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HMAGLOFDB v1.0 – a comprehensive and version controlled database of glacier lake outburst floods in high mountain Asia

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Abstract. Glacier lake outburst floods (GLOFs) have been intensely investigated in High Mountain Asia (HMA) in recent years and are often the first hazard related to the cryosphere mentioned in the region. As glaciers recede and surrounding slopes become increasingly unstable, such events are expected to increase, although this trend has yet to manifest. Many studies have investigated individual events and while several regional inventories exist, they either do not cover all types of GLOF or are geographically constrained. Further, downstream impacts are rarely discussed. Previous inventories have relied on academic sources and have not been combined with existing inventories of glaciers and lakes. In this study, we present the first comprehensive inventory of GLOFs in HMA, including details on the time of their occurrence, processes of lake formation and drainage involved as well as downstream impacts. We document 682 individual GLOFs that occurred between 1833 and 2022. Of these, 20% were recurring events from just three ephemeral ice-dammed lakes. In combination, the documented events resulted in 6907 fatalities, with 6000 of these linked to a single GLOF, three times higher than a previous assessment for the region. The integration of previous inventories of glaciers and lakes within this database will inform future assessments of potential drivers of GLOFs, allowing more robust projections to be developed. The presented database and future updated versions are traceable, version controlled and can be directly incorporated into further analysis.

1 Introduction

High Mountain Asia (HMA) has the largest expanse of glacier ice beyond the two poles and, consequently, also has a large number (~30000) of glacial lakes, covering ~2000 km^2 (Wang et al., 2020). Glaciers in the region have retreated and lost mass on a large scale (Bhattacharya et al., 2021), often associated with the formation and rapid expansion of glacial lakes (Nie et al., 2017; Shugar et al., 2020; Zhang et al., 2021). Many of these lakes previously resulted in glacial lake outburst floods (GLOFs; Carrivick and Tweed, 2013; Nie et al., 2018; Song et al., 2016; Veh et al., 2019b). GLOFs have been recorded for many decades in different parts of the world (Emmer et al., 2022; Veh et al., 2022), such as the European Alps (Huss et al., 2007), the Andes (Iribarren Anacona et al., 2014), North America (Wilcox et al., 2014) and the HKH (Ives et al., 2010; Mool et al., 2001; Rounce et al., 2017). Numerous studies suggest that glacial lakes in HMA have grown in total area and number since the 1990s (Chen et al., 2021; Shugar et al., 2020; Wang et al., 2020; Zhang et al., 2015; Zheng et al., 2021a). An overall increase of 5.9% in lake number and 6.8±0.1% in area was reported between 1990 and 2015 (Zheng et al., 2021a). Other studies find an increase by n=2916 and 273.65 km^2 between 1990 and 2018 (Wang et al., 2020) and by n=3342 and 220.64 km^2 between 2009 and 2017 (Chen et al., 2020). Findings imply that the total area increase has been driven by the expansion of proglacial moraine-dammed lakes (Zheng et al., 2021; Nie et al., 2013, Gardelle et al., 2011). The number of proglacial lakes in contact with glaciers increased by 31.3± 0.3% between 1990 and 2015 (Zheng et al., 2021), and by 96.27 km^2 (57%) between 1990 and 2018 (Wang et al., 2020) in HMA.

Regional studies suggest that ongoing expansion of lakes (Gardelle et al., 2011; Shugar et al., 2020) is expected to create new hotspots of potentially dangerous lakes (Furian et al., 2022; Linsbauer et al., 2015; Zhang et al., 2022a; Zheng et al., 2021a) with implications for GLOF hazards and risk (Haeberli et al., 2016). Numerous processes have been previously identified as direct or indirect triggers of GLOFs. Dynamic slope movements (ice/snow falls, rockfalls, or landslides) into a lake can rapidly displace lake water (Awal et al., 2010; Jiang et al., 2004), similarly to glacial calving creating a displacement wave to overtop the dam (Emmer and Cochachin, 2013; Westoby et al., 2014; Worni et al., 2014). Intense rainfall or ice melt leading to sudden increases in water levels also have the potential to strain dams (Allen et al., 2016; Cook et al., 2018; Worni et al., 2012). Seismic events can destabilize moraine dams, contributing to an eventual failure (Osti et al., 2011; Somos-Valenzuela et al., 2014; Westoby et al., 2014). Seepage, piping, and degradation of an ice-cored moraine can eventually lead to dam failure (Mool et al., 2001; Yamada and Sharma, 1993). Past global assessments indicated that GLOFs have caused more than 12,000 fatalities in the last century alone and caused significant damages to infrastructure and farmland (Carrivick and Tweed, 2016). With growing populations, settlements, and infrastructural development in downstream areas, the exposure of communities and structures in the shadow of these lakes is rising (Li et al., 2022). Timely GLOF risk reduction measures and implementation of risk reduction strategies have become increasingly crucial but remain challenging, especially in politically sensitive regions (Allen et al., 2019; Khanal et al., 2015).

Several studies have focused on the causes, mechanisms and trends of GLOFs over the past few decades (Allen et al., 2016; Dwiwedi et al., 2000; Ives, 1986; Mool et al., 2001; Nie et al., 2020; Zheng et al., 2021c), and the number of individual studies, especially in HMA, has increased sharply over recent years (Emmer et al., 2022). A large number of these studies have focused on individual events. While some have attempted to collect information on GLOFs in HMA and have also made data accessible, they are often geographically constrained (Nie et al., 2018; Zhang et al., 2021; Zheng et al., 2021b) or focus on certain types of GLOFs (Veh et al., 2019a). A recent global study has bridged this gap (Veh et al., 2022). However, it does not cover impacts. Recent studies have noted that a large number of GLOF events were ommitted from previous records as they remained unreported or were recorded in local media and had not been documented in scientific literature (Veh et al., 2022; Zheng et al., 2021b). Developing more comprehensive datasets is crucial (Emmer et al., 2022), and these have become increasingly

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necessary as research has shifted from an evaluation of GLOF hazards to risks, including transboundary dimensions (Zheng et al., 2021a). Recent studies of the cryosphere have also made immense progress in demonstrating the potential benefits of traceable datasets to the scientific community and establishing standards that need to be followed to make records accessible (Mankoff et al., 2021; Welty et al., 2020).

In this study, we therefore attempt to (a) provide the first comprehensive dataset of GLOFs in HMA including their location, timing, associated processes and downstream impacts; (b) complement records from scientific literature with a rigorous evaluation of local sources on previously unrecorded events; and (c) show the potential of making such a dataset fully accessible and interoperable to couple it to other geospatial datasets (incl. lakes and their temporal evolution).

2 Methods and data

2.1 Compilation of lake data

Knowledge about the presence and characteristics of glacial lakes is arguably the most important baseline for an investigation into GLOFs. In this study, we rely on a previously developed and publicly available dataset of glacial lakes for the Hindu Kush Himalaya (HKH) region (Maharjan et al., 2018). This inventory was prepared using automatic approaches with manual correction, employing Landsat satellite imagery from 2005±2 years. It was delineated for five major river basins within the boundary of the HKH region as defined by ICIMOD (International Centre for Integrated Mountain Development). This database includes moraine-dammed, ice-dammed, supraglacial, bedrock-dammed, as well as lakes created from damming due to debris flows and landslides. For the years 2000, 2010, and 2020 using the same methodology, only moraine-dammed, and ice-dammed lakes were delineated across the HKH (see Figure 1 for the respective regional outlines). Each mapped lake has a time stamp through the image file name as well as an ID in the format previously used for glaciers (GLIMS ID). This allows lakes to be linked to associated glaciers as well as GLOFs. We refer to this dataset as ICIMODDB.

We also rely on two previously compiled lake databases, that cover all of HMA but have similar data structures (same GLIMS ID) and equally rely on Landsat imagery. Wang et al. (2020) provide an inventory of lakes identified in 1990 and 2018, respectively, relying on a mix of automated detection and manual correction. (Chen et al., 2021) provide a dataset of lakes mapped at 30 m resolution each year between 2008 and 2017 without any manual correction. We refer to these two datasets as WangDB and ChenDB throughout the manuscript, respectively.

2.2 Compilation of GLOF data

Historical GLOF data was compiled by searching peer-reviewed articles, news articles, book chapters, technical reports, and personal communication with the final cut-off date 30th June 2022. The database covers entries from 122 publications, including 79 peer-reviewed journal articles, 16 book chapters, and 15 technical reports. Additionally, online news articles (n=9), and social media posts (n=3) were also assessed. Beyond this, the authors also included events reported by anecdotal accounts from local sources.

