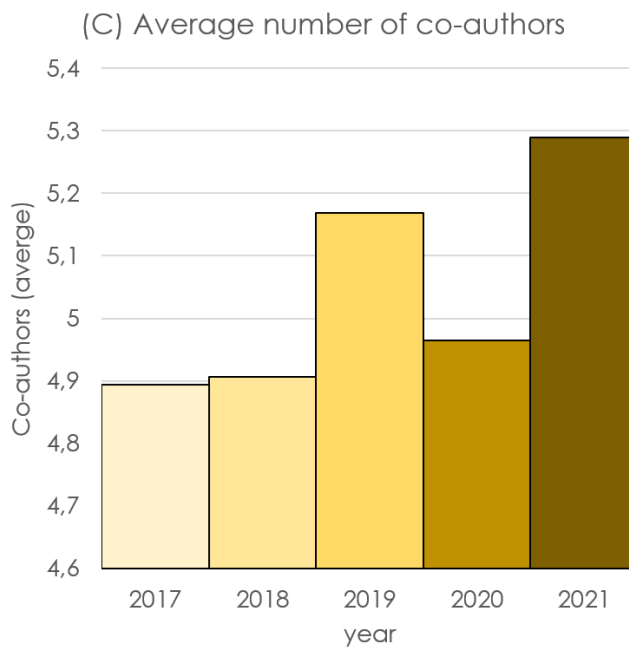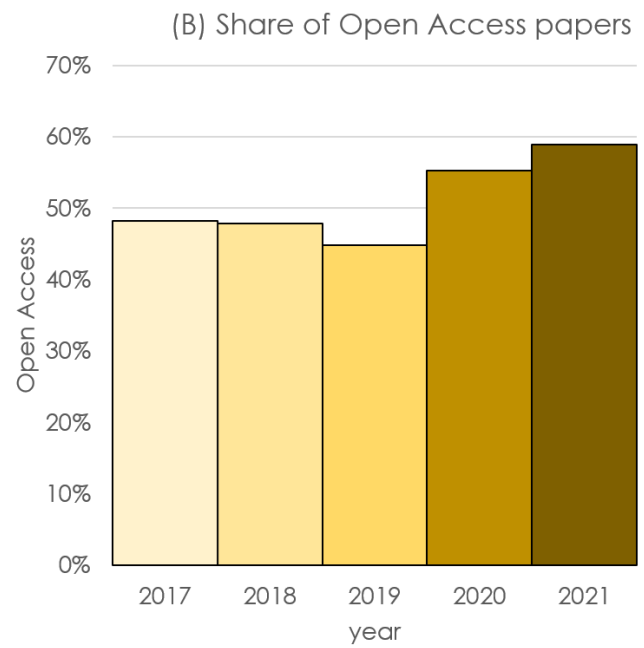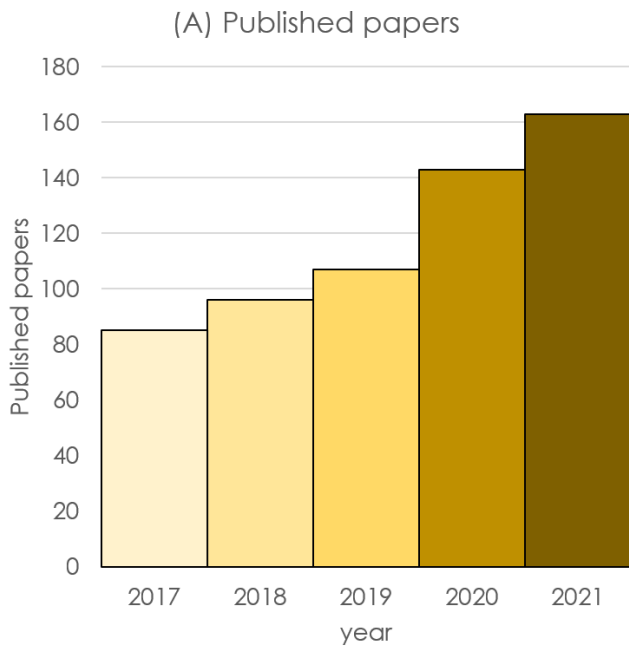
160 ~~Fig. 1: Basic characteristics of published GLOF papers covered by WOS and Scopus databases. (A) Published GLOF papers in each year, a share of papers available for subscribers only and a share of Open Access papers; (B) An average number of co-authors, a share of papers written by individuals and a share of papers written by international teams.~~



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An increasing trend is observed in the number of GLOF papers published in individual years: while 85 GLOF papers were published in 2017, this number increased to 96 in 2018, 107 in 2019, 143 in 2020 and ~~139~~ 163 in 2021 (see Fig. 1A). ~~However, the 2021 number might not be final because of differently lagged uploads of individual journals and publishers into the WOS and Scopus databases.~~ In comparison, Emmer (2018) identified a total of 52 papers published in 2010, 24 papers in 2000, and only 2 papers in 1990. While this is a general publishing trend (Fire and Guestrin, 2019), the number of published GLOF papers seems to be increasing even more remarkably compared to other research fields. The gradually increasing number of GLOF papers may be explained by: (i) increasing interest of research community and funding agencies in GLOFs; (ii) growing GLOF research community; and (iii) changing publication habits (increasing need of publishing induced by changing research evaluation indicators (Emmer, 2018; Fire and Guestrin, 2019). It can also be explained by possibly expanding coverage of analysed databases. Slightly more than half of all GLOF papers (n = ~~292~~310; 5~~1~~2.~~21~~% ) were published in any kind of open access mode, with the share varying from 44.9% in 2019 to 5~~6~~8.~~1~~9% in 2021 (see Fig. 1~~B~~A).

Fig. 1: Basic characteristics of published GLOF papers covered by WOS and Scopus databases. (A) Published GLOF papers in each year; (B) Share of Open Access papers; (C) Average number of co-authors (Section 3.4); (D) Share of papers (co-)authored by authors from countries in High Mountain Asia (see Section 3.4 for more details).

**(A) Published papers**

**(B) Share of Open Access papers**

**(C) Average number of co-authors**

**(D) Share of papers (co-)authored by researchers from countries in High Mountain Asia (HMA)**

### 3.2 Word cloud analysis - insights into study content
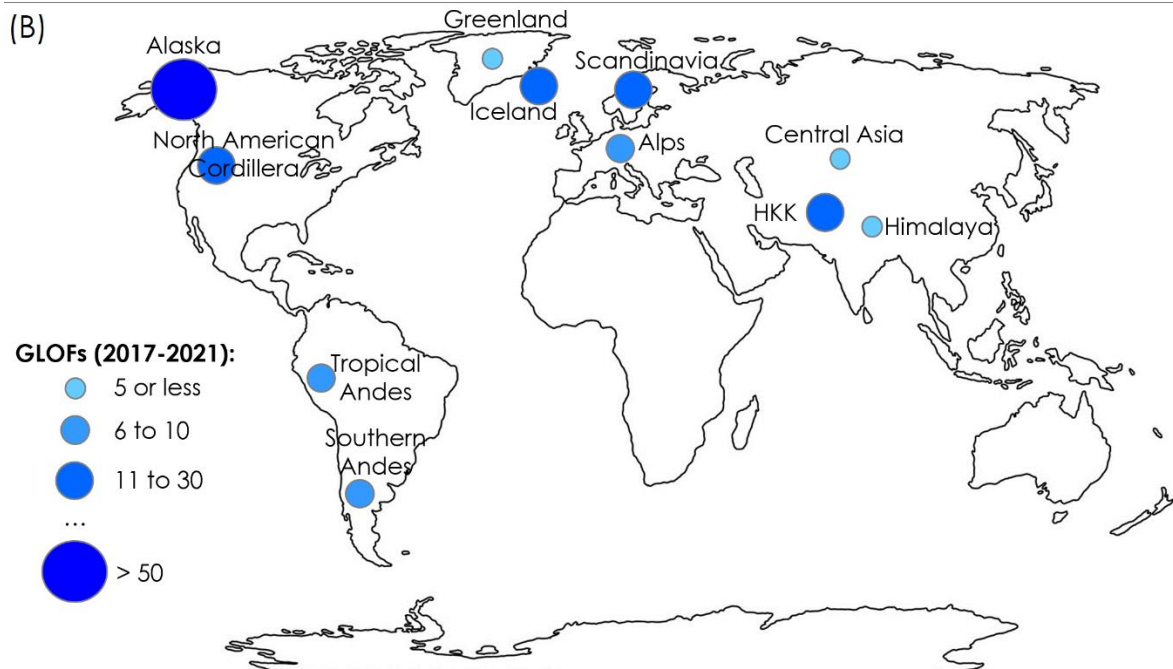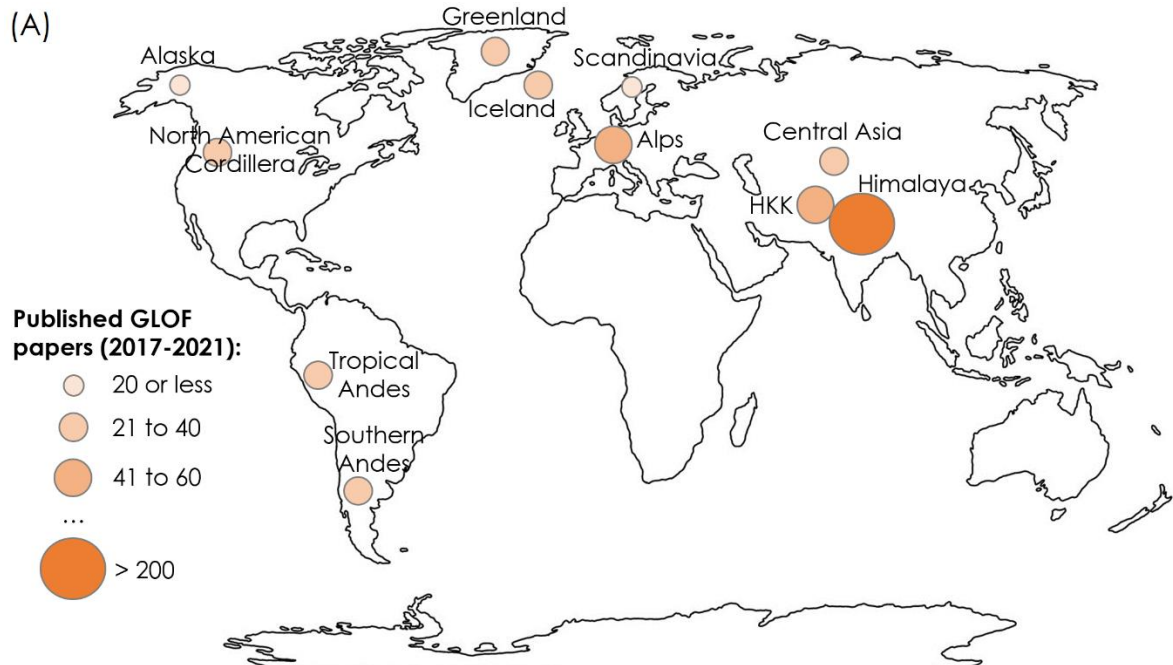
The word cloud analysis is a visual representation of the most frequent words in the abstracts and titles of 570 594 analysed
GLOF papers (see Fig. 2). We grouped these most frequent words into thematic clusters: (i) glacier-related words; (ii) lake-

and GLOF-related words; (iii) system- and change/dynamics related words; (iv) data-, methods- and approach-related words; (v) scale-related words; and (vi) geographic names. Clearly, some of the recurring words may be assigned to more than one cluster (e.g., retreat* can be interpreted as a glacier-related word as well as a system- and change-dynamics related word) and are, therefore, marked in two colours in Fig. 2.

185 The most frequent words are related to lakes, floods and glaciers in both word clouds. Words related to data, methods and approaches (e.g., *model\**, *hazard(s)*, *assessment(s)*, *inventory* and *risk(s)*) confirmed the interest in lake and GLOF inventorying, hazard (susceptibility, risk) assessments (Frey et al., 2018; Wang et al., 2018; Schmidt et al., 2020) and modelling of GLOFs (both back calculations and predictive; e.g., Kougkoulos et al., 2018a; Mergili et al., 2018a, 2020; Sattar et al., 2019a,b). However, studies addressing vulnerabilities to GLOFs are still rare (only mentioned in eleven abstracts and three

190 titles; e.g., Ghosh et al., 2019), while flood vulnerabilit~~y~~ies studies focusing on mountain environments in general are more common (e.g., Papathoma-Köhle et al., 2022).