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Correctly identifying historical events is challenging. It is highly likely that previous estimates of GLOF numbers have underestimated actual occurrences, due to a lack of accessible reports as well as many GLOFs that occurred in remote areas with no discernible impacts on livelihoods or infrastructure (Veh et al., 2022; Zheng et al., 2021b). In this study, we have included events previously reported in scientific literature as well as reports from regional media or records from local civil society organisations. Reliance on this expanded source list introduces an inherent risk of overreporting, which must be accounted for. When debris flows or even pluvial floods reach mountain settlements they are often identified as GLOFs, without proof of their source. This happened, for example, after the Chamoli rockslide (Shugar et al., 2021) and regularly happens when debris flows occur in the Upper Indus Basin. Verification of the source is, therefore, essential. If satellite imagery is available, we verified whether the typical v-shaped moraine breach as well as deposits are visible (Zheng et al., 2021b). For historic events, we ascertained whether a GLOF is technically possible (i.e., if there are lakes in the upstream). High resolution 15 cm HD Maxar satellite images (available through ArcMap) were consulted to confirm doubtful events. Being able to rely on a variety of independent sources, and check with stakeholders involved in hazard response in affected regions, we are able to corroborate between multiple sources. As a result, we discarded numerous previous events as unlikely or not verifiable in a separate table (HMAGLOFDB_removed.csv).

Although the term GLOF would suggest that a glacier needs to be somewhere adjacent, we also include lake outburst floods that have happened far away from any glacier (e.g., Lang Co in the Eastern Himalaya in 2007, 91.807 E 27.828 N) as they appear in a landscape that was most likely glaciated at one point.

A number of regional delineations exist for HMA, including the one following RGI (Pfeffer et al., 2014), the HiMAP report (Bolch et al., 2019), an outline favoured by scientists focusing on the Tibetan Plateau (Nie et al., 2017) and the outline of the HKH by ICIMOD. None of these agree with each other, making comparisons of regional statistics very difficult. All our GLOFs are consequently georeferenced and the respective area codes for the RGI and HiMAP inventory are provided to allow aggregation. Discussing regional patterns, we follow the delineation of the HiMAP report, but bin together all subregions of the Tien Shan (inventory OBJECTIDs 1-3) to ‘Tien Shan’, Pamir and Alay (5 - 7) to ‘Pamir’, West (10) and Central (11) Himalaya to ‘Himalaya West/Central’, the Western Kunlun Shan (13) and the Karakoram (9) to ‘Karakoram’, Nyainqentanglha (18), Gangdise Shan (17), Hengduan Shan (20) and Eastern Himalaya (12) to ‘Himalaya East/Hengduan Shan’ and all remaining subregions on the Tibetan Plateau and its fringes (14 - 16, 19, 21, 22) to ‘Tibet’.

2.3 Data structure

Only a few studies on GLOFs have accessible inventories of events and those are limited to global assessments (Carrivick and Tweed, 2016; Veh et al., 2022). Studies with more detailed information on individual events generally do not have accessible inventories, focus on only a certain type of GLOF (Veh et al., 2019a) or do not include more than type of lake and location (Zheng et al., 2021b). As information on individual events may be added in future (e.g., on triggers or direct and indirect impacts) and continuously more GLOFs are reported, a database where changes can be traced and new releases are possible in the future (Blischak et al., 2016) is crucial and has been successfully employed for cryosphere data (Welty et al., 2020). A database with a clear structure should also be accessible by non-academic stakeholders who are not well versed in machine-readable data (i.e., simple and easily understandable .csv or .txt files with clear Metadata) as well as scientists who may want to couple it to other regional datasets. Multiple datasets related to the cryosphere are already easily accessible (e.g., historic glacier outlines, dh/dt, glacier lakes, permafrost extents) and can be easily combined with an inventory of GLOFs.

Future events will be updated directly in the database in .git on a rolling basis. Quality control will be performed on new events each year, at which time the database will also be updated on the RDS, where the DOI will remain the same.

All GLOF events are stored in a single *.csv file. Each event has a unique identifier, which follows the same format used previously for glaciers (GLIMS ID), here using the format GFXXXXXXEYYYYYN_Z, where X denotes the longitude, Y the latitude and Z is a counter for GLOFs that repeatedly occur from a single lake, starting at 0. Where available, coordinates of the source of the GLOF as well as the final impact location downstream are provided. IDs of the source lake and associated glacier are given where known and existent. Information on impacts on livelihoods and infrastructure are provided in quantitative as well as qualitative terms, making it possible to machine read the database, while retaining information that may not be readily quantifiable. Sources of all events are provided (scientific, media, oral). A separate metadata file specifying input format and units is provided as a *.txt file (HMAGLOFDB_Metadata.txt), which is also machine-readable.

GLOFs that have been found in other sources but were found not to be associated to lake drainage or breach are stored in a *.csv with the same format as described above, with a separate column explaining what the reason for exclusion was.

Table 1: Variables for the GLOF database. Format is either alphanumerical (*A/N*), random text (*TXT*), text from a prescribed list (*STR*) or an integer (*INT*). If an exact number is not available but is non-zero a '+' is provided (e.g. 'multiple injured'). '*NA*' is used for unknown input. Note that the Metadata file itself provides further details on the individual variables as well as a discussion on naming.

Variable	***Format***	***Description and unit***
GF_ID	A/N	Unique identifier based on the GLOF location and repeat occurrence if applicable (GLIMS format)
Year_approx	TXT	Year of occurrence; given approximately if GLOF has been identified from imagery with no definite account.
Year_exact	INT	Exact year of occurrence
Month	INT	Month of occurrence
Day	INT	Day of occurrence
Lake_name	TXT	Local name of the lake if available.
Glacier_name	TXT	Local name of the glacier associated with the lake.
GL_ID	A/N	Unique identifier for the lake (GLIMS format)
G_ID	A/N	Unique identifier for the glacier (GLIMS format) associated to the lake
LakeDB_ID	INT	Identifier in which lakes database the lake has been mapped

Lat_lake	INT	Decimal latitude of lake
Lon_lake	INT	Decimal longitude of lake
Elev_lake	INT	Elevation of lake [m a.s.l.]
Lat_impact	INT	Decimal latitude of lowest known impact of the GLOF
Lon_impact	INT	Decimal longitude of lowest known impact of the GLOF
Elev_impact	INT	Elevation of lowest known impact of the GLOF [m a.s.l.]
Impact_type	STR	Quality of impact record; 'Observation' refers to lowest observed high flow or damages; 'Deposit' refers to lowest visible deposit of sediments (from satellite imagery). Impacts are therefore conservative, and are likely always further downstream than recorded
Lake_type	STR	Type of lake (e.g., moraine dammed, ice dammed, bedrock etc.)
Transboundary	STR	Denotes if impact is potentially transboundary
Repeat	STR	GLOF that occurred again in past or future
Country	STR	Current national borders (2022) the source lake lies in
Region_RGI	STR	Region ID as used in the RGI 6.0 (Pfeffer, 2017)
Region_HiMAP	INT	Region ID as used in the HiMAP report (Bolch et al., 2019)
Province	STR	1st level province name
River Basin	STR	River basin the lake is located in
Driver_lake	STR	Driver that caused the lake to form
Driver_GLOF	STR	Driver that caused the GLOF to occur
Mechanism	STR	Mechanism involved in lake breach or drainage
Area	INT	Lake area [m^2]
Volume	INT	Volume of the drained lake water [m^3]
Discharge_water	INT	Measured or estimated water discharge downstream [m^3s^{-1}]
Discharge_solid	INT	Measured or estimated debris flow discharge downstream [m^3s^{-1}]
Impact	TXT	Narrative description of downstream impacts
Lives_total	INT	Total lives lost
Lives_male	INT	Total male lives lost
Lives_female	INT	Total female lives lost
Lives_disabilities	INT	Total lives of people with disabilities lost
Injured_total	INT	Total injured
Injured_male	INT	Total male injured

Injured_female	INT	Total female injured
Injured_disabilities	INT	Total people with disabilities injured
Displaced_total	INT	Total people displaced
Displaced_male	INT	Total male displaced
Displaced_female	INT	Total female displaced
Dispaced_disabilities	INT	Total people with disabilities displaced
Livestock	INT	Livestock lost
Residential_destroyed	INT	Number of residential houses destroyed
Commercial_destroyed	INT	Number of commercial houses destroyed
Residential_damaged	INT	Number of residential houses damaged
Commercial_damaged	INT	Number of commercial houses damaged
Infra	TXT	Other destroyed infrastructure
Agricultural	INT	Area of farmland destroyed [m^2]
Hydropower	INT	Installed hydropower capacity destroyed [MW]
Econ_damage	INT	Total economic damage [USD]
Ref_scientific	TXT	Citation of scientific source
Ref_other	TXT	Description of other sources
Remarks	TXT	Any other remarks
Removal_reason	TXT	Reason for removal (only for separate database of removed events)
Certainty	INT	Certainty that the removed case is either definitely not a GLOF (0) or may be but was removed due to lack of evidence (1)

3 Results

3.1 Lakes

For the years 2000, 2010 and 2020, respectively, a total of 1610, 1666, and 1725 glacial lakes larger than 0.003 km^2 were identified with a total area of 221.40 km^2, 250.63 km^2, and 269.28km^2. In 2020, lakes were more densely distributed in the Central (34%) and Eastern (29.6%) Himalaya, and sparsely distributed in the Karakoram (4.3%). During the past 20 years, the number of lakes increased by 7.1% and the total area by 21.6%, indicating growth rates of about 0.4% a^{-1} and 1.1% a^{-1}, respectively.

Lakes smaller than 0.1 km^2 made up the largest proportion of all lakes (1180; 68%) in 2020, but lakes larger than 0.1 km^2 contributed 83.08% of the total area. Lakes between 0.2 to 1 km^2 contributed most to the total expansion of glacial lakes, with

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an area increase of 16.2% during the 20 year period. Only 8 lakes were larger than 3 km^2, but they contributed 13.7% of the total area which is equal to the area contributed by 253 glacial lakes between 0.1 and 0.2 km^2.

Glacial lakes were found between 2500 and 6000 m a.s.l., with more than 70% of the lakes being concentrated between 4500 and 5500 m asl. Only 0.4% of the lakes were situated below 3500 m a.s.l., while 15% were above 5500 m a.s.l. Between 2000 and 2020 the expansion of glacial lake area was highest between 2500 and 3500 m (47%) and 5500 and 6000 m a.s.l. (25%).

3.2 GLOFs

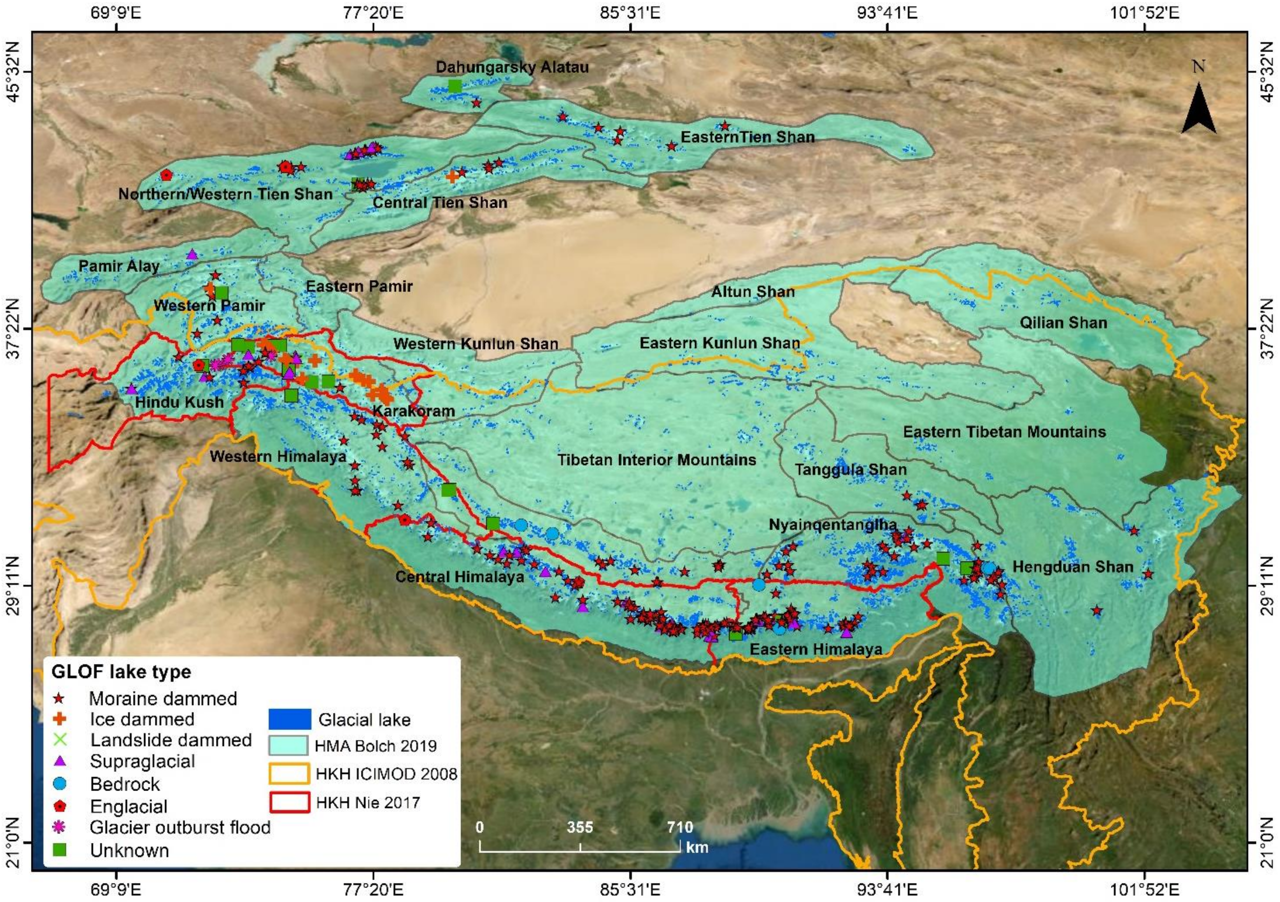

Figure 1: Overview map showing all recorded GLOFs in HMA according to the lake type. The 2018 lake inventory shown here is from (Wang et al., 2020). The HMA outline used is following (Bolch et al., 2019). The external lake database (WangDB, ChenDB) fall within this outline. The HKH outline is based on ICIMOD[1] and (Nie et al., 2017)

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[1] https://rds.icimod.org/Home/DataDetail?metadataId=3924

Figure 2: (A) Dig Tsho GLOF (1985; database ID GF086586E27874N_0) in the Central Himalaya (Nepal) from a moraine-dammed lake. Note the settlements and agricultural land impacted in the lower reach of the deposit. The photo was taken in 2009 (Sharad Joshi). (B) Bam Tanab GLOF in the Hindukush (Afghanistan) in 2021 from a supraglacial lake (GF069638E35460E_0). The ice tunnel, through which the lake drained is visible in the center. Note the two persons sitting on top of the ice cliff, just right of the top of the big boulder in the foreground. The photo was taken several days after the event (Milad Dildar). (C) Ice tunnel exit at the terminus of the tributary to Badswat Glacier that caused a GOF in 2018, eroding substantial amounts of the moraine in the immediate downstream (Karakoram, Pakistan, GF074060E36505E_0; Sher Wali). (D) Ice dam at Khurdopin Glacier caused by a surge. The terminus moraine is visible in light grey on the left, partly covered by the spillover ice from the surge. The lake at this location refills multiple times after the surge, sometimes up to half of the moraine height (note the water line is slightly visible from a change of colour). Photo taken from the location where the lake drains under the surged ice (multiple events under GF075474E36344N; Sher Wali).

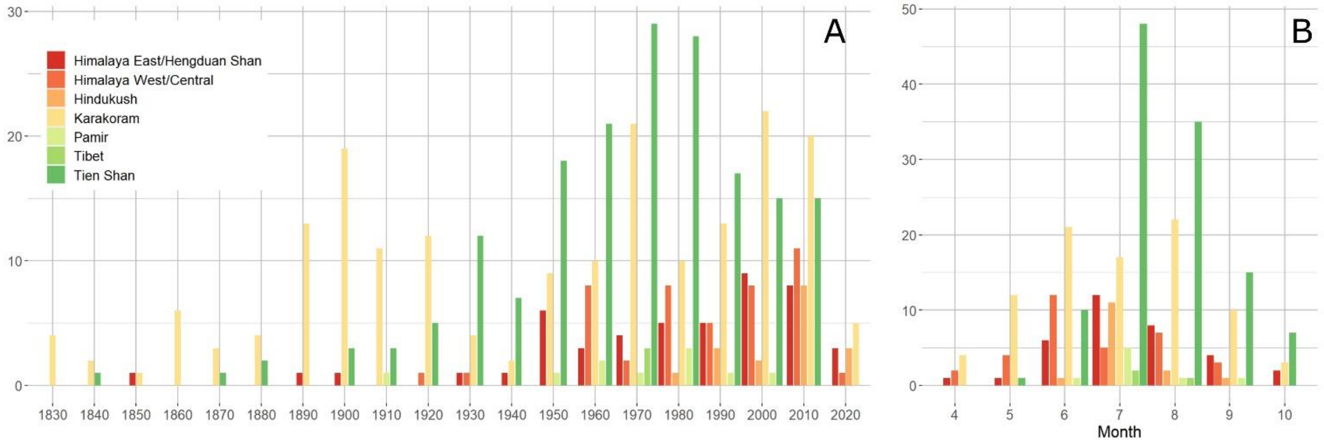

Figure 3: (a) Temporal evolution of recorded GLOF occurrence per region and decade. (b) Seasonal occurrence of GLOFs. Months November to March are not shown, with total events <5.

Our database includes 682 individual GLOF events (Figure 1, Figure 2), recorded between 1833 (with 4 historic events before that date, where any validation of processes is virtually impossible) and 2022 (Figure 3a). 7% (45 of 682) of the reported GLOFs here have not been mentioned in any previous study. Conversely, 120 previously reported GLOFs were removed based on new evidence to the contrary (16) or a lack of strong evidence (104) for it being a GLOF.

29% of these were recorded in China, 22% in Kyrgyzstan, 21% in Pakistan, 9% in India, 8% in Nepal, 5% in Kazakhstan, 3% in Bhutan, 1.6% in Tajikistan and 0.6% in Afghanistan. Following the RGI delineation, 29% of the GLOFs were recorded in the Karakoram, 19% in the Eastern Himalaya and 28% in the Western Tien Shan. Due to different choices in delineations, this looks considerably different for the HiMAP outlines where 29% are in the Karakoram, 17% in the Northern/Western Tien Shan, 15% in the Central Himalaya and 11% in the Eastern Himalaya.