The scale of GLOF studies varies from *valley*-, *river*-, *basin*-, *mountain range*- to *region*-wide, while global studies are less frequent (e.g., Harrison et al., 2018; Shugar et al., 2020). The word clouds of titles also indicate a geographical focus with dominant occurrence of *Himalaya\** (1~~130~~13~~09~~ titles, i.e. 19.0~~1~~% of all), followed by *Peru, Andes, Nepal, India, Asia* and

195 *Greenland* (see Fig. 2). Within the system- and change-dynamics cluster, words such as *evolution* and *dynamics* are among the most frequently occurring, mostly referring to dynamics of glacier retreat and associated lake evolution (e.g., Aggarwal et al., 2017; Kumar et al., 2020), though they allow for broader interpretations. Both word clouds contain *climate* and *change(s)*, illustrating the overarching storyline of many GLOF studies (Harrison et al., 2018; Zheng et al., 2021c). Word cloud analysis also showed decreasing use of the word *jökulhlaup(s)* (i.e. subglacial volcanic activity-induced floods) in recent years. While

200 up to 83.3% of published GLOF papers in 2000 – 2004 period included this keyword, this share decreased to 47.2% in the 2010 – 2015 period and to less than 25% in 2017 – 2021 period (with ~~11.9~~12.3% share in 2021). This trend could indicate proportionally less focus on subglacial volcanic activity-induced floods compared to other GLOF triggers and mechanisms, proportionally less focus on Iceland (Emmer, 2018), or a change in terminology towards the use of the more general term 'GLOF'.

205 **Fig. 2: Word clouds of abstracts (A) and titles (B) of GLOF papers. The size of individual words indicates frequency of occurrence while the background color groups individual words to thematic clusters. The 50 most frequently occurring words are shown in both word clouds.**

Fig. 3: Geographical focus of published GLOF papers (A), and reported GLOFs which happened from 2017 to 2021 (B) (data from Veh et al. (2022) in May 2022; HKK = Hindu Kush & Karakoram).

**3.3 Geographical focus**

Following previously observed trends (Emmer, 2018), a prominent hotspot of GLOF research in 2017-2021 has been in the Himalaya (HKH) – a total of 20154 papers (356.82% of all) focus on this region, far exceeding the number of studies focusing on any other region (Fig. 3A). About 10% of GLOF studies focus on the European Alps, followed by Hindu Kush-Karakoram, Tropical Andes, Iceland, Southern Andes, North-American Cordillera and Central Asia. The least studies focus on Scandinavia and Alaska. This observation is in strong contrast with the number of reported GLOFs, which show most GLOFs have occurred in Alaska (Veh et al., 2022; Fig. 3B). Hence, the geographical focus of research appears to be driven by potential societal impacts and relevance of GLOFs and the size of these mountain regions, rather than the physical GLOF processes themselves.

(A)

Greenland
Alaska
Scandinavia
Iceland
Alps
Central Asia
North American
Cordillera
HKK    Himalaya

**Published GLOF
papers (2017-2021):**
○ 20 or less
○ 21 to 40
○ 41 to 60
...
⬤ > 200

Tropical
Andes
Southern
Andes

(B)

Greenland
Alaska
Scandinavia
Iceland
Alps
Central Asia
North American
Cordillera
HKK    Himalaya

**GLOFs (2017-2021):**
○ 5 or less
○ 6 to 10
⬤ 11 to 30
...
⬤ > 50

Tropical
Andes
Southern
Andes

220

Tens of individual GLOF events have been reported since 2017 in different parts of the world including Hindu Kush –
Karakoram – Himalaya (Byers et al., 2018; Yin et al., 2019; Khan et al., 2021; Maharjan et al., 2021; Muhammad et al., 2021),

Tien-Shan (Dayirov and Narama, 2020), Tibetan Plateau (Zheng et al., 2021b), Tropical Andes (Vilca et al., 2021; Emmer et al., 2022), Southern Andes (Anyia et al., 2020; Vandekerkhove et al., 2021), ~~the~~ European Alps (Troilo, 2021; Ogier et al., 2021; Stefaniak et al., 2021); Alaska (Kienholz et al., 2020; Abdel-Fattah et al., 2021), ~~mountain ranges of~~ British Columbia (Geertsema et al., 2022), Greenland (Tomczyk et al., 2021) and Scandinavia (Andreassen et al., 2022). Recently, Veh et al. (2022) compiled globally by far the most complete GLOF inventory (total of >2,800 GLOFs ~~in~~ until March 2022; available from: http://glofs.geoecology.uni-potsdam.de). This compilation shows that most of the recent GLOFs have been documented in Alaska, followed by Iceland, Scandinavia (mainly Norway), the North American Cordillera and the Hindu Kush – Karakoram (Fig. 3B). Most of these GLOFs originated from ice-dammed lakes whereas GLOFs from other lake types (moraine- or bedrock-dammed) are less frequent, partly owing to the recurrence of multiple GLOFs from individual ice-dammed lakes. Repeated GLOFs from ice-dammed lakes were documented for the Karakoram (e.g. Yin et al., 2019; Khan et al., 2021), Alaska (Kienholz et al., 2020; Abdel-Fattah et al., 2021), Southern Andes (Anyia et al., 2020; Correas-Gonzalez et al., 2020; Vandekerkhove et al., 2021), and the European Alps (Stefaniak et al., 2021).

## 3.4 Authors of GLOF papers and international cooperation

The ~~570~~ 594 GLOF papers were published by a total of 2,173~~1,960~~ authors, resulting in an average of about ~~three~~ 3.7 authors per paper. However, ~~out of these 1,960 authors,~~ a total of ~~449~~ 455 researchers published more than one GLOF paper each, ~~59~~ 61 researchers published five or more papers each and ~~10~~ 11 researchers published ten or more papers each. The most productive ~~10~~ 11 researchers published together about one fifth of all papers while the most productive ~~59~~ 61 authors (~~3.0~~2.8% of all) published all together almost two fifths of all papers. Noticeably, these papers are frequently characterized by above-average citations per year, indicating influence of a relatively small group of researchers in determining the progress direction of this growing research field.

Most GLOF papers are written by a group of co-authors, while only 4.~~7~~9% are single-authored (Fig. 1B). Compared to the previous period 1970 – 2016 analysed by Emmer (2018), this share decreased from 16.4% and is further expected to decrease considering the general declining trend in publishing single-author papers (Emmer, 2019). A GLOF paper is written by 5.0~~75~~ co-authors on average. However, a tendency towards more co-authors involved in GLOF papers is observed (Fig. 1C). While on average 3.49 co-authors were involved in a GLOF paper in 1970 – 2016 (Emmer, 2018), on average 4.89 co-authors were involved in a GLOF paper published in 2017, this increased up to on average 5.~~25~~29 co-authors among GLOF papers published in 2021, possibly indicating (i) more complexity (and more interdisciplinarity) in GLOF papers being published or (ii) influence of research performance assessments (further strengthened by journal marketing), which account number of published papers but do not take into account the number of researchers involved. Figure 1B also reveals that the share of GLOF papers written by international research teams oscillates around 30%, which is comparable to the previous period (29.1%; Emmer, 2018).

According to the WOS Core Collection Database, a total of 7876 unique institutes located in 58 countries published their GLOF research from 2017 to 2021. GLOF research was dominated by researchers affiliated with institutes located in the USA (one in four papers co-authored), followed by China (one in five papers), England, India (one in six papers each) and Switzerland (one in eight papers). Authors affiliated with institutes in these five countries all together produced about 70% of GLOF papers. Researchers from five other countries (Germany, Canada, Czechia, Norway and Pakistan) contributed to > 5% of GLOF papers each. Thirty top-productive institutes contributed to ten or more GLOF papers each. A nearly identical geographical pattern is observed also among the papers covered by the Scopus database.

Importantly The share of papers (co-)authored by researchers from countries in High Mountain Asia (India, Nepal, Bhutan, Pakistan, Kazakhstan, Kyrgyzstan, Uzbekistan) is oscillating between 23% (2020) and 31% (2019; Fig. 1D), However, we observe a clearly continuing increasing trend of publications written (co-)authored by local researchers in some of these countries on a longer timescale. While the share of Himalaya-focusing papers written by local researchers was about 15% in late 1990s, it increased to > 30% share in 2000s (+another 20% published by international teams including local researchers) and > 40% share in early 2010s (+another 15% published by international teams including local researchers; Emmer, 2018). Our study reveals that > 60% of India-focusing GLOF papers published in 2017 – 2021 were written by researchers affiliated with institutions based in India, another 20% of papers were published by international teams including Indian researchers while remaining < 20% of India-focusing papers were written by foreign researchers (without the involvement of local researchers). This is important progress because studies done by local researchers are by default often very close to government actions on disaster risk reduction and climate adaptation (see also Section 4.6). Similarly, an increasing research attention to GLOFs has been paid by local researchers in Pakistan. The number of papers (co-)authored by Pakistani researchers in 2021 (n = 15) is equal to the cumulative number of papers published by local researchers in the previous four years (2017 to 2020). In contrast, the slightly increasing or stagnant involvement of local researchers in Central Asia (e.g. Kyrgyzstan) corresponds with the overall increase of published papers but suggests no trend or even a decrease in share.

**4 Trends, challenges, emerging directions and ways forward: results from the 2021 GLOF conference ad workshop**

During the GLOF conference and workshop held in July 2021, we identified and discussed trends, challenges and proposed ways forward in four thematic areas of GLOF research, which we designed based on the analysis of published GLOF papers (see Section 3.2): (i) understanding GLOFs – timing and processes; (ii) modelling GLOFs and GLOF process chains; (iii) GLOF risk management, prevention and warning; and (iv) human dimensions of GLOFs and GLOF attribution to climate change. The key outcomes of these discussions are summarized in Tab les 2 to 5. Further, we elaborate in detail on the main issues which resonated in our discussions (Sections 4.1 to 4.7). We admit that this list may be far from exhaustive; instead, we rather interpret this section as GLOF research community perspectives on the current state of GLOF research.

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Tab. 2: The summary of the key topics discussed during the first GLOF conference and workshop, observed trends, identified challenges and proposed ways forward.

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|---|
| **1) Understanding GLOFs – timing and processes** |
| Observed trends and progress: |
| - Building regional to global lake inventories, including identification of future lake (see Section 4.1) and GLOF inventories (see Sections 3.3 and 4.1)<br>- Efforts towards better understanding of GLOF preconditions and triggers (see Section 4.2) |
| Identified challenges: |
| - Understanding lagged response of glaciers and glacial lakes to climate change signal (Harrison et al., 2018); distinguishing GLOFs associated with climate change (see also attribution part)<br>- Selecting and validating GLOF susceptibility indicators relevant for given geographical context (Kougkoulos et al., 2018b) |
| Proposed ways forward: |
| - Linking glacier behavior with GLOF occurrence in space and time (and triggers-oriented GLOF understanding and hazard assessment in general)<br>- Revision and data-driven analysis of assumed GLOF susceptibility indicators  such as rapid lake growth (Fischer et al., 2021) or earthquake GLOF triggering (Wood et al., in review)  building on recently enhanced GLOF inventories |
| **2) Modelling GLOFs and GLOF process chains** |
| Observed trends and progress: |
| - Substantial progress in understanding the physics of the underlying processes of GLOF initiation and propagation (see Section 4.3) such as multi-phase flows, landslide-lake interactions, entrainment and deposition, or phase separation in debris flows (Pudasaini, 2012, 2020; Pudasaini and Fischer, 2020a,b; Pudasaini and Krautblatter, 2021)<br>- The inclination towards integrated GLOF process chain simulations (Mergili et al., 2017; Mergili and Pudasaini, 2021) and an advancement of full 3D models capable of reproducing the relevant phenomena in a realistic way (Gaume et al., 2018; Cicoira et al., 2021) |
| Identified challenges: |

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|---|
| - Obtaining (in situ) parameters required by the model (e.g., breach parameters, lake bathymetry) and addressing their uncertainties (e.g., Schaub et al., 2016; Mergili et al., 2018b, 2020; Sattar et al., 2020); see Section 4.4) |
| - Defining realistic GLOF scenarios in predictive GLOF modelling, accounting also for future environmental conditions (e.g., Worni et al., 2013, 2014; GAPHAZ, 2017; Sattar et al., 2021; Zheng et al., 2021c) |

Proposed ways forward:

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|---|
| - Extending a set of detail-modelled events in order to obtain a plausible range of parameters for predictive modelling (e.g., Mergili et al., 2018a,b, 2020) |
| - Improving availability of high-performance computers will facilitate the use of full 3D models (Gaume et al., 2018; Cicoira et al., 2021), which are currently limited by computational demands, towards operational use |

**3) GLOF risk management, prevention and warning**

Observed trends and progress:

| |
|---|
| - Unbalanced research focus on individual GLOF risk components (research of GLOF hazard still outweighs research on GLOF vulnerability and exposure, at least among the papers covered by the WOS and Scopus databases (Emmer, 2018), with relatively few integrated or holistic GLOF studies (Carey et al., 2012; Drenkhan et al., 2019, Motschmann et al., 2020b) |
| - Increased exposure to GLOFs across some regions in past decades due to tourism (e.g., Iceland and Peru; Matti et al., 2022a) as well as rapid and often unregulated development in GLOF-prone areas (e.g., in India and Peru; Schwanghart et al., 2016; Huggel et al., 2020a; Carey et al., 2021) |

Identified challenges:

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|---|
| - Identification of overlooked or underestimated GLOF risk drivers and their consideration in GLOF risk management<br>- Research often does not lead to tangible actions, partly because research projects often bypass decision-making stakeholders. Scientific studies are often not well connected to the applied works of practitioners.<br>- Ever growing number of lake hazard/risk assessment schemes, with different scopes (susceptibility, hazard, risk assessment) and approaches. For decision makers, differing results and contradicting information on "potentially dangerous lakes" are difficult to interpret.<br>- Design and implementation of GLOF risk reduction measures and their acceptance by hazard exposed communities (see also Section 4.5) |

Proposed ways forward:

- Interdisciplinary cooperation in GLOF research, consideration of diverse dimensions and drivers of GLOF risk beyond traditional GLOF hazard studies (see Section 4.5), connecting natural and social science communities (see Huggel et al., 2020; Carey et al., 2021; Drenkhan et al., 2019; Motschmann et al., 2020b)

- Combine disaster risk and water management under a framework of prospective lake water management with adaptive disaster risk planning considering synergies and conflicts of GLOF risk reduction measures with human water use (Haeberli and Drenkhan, 2022; Motschmann et al., 2020b)

- Work with local communities, decision makers and stakeholders and their involvement in GLOF risk analysis process from the beginning (knowledge co-production, experience exchange, bottom-up and community-centered approaches; see Thompson et al. 2020; Matti and Ögmundardóttir 2021; Haeberli and Drenkhan, 2022; and Section 4.6)
- Use a consensus-based approach to identify high priority lakes for risk management, drawing across the full range of published GLOF hazard and risk studies in any given region (e.g., Mal et al. 2021)

**4) Human dimensions of GLOFs and attribution to anthropogenic climate change**

Observed trends and progress:

- Human dimensions are generally underrepresented in GLOF papers covered by WOS and Scopus databases, partially reflecting on publishing paradigm of individual disciplines (for instance, a tendency towards publishing books in social science domain)

- Recently increased focus on GLOF attribution to (anthropogenic) climate change (see Section 4.7), with natural scientists generally driving this research and only at times involving social science or humanities researchers (Harrison et al., 2018; Huggel et al., 2020a; Stuart-Smith et al., 2021)

Identified challenges:

- Better consideration and appreciation of cultural and spiritual values of glacier lakes and high mountain environments, and local and indigenous knowledges in GLOF research (Lambert and Scott, 2019; Abdel Fattah et al., 2021; Matti and Ögmundardóttir 2021; Haeberli and Drenkhan, 2022)

- More sustained, detailed work needed to understand diverse and intersecting drivers of risk and vulnerability in communities (Matti et al. 2022b; see Section 4.6), to reveal how societal variables making diverse populations vulnerable overall intertwine with GLOF risks (Carey et al., 2020)

- The politics and cultures of GLOF risk management and responses are only partially understood and analysed (Moulton et al., 2021)

- Linking GLOF occurrence patterns with anthropogenic climate change signal (Roe et al., 2021; see Section 4.7)

## 4.1 Recent progress in lake and GLOF inventories

A pronounced trend in understanding the occurrence of GLOFs from the large-scale perspective (mountain ranges, large regions) is the building of updated GLOF inventories, typically revealing incompleteness of existing GLOF records (Tab. 2). Recent examples are GLOF inventories from Iceland and Greenland (Carrivick and Tweed, 2019), Tropical Andes (Emmer, 2017; Bat'ka et al., 2020; Emmer et al., 2022), Patagonia (e.g. Jacquet et al., 2017) and High Mountain Asia (~~; Emmer, 2017; Carrivick and Tweed, 2019;~~ Nie et al., 2018; Veh et al., 2019; ~~Bat'ka et al., 2020;~~ Zheng et al., 2021a~~; Emmer et al., 2022~~). This trend is associated with increasing availability and resolution of satellite images (Kirschbaum et al., 2019; Taylor et al., 2021), allowing detailed analysis of persistent geomorphic GLOF diagnostic features, both in a manual as well as in a semi-automatic way (Veh et al., 2018). Geomorphic GLOF diagnostic features are frequently combined with analysis of documentary data sources (Emmer, 2017; Nie et al., 2018). More comprehensive GLOF inventories are essential for better understanding frequency of GLOF occurrence in changing mountain environments (Veh et al., 2019; Emmer et al., 2020), for revealing frequency-magnitude relationships (Hewitt, 1982; Haeberli, 1983), as well as for GLOF attribution to anthropogenic climate change (Harrison et al., 2018; see also Section 4.7).

**Tab. 2: The summary of the key topics, observed trends, identified challenges and proposed ways forward in thematic area Understanding GLOFs – timing and processes.**

Observed trends and progress:

·   Building regional to global lake inventories, including identification of future lake (see Section 4.1) and GLOF inventories (see Sections 3.3 and 4.1)
·   Efforts towards better understanding of GLOF preconditions and triggers (see Section 4.2)

Identified challenges:

| |
|---|
| ·   Understanding lagged response of glaciers and glacial lakes to climate change signal (Harrison et al., 2018); distinguishing GLOFs associated with climate change (see also attribution part)<br>·   Selecting and validating GLOF susceptibility indicators relevant for given geographical context (Kougkoulos et al., 2018b) |
| Proposed ways forward: |
| ·   Linking glacier behavior with GLOF occurrence in space and time (and triggers-oriented GLOF understanding and hazard assessment in general)<br>·   Revision and data-driven analysis of assumed GLOF susceptibility indicators–such as rapid lake growth (Fischer et al., 2021) or earthquake GLOF triggering (Wood et al., in prep.)--building on recently enhanced GLOF inventories |

On a global scale, Carrivick and Tweed (2016) observed increased GLOF frequency until the 1990s, followed by a decrease in most mountain regions. The reasons for this trend, however, remained unclear. Harrison et al. (2018) observed a similar
305   trend in outbursts from moraine-dammed lakes, possibly because of a lagged response of GLOF occurrence to climate forcing, glacier retreat, and lake formation, a concept further elaborated in the Peruvian Cordillera Blanca (Emmer et al., 2020). However, the number of GLOFs recorded may be underestimated in some regions because of low research activitymonitoring. For example, Veh et al. (2019) produced an updated GLOF inventory for the Himalayas where they observed no change in GLOF frequency since the 1980s (considering moraine-dammed lakes only). Emmer et al. (2022) prepared and updated GLOF
310   inventory for the Tropical Andes of Peru and Bolivia, where they observed an increasing occurrence of low-magnitude GLOFs in recent decades. This trend is lake type-specific (dominance of GLOFs from bedrock-dammed lakes, reflecting later stages of deglaciation in the Tropical Andes) and may also be biased by decreasing amount and availability of remote sensed and documentary data, and vanishing geomorphological GLOF imprints of events further back in time (Emmer et al., 2022). Most recently, Veh et al. (2022) compiled an open accessa global inventory of >2,800 GLOFs (http://glofs.geoecology.uni-
315   potsdam.de/) and observed a flatter trend in GLOF occurrence since the 1970s.

An emerging trend in GLOF research is tied with the identification of locations suitable for future lake formation. Considering sustained glacier retreat under different Representative Concentration Pathways or complete deglaciation, several recent studies have attempted to locate potential future lakes and quantify their volumes, for instance in the Swiss Alps (Gharehchahi et al. 2020), in the Austrian Alps (Otto et al., 2021), in High Mountain Asia (Furian et al., 2021; Zheng et al., 2021c), and on
320   the global scale (Frey et al., 2019). Recent progress also highlights the needs to consider the impacts of increasing sedimentation on future glacial lakes under a changing climate (Li et al., 2021; Steffen et al., 2022).

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## 4.2 GLOF triggers and GLOF susceptibility indicators

A remaining issue is the appropriate selection of GLOF susceptibility indicators in regional GLOF susceptibility and hazard assessment studies (Tab. 2). Kougkoulos et al. (2018b) identified 79 different GLOF indicators in previous studies. The selection of GLOF susceptibility indicators frequently relies on an expert-based analytical hierarchy process (AHP) with subjectively defined or adopted thresholds (e.g., Aggarwal et al., 2017; Muneeb et al., 2021; Rinzin et al., 2021), while statistic-based studies building on rigorous analysis of previous GLOFs are rare (McKillop and Clague, 2007a,b; Fischer et al., 2021). For a given lake, characterising the current conditions and those prior to outburst remains challenging, highlighting the need for comprehensive regional lake inventories and lake evolution studies (Petrov et al., 2017; Buckel et al., 2018; Wilson et al., 2018; ~~Bat'ka et al., 2020; Shugar et al., 2020;~~ Zhang et al., 2019; How et al., 2021; Lindgren et al., 2021; Mölg et al., 2021; Wood et al., 2021; Andreassen et al., 2022;), global lake inventories (Shugar et al., 2020), ~~and~~ regional GLOF inventories (e.g. ; Bat'ka et al., 2020; ~~Petrov et al., 2017; Buckel et al., 2018; Wilson et al., 2018; Bat'ka et al., 2020; Shugar et al., 2020; How et al., 2021; Lindgren et al., 2021; Mölg et al., 2021; Wood et al., 2021; Andreassen et al., 2022;~~ Emmer et al., 2022) and global GLOF inventories~~;~~ (Veh et al., 2022). Recent research efforts revealed that some of the broadly accepted indicators of GLOF susceptibility assessments may have ambiguous roles. An example is the control of earthquakes in triggering GLOFs. While numerous GLOF susceptibility assessment studies consider earthquakes as possible triggers of GLOFs, recent studies showed that very few GLOFs have been actually triggered by earthquakes globally (Kargel et al., 2016; Wood et al., in prep). Another example is rapid lake growth, which is also frequently used as GLOF susceptibility indicator (see the overview of Kougkoulos et al., 2018b); however, Fischer et al. (2021) showed that this characteristic may not be an indicator of GLOF occurrence in the Himalaya.

On local scale, a recent trend goes toward better understanding of controls, preconditions, triggers of, and interactions during individual GLOFs (Carrivick et al., 2017; Blauvelt et al., 2020; Vilca et al., 2021), considering also the role of climate and climate change (Zheng et al., 2021b). Numerous studies describe, analyse and model not only the hydrodynamics and geomorphological imprints of GLOFs (e.g. Clague and Evans, 2000; Emmer, 2017; Jacquet et al., 2017), but also assess pre-GLOF conditions, hazard drivers (climatological, glaciological, geological), and elucidate plausible GLOF scenarios (e.g., Carrivick et al., 2017; Mergili et al., 2020; Klimeš et al., 2021; Zheng et al., 2021b; Emmer et al., 2020, 2022).

Importantly, a proper terminology should be maintained among researchers and also among disaster risk reduction practitioners and authorities in order to avoid misinterpretation of individual events. Many mass flow events are often immediately termed as GLOFs, because GLOFs have ~~gotten~~ received ~~so much~~ major attention recently. An example is an early interpretation of the 2021 Chamoli disaster, which was shortly after it happened described as GLOF by some (e.g. https://indianexpress.com/article/explained/uttarakhand-glacier-flash-flood-rishiganga-death-toll-7180258/). However, detailed analysis revealed that it originated as rock and ice avalanche and no lake was involved in the process chain propagation (Shugar et al., 2021).

### 4.3 Two decades of GLOF modelling

355  Simulations of GLOF process chains have been performed since the early 2000s and at least three stages of research evolution can be distinguished:

1. Relatively simple empirical mass point models such as MSF (Huggel et al., 2003, 2004), mainly suited for regional-scale applications, and still applied more recently at such scales (r.randomwalk and its predecessors: Gruber and Mergili, 2013; Mergili et al. 2015).

360  2. More advanced model chains, applying tailored physically-based simulation tools for each component of the process chain and coupling them at the process boundaries (Schneider et al., 2014; Worni et al., 2014; Schaub et al., 2016).

3. With the emergence of two-phase (Pudasaini, 2012) and later three-phase (Pudasaini and Mergili, 2019) mass flow models and related simulation tools (Mergili et al., 2017; Mergili and Pudasaini, 2021), the trend has moved towards integrated simulations, considering the entire GLOF process chain in one single simulation step.