For 306 events (45%) we know the month of occurrence and, of these, 74% took place between June and August (Figure 3b). Only 3% of all GLOFs were recorded between November and March. For 256 events (27%) the day of the GLOF is known, potentially allowing an analysis of prevailing weather patterns preceding the outburst.

The mean elevation of lakes associated to a GLOF was 4175 m a.s.l. (n = 675; min = 2530 m a.s.l., max = 5982 m a.s.l.). For the GLOFs where impacts were recorded (n=462; 68%) the average elevation difference between lake and lowest recorded impact was 1138 m a.s.l. (min = 19 m a.s.l., max = 4431 m a.s.l.).

49% of GLOFs originated from moraine-dammed lakes, 32% from ice-dammed and 11% from supraglacial lakes (Figure 1). Other types occurred infrequently and particular glaciers were associated with repeated flood events, including englacial outbursts (3%), outbursts from bedrock lakes in periglacial terrain (1%), outbursts from landslide dammed lakes that formed below glaciers (0.5%) and rapid drainage from supersaturation of meltwater in crevasses at the tongue that subsequently led to moraine failure (0.6%). This latter case, only reported in 4 cases between 2005 and 2018 all in the Upper Indus Basin are technically not a GLOF, since no lake ever exists, and we refer to it as a glacier outburst flood (GOF). Multiple events in the Bagrot subbasin in the Upper Indus, as well as in the Ala Archa basin in Kazakhstan may be of similar origin. For the latter, we have removed many, as even previous authors did not insist on all being GLOFs (Medeu et al., 2016). These events all occurred at the terminus of very steep glacier tongues and some observed characteristics of these events (e.g. melt water to the base resulting in ice and terrain collapse) resemble glacier detachments (Kääb et al., 2018). However, the eventual runout as a debris flow with high water content is markedly different. For 4% of the cases, the lake type was unknown, in general, for GLOFs for which no satellite imagery exists for validation.

Our knowledge of the mechanisms of how lakes are formed (known for 20% of the cases), triggering (12%) and failure mechanisms of the outburst is (23%) remains limited (Figure 4). Even less is known about the drained total volume (m^3, 12%), discharge of water (m^3 s^{-1}, 11%) or discharge of solids (m^3 s^{-1}, 2%), important variables for modelling studies. Additionally, these reported values are often associated with large uncertainties.

Of all GLOFs, 2 were located in an area where no glacier could be found anywhere upstream. However, they are located in areas that were most likely glaciated. 22 occurred below glaciers that were not mapped in RGI 6.0, showing the still considerable number of glaciers that are missed from global inventories. Similarly, 10 GLOFs (at moraine-dammed lakes) were recorded where no lake was apparent in any satellite imagery. This is possible for GLOFs recorded before the satellite age. In 97 cases, a lake or depression was visible but not mapped in any of the inventories. In 192 cases (28%) the lake is ephemeral and hence not in any inventory, especially the case for ice-dammed or supraglacial lakes. Some ice-dammed lakes were in inventories, if they were present at the time of the inventorization. However, when comparing this data to a GLOF, their area should be taken with caution, considering their rapid change with a change in meltwater availability.

26 GLOFs (4%) have 6907 recorded fatalities (Table 2), although 6000 were attributable to a single event in India in 2013, where fatalities were caused by a multitude of factors in a complex compound event (Allen et al., 2016). This latter event, until recently, accounted for nearly 50% of recorded global GLOF deaths (Carrivick and Tweed, 2016). Nearly all casualties have been attributable to GLOFs from moraine-dammed or supraglacial lakes, while no fatalities have been linked to ice-dammed lake breaches (Table 2), while there may of course have been unrecorded impacts (Hewitt and Liu, 2010). Numbers on injured or displaced remain rare, but are likely much higher, especially considering people moving away, many in the months after an event due to the long-term negative impacts of damaged infrastructure. Nearly 2000 livestock were reported killed. More than 2200 residential and commercial buildings were reported destroyed or significantly damaged and numerous bridges were destroyed. At least 71 km^2 of agricultural land was destroyed and hydropower structures with a combined capacity of 164 MW were destroyed or heavily damaged. In only a few cases (n=13) were estimates of economic damages in monetary values attempted (5.3 billion USD). These were limited to damages associated with the flooding and did not include considerations of the longer-term economic toll of damaged infrastructure, disablement, destroyed farmlands, or the long term impacts on accessibility of health, education or market facilities due to impacts on transport infrastructure.

Table 2: Number of GLOFs per region and type of lake with associated fatalities (N/fatalities).

	Pamir	Tien Shan	Tibet	Hindukush	Karakoram	Himalaya West/Central	Himalaya East/Hengduan Shan
Moraine-dammed	6/25	96/65	4/0	10/20	7/0	78/6236	132/454
Ice-dammed	4/0	67/0	0/0	0/0	144/0	0/0	0/0
Supraglacial	1/100	17/0	1/0	3/0	26/1	19/0	1/0
Others/unknown	1/0	16/0	0/0	6/3	19/2	2/0	15/0
TOTAL	**12/125**	**195/65**	**4/0**	**19/23**	**196/3**	**99/6236**	**157/454**

342 lakes were associated with 682 GLOFs, with 64 (9%) of the lakes causing a GLOF more than once and the 17 (2%) lakes releasing GLOFs at least five times, made up more than 40% of all GLOFs (Table 3). The return period of some of these GLOFs is rapid, occurring repeatedly over consecutive years such as at Merzbacher or Khurdopin, while for others a GLOF may occur more than decades apart. In many cases, for ice-dammed lakes, this is coupled with the return period of the respective glacier surge. Many of these lakes have resulted in GLOFs until very recently and we hence consider *active*. Others, like the GLOFs at Chong Kumden (ice-dammed), are considered inactive as the tongue has receded so far that even during a surge it cannot block the valley anymore. For Salyk or Topkaragay (moraine-dammed), the tongue recession has presumably also resulted from a lack of direct meltwater supply to the local depression. While the three lakes draining most frequently (and all still *active*) are all ice-dammed, repeat GLOFs are common from all major types of glacial lakes (Table 3). However, repeat drainages are decidedly uncommon in the Himalaya or the Tibetan Plateau.

191 (28%) were potentially transboundary GLOFs, 55 of which originated in China. Fewer than 10 potentially transboundary GLOFs have impacted across borders (China to Nepal and Uzbekistan to Kyrgyzstan).

Table 3: Lakes with more or equal to five recurring GLOFs in HMA.

Lake/Glacier name	Lat (°)	Lon (°)	Elev (m a.s.l.)	Region	Outburst recurrence	Period of GLOFs	Lake type
Merzbacher/ Southern Inylshek	42.20	79.85	3271	Central Tien Shan	67	1902 - 2015	Ice dammed
Khurdopin/Khurdopin	36.34	75.47	3482	Karakoram	37	1882 - 2021	Ice dammed
Kyagar/Kyagar	35.68	77.19	4880	Karakoram	34	1880 -2019	Ice dammed
Unnamed/Aksay	42.53	74.54	3637	Northern/Western Tien Shan	30	1877 - 2015	Moraine dammed

Lake/Glacier name	Lat (°)	Lon (°)	Elev (m a.s.l.)	Region	Outburst recurrence	Period of GLOFs	Lake type
Unnamed/Kuturgansuu	42.52	74.61	3470	Northern/Western Tien Shan	17	1846 - 2010	Moraine dammed
Unnamed/Chong Kumden	35.17	77.70	4691	Karakoram	14	1533 - 1934	Ice dammed
Hassanabad/Shisper (both names for lake and glacier)	36.39	74.51	3370	Karakoram	13	1894 - 2022	Ice dammed
Karambar/Karambar	36.62	74.08	2935	Karakoram	11	1844 - 1994	Ice dammed
Unknown/Teztor	42.54	74.43	3606	Northern/Western Tien Shan	11	1910 - 2012	Moraine dammed
Ghulkin/Ghulkin	36.42	74.88	2692	Karakoram	8	1980 - 2009	Supraglacial
Lake number 6/ Glacier No 182/Bezymyannyi/TEU-Severny	43.14	77.28	3380	Northern/Western Tien Shan	8	1973 - 2014	Supraglacial
Unnamed/Halji	30.27	81.48	5347	Central Himalaya	6	2004 - 2011	Supraglacial
Unnamed/Salyk	42.52	74.72	3390	Northern/Western Tien Shan	6	1938 - 1980	Moraine dammed
Unnamed/Topkaragay	42.49	74.52	3680	Northern/Western Tien Shan	6	1928 - 1993	Moraine dammed
Unnamed/Central Rimo	35.42	77.61	5100	Karakoram	5	1976 - 2014	Ice dammed
Unnamed/Batura	36.51	74.85	2713	Karakoram	5	1873 - 1974	Supraglacial
Unnamed/North Terong	35.25	77.31	4400	Karakoram	5	1975 - 2002	Ice dammed

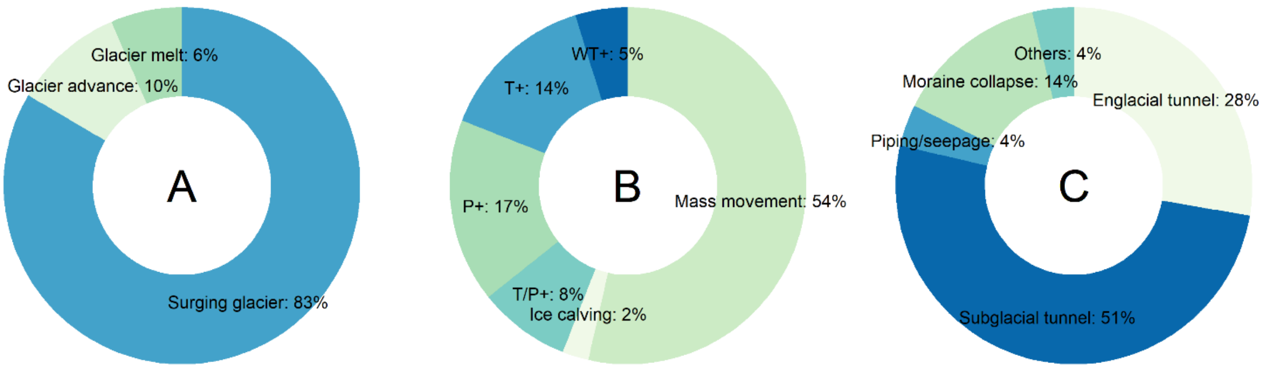

Figure 4: Different drivers that caused the lake to form (n=139) (A), caused GLOF to occur (n=84) (B), and mechanisms involved in lake breach/drainage (n=159) (C). T, P and WT+ stand for reported temperature, precipitation and water table and temperature increases, respectively. Mass movements include ice and rock avalanches as well as landslides, debris flows and other flood events. Moraine collapse is most often characterized by ice core thawing.

3.2.1 Uncertainty of individual variables

GLOFs often occur in remote areas, where reports are scant and confirming process chains and quantifying associated volumes and impacts is challenging. Here we discuss the uncertainties related to variables documented in this database. For many GLOFs (187; 27%) even the year of occurrence is uncertain, which is reflected in the database by either providing NA or a time window during which it must have happened. Days of occurrence (available for 27% of the records) are often also different between reports on the same event, either due to erroneous records or the magnitude of certain GLOFs resulting in floodwaters reaching areas over more than one day. Any recorded day hence likely has an uncertainty of +/-3 days. Coordinates of the source lake are correct if provided, however, do not reflect the exact location of the breach but any coordinate within the perimeter of the lake. Coordinates of the impact area are a lot more uncertain. If provided they show either the lowest location were deposits are still visible on Maxar imagery from 2021 (*Deposit*) or where high flow or damages were reported (*Observation*). This naturally is a conservative estimate and high flows likely have reached hundreds of meters further downstream and even deposition or erosion may have occurred in the riverbed, but may not be visible on imagery. Elevation values are generally retrieved via the coordinates from the SRTM, hence resulting in a vertical accuracy between 10 and 50 m, considering we are in steep terrain, where errors are frequent.

When reporting the area or lakes associated to GLOFs we refer to the reported value in the respective study or estimates from a satellite imagery close before the drainage date, while for further analysis we use lake areas reported in the inventories. Lakes that eventually drain often change their area rapidly in the weeks and days leading up to eventual failure of the dam or opening of the tunnel. This is especially true for ephemeral ice dammed lakes (Muhammad et al., 2021; Round et al., 2017; Steiner et al., 2018). Therefore, the lake area mapped many weeks or even months before a drainage event is not necessarily a good proxy for the actual water volume that drained. We report estimated drained volumes and sometimes even estimates of discharge exist, however the accuracy of such estimates is impossible to verify and measurements during GLOFs rarely possible (Muhammad et al., 2021).

Estimates on impacts are conservative. Often there exists no regular media coverage on remote villages and reported numbers of people killed or infrastructure impacted can either be deflated or inflated either due to inaccurate transmission of information or wilful tampering with data for political reasons. If impacts couldn’t be verified by generally trustworthy sources they were not reported.

4 Discussion

4.1 Comparison of lake databases

We join the database of GLOFs with two existing and a new lake database. This allows us to evaluate our ability to capture potentially dangerous glacial lakes with satellite imagery. As the database using manual delineations is only available for the HKH region, the following comparison is only done for lakes and GLOFs that took place within this region. Figure 5a shows that the manually delineated inventories for lakes (Maharjan et al., 2018; Wang et al., 2020) is able to capture more smaller lakes. For 380 GLOFs (56%) a mapped lake can be associated from any of the inventories, the rest are not mapped (14%), of ephemeral nature (28%) or there is no lake apparent (1%). Their mean area is 174983 m^2 (min 1752, max: 5623530, σ=526176). The smallest lake captured is 1752 m^2 for the database presented in this manuscript and 4644 m^2 (Wang et al., 2020) respectively, while the fully automated product (Chen et al., 2021) does not capture lakes smaller than 8100 m^2. 6 lakes associated to GLOFs were smaller than 4644 m^2 (3% of all GLOFs with areas), 23 smaller than 8100 m^2 (10%).

The lakes are similarly distributed across altitude, but it is also obvious here that the manual approaches manage to capture more lakes, especially at high elevations, considering that the ICIMOD dataset covers only one year in this case (2005, WangDB covers two (1990 and 2018) and ChenDB covers ten (2008 – 2017; Figure 5b). The distribution of lakes that caused outburst floods, suggests that the susceptibility simply follows the presence of lakes and the highest lakes (>5000 m a.s.l. compared to lakes between 3500 and 5500 m a.s.l.) are not less likely to cause a flood. However a larger number of GLOFs happened low elevations (<3500 m a.s.l.), where relatively fewer lakes were mapped. This suggests that lakes at this elevation in general have a higher probability to cause a GLOF.

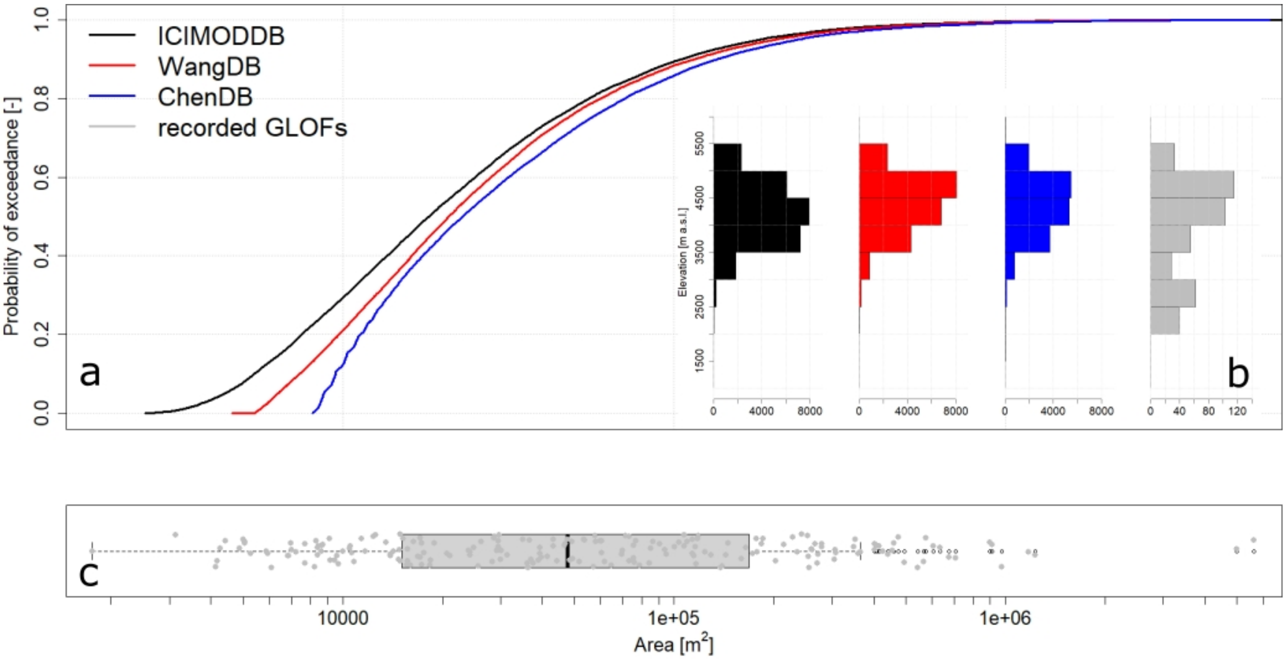

Figure 5: (a) Cumulative distribution function for areas of all lakes mapped within the HKH (see text for description of spatial domain). Note that for the ICIMOD dataset only data from 2005 is used, as other years were only covered for a subset of the HKH. (b) Elevation distribution of lakes of all inventories in the HKH domain as well as lakes with recorded GLOFs in the same area. (c) Distribution of areas of all recorded GLOFs within the HKH.