365  We now mainly focus on the latest stage, the integrated modelling of GLOF process chains, and identify three main lines of challenges: (i) defining GLOF scenarios; (ii) exploring the field of tension between the physical details and practical applicability of the available simulation tools; and (iii) moving from successful back-calculations to reliable future predictions. With regard to GLOF scenarios, it is often the worst-case scenarios ~~which~~ that are most relevant for informing risk management. However, the decision on what are realistic worst-case scenarios for specified time horizons, and what are 370  unrealistically apocalyptic assumptions, is sometimes disputed.

With regard to modelling the dynamics of GLOFs, we note recent progress in the underlying physical processes during lake outbursts, such as multi-phase flows, landslide-lake interactions, entrainment and deposition of sediments, or phase separation in debris flows (Pudasaini, 2020; Pudasaini and Fischer, 2020a,b; Pudasaini and Krautblatter, 2021). Also, the prevailing depth-averaged models are challenged by machine learning techniques and full 3D models, which are able to reproduce the 375  studied phenomena in a highly realistic way (Gaume et al., 2018), but are still computationally too demanding for operational application on complex, long-runout process chains – a situation which might improve in the coming years and decades (Tab. 3).

**Tab. 3: The summary of the key topics, observed trends, identified challenges and proposed ways forward in thematic area Modelling GLOFs and GLOF process chains.**

Observed trends and progress:

| |
|---|
| · Substantial progress in understanding the physics of the underlying processes of GLOF initiation and propagation (see Section 4.3) such as multi-phase flows, landslide-lake interactions, entrainment and deposition, or phase separation in debris flows (Pudasaini, 2012, 2020; Pudasaini and Fischer, 2020a,b; Pudasaini and Krautblatter, 2021) <br> · The inclination towards integrated GLOF process chain simulations (Mergili et al., 2017; Mergili and Pudasaini, 2021) and an advancement of full 3D models capable of reproducing the relevant phenomena in a realistic way (Gaume et al., 2018; Cicoira et al., 2021) |
| Identified challenges: |
| · Obtaining (in situ) parameters required by the model (e.g., breach parameters, lake bathymetry) and addressing their uncertainties (e.g., Schaub et al., 2016; Mergili et al., 2018b, 2020; Sattar et al., 2020); see Section 4.4) <br> · Defining realistic GLOF scenarios in predictive GLOF modelling, accounting also for future environmental conditions (e.g., Worni et al., 2013, 2014; GAPHAZ, 2017; Sattar et al., 2021; Zheng et al., 2021c) |
| Proposed ways forward: |
| · Extending a set of detail-modelled events in order to obtain a plausible range of parameters for predictive modelling (e.g., Mergili et al., 2018a,b, 2020) <br> · Improving availability of high-performance computers will facilitate the use of full 3D models (Gaume et al., 2018; Cicoira et al., 2021), which are currently limited by computational demands, towards operational use |

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## 4.4 Required but hard-to-obtain modelling parameters

A particular challenge is the dependence of advanced physically based models on unknown parameters required for modelling erosion and deposition (Pudasaini and Fischer, 2020a; Pudasaini and Krautblatter, 2021; Tab. 3). In the physically based models, it is mainly the difference between the mechanical properties of the flow and those of the basal surface which

385 determines whether erosion or deposition of solid material occurs, resulting in an extremely high sensitivity of the model results on barely known material properties. Even though such models have been implemented at least in semi-operational software tools such as r.avaflow (Mergili and Pudasaini, 2021), practitioners still prefer models which are more straightforward to parameterize, and where guiding parameter values for different processes and process magnitudes are available.

Such guiding parameter values would be extremely valuable for predictive simulations of future GLOF scenarios, but in

390 contrast to "ordinary" debris flows or snow avalanches, which occur at much higher frequency, they are not yet available for GLOF process chains. While several such cascades have been successfully back-calculated in the last years (Mergili et al., 2018, 2020; Vilca et al., 2021; Zheng et al., 2021), predicting future GLOF process chains remains a major challenge – not

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only in terms of defining scenarios of lake growth or volumes of possibly impacting landslides, but also in defining appropriate sets of model parameters.

With the growing need for hazard assessments in areas with limited access, where potential GLOF exposure in the downstream regions is high (Allen et al., 2016, 2019;; Schwanghart et al.,2016; Allen et al., 2019), predictive GLOF modelling serves a purpose (e.g., Sattar et al., 2019; 2021). However, such modelling demands prior evaluation of the breach parameters such as breach depth, width, and the breach formation time. These parameters are difficult to estimate and depend on multiple factors such as the nature of the damming material, the trigger event (e.g., avalanche, landslide, internal moraine failures), nature of the impact wave, freeboard of the lake and lake bathymetry. Therefore, one must rely on empirical methods or scenarios definition as alternatives to determine these parameters exactly. Although numerous empirical approaches have been developed to calculate the breaching parameters (MacDonald and Langridge-Monopolis, 1984; Costa, 1985; Bureau of Reclamation, 1988; Von Thun and Gillette, 1990; Froehlich, 1995), a consensus on their suitability for glacial lakes has not yet been established. With the advancement of numerical modelling approaches where GLOF process chains can be efficiently modelled (e.g., r.avaflow) these parametric uncertainties of moraine breach can be minimized as breaching would depend on the kinetic energy over the entrainable material (moraine in this case) of the modelled GLOF process chain.

### 4.5 GLOFs and human dimension contexts

Given the community diversity and range of disciplines among GLOF researchers as well as the broad range of local and Indigenous knowledges, there is a wide variety of methods, questions, motivations, objectives, and framings around the GLOF problem itself. Indigenous communities may have their own knowledge about glacial lakes, and put their knowledge into larger histories of colonialism, dispossession, and racism, not to mention into larger reciprocal interactions between a fluid human and non-human world. Natural scientists work to understand physical drivers of GLOFs and predict their impacts. Social scientists often hope their research can contribute to local empowerment, community sovereignty, self-determination, and environmental justice, which significantly transcend analyses of the water flowing downstream from, for example, an overtopped moraine dam. It is important to recognize and discuss these different underlying goals that influence not just research questions but also methodological approaches to the research and larger politics of knowledge systems. GLOF research now increasingly recognizes the need to work with communities, co-produce knowledge, and co-manage landscapes. At the same time, there is perhaps not enough attention to the ways in which different researchers and stakeholders fundamentally define the GLOF problem differently from the outset.

Given the existing research gaps around the human dimensions of GLOFs and the pressing need for future studies to address attribution of GLOFs (Tab. 4), there are three key emerging trends in GLOF research that could be productively engaged and expanded: (i) GLOF contexts, particularly for people living near glaciers; (ii) GLOF governance and the broadening of stakeholders involved in GLOF prevention, risk reduction, and management; and (iii) better understandings of GLOF

attribution, to pinpoint whether anthropogenic climate change affects GLOF risk and to explore how different social groups

425 understand cause-effect related to GLOFs.

**Tab. 4: The summary of the key topics, observed trends, identified challenges and proposed ways forward in thematic area Human dimensions of GLOFs and attribution to anthropogenic climate change.**

| Observed trends and progress: |
|---|
| ·    Human dimensions are generally underrepresented in GLOF papers covered by WOS and Scopus databases, partially reflecting on publishing paradigm of individual disciplines (for instance, a tendency towards publishing books in social science domain)<br><br>·    Recently increased focus on GLOF attribution to (anthropogenic) climate change (see Section 4.7), with natural scientists generally driving this research and only at times involving social science or humanities researchers (Harrison et al., 2018; Huggel et al., 2020a; Stuart-Smith et al., 2021) |
| Identified challenges: |
| ·    Better consideration and appreciation of cultural and spiritual values of glacier lakes and high-mountain environments, and local and indigenous knowledges in GLOF research (Lambert and Scott, 2019; Abdel-Fattah et al., 2021; Matti and Ögmundardóttir 2021; Haeberli and Drenkhan, 2022)<br><br>·    More sustained, detailed work needed to understand diverse and intersecting drivers of risk and vulnerabilities in communities (Matti et al. 2022b; see Section 4.6), to reveal how societal variables making diverse populations vulnerable overall intertwine with GLOF risks (Carey et al., 2020)<br><br>·    The politics and cultures of GLOF risk management and responses are only partially understood and analysed (Moulton et al., 2021)<br><br>·    Linking GLOF occurrence patterns with anthropogenic climate change signal (Roe et al., 2021; see Section 4.7) |
| Proposed ways forward: |
| ·    Recognition and empowerment of (often powerful) local communities and indigenous knowledges (Mercer et al., 2010; Kelman et al., 2012; Carey et al., 2021; see Section 4.6), avoid research colonialism (come, do research and leave) and involve local researchers<br><br>·    Employment of integrated, holistic, interdisciplinary approaches (Carey et al., 2012; Gall et al., 2015) and consideration of overlooked dimensions and aspects (e.g., spiritual and cultural), knowledge co-production and exchange<br><br>·    Development of robust methods (statistical methods and process-based models) for attributing GLOF occurrence and impacts to anthropogenic climate change (Stuart-Smith et al., 2021) |

First, local communities living near ice face multiple risks including, but also beyond, GLOFs, which implies that GLOF risk
430 needs to be seen in a more comprehensive social-environmental context. Long-standing research has shown that communities
exposed to GLOFs are diverse with respect to raceethnicity, class, gender, age, religion, education, language, geographical
location, and other socioeconomic variables specific to places and historical contexts (Gagné, 2019; Sherry et al., 2018;
Haverkamp, 2021; Carey, 2010). Mountain communities are often distant from cities and centers of power, making them
marginalized politically and neglected when it comes to infrastructure, hazard mitigation, government assistance, health care,
435 education, and economic investments. These factors increase the vulnerabilitiesy of mountain communities to GLOFs.

In many cases, mountain people have been subjected historically to intrusions by outsiders, from missionaries and mining
companies to tourists and national park administrators who can restrict local access to high-mountain spaces and resources.
Research thus shows that risk is distributed unequally across populations and that GLOFs are far from the only hazard
communities face (Matti and Ögmundardóttir 2021; Matti et al., 2022b). GLOF studies focusing on the human dimensions
440 must therefore recognize these other risks beyond the glaciers, from other geohazards such as earthquakes, floods and
landslides, through to food insecurity and misogyny to land loss, droughts, cold waves, and water contamination.

Yet it is also important to recognize that local communities downstream from glacial lakes are not simply victims; they do
more than just struggle against perpetual and widespread risks. Many have chosen historically to live outside hazard zones,
such as Peru's Indigenous communities around the Cordillera Blanca (Figueiredo et al., 2019). Others have migrated away
445 from regions exposed to GLOFs either in response to disasters in the Andes (Wrathall et al., 2014) or interpret risk through
community-specific conceptualizations and culture, as Sherry et al. (2018) examine below Nepal's glacial lake Tsho Rolpa.
Others understand that glacial lakes can generate floods, but they also deem lakes important for water storage, hydropower,
and tourism (Moulton et al. 2021; Matti et al. 2022b). Still, others maintain cultural and spiritual relations with glaciers, though
these have sometimes had to transform due to ice loss (Allison, 2015; Gagné, 2019). What is more, cosmology and religion
450 are important to understand with GLOFs because religious leaders are community leaders, and because state authority and
politics flow into communities through spiritual organizations and structures (Hovden and Havnevik, 2021). Given the
diversity of communities and experiences, it is crucial for GLOF researchers to analyse local populations in ways that
acknowledge this diversity without simply lumping all community members together, by recognizing the various contexts and
forces that influence people near glacial lakes.

455 **4.6 Participation, Management, and Governance of GLOFs**

Researchers increasingly recognize that local communities should be involved in GLOF studies, climate adaptation, and
disaster risk reduction policies and initiatives that could affect them and their region (Tab. 5). Examples show that even when
communities have been involved in, and supportive of, projects, conflicts can still emerge around GLOF prevention or other
glacier research. In Peru, for example, local residents have resisted hazard zoning policies to prevent construction inside

460 potential outburst flood paths. In another case, some local residents destroyed a GLOF early warning system at Laguna 513 (Huggel et al., 2020b), while others fought against glacier ice core research on Mount Huascarán, both sites located in the Cordillera Banca, Peru. In the Everest region, there was a disconnect between the local communities and the outside agencies regarding their priorities on cryospheric hazards and risks (Sherpa et al., 2019; Thompson et al 2020). These examples highlight the importance of building relationships with local communities and engaging them with research and adaptation planning

465 from an early stage.