4.2 Temporal and spatial trends

The discussion on whether GLOFs are increasing with a changing climate trend goes beyond the scope of this manuscript and has been dealt with elsewhere in detail (Harrison et al., 2018; Veh et al., 2022). We here provide just a brief discussion that stems from the compilation of the data. Figure 3a shows a clear and rapid increase of recorded events in the Tien Shan from mid century with a subsequent decrease in the 1990s. If we would have considered the 104 doubtful events, many of which were recorded in this region between the 1970s and 1990s, this peak would be even more pronounced. There is little indication for this being climate related but we hypothesize that it is more related to the extensive efforts of scientists at the end of the Soviet era to monitor debris flows (and as a consequence related GLOFs), which died down as the Central Asian states became independent. Conversely for the Karakoram there are many peaks starting at the turn of the 19th century, which could be either explained by surge cycles occurring around the same time, resulting in ephemeral ice dammed lakes or the interest of the British Empire around the turn of the century in the region during the Great Game (most reports on GLOFs stem from British officers stationed in the region, cf. Hewitt and Liu, 2010), a decrease in interest until Independence and finally an increase again as seen in other areas with increased infrastructure development and the arrival of media. There is a more consistent increase of events in the Hindukush and the Himalaya region, albeit at a lower number (i.e. <1 event yr^{-1} for a whole region) and going in line with a general steep increase in the topic in the region (Emmer et al., 2022).

The seasonal patterns (Figure 3b) are instructive as they show a clear earlier peak in the year for the Himalaya region, a more stretched out peak in the Karakoram and shift in the Tien Shan, influenced by Westerlies rather than the South Asian Monsoon.

4.3 Statistics of lakes with and lakes without GLOFs

Combining the lake and GLOF inventories allows for a comparison of topographic as well as meteorological characteristics of lakes that resulted in GLOFs and those that did not. This is useful for the identification of potentially dangerous lakes (Ahmed et al., 2022; Ashraf et al., 2021, 2012; Bajracharya et al., 2020; Bolch et al., 2008; Duan et al., 2020; Zhang et al., 2022b). The evaluation of meteorological conditions would require an in depth discussion of the respective datasets and wider synoptic conditions, attempted previously for mudflows (Mamadjanova et al., 2018), but going beyond the scope of this study. Topographic data is more straightforward to evaluate. Figure 6 shows area, area change, horizontal distance to the nearest glacier and the average slope in the immediate environment of the lake for all lakes in HMA in the WANGDB as well as for all lakes where a GLOF was recorded. The hypothesis would be that lakes resulting in GLOFs are on average larger (providing more volume for an outburst), show a larger increase in area (resulting in moraine instabilities), are located closer to the glacier itself (favouring calving events), and are located in generally steeper terrain, favouring mass movements into the lake, a frequent driver (Figure 4), as well as a rapid propagation downstream. Lakes that resulted in a GLOF are on average larger (175000 m^2) than the average lake (60000 m^2), however also many small lakes that do not even appear in the lake inventory resulted in GLOFs. The change in lake area (here only shown between 1990 and 2018) is positive on average for all lakes ($\mu = 372$ m^2 yr^{-1}), in line with the general trend of lake area increase in the region, but lakes with GLOFs do not show a distinctly larger increase (or decrease) in area over that time period (μ = 76 m^2 yr^{-1}). Future studies should make use of inventories that are available at shorter time intervals and investigate time periods specifically before the actual GLOF events. Lakes that resulted in GLOFs are furthermore not located closer to glaciers on average (μ = 1600 m and 1800 m respectively). Note however that we are using a glacier inventory from a specific point in time, that may not be accurate for the time step the lake or GLOF was observed. The point to make here is that to simply take a glacier inventory like RGI and any lake inventory may not be useful in finding lakes that are more or less likely to result in GLOFs in future. Comparing slopes around lakes, suggests that GLOFs are indeed more likely when the lake is in steeper terrain (μ = 18.5 and 22.4° respectively). Future investigation should differentiate between areas above and below lakes, focusing specifically on surrounding headwalls and the immediate downstream area potentially subject to a flood.

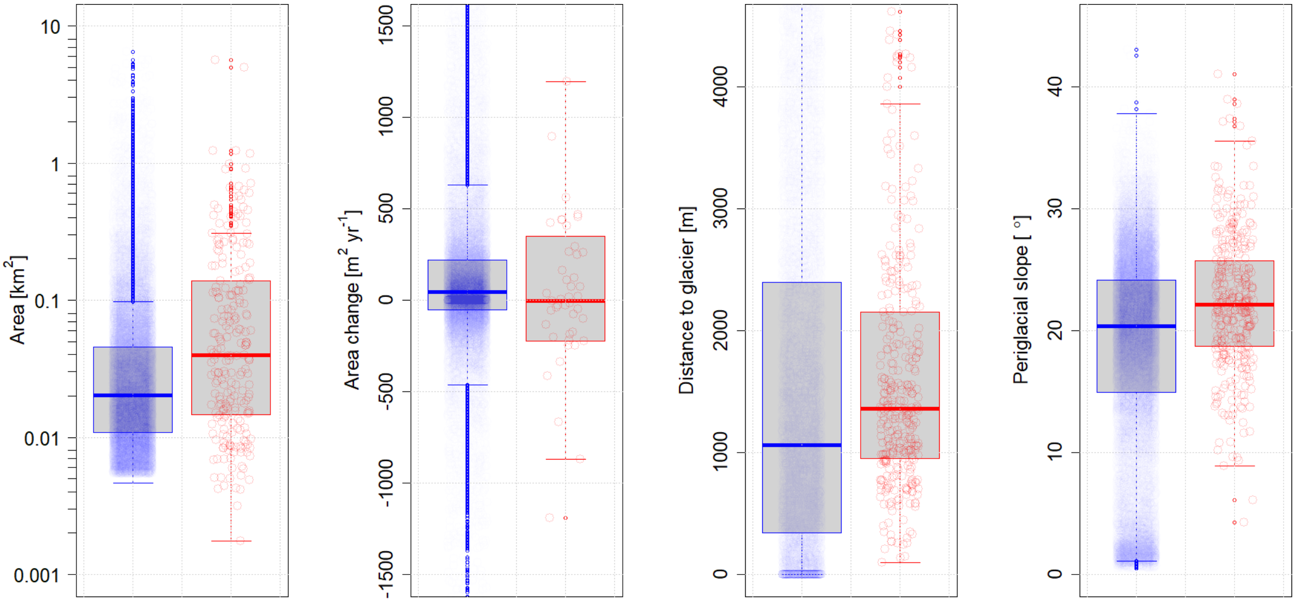

Figure 6: Properties of all lakes (blue; from WangDB) and lakes that experienced GLOF events (red). Area change is calculated only between the two time steps available (1990 and 2018). Distance to glacier is the horizontal distance to the closest glacier mapped in RGI 6.0. Periglacial slope is the mean terrain slope in a square with 2km width around the lake.

4.4 GLOF paths

Records of the extent of GLOF events (n=463) allows for an evaluation of GLOF paths (Figure 7). Exploiting other spatial datasets this can help in evaluating possible drivers as well as impacts. Repeat spatial products related to the cryosphere available in HMA include decadal glacier outlines (Bajracharya et al., 2014; He and Zhou, 2022; Lee et al., 2021; Vatsal et al., in review; Xie et al., in review), distributed data on ice mass loss (Brun et al., 2017; Hugonnet et al., 2021), permafrost probability (Obu, 2021) and snow cover (Muhammad and Thapa, 2021). Such datasets can be compared against recorded GLOF events as well as all other lakes that never resulted in GLOFs to evaluate potential drivers. The risk of a GLOF is closely associated to moraine stability, which in turn is linked to the immediate history of glacier retreat in the area. Areas of recent permafrost change are likely also more susceptible to mass movements, which have already been identified as important drivers of GLOF events (Figure 4).

On the downstream, distributed datasets on infrastructure, population or ecosystems allow for assessments of impacts and vulnerabilities (Figure 7). Coupling of GLOF paths with distributed population data would allow for the computation of people actually impacted, combining with remotely sensed vegetation and agriculture data would allow for estimates on local economic and ecological impacts. GLOF paths could also be used to develop hazard zonation maps, as is standard practice for avalanches in many regions.

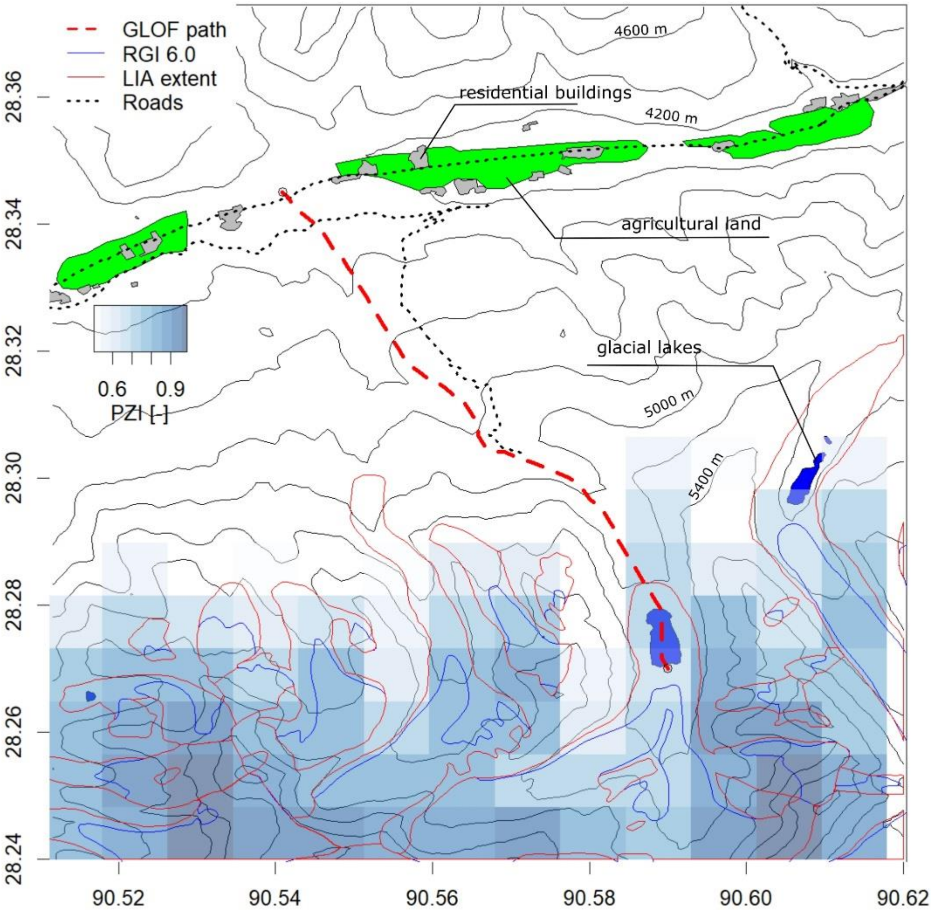

Figure 7: Extracted GLOF path for one event (ID GF090590E28274N_0), showing the RGI 6.0 outline, the possible glacier extent during the little ice age (Lee et al., 2021) and probability of permafrost occurrence (PZI, Obu, 2021). Shape files of roads are taken from OSM, residential and agricultural areas are mapped from Maxar imagery. With exception of labels the figure can be directly created in the available R code from the data database.

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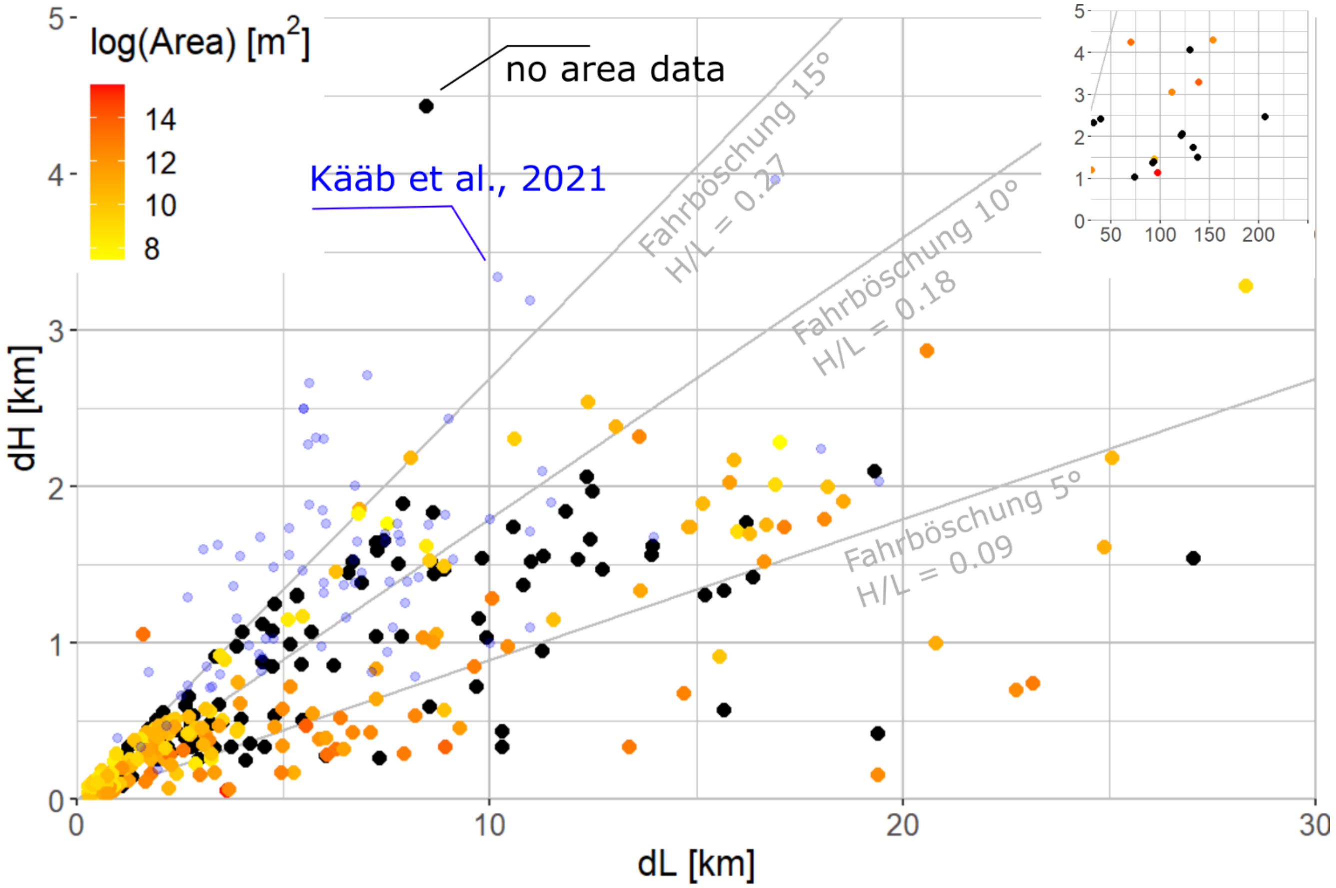

Figure 8: Reach angles (*Fahrböschung*) for all GLOF events with recorded downstream impact location (n=463). Black dots are events where no recorded lake areas exist. Shaded from yellow to red are GLOFs for which some record of lake area exists (either from the original source or a lake database), that may not necessarily be the lake area just before the event. In light blue records from (Kääb et al., 2021) are shown, which largely relate to glacier detachments or historic large scale debris flows and GLOFs.

For GLOFs where the location of the lake and the lowest recorded evidence of the outburst flood wave (either reported flood or observed debris deposits), we are able to calculate reach angles, i.e. the elevation difference over the distance of the flood path between start and end point (Figure 8). With a median runout length of 7.2 km (μ = 32 km, biased towards a few events of exceptional reach; Figure 8 inset) and a median elevation drop of 1032 m (μ = 1138 m), the mean reach angle is 0.14 (σ=0.09; 8°). Nearly all of the markedly cluster below a reach angle of 0.27 (15°, Figure 8), considerably shallower than large scale mass flow events like glacier detachments (Kääb et al., 2021). While it would be possible to establish lake volumes from lake areas (Cook and Quincey, 2015), the inherent uncertainties in these approaches and the discrepancy between date of lake mapping and GLOF event makes this unfeasible for an adequate discussion within this manuscript. We therefore only use areas from the available WangDB inventory or mapped areas from just before the event as a proxy (Figure 8). Lakes with an area larger than 10^5 m^2 (n=87) result in reach angles of 0.09 (4.9°), lakes smaller (n=179) in slightly steeper angles of 0.13

(7.5°), suggesting that the size of a GLOF holds some potential for projecting its reach, apart from the many other factors influencing.

4.5 Downstream impacts

Not considering the single Kedarnath event in 2013, where 6000 people were reported killed but that included a number of other hazards beyond the GLOF, 907 people were reported to be killed directly by 24 GLOFs. This number is three times higher than the previous record of 300 (Carrivick and Tweed, 2016). Comparing this number to other mountain hazards in the region is difficult, as data are rare. Snow and ice avalanches (excluding mountaineering accidents) in the same region have resulted in more than 3000 fatalities, with records only starting in the 1970s (Acharya et al., in review). Nepal alone reports more than 100 fatalities due to lightnings per year (Sharma et al., 2022). Landslide fatalities for countries entirely in HMA suggest 67 deaths in Afghanistan, 50 in Bhutan, 809 in Nepal and 75 in Tajikistan between 2004 and 2010 (Petley, 2012), suggesting this hazard to be considerably more dangerous to human life.

Impacts beyond fatalities have been recorded in numerous cases, but a socioeconomic valuation of the same remain lacking. While few individual events have records of some monetary damage by the immediate event, this often only includes the value of expensive national infrastructure like hydropower projects. Value of agricultural land, residential or commercial buildings, or long term damage due to damage to road, health or education infrastructure are never assessed. Infrastructure datasets that allow for a rapid assessment of damage are generally not available. Such an assessment was attempted for GLOFs globally before (Carrivick and Tweed, 2016), would however require a more thorough discussion of available impact datasets for HMA. Many of these data are available in reports prepared for disaster response (e.g. for the Upper Indus basin, both Afghanistan and Pakistan, prepared by AKAH or UNDP (Ashraf et al., 2015; Gohar, 2014) or Kazakhstan prepared by scientists from local Universities (Medeu et al., 2016)) but have so far not been compiled in a standardized manner.