**Tab. 5: The summary of the key topics, observed trends, identified challenges and proposed ways forward in thematic area GLOF risk management, prevention and warning.**

| Observed trends and progress: |
| --- |
| · Unbalanced research focus on individual GLOF risk components (research of GLOF hazard still outweighs research on GLOF vulnerabilities and exposure, at least among the papers covered by the WOS and Scopus databases (Emmer, 2018), with relatively few integrated or holistic GLOF studies (Carey et al., 2012; Drenkhan et al., 2019, Motschmann et al., 2020b) <br><br> · Increased exposure to GLOFs across some regions in past decades due to tourism (e.g., Iceland and Peru; Matti et al., 2022a) as well as rapid and often unregulated development in GLOF-prone areas (e.g., in India, Nepal and Peru; Schwanghart et al., 2016; Huggel et al., 2020a; Carey et al., 2021; Li et al., 2022) |
| Identified challenges: |
| · Identification of overlooked or underestimated GLOF risk drivers and their consideration in GLOF risk management <br> · Research often does not lead to tangible actions, partly because research projects often bypass decision-making stakeholders. Scientific studies are often not well connected to the applied works of practitioners. <br> · Ever-growing number of lake hazard/risk assessment schemes, with different scopes (susceptibility, hazard, risk assessment) and approaches. For decision-makers, differing results and contradicting information on "potentially dangerous lakes" are difficult to interpret. <br> · Design and implementation of GLOF risk reduction measures and their acceptance by hazard exposed communities (see also Section 4.5) |
| Proposed ways forward: |
| · Interdisciplinary cooperation in GLOF research, consideration of diverse dimensions and drivers of GLOF risk beyond traditional GLOF hazard studies (see Section 4.5), connecting natural and social science communities (see Huggel et al., 2020; Carey et al., 2021; Drenkhan et al., 2019; Motschmann et al., 2020b) |

· Combine disaster risk and water management under a framework of prospective lake water management with adaptive disaster risk planning considering synergies and conflicts of GLOF risk reduction measures with human water use (Haeberli and Drenkhan, 2022; Motschmann et al., 2020b)

· Work with local communities, decision-makers and stakeholders and their involvement in GLOF risk analysis process from the beginning (knowledge co-production, experience exchange, bottom-up and community-centered approaches; see Thompson et al. 2020; Matti and Ögmundardóttir 2021; Haeberli and Drenkhan, 2022; and Section 4.6)

- Use a consensus-based approach to identify high priority lakes for risk management, drawing across the full range of published GLOF hazard and risk studies in any given region (e.g., Mal et al. 2021)

Building trust with communities is key and implies a number of responsibilities, also for GLOF researchers, such as following community-driven processes and working toward co-production of knowledge and co-management of the projects. As Carey et al. (2020) note in their concept of "glacier justice", research should be driven by communities, include multiple forms of knowledge including local and Indigenous knowledges, and recognize diverse aspects of vulnerabilities for communities near glaciers. Haverkamp (2021) has examined glacier-related research and adaptation work in the Peruvian Andes to show that top-down, techno-scientific, and developmentalist approaches tend to drive outsiders' projects, thereby perpetuating a form of colonialism, intervention, or extraction. She thus calls for "adaptation otherwise" as an approach that works with and in support of highland communities so that glacier studies do not further marginalize and disempower them. The preparation of ethical guidelines for GLOF researchers working in places with communities might help to promote these efforts. Further insights are also available from other fields and environments; for instance, Holm et al. (2011) offer guidance for ethical research practices in Greenland, and explain that research should follow established institutional guidelines in the research country and the researcher's home country. It also includes partnerships with residents of the country and community, the sharing of results in the country and communities of research, and the need to help build scientific literacy and research expertise within the country and communities of research. Furthermore, Whyte (2020) calls for research that is guided fundamentally by consent, trust, accountability, and reciprocity with local communities, particularly indigenous people.

## 4.7 Attribution of GLOF events to anthropogenic climate change

A direction of interdisciplinary research that has gained considerable traction in recent years examines the multiple drivers of risks related to GLOF events. A particularly debated question is whether anthropogenic climate change causes GLOF hazards, and if so, to what extent (Tab. 4). Recent research has established clear causality from greenhouse gas emissions to glacier shrinkage, lake growth and formation and, possibly to GLOF hazard (Harrison et al., 2018; Huggel et al., 2020a; Stuart-Smith et al., 2021). This research now starts to inform climate litigation. The most prominent case internationally is currently being debated at a German court and is based on a claim of a citizen of Huaraz, Peru, who understand that the emissions of the

German energy company RWE have contributed to placing his home at risk of flooding from glacier lake Palcacocha. The case has not yet been decided but a court has admitted such a case to the evidentiary stage, implying that the defendant (RWE) will be held liable for the damage or risks at a place thousands kilometeres away if causality between their emissions and the (potential) damage can be established.

495 The fact that research can inform such climate litigation cases should not prevent from putting the issue at stake into a broader and more comprehensive perspective of responsibilities and justice. For the case of Lake Palacacocha, Huggel et al. (2020a) have analysed both climatic and non-climatic drivers of risk, including governance, social and economic conditions and development, or cultural traits that all strongly influence how people and values are exposed and vulnerable to GLOF hazards, and what type of local, national and global responsibilities are implied as a consequence.


500 **5 Concluding remarks and recommendations**

Our analysis of 570 594 GLOF papers published in 2017-2021 revealed that: (i) the amount of published GLOF papers experienced a sharp rise (+70110% more papers in 5 years) and the majority of these papers were published in journals indexed primarily under geoscientific categories; (ii) a relatively small group of researchers produced a substantially large amount of influential GLOF papers (3% of the most productive researchers contributed to 40% of GLOF papers); a similarly unbalanced
505 pattern is observed among countries and institutes involved in GLOF research; (iii) an average number of co-authors of a GLOF paper had gradually increased, possibly indicating more interdisciplinarity and complexity in GLOF research; (iv) detailed insights from Himalaya High Mountain Asia reveal gradually increasing share of publications written by local researchers in some of the countries (e.g. India, Pakistan), suggesting improved chances for the acceptance of research result and the implementation of appropriate disaster risk reduction measures; (v) a prominent hotspot of GLOF research is the
510 Himalaya region, while the majority of recent GLOFs are documented from repeated outbursts of ice-dammed lakes in Alaska, Karakoram, Iceland and Scandinavia, revealing a geographical discrepancy and potential societal impacts as driver of GLOF research; and (vi) a word cloud analysis tracked a trend towards linking GLOFs to changing climate and an upswing of modelling approaches; it also confirmed a lack of studies addressing vulnerabilityies and exposure to GLOFs.

Discussions and insights from the first global GLOF conference and workshop, with attendance of GLOF research community
515 members from all over the world and from various scientific background and career stages, allowed us to identify challenges and outline general recommendations for ways forward in GLOF research (see Tabs. 2 to 5). To navigate future GLOF research towards addressing identified challenges, we especially recommend: (i) to promote GLOF triggers-focusing analysis and hazard assessments, data-driven re-analysis of GLOF susceptibility indicators; (ii) to back-calculate relevant events in order to refine model parameters and define plausible sets of parameters for predictive modelling of potential future events; (iii) to
520 foster interdisciplinary cooperation, and the employment of integrated holistic approaches in GLOF research enabling the identification and consideration of diverse drivers, aspects and components of complex GLOF risk; and (iv) to support the

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involvement of local researchers, communities, decision-makers, authorities and other stakeholders promoting diverse knowledge co-production including local and indigenous knowledges, and experience exchange that are fundamental for the consideration, acceptance and utilization of GLOF research outcomes and improved future GLOF risk management.

**References:**

Abdel-Fattah, D., Trainor, S., Hood, E., Hock, R. and Kienholz, C.: User Engagement in Developing Use-Inspired Glacial Lake Outburst Flood Decision Support Tools in Juneau and the Kenai Peninsula, Alaska. Frontiers in Earth Science, 9, 635163, doi:10.3389/feart.2021.635163, 2021.

545 Aggarwal, A., Frey, H., McDowell, G., Drenkhan, F., Nüsser, M., Racoviteanu, A. and Hoelzle, M.: Adaptation to climate change induced water stress in major glacierized mountain regions. Climate and Development, doi:10.1080/17565529.2021.1971059, 2021.

Aggarwal, S., Rai, S., Thakur, P.K. and Emmer, A.: Inventory and recently increasing GLOF susceptibility of glacial lakes in Sikkim, Eastern Himalaya. Geomorphology, 30(295), 39-54, doi: 10.1016/j.geomorph.2017.06.014, 2017.

550     Allison, E.A.: The spiritual significance of glaciers in an age of climate change. WIREs Climate Change 6, 493-508, doi: 10.1002/wcc.354, 2015.

Anacona, P.I., Kinney, J., Schaefer, M., Harrison, S., Wilson, R., Segovia, A., Mazzorana, B., Guerra, F., Farias, D., Reynolds, J.M. and Glasser, N.F.: Glacier protection laws: Potential conflicts in managing glacial hazards and adapting to climate change. Ambio, 47(8), 835-845, doi:10.1007/s13280-018-1043-x, 2018.

555     Andreassen, L.M., Nagy, T., Kjøllmoen, B. and Leigh, J.R.: An inventory of Norway's glaciers and ice-marginal lakes from 2018-2019 Sentinel-2 data. Journal of Glaciology, online first, doi:10.1017/jog.2022.20, 2022.

Anyia, M., Dusaillant, A., O'Kuinghttons, J., Barcaza, G. and Bravo, S.: GLOFs of Laguna Témpanos, glacier-dammed side lake of Glaciar Steffen, Hielo Patagónico Norte, Chile, since 1974. Bulletin of Glaciological Research, 38, 13-24, doi:10.5331/bgr.20R01, 2020.

560     Atenstaedt, R.: Word cloud analysis of the BJGP: 5 years on. Br. J. Gen. Pract. 67, 231–232, doi:10.3399/bjgp17X690833, 2017.

Bat'ka, J., Vilímek, V., Štefanová, E., Cook, S.J. and Emmer, A.: Glacial Lake Outburst Floods (GLOFs) in the Cordillera Huayhuash, Peru: Historic Events and Current Susceptibility. Water, 12(10), 2664, doi:10.3390/w12102664, 2020.

Blauvelt, D.J., Russell, A.J., Large, A.R.G., Tweed, F.S., Hiemstra, J.F., Kulessa, B., Evans, D.J.A. and Waller, R.I.: Controls
565     on jokulhlaup-transported buried ice melt-out at Skeioararsandur, Iceland: Implications for the evolution of ice-marginal environments. Geomorphology, 360, 107164, doi:10.1016/j.geomorph.2020.107164, 2020.

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

Byers, A.C., Rounce, D.R., Shugar, D.H., Lala, J.M., Byers, E.A. and Regmi, D.: A rockfall-induced glacial lake outburst
570     flood, Upper Barun Valley, Nepal. Landslides, 16, 533-549, doi:10.1007/s10346-018-1079-9, 2019.

Carey, M., 2005. Living and dying with glaciers: people's historical vulnerability to avalanches and outburst floods in Peru. Glob. Planet. Change 47 (2-4), 122-134, doi:10.1016/j.gloplacha.2004.10.007, 2005.

Carey, M.: In the Shadow of Melting Glaciers: Climate Change and Andean Society. Oxford University Press, New York. doi:10.1093/acprof:oso/9780195396065.001.0001, 2010.

575     Carey, M., Huggel, C., Bury, J., Portocarrero, C. and Haeberli, W.: An Integrated Socio-Environmental Framework for Glacier Hazard Management and Climate Change Adaptation: Lessons from Lake 513, Cordillera Blanca, Peru. Climatic Change 112, 733-767, doi:10.1007/s10584-011-0249-8, 2012.

Carey, M., Moulton, H., Barton, J., Craig, D., Provant, Z., Shoop, C., Travers, J., Trombley, J. and Uscanga, A.: Justicia glaciar en Los Andes y más allá. Ambiente, Comportamiento y Sociedad, 3(2), 28-38, doi:10.51343/racs.v3i2.584, 2020.

580     Carey, M., McDowell, G., Huggel, C., Marshall, B., Moulton, H., Portocarrero, C., Provant, Z., Reynolds, J.M. and Vicuña, L.: A socio-cryospheric systems approach to glacier hazards, glacier runoff variability, and climate change. In: Haeberli, W., Whiteman, C. (Eds.): Snow and Ice-Related Hazards, Risks, and Disasters. Elsevier, Amsterdam, 215-257, doi:10.1016/B978-0-12-817129-5.00018-4 2021.

Carrivick, J.L. and Tweed, F.S.: A global assessment of the societal impacts of glacier outburst floods. Glob. Planet. Chang.

585    144, 1–16, doi:10.1016/j.gloplacha.2016.07.001, 2016.

Carrivick, J.L. and Tweed, F.S.: A review of glacier outburst floods in Iceland and Greenland with a megafloods perspective. Earth-Science Reviews, 196, 102876, doi:10.1016/j.earscirev.2019.102876, 2019.

Carrivick, J.L., Tweed, F.S., Ng, F., Quincey, D.J., Mallalieu, J., Ingeman-Nielsen, T., Mikkelsen, A.B., Palmer, S.J., Yde, J.C., Homer, R., Russell, A.J. and Hubbard, A.: Ice-dammed lake drainage evolution at Russell Glacier, West Greenland.

590    Frontiers in Earth Science, 5,100, doi:10.3389/feart.2017.00100, 2017.

Cenderelli D.A, and Wohl E.E.: Flow hydraulics and geomorphic effects of glacial-lake outburst floods in the Mount Everest region, Nepal. Earth Surface Processes and Landforms, 28(4), 385-407, doi:10.1002/esp.448, 2003.

Cicoira, A., Blatny, L., Li, X., Trottet, B. and Gaume, J.: Towards a predictive multi-phase model for alpine mass movements and process cascades. Preprint, available from: https://doi.org/10.31223/X59S51, 2021.

595    Clague, J.J. and Evans, S.G.: A review of catastrophic drainage of moraine-dammed lakes in British Columbia. Quat. Sci. Rev., 19(17–18), 1763–1783, doi:10.1016/S0277-3791(00)00090-1, 2000.

Clague, J.J. and O'Connor, J.E.: Glacier-related outburst floods. In: W. Haeberli, C. Whiteman (Eds.): Snow and ice-related hazards, risks, and disasters. Amsterdam, The Netherlands: Elsevier, 487-519, doi:10.1016/B978-0-12-817129-5.00019-6, 2015.

600    Clague, J.J., Huggel, C., Korup, O. and McGuire, B.: Climate change and hazardous processes in high mountains. Revista de la Asociación Geológica Argentina. 69(3): 328–338, doi:10.5167/uzh-77920, 2012.

Cook, K.L., Andermann, C., Gimbert, F., Adhikari, B. R. and Hovius, N.: Glacial lake outburst floods as drivers of fluvial erosion in the Himalaya. Science, 362(6410), 53-57, doi:10.1126/science.aat4981, 2018.

Correas-Gonzalez, M., Moreiras, S., Jomelli, V. and Arnaud-Fassetta, G.: Ice-dammed lake outburst flood risk in the Plomo

605    basin, Central Andes (33º S): Perspectives from historical events. Cuadernos de Investigación Geográfica, 46(1), 223-249, 2020.

Costa, J.E. and Schuster, R.L.: The formation and failure of natural dams. Geol. Soc. Am. Bull. 100 (7), 1054-1068, doi:10.1130/0016-7606(1988)100<1054:TFAFON>2.3.CO;2, 1988.

Da Silva, J.A.T. and Dobranszki, J.: Multiple versions of the h-index: Cautionary use for formal academic purposes.

610    Scientometrics, 115(2), 1107–1113, doi: 10.1007/s11192-018-2680-3, 2018.

Dayirov, M. and Narama, C.: Formation and Outburst of the Toguz-Bulak Glacial Lake in the Northern Teskey Range, Tien Shan, Kyrgyzstan. Geosciences, 10(11), 468, doi: 10.3390/geosciences10110468, 2020.

Drenkhan, F., Huggel, C., Guardamino, L. and Haeberli, W.: Managing risks and future options from new lakes in the deglaciating Andes of Peru: The example of the Vilcanota-Urubamba basin. Science of the Total Environment, 665, 465-483,

615    doi:10.1016/j.scitotenv.2019.02.070, 2019.

Emmer, A.: Geomorphologically effective floods from moraine-dammed lakes in the Cordillera Blanca, Peru. Quat. Sci. Rev., 177, 220–234, doi:10.1016/j.quascirev.2017.10.028, 2017.

Emmer, A.: GLOFs in the WOS: bibliometrics, geographies and global trends of research on glacial lake outburst floods (Web of Science, 1979-2016). Natural Hazards and Earth System Sciences, 18, 813-827, doi:10.5194/nhess-18-813-2018, 2018.

620 Emmer, A.: The careers behind and the impact of solo author articles in Nature and Science. Scientometrics, 120(2), 825-840, doi: 10.1007/s11192-019-03145-5, 2019.

Emmer, A., Cuřín, V., Daněk, J., Duchková, H. and Krpec, P.: The Top-Viewed Cryosphere Videos on YouTube: An Overview. Geosciences, 9(4), 181, doi:10.3390/geosciences9040181, 2019.

Emmer, A., Harrison, S., Mergili, M., Allen, S., Frey, H. and Huggel, C.: 70 years of lake evolution and glacial lake outburst

625 floods in the Cordillera Blanca (Peru) and implications for the future. Geomorphology, 365, 107178, doi:10.1016/j.geomorph.2020.107178, 2020.

Emmer, A., Wood, J.L., Cook, S.J., Harrison, S., Wilson, R., Diaz-Moreno, A., Reynolds, J.M., Torres, J.C., Yarleque, C., Mergili, M., Jara, H.W., Bennett, G., Caballero, A., Glasser, N.F., Melgarejo, E., Riveros, C., Shannon, S., Turpo, E., Tinoco, T., Torres, L., Garay, D., Villafane, H., Garrido, H., Martinez, C., Apaza, N., Araujo, J. and Poma, C.: 160 Glacial lake outburst

630 floods (GLOFs) across the Tropical Andes since the Little Ice Age. Global and Planetary Change, 208, 103722, doi:10.1016/j.gloplacha.2021.103722, 2022.

Evans, S.G. and Clague, J.J.: Recent climatic change and catastrophic processes in mountain environments. Geomorphology, 10, 107–128: doi:10.1016/0169-555X(94)90011-6, 1994.

Field, H.R., Armstrong, W.A. and Huss, M.: Gulf of Alaska ice-marginal lake area change over the Landsat record and

635 potential physical controls. The Cryosphere, 15, 3255–3278, doi:10.5194/tc-15-3255-2021, 2021.

Figueiredo, A.R.d., Simões, J.C., Menegat, R., Strauss, S. and Rodrigues, B.B.: Perceptions of and adaptation to climate change in the Cordillera Blanca, Peru. Sociedade & Natureza 31, 1-22, doi:0.14393/SN-v31-2019-45623, 2019.

Fischer, M., Korup, O., Veh, G. and Walz, A.: Controls of outbursts of moraine-dammed lakes in the greater Himalayan region. The Cryosphere, 15, 4145-4163, doi:10.5194/tc-15-4145-2021, 2021.

640 Fire, M. and Guestrin, C.: Over-optimization of academic publishing metrics: observing Goodhart's Law in action. Gigascience, 8(6), giz053, doi:10.1093/gigascience/giz053, 2019.

Frey, H., Huggel, C., Chisolm, R.E., Baer, P., McArdell, B., Cochachin, A. and Portocarrero, C.: Multi-Source Glacial Lake Outburst Flood Hazard Assessment and Mapping for Huaraz, Cordillera Blanca, Peru. Frontiers in Earth Science, 6, 210, doi:10.3389/feart.2018.00210, 2018.

645 Frey, L., Frey, H., Huss, M., Allen, S., Farinotti, D., Huggel, C., Emmer, A. and Shugar, D.: A global inventory of potential future glacial lakes. EGU General Assembly 2021, EGU21-4774, doi: 10.5194/egusphere-egu21-4774, 2021.

Furian, W., Loibl, D. and Schneider, C.: Future glacial lakes in High Mountain Asia: an inventory and assessment of hazard potential from surrounding slopes. Journal of Glaciology, 67(264), 653-670, doi:10.1017/jog.2021.18, 2021.

Gagné, K.: Caring for Glaciers: Land, Animals, and Humanity in the Himalayas. University of Washington Press, Seattle, 258

650 p., 2019.

Gall, M., Nguyen, K.H. and Cutter, L.S.: Integrated research on disaster risk: Is it really integrated? International Journal of Disaster Risk Reduction, 12, 255-267, doi: 10.1016/j.ijdrr.2015.01.010, 2015.

GAPHAZ, 2017. Assessment of Glacier and Permafrost Hazards in Mountain Regions – Technical Guidance Document. Prepared by Allen, S., Frey, H., Huggel, C. et al. (Eds). Standing Group on Glacier and Permafrost Hazards in Mountains (GAPHAZ) of the International Association of Cryospheric Sciences (IACS) and the International Permafrost Association (IPA). Zurich, Switzerland / Lima, Peru, 72 p., doi:10.13140/RG.2.2.26332.90245, 2017.

Gaume, J., Gast, T., Teran, J., van Herwijnen, A. and Jiang, C.: Dynamic anticrack propagation in snow. Nature Communications, 9, 3047, doi:10.1038/s41467-018-05181, 2018.

Gearheard, S.F., Kielsen Holm, L., Huntington, H., Mello Leavitt, J., Mahoney, A.R., Opie, M., Oshima, T., Sanguya, J. (Eds.): The Meaning of Ice: People and Sea Ice in Three Arctic Communities. Hanover, NH: International Polar Institute Press, 366 p, 2013.

Geertsema, M., Menounous, B., Bullard, G., Carrivick, J.L., Clague, J.J., Dai, C., Donati, D., Ekstrom, G., Jackson, J.M., Lynett, P., Pichierri, M., Pon, A., Shugar, D.H., Stead, D., Del Bel Belluz, J., Friele, P., Giesbrecht, I., Heathfield, D., Millard, T., Nasonova, S., Schaeffer, A.J., Ward, B.C., Blaney, E., Brillon, C., Bunn, C., Floyd, W., Higman, B., Hughes, K.E., McInnes, W., Mukherjee, K., Sharp, M.A., The 28 November 2020 Landslide, Tsunami, and Outburst Flood – A Hazard Cascade Associated With Rapid Deglaciation at Elliot Creek, British Columbia, Canada, Geophysical Research Letter, 49(6), e2021GL096716, doi: e2021GL096716, 2022.

Gharehchahi, S., James, W., Bhardwaj, A., Jensen, J., Sam, L., Ballinger, T.J. and Butler, D.R.: Glacier Ice Thickness Estimation and Future Lake Formation in Swiss Southwestern Alps-The Upper Rhône Catchment: A VOLTA Application. Remote Sensing, 12(20), 3443, doi:10.3390/rs12203443, 2020.

Ghosh, T.K., Jakobsen, F., Joshi, M. and Pareta, K.: Extreme rainfall and vulnerability assessment: case study of Uttarakhand rivers. Natural Hazards, 99(2), 665-687, doi:10.1007/s11069-019-03765-3, 2019.

Haeberli, W. and Drenkhan, F.: Future Lake Development in Deglaciating Mountain Ranges. In: L.S. Cutter (ed.): Oxford research encyclopedias – natural hazard science; Oxford University Press. pp. 1-45, doi:10.1093/acrefore/9780199389407.013.361, 2022.

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

Harrison, S., Kargel, J.S., Huggel, C., Reynolds, J., Shugar, D.H., Betts, R.A., Emmer, A., Glasser, N., Haritashya, U.K., Klimeš, J., Reinhardt, L., Schaub, Y., Wilyshire, A., Regmi, D. and Vilímek, V.: Climate change and the global pattern of moraine-dammed glacial lake outburst floods. Cryosphere, 12, 1195–1209, doi:10.5194/tc-12-1195-2018, 2018.

Haverkamp, J.: Collaborative survival and the politics of livability: Towards adaptation otherwise. World Development, 137, 1-14, doi:10.1016/j.worlddev.2020.105152, 2021.

Holm, L.K., Grenoble, L.A. and Virginia, R.A.: A praxis for ethical research and scientific conduct in Greenland. Etudes Inuit. Inuit Studies, 35, 187-200, doi:10.7202/1012841ar, 2011.

685 Hovden, A. and Havnevik, H.: Balancing the sacred landscape: environmental management in Limi, North-Western Nepal, in: Kuyakanon, R., Diemberger, H., Sneath, D. (Eds.), Cosmopolitical Ecologies Across Asia: Places and Practices of Power in Changing Environments. Routledge, New York, 83-101, 2021.

How, P., Messerli, A., Mätzler, E., Santoro, M., Wiesmann, A., Caduff, R., Langley, K., Bojesen, M.H., Kääb, A. and Carrivick, J.: Greenland-wide inventory of ice marginal lakes using a multi-method approach. Scientific Reports, 11, 4481, 690 doi:10.1038/s41598-021-83509-1, 2021

Huggel, C., Carey, M., Clague, J. and Kääb, A. (Eds.).: The High-Mountain Cryosphere: Environmental Changes and Human Risks. New York: Cambridge University Press, 376 p., doi:10.1017/CBO9781107588653, 2015.