A few GLOF events have now been recorded already that have reached urban (e.g. GF077083E43066N south of Almaty, where dam structures were erected as adaptation measures) and semi-urban (e.g. GF085514E28131N north of Melamchi) space. As more and more infrastructure is being built in upstream areas and close to river channels, vulnerabilities are expected to increase. Future studies should investigate potential flood impacts on built up areas, which often require different model setups than for environments with infrastructure only including roads and single houses (Fischer et al., 2022).

While nearly one third of all GLOFs could potentially be transboundary (i.e. the downstream path eventually crosses a current national border), less than ten events actually resulted in transboundary impacts. While a lot of attention has been given to transboundary climate risks in the recent past, our data suggests that it may be less the actual flood wave that is of transboundary concern but impacts in one country (e.g. road disruptions with impacts on trade) that could have ripple effects across borders.

Mass flow events like GLOFs have been previously identified as an important part of the sediment balance in mountain rivers (Cook et al., 2018), with potential implications for landscape formation as well as hazards (Li et al., 2022). The database does include recorded values of discharge of water (n=72; μ = 3250 $m^3\ s^{-1}$; 3.3 – 21300 $m^3\ s^{-1}$) as well as sediment (n=19; μ = 620 $m^3\ s^{-1}$; 25 – 2000 $m^3\ s^{-1}$) but those observations are already associated to large uncertainties. An appraisal of the existing data and estimates of drained volumes based on satellite imagery from before and after the GLOF events could provide an approach to estimate the role this large number of GLOFs plays in overall sediment fluxes.

4.6 Comparison to previous inventories and limitations

The most comprehensive databases of GLOFs covering HMA were produced by (Veh et al., 2019a), focusing on moraine dammed lakes only but identifying many previously unidentified ones as well as (Zheng et al., 2021b) also finding many more previously unidentified ones. Both studies have been consulted for this study. 144 GLOFs in this inventory (19% of the total) were previously only reported in (Zheng et al., 2021b), 15 (2%) in (Veh et al., 2019a). We also followed the approach of (Zheng et al., 2021b) to question any previous records and keep a separate record of events that were initially identified as GLOFs but turned out not to be or cannot be ascertained to be. Future studies should investigate what we identify as glacier outburst floods (GOFs; 4 definite and 17 potential cases as well as potentially more cases in what we have discarded as GLOFs in a separate database), to better understand involved processes. All originating at the terminus of relatively steep glacier tongues, they may have some similarity in genesis to glacier detachments (Kääb et al., 2021, 2018) but runout properties – fast debris flows with no visible fraction of ice - are distinctly different. (Veh et al., 2022), a global study that also covers the region already provides an accessible database, however a considerable smaller number of recorded events (459, not all of which are definitely GLOFs; 11 events in our database were sourced from this database).

A large motivation for GLOF studies has been the question whether GLOFs have been increasing in the recent past with a change in climate. Recent global and regional studies on moraine dammed lakes have shown that there is no apparent trend, but suggest a possible lag eventually resulting in an increase in future (Harrison et al., 2018; Veh et al., 2019a), and a recent global study investigating all types of outbursts suggests a weak coupling of temperature rise and GLOF frequency (Veh et al., 2022). It is beyond the scope of this manuscript to investigate trends, however confirming findings from Veh et al. (2022) the fact that we still seem to overlook past events easily and the strong regional variability seem to make it at least very difficult to find definite climate relations and any such statements should be taken with caution. For some individual lakes that have a documented history of draining since the end of the 19th century (e.g. Hassanabad/Shisper, Kyagar, Merzbacher, Karambar) no apparent trend is visible, while damages may have increased due to increased exposure of infrastructure (Li et al., 2022). Other hotspots of ice dammed lake outbursts have even completely ceased to exist as the glacier tongues have receded so far that they cannot dam the main valley anymore (e.g., the Shyok glaciers).

The attention that GLOFs in general have received in the region in the past (see Emmer et al., 2022) for a comparison of events versus actual studies globally, with a notable discrepancy for the Himalaya) has possibly led to one important deficiency of records, the overestimation of GLOF events. Flash floods and debris flows where source regions are not well known are often immediately recorded as GLOFs in media (especially in the Western Himalaya, the Karakoram and Hindukush). Conversely, due to a lack of records in unpopulated areas many GLOFs may have gone unrecorded (Veh et al., 2022; Zheng et al., 2021b), which our records confirm. What remains poorly documented so far are impacts in a number of dimensions. Not only are direct impacts poorly recorded in accessible format, secondary medium and long term effects remain missing from literature. People injured (qualitatively and quantitatively), people displaced temporarily and permanently, gender and age group of people affected are rarely reported. Effects on mental health have been recently reported but no studies exist in scientific literature (Ebrahim, 2022). With high rates of both erosion and deposition, GLOFs can cause damage to agricultural land as well as infrastructure for years after the actual event, eventually causing damage from the remaining devaluation of land or lack of access to health facilities, markets, or education. Information on the severity of deposits would be needed for actual economic impacts and is crucial to further contextualize GLOFs in loss and damage frameworks (Huggel et al., 2019).

5 Conclusion

In this manuscript we present a comprehensive compilation of GLOF events in high mountain Asia from the mid 19th century until 2022. The inventory is machine readable, and version controlled and will be updated as information on new events become available in future. It includes basic information on time and location, involved processes and impacts and is linked to other inventories of glacial lakes and glaciers allowing for future investigations into drivers of outburst floods. Of 682 individual events, 45% have a known month of occurrence, allowing investigations into seasonalities, and 27% have a recorded day of drainage, allowing future investigations of prevailing weather preceding the event. 55% of all GLOFs can be associated to a lake mapped in at least one glacial lake inventory, and 95% to a mapped glacier, allowing for straightforward analysis on how upstream glacier mass loss and lake area change influences the occurrence of outburst events. We have a good overview on what type of lake was the source, revealing that large regional differences exist with hardly any ice dammed lakes in the Himalaya and only very few moraine dammed lakes in the Karakoram. For only very few GLOFs are mechanisms in lake formation or drainage documented. Volumes of floods are not only seldom documented but also highly uncertain. However, the combination with lake inventories allows for approximate estimates, with lake area changes as a proxy. With a record of minimal potential reach of GLOF events in 69% of all cases we can show that GLOF events generally do not exceed reach angles of 15° (and events with higher volumes even less), information that can be useful for future hazard mapping.

Our dataset suggests that 907 deaths can be directly associated to a GLOF event, three times as many as previously reported for the region. Compared to other mountain hazards in the region, GLOFs however have caused a relatively small loss of human life. Other impacts however remain relatively poorly documented.

With 7% of all events recorded here never mentioned in literature before and 7% coming from local and oral information rather than other academic publications, our study emphasizes the importance of considering all types of sources and acknowledge the high likelihood, that our current records of GLOFs probably remain an underestimation of actual events. Conversely, we also emphasize the importance of cross checking sources carefully as previously mass flow events in the region have been mistakenly recorded as GLOFs all too rapidly. While this is the first GLOF inventory to comprehensively address downstream impacts as well, a lot of information in this regarded has never been recorded. Injuries are rarely recorded nor are the monetary values of damaged property or the long term economic effect of damaged infrastructure. Future studies should evaluate methods to estimate damages rapidly, which will require more interdisciplinary approaches including social scientists for field assessments and economists for ways to upscale risk and damage assessments. Further focus should also be given to documenting local and indigenous knowledge on GLOF hazards, which could reveal impacts that so far have been overlooked. As our understanding of the changing cryosphere in HMA is ever increasing, especially also for previously less investigated topics as snow melt and permafrost, future studies should attempt to combine inventories of lakes and GLOFs with potential processes even further upstream that may result in cascading hazards in future, an issue expected to increase in future. Other hazards should ideally also be documented in formats that make it possible to pair it with already existing inventories for regional studies and modelling attempts.

6 Data availability

The GLOF database is published under https://doi.org/10.26066/RDS.1973283. The dataset will be updated annually at this database. Regular traceable updates and possible additions in terms of variables are accessible on github (https://github.com/fidelsteiner/HMAGLOFDB) and Zenodo (https://DOI:10.5281/zenodo.7271188); (Steiner and Shrestha, 2022). The database is also accessible in interactive format at https://experience.arcgis.com/experience/20a0ef1d86ec4a77b2744df9e495214e. The lake datasets discussed in this paper for the years 2000, 2010 and 2020 are also available on the github repository. The previously published lake dataset for the year 2005 covering the HKH (Maharjan et al., 2018) is available at https://doi.org/10.26066/RDS.35856.

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FS incepted the study and compiled and analysed the database with JFS. FS and JFS wrote the manuscript. RS, YD, SPJ and SI helped with the initial compilation of the database. AA and SW helped with compilation of data from the Indus basin, KMW helped with data from Afghanistan and Central Asia and TZ provided input from Chinese events. All authors contributed to the final version of the manuscript. The authors gratefully acknowledge the support of Sudip Pradhan, Prabhat Shrestha and Narayan Thapa in the development of the regional database system and interactive dashboard for the database. The views and interpretations in this publication are those of the authors and are not necessarily attributable to ICIMOD. This study was made possible with core funds from ICIMOD contributed by the governments of Afghanistan, Australia, Austria, Bangladesh, Bhutan, China, India, Myanmar, Nepal, Norway, Pakistan, Switzerland and the United Kingdom.

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