Huggel, C., Carey, M., Emmer, A., Frey, H., Walliman-Helmer, I. and Walker-Crawford, N.: Anthropogenic climate change and glacier lake outburst flood risk: local and global drivers and responsibilities. Natural Hazards and Earth System Sciences, 695 20, 2175-2193, doi:10.5194/nhess-20-2175-2020, 2020a.

Huggel, C., Cochachin, A., Drenkhan, F., Fluixá-Sanmartín, J., Frey, H., García Hernández, J., Jurt, C., Muñoz, R., Price, K. and Vicuña, L.: Glacier Lake 513, Peru: Lessons for early warning service development. WMO Bull., 69, 45–52, 2020b.

Jacquet, J., McCoy, S.W., McGrath, D., Nimick, D.A., Fahey, M., O'Kuinghttons, J., Friesen, B.A. and Leidich, J.: Hydrologic and geomorphic changes resulting from episodic glacial lake outburst floods: Rio Colonia, Patagonia, Chile. Geophysical 700 Research Letters, 44, 854-864, doi:10.1002/2016GL071374, 2017.

Kelman, I., Mercer, J. and Gaillard, J.C.: Indigenous knowledge and disaster risk reduction. Geography, 97, 12-21, 2012.

Khan, G., Ali, S., Xu, X.K., Qureshi, J.A., Ali, M. and Karim, I.: Expansion of Shishper Glacier lake and recent glacier lake outburst flood (GLOF), Gilgit-Baltistan, Pakistan. Environmental Science and Pollution Research, 28(16), 20290-20298, doi:10.1007/s11356-020-11929-z, 2021.

705 Kienholz, C., Pierce, J., Hood, E., Amundson, J.M., Wolken, G.J., Jacobs, A., Hart, S., Jones, K.W., Abdel-Fattah, D., Johnson, C. and Conaway, J.S.: Deglacierization of a Marginal Basin and Implications for Outburst Floods, Mendenhall Glacier, Alaska. Frontiers in Earth Science, 8, 137, doi:10.3389/feart.2020.00137, 2020.

Klimeš, J., Novotný, J., Cochachin, A.R., Balek, J., Zahradníček, P., Sana, H., Frey, H., René, M., Štěpánek, P., Meitner, J. and Junghardt, J.: Paraglacial Rock Slope Stability Under Changing Environmental Conditions, Safuna Lakes, Cordillera 710 Blanca Peru. Frontiers in Earth Science, 9, 607277, doi:10.3389/feart.2021.607277, 2021.

Kougkoulos, I., Cook, S.J., Edwards, L.A., Clarke, L.J., Symeonakis, E., Dortch, J.M. and Nesbitt, K.: Modelling glacial lake outburst flood impacts in the Bolivian Andes. Natural Hazards, 94(3), 1415-1438, doi:10.1007/s11069-018-3486-6, 2018a.

Kougkoulos, I., Cook, S.J., Jomelli, V., Clarke, L., Symeonakis, E., Dortch, J.M., Edwards, L.A. and Merad, M.: Use of multi-criteria decision analysis to identify potentially dangerous glacial lakes. Science of the Total Environment, 621, 1453-1466, 715 doi:10.1016/j.scitotenv.2017.10.083, 2018b.

Kumar, R., Bahuguna, I.M., Ali, S.N. and Singh, R.: Lake Inventory and Evolution of Glacial Lakes in the Nubra-Shyok Basin of Karakoram Range. Earth Systems and Environment, 4(1), 57-70, doi:10.1007/s41748-019-00129-6, 2020.

Lambert, S.J. and Scott, J.C.: International Disaster Risk Reduction Strategies and Indigenous Peoples. International Indigenous Policy Journal, 10(2), 2, doi:10.18584/iipj.2019.10.2.2, 2019.

720 Li, D.Y. and Zhou, X.L. : "Leave your footprints in my words"-A georeferenced word-cloud approach. Environ. Plan. A, 49, 489–492, doi:10.1177/0308518X16662273, 2017.

Li, D., Lu, X., Overeem, I., Walling, D.E., Syvitski, J., Kettner, A.J., Bookhagen, B., Zhou, Y., Zhang, T.: Exceptional increases in fluvial sediment fluxes in a warmer and wetter High Mountain Asia. Science, 374(6567), 599-603, doi:10.1126/science.abi9649, 2021.

725 Li, D., Lu, X., Walling, D.E., Zhang, T., Steiner, J.F., Wasson, R.J., Harrison, S., Nepal, S., Nie, Y., Immerzeel, W.W., Shugar, D.H., Koppes, M., Lane, S., Zeng, Z., Sun, W., Yegorov, A. and Bolch, T:: High Mountain Asia hydropower systems threatened by climate-driven landscape instability. Nat. Geosci. 15, 520–530, 2022.

Lindgren, P.R., Farquharson, L.M., Romanovsky, V.E. and Grosse, G.: Landsat-based lake distribution and changes in western Alaska permafrost regions between the 1970s and 2010s. Environmental Research Letters, 16(2), 025006, doi:10.1088/1748-730 9326/abd270, 2021.

Maharjan, S.B., Steiner, J.F., Shrestha, A.B., Maharjan, A., Nepal, S., Shrestha, M.S., Bajracjarya, B., Rasul, G., Shrestha, M., Jackson, M. and Gupta, N.: The Melamchi flood disaster: cascading hazard and the need for multihazard risk management. 26International Centre for Integrated Mountain Development (ICIMOD), Káathmaándúu, 19 p., 2021.

Mal, S., Allen, S., Frey, H., Huggel, C. and Dimri, A.P.: Sector-wise assessment of Glacial Lake Outburst Flood danger in the 735 Indian Himalayan Region. Mountain Research and Development, 41(1), doi:10.1659/MRD-JOURNAL-D-20-00043.1, 2021.

Matti, S. and Ögmundardóttir, H.: Local knowledge of emerging hazards: Instability above an Icelandic glacier. International Journal of Disaster Risk Reduction, 58, 102187, doi:10.1016/j.ijdrr.2021.102187, 2021.

Matti, S., Ögmundardóttir, H., Aðalgeirsdóttir, G. and Reichardt, U.: Psychosocial response to a no-build zone: Managing landslide risk in Iceland. Land Use Policy, 117, 106078, doi:10.1016/j.landusepol.2022.106078, 2022a.

740 Matti, S., Ögmundardóttir, H., Aðalgeirsdóttir, G. and Reichardt, U.: Communicating the risk of a large landslide above a glacier with foreign tourism employees in Iceland. Mountain Research and Development. 42(2), doi:10.1659/MRD-JOURNAL-D-21-00051.1, 2022b.

Martín-Martín, A., Orduna-Malea, E., Thelwall, M. and Delgado López-Córzar, E.: Google Scholar, Web of Science, and Scopus: A systematic comparison of citations in 252 subject categories. Journal of Informetrics, 12(4), 1160-1177, 745 doi:10.1016/j.joi.2018.09.002, 2018.

McGee, R.G. and Craig, J.C.: What is being published? A word cloud of titles from the journal of paediatrics and child health. J. Paediatr. Child Health, 48, 452, doi:10.1111/j.1440-1754.2012.02455.x, 2012.

Mercer, J., Kelman, I., Taranis, L. and Suchet-Pearson, S.: Framework for integrating indigenous and scientific knowledge for disaster risk reduction. Disasters, 34(1), 214-239, doi:10.1111/j.1467-7717.2009.01126.x, 2010.

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

Mergili, M., Emmer, A., Juřicová, A., Cochachin, A., Fischer, J.-T., Huggel, C. and Pudasaini, S.P.: How well can we simulate complex hydro-geomorphic process chains? The 2012 multi-lake outburst flood in the Santa Cruz Valley (Cordillera Blanca, Perú). Earth Surface Processes and Landforms, 43(7), 1373-1389, doi:10.1002/esp.4318, 2018a.

Mergili, M., Frank, B., Fischer, J.-T., Huggel, C. and Pudasaini, S. P.: Computational experiments on the 1962 and 1970 landslide events at Huascarán (Peru) with r.avaflow: Lessons learned for predictive mass flow simulations. Geomorphology, 322, 15–28, doi:10.1016/j.geomorph.2018.08.032, 2018b.

Mergili, M., Pudasaini, S.P., Emmer, A., Fischer, J.-T., Cochachin, A. and Frey, H.: Reconstruction of the 1941 GLOF process chain at Lake Palcacocha (Cordillera Blanca, Perú). Hydrology and Earth System Sciences, 24, 93-114, doi:10.5194/hess-24-93-2020, 2020.

Mergili, M. and Pudasaini, S.P.: r.avaflow – The open source mass flow simulation model. https://www.avaflow.org/. Last access: 1 October 2021, 2021.

Mongeon, P. and Paul-Hus, A.: The journal coverage of Web of Science and Scopus: a comparative analysis. Scientometrics, 106(1), 213-228, doi:10.1007/s11192-015-1765-5, 2016.

Moulton, H., Carey, M., Huggel, C. and Motschmann, A.: Narratives of ice loss: New approaches to shrinking glaciers and climate change adaptation. Geoforum, 125, 47-56, doi:10.1016/j.geoforum.2021.06.011, 2021.

Motschmann, A., Huggel, C., Carey, M., Moulton, H., Walker-Crawford, N. and Muñoz, R.: Losses and damages connected to glacier retreat in the Cordillera Blanca, Peru. Climatic Change, 162, 837-858, doi:10.1007/s10584-020-02770-x, 2020a.

Motschmann, A., Huggel, C., Muñoz, R. and Thür, A.: Towards integrated assessments of water risks in deglaciating mountain areas: water scarcity and GLOF risk in the Peruvian Andes, Geoenvironmental Disasters, 7, 1–18, doi:10.1186/s40677-020-00159-7, 2020b.

Mölg, N., Huggel, C., Herold, T., Storck, F., Allen, S., Haeberli, W., Schaub, Y. and Odermatt, D.: Inventory and evolution of glacial lakes since the Little Ice Age: Lessons from the case of Switzerland. Earth Surface Processes and Landforms, 46(13), 2551-2564, doi:10.1002/esp.5193, 2021.

Muhammad, S., Li, J., Steiner, J.F., Shrestha, F., Shah, G.M., Berthier, E., Guo, L., Wu, L.-X. and Tian, L.: A holistic view of Shisper Glacier surge and outburst floods: from physical processes to downstream impacts. Geomatics, Natural Hazards and Risk, 12(1), 2755-2775, doi:10.1080/19475705.2021.1975833, 2021.

Muneeb, F., Baig, S.U., Khan, J.A. and Khokhar, F.: Inventory and GLOF Susceptibility of Glacial Lakes in Hunza River Basin, Western Karakorum. Remote Sensing, 13(9), 1794, doi:10.3390/rs13091794, 2021.

Nie, Y., Liu, Q., Wang, J., Zhang, Y., Sheng, Y. and Liu, S.: An inventory of historical glacial lake outburst floods in the Himalayas based on remote sensing observations and geomorphological analysis. Geomorphology, 308, 91-106, doi:10.1016/j.geomorph.2018.02.002, 2018.

Ogier, C., Werder, M.A., Huss, M., Kull, I., Hodel, D. and Farinotti, D.: Drainage of an ice-dammed lake through a supraglacial stream: hydraulics and thermodynamics. The Cryosphere Discussions, preprint, doi: 10.5194/tc-2021-151, 2021.

Otto, J.-C., Helfricht, K., Prasicek, G., Binder, D. and Kueschnig, M.: Testing the performance of ice thickness models to estimate the formation of potential future glacial lakes in Austria. Earth Surface Processes and Landforms, online first, doi:10.1002/esp.5266, 2021.

Papathoma-Köhle, M., Schlögl, M., Dosser, L., Roesch, F., Borga, M., Erlicher, M., Keiler, M. and Fuchs, S.: Physical vulnerability to dynamic flooding: Vulnerability curves and vulnerability indices. Journal of Hydrology, 607, 127501, doi: 10.1016/j.jhydrol.2022.127501, 2022.

Petrov, M.A., Sabitov, T.Y., Tomashevskaya, I.G., Glazirin, G.E., Chernomorets, S.S., Savernyuk, E.A., Tutubalina, O.V., Petrakov, D.A., Sokolov, L.S., Dokukin, M.D., Mountrakis, G., Ruiz-Villanueva, V. and Stoffel, M.: Glacial lake inventory and lake outburst potential in Uzbekistan. Science of the Total Environment, 592, 228-242, doi:10.1016/j.scitotenv.2017.03.068, 2017.

Pudasaini, S.P.: A general two-phase debris flow model. Journal of Geophysical Research 117: F03010, doi:10.1029/2011JF002186, 2012.

Pudasaini, S.P.: A full description of generalized drag in mixture mass flows. Engineering Geology 265, 105429, doi:10.1016/j.enggeo.2019.105429, 2020.

Pudasaini, S.P. and Fischer, J.T.: A mechanical erosion model for two-phase mass flows. International Journal of Multiphase Flows 132, 103416, doi:10.1016/j.ijmultiphaseflow.2020.103416, 2020a.

Pudasaini, S.P. and Fischer, J.T.: A mechanical model for phase separation in debris flow. International Journal of Multiphase Flows 129, 103292, doi:10.1016/j.ijmultiphaseflow.2020.103292, 2020b.

Pudasaini, S.P. and Krautblatter, M.: The Mechanics of Landslide Mobility with Erosion. Perprint, arXiv:2103.14842 [physics.geo-ph], 2021.

Richardson, S.D. and Reynolds, J.M.: An overview of glacial hazards in the Himalayas. Quaternary International. 65/66: 31–47, doi:10.1016/S1040-6182(99)00035-X, 2000.

Rinzin, S., Zhang, G., Wangchuk, S.: Glacial Lake Area Change and Potential Outburst Flood Hazard Assessment in the Bhutan Himalaya. Frontiers in Earth Science, 9, 775195. doi:10.3389/feart.2021.775195, 2021.

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

Sandstrom, U. and van den Besselaar, P.: Quantity and/or quality? The importance of publishing many papers. PLoS ONE, 11(11), e0166149, doi:10.1371/journal.pone.0166149, 2016.

Sattar, A., Goswami, A. and Kulkarni, A.: Application of 1D and 2D hydrodynamic modeling to study glacial lake outburst flood (GLOF) and its impact on a hydropower station in Central Himalaya. Natural Hazards, 97(2), 535-553, doi: 10.1007/s11069-019-03657-6, 2019a.

Sattar, A., Goswami, A. and Kulkarni, A., 2019b. Hydrodynamic moraine-breach modeling and outburst flood routing - A hazard assessment of the South Lhonak lake, Sikkim. Science of the Total Environment, 668, 362-378, doi:10.1016/j.scitotenv.2019.02.388, 2019b.

820    Sattar, A., Goswami, A., Kulkarni, A.V. and Emmer, A.: Lake Evolution, Hydrodynamic Outburst Flood Modeling and Sensitivity Analysis in the Central Himalaya: A Case Study. Water, 12(1), 237, doi:10.3390/w12010237, 2020.

Sattar, A., Haritashya, U.K., Kargel, J.S., Leonard, G.J., Shugar, D.H. and Chase, D.V.: Modeling lake outburst and downstream hazard assessment of the Lower Barun Glacial Lake, Nepal Himalaya. Journal of Hydrology, 598, 126208, doi:10.1016/j.jhydrol.2021.126208, 2021.

825    Schmidt, S., Nusser, M., Baghel, R. and Dame, J.: Cryosphere hazards in Ladakh: the 2014 Gya glacial lake outburst flood and its implications for risk assessment. Natural Hazards, 104(3), 2071-2095, doi:10.1007/s11069-020-04262-8, 2020.

Scopus. Scopus - abstract and citation database. Elsevier. Available from: www.scopus.com last access: March 2022, 2022.

Schaub, Y., Huggel, C. and Cochachin, A.: Ice-avalanche scenario elaboration and uncertainty propagation in numerical simulation of rock-/ice-avalanche-induced impact waves at Mount Hualcán and Lake 513, Peru. Landslides 13, 1445-1459,

830    doi:10.1007/s10346-015-0658-2, 2016.

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

Sherpa, S.F., Shrestha, M., Eakin, H. and Boone, C.G.: Cryospheric hazards and risk perceptions in the Sagarmatha (Mt.

835    Everest) National Park and Buffer Zone, Nepal. Natural Hazards, 96, 607-626, doi: 10.1007/s11069-018-3560-0, 2019.

Sherry, J., Curtis, A., Mendham, E., Toman, E..: Cultural landscapes at risk: Exploring the meaning of place in a sacred valley of Nepal. Global Environmental Change, 52, 190-200, 10.1016/j.gloenvcha.2018.07.007, 2018.

Shugar, D.H., Burr, A., Haritashya, U.K., Kargel, J.S.,Watson, C.S., Kennedy, M.C., Bevington, A.R., Betts, R.A., Harrison, S. and Strattman, K.: Rapid worldwide growth of glacial lakes since 1990. Nature Climate Change, 10, 939–945,

840    doi:10.1038/s41558-020-0855-4, 2020.

Shugar, D.H., Jacquemart, M., Shean, D., Bhushan, S., Upadhyay, K., Sattar, A., Schwanghart, W., McBride, S., Van Wyk de Vries, M., Mergili, M., Emmer, A., Deschamps-Berger, C., McDonnell, M., Bhambri, R., Allen, S., Berthier, E., Carrivick, J.L., Clague, J.J., Dokukin, M., Dunning, S.A., Frey, H., Gascoin, S., Haritashya, U.K., Huggel, C., Kääb, A., Kargel, J.S., Kavanaugh, J.L., Lacroix, P., Petley, D., Rupper, S., Azam, M.F., Cook, S.J., Dimri, A.P., Eriksson, M., Farinotti, D., Fiddes,

845    J., Gnyawali, K.R., Harrison, S., Jha, M., Koppes, M., Kumar, A., Leinss, S., Majeed, U., Mal, S., Muhuri, A., Noetzli, J., Paul, F., Rashid, I., Sain, K., Steiner, J., Ugalde, F., Watson, C.S. and Westoby, M.J.: A massive rock and ice avalanche caused the 2021 disaster at Chamoli, Indian Himalaya. Science, 373(6552), 300-306, doi:10.1126/science.abh4455, 2021.

Stefaniak, A.M., Robson, B.A., Cook, S.J., Clutterbuck, B., Midgley, N.G., Labadz, J.C.: Mass balance and surface evolution of the debris-covered Miage Glacier, 1990–2018. Geomorphology, 373, 107474, doi:10.1016/j.geomorph.2020.107474, 2021.

850 Steffen, T., Huss, M., Estermann, R., Hodel, E., Farinotti, D.: Volume, formation and sedimentation of future glacier lakes in Switzerland. Earth Surf. Dynam., 10, 723–741, doi:10.5194/esurf-10-723-2022, 2022.

Stuart-Smith, R.F., Roe, G.H. and Allen, M.R.: Increased outburst flood hazard from Lake Palcacocha due to human-induced glacier retreat. Nature Climate Change, 14, 85-90, doi: 10.1038/s41561-021-00686-4, 2021.

Thelwall, M., and Sud, P.: National, disciplinary and temporal variations in the extent to which articles with more authors have 855 more impact: Evidence from a geometric field normalised citation indicator. Journal of Informetrics, 10(1), 48–61, doi:10.1016/j.joi.2015.11.007, 2016.

Thompson, I., Shrestha, M., Chhetri, N., Agusdinata, D.B.: An institutional analysis of glacial floods and disaster risk management in the Nepal Himalaya. International Journal of Disaster Risk Reduction, 47, 101567. doi:10.1016/j.ijdrr.2020.101567, 2020.

860 Tomczyk, A.M., Ewertowski, M.W., Carrivick, J.L.: Geomorphological impacts of a glacier lake outburst flood in the high arctic Zackenberg River, NE Greenland. Journal of Hydrology, 591, 125300, doi:10.1016/j.jhydrol.2020.125300, 2021.

Troilo, F.: The Grand Croux Lake Outburst flood: monitoring and protection measure from the 2016 event to future scenarios. The GLOF conference & workshop 2021, 7th to 9th July, online, 2021.

Vandekerkhove, E., Bertrand, S., Torrejon, F., Kylander, M.E., Reid, B. and Saunders, K.M.: Signature of modern glacial lake 865 outburst floods in fjord sediments (Baker River, southern Chile). Sedimentology, online first, doi: 10.1111/sed.12874, 2021.

Veh, G., Korup, O., von Specht, S., Roessner, S. and Walz, A.: Unchanged frequency of moraine-dammed glacial lake outburst floods in the Himalaya. Nature Climate Change, 9, 379-383, doi: https://doi.org/10.1038/s41558-019-0437-5, 2019.

Veh, G., Lützov, N., Kharlamova, V., Petrakov, D., Hugonnet, R. and Korup, O.: Trends, breaks, and biases in the frequency of reported glacier lake outburst floods. Earth's Future, online first, doi:10.1029/2021EF002426, 2022.

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

Wang, W.C., Gao, Y., Anacona, P.I., Lei, Y.B., Xiang, Y., Zhang, G.Q. and Li, S.H.: Integrated hazard assessment of Cirenmaco glacial lake in Zhangzangbo valley, Central Himalayas. Geomorphology, 306, 292-305, doi:10.1016/j.geomorph.2015.08.013, 2018.

875 Whyte, K.: Too Late for Indigenous Climate Justice: Ecological and Relational Tipping Points. WIREs Climate Change 11, e603, doi:10.1002/wcc.603, 2020.

Wilson, R., Glasser, N.F., Reynolds, J.M., Harrison, S., Anacona, P.I., Schaefer, M. and Shannon, S.: Glacial lakes of the Central and Patagonian Andes. Global and Planetary Change, 162, 275-291, doi:10.1016/j.gloplacha.2018.01.004, 2018.

Wood, J.L., Harrison, S., Wilson, R., Emmer, A., Yarleque, C., Glasser, N.F., Torres, J. C., Caballero, A., Araujo, J., Bennett, 880 G.L., Diaz, A., Garay, D., Jara, H., Poma, C., Reynolds, J.M., Riveros, C.A., Romero, E., Shannon, S., Tinoco, T., Turpo, E. and Villafane, H., 2021. Contemporary glacial lakes in the Peruvian Andes. Global and Planetary Change, 204, 103574, doi:10.1016/j.gloplacha.2021.103574, 2021.

Wood, J., Harrison, S., Wilson, R., Emmer, A., Kargel, J.S., Cook, J.S., Glasser, N.F., Reynolds, J.M., Shugar, D.H. and Yarleque, C.: Earthquakes are not a major trigger of Glacier Lake Outburst Floods, in ~~review~~prep.

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

WOS. Web of Science – citation database. Clarivate Analytics. Available from: www. webofscience.com last access: March 2022, 2022.

Wrathall, D.J., Bury, J., Carey, M., Mark, B.G., McKenzie, J., Young, K., Baraer, M., French, A. and Rampini, C.: Migration
890    Amidst Climate Rigidity Traps: Resource Politics and Social–Ecological Possibilism in Honduras and Peru. Annals of the Association of American Geographers 104, 292-304, doi:10.1080/00045608.2013.873326, 2014.

Yin, B.L., Zeng, J., Zhang, Y.L., Huai, B.J. and Wang, Y.T.: Recent Kyagar glacier lake outburst flood frequency in Chinese Karakoram unprecedented over the last two centuries. Natural Hazards, 95(3), 877-881, doi:10.1007/s11069-018-3505-7, 2019.

895    Zhang, G., Bolch, T., Allen, S., Linsbauer, A., Chen, W., Wang, W.: Glacial lake evolution and glacier–lake interactions in the Poiqu River basin, central Himalaya, 1964–2017. Journal of Glaciology, 65(251), 347-365, doi:10.1017/jog.2019.13.

Zheng, G., Bao, A., Allen, S., Ballesteros-Canovas, J.A., Yuan, Y., Jiapaer, G., and Stoffel, M.: Numerous unreported glacial lake outburst floods in the Third Pole revealed by high-resolution satellite data and geomorphological evidence. Science Bulletin, 66(13), 1270-1273, doi:10.1016/j.scib.2021.01.014, 2021a.

900    Zheng, G., Mergili, M., Emmer, A., Allen, S., Bao, A., Guo, H. and Stoffel, M.: The 2020 glacial lake outburst flood at Jinwuco, Tibet: causes, impacts, and implications for hazard and risk assessment. The Cryosphere, 15, 3159-3180, doi:10.5194/tc-15-3159-2021, 2021b.

Zheng, G., Allen, S.K., Bao, A., Ballesteros-Cánovas, J.A., Huss, M., Zhang, G., Li, J., Yuan, Y., Jiang, L., Yu, T., Chen, W. and Stoffel, M.: Increasing risk of glacial lake outburst floods from future Third Pole deglaciation. Nature Climate Change,
905    11, 411-417, doi: 10.1038/s41558-021-01028-3, 2021c.