~~**Redefining potentially dangerous glacial lakes in Bhutan by integrating hydrodynamic flood mapping and downstream exposure data**~~

# Advancing Glacial Lake Hazard and Risk Assessment in Bhutan through Hydrodynamic Flood Mapping and Exposure Analysis

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## Abstract

Hazard and risk from glacial lake outburst floods (GLOFs) in Bhutan have traditionally been assessed with limited consideration of the downstream exposure and vulnerability associated with individual lakes. However, exposure and vulnerability are key components of risk, and~~,~~ when explicitly attributed to each lake, can provide a more robust basis for prioritising hazard investigations and mitigation efforts. ~~Potentially dangerous glacial lakes (PDGLs) in Bhutan have primarily been identified considering the likelihood of producing a GLOF, which in turn has been assessed based on upstream lake area/volume and their surrounding topographic conditions. However, this approach is incomplete as it ignores the downstream exposure and vulnerability, and thus the actual impacts. Here, we redefined PDGLs by considering the impact of a simulated GLOF scenario from each lake on downstream exposed elements at risk.~~ We modelled hypothetical GLOF scenarios for all glacial lakes with an area greater than 0.05 km² and located within 1 km of a glacier terminus. We then ~~identified~~determined GLOF risk by explicitly accounting for downstream impacts using~~;~~ depth–velocity outputs at each exposed element affected by the simulated GLOF from each lake, as well as the vulnerability of the affected community. ~~Here, we redefined PDGLs by considering the impact of a simulated GLOF scenario from each lake on downstream exposed elements at risk.~~ Our study shows that ~~a total of~~ approximately >11,~~322~~ 000 people, >2,~~613~~ 500 buildings, >25~~7~~0 km of road, >400~~2~~ bridges and ~20 km² of farmland are exposed to potential GLOF in Bhutan. We

classified lake130 (Thorthormi Tsho) as a very high ~~danger~~ hazard glacial lake in Bhutan, five lakes as high ~~danger~~ hazard and 21 other lakes as moderate ~~danger~~hazardd~~d~~. Among these high hazard~~danger~~ glacial lakes, three of them: lake93 (Phudung Tsho), lake251, and lake278 (Wonney Tsho) were not ~~recognized~~ recognised as being ~~dangerous~~ high hazard in previous studies. ~~Our assessment further revealed that f~~Five~~five~~ downstream local government administrative units (LGUs) ~~are~~ were associated with very high GLOF ~~danger~~risk, while eight others are associated with high GLOF ~~danger~~risk. Five of these very high and high risk LGUs had not been previously documented as being at risk from GLOF~~, including: Chhoekhor and Bumthang town in Bumthang, Paro town and Lamgong in Paro, and Nubi in Trongsa~~. Our study underscores the significance of integrating potential inundation mapping and downstream exposure data to define ~~dangerous~~ high ~~hazard~~~~risk~~hazard glacial lakes. We recommend strengthening and expanding the existing GLOF preparedness and risk mitigation efforts in Bhutan, particularly in the LGUs, as having high GLOF ~~danger~~ risk identified in this study, to reduce potential future damage and loss.

## 1 Introduction

There are currently 110,000 glacial lakes globally, with a total area of ~15,000 km$^2$. The~~se~~ glacial lakes have increased in area by ~22% between 1990 and 2020, primarily due to the accumulation of meltwater on newly exposed depressions left by retreating glaciers (Zhang et al., 2024)~~ (Zhang et al., 2024)~~. Glacial lakes across the world have produced 3,152 GLOF events between 850 and 2022 C.E. (Lützow et al., 2023), which caused more than 12,400 human deaths and damaged infrastructure worth hundreds of millions of USD (Carrivick and Tweed, 2016; Lützow et al., 2023). In High Mountain Asia (HMA), 682 GLOF events have occurred between 1833 and 2022, causing 6,907 fatalities (Shrestha et al., 2023). However, this reported number is highly uncertain, primarily because of scarce/incomplete documentation of ~~the~~ many past events. Moreover, ~80% these reported deaths in HMA are associated with a single compounding event involving Chorabari glacial lake and a cloud-burst ~~outburst~~ induced debris flow in 2013 (Allen et al., 2015; Das et al., 2015). Moraine-dammed GLOF events have caused an order of magnitude more damage than the combined damage from all other types of glacial lakes in HMA, despite moraine-dammed GLOF events only accounting for one-third of total GLOF events in HMA (Shrestha et al., 2023; Carrivick and Tweed, 2016). This is because GLOFs from moraine-dammed lakes are (usually) high magnitude ~~yet~~ but ~~episodic, making them~~ highly unpredictable through space and time, posing a high risk for ~~the~~ downstream settlements (Zhang et al., 2025b; Shrestha et al., 2023; Lützow et al., 2023)~~ ~~(Sattar et al., 2025b; Watanbe and Rothacher, 1996). In ~~Likewise~~addition, moraine-dammed lakes are often located upstream of ~~in~~ densely populated areas such as are found in ~~the~~ HMA, the Andes and Alps, in contrast to other types of glacial lakes, such as ice-dammed or supraglacial ponds/lakes (Emmer, 2024). Thus, it is important to quantify the ~~danger~~ risk they pose to the downstream settlements.

Using the concept of so called ‘potentially dangerous glacial lake (PDGL), ~~E~~existing hazards and risks from glacial lakes in ~~potentially dangerous glacial lakes (PDGLs) in~~ Bhutan are ~~defined~~ identified based on the likelihood and magnitude of potential GLOF ~~they will produce~~, which in turn are assessed based on the inherent stability of the lake’s dam and factors that influence the potential for an external triggering event, such as a mass movement entering the lake~~ ~~ (Allen et al., 2019; Zheng et al., 2021b)~~(Allen et al., 2017; Zheng et al., 2021b)~~. Commonly used parameters include topographic potential for mass input into the lake from the surrounding hillslopes, lake volume (usually derived from a relationship to lake area), lake growth, moraine dam geometry and composition, and catchment area (Zhang et al., 2023b; Zheng et al., 2021b; Fujita et al., 2013; Nagai et al., 2017). Although the approaches and factors selected are influenced by study objectives and expert judgment, they are largely based on historical events, often backed with limited observed data (Shrestha et al., 2023; Zheng et al., 2021b). Constraining certain parameters, such as the location and magnitude of possible/probable mass movements entering a lake, is challenging even with field-based assessments and more so when using coarse, globally available, open-access data, but ~~the~~ previous studies show that this parameter may be fundamental for the resulting GLOF magnitude (Rinzin et al., 2025). Moreover, the dynamic nature of cryospher~~e~~ic processes, exacerbated under climate warming,~~,~~ means that these reconstructed GLOF characteristics cannot necessarily be applied to contemporary or future conditions (Allen et al., 2017). This is evident from some GLOF events which have occurred from glacial lakes which ~~are~~had been deemed less susceptible to GLOF, for example, Lagmale glacial lake in the Nepalese Himalaya in 2017 (Byers et al., 2018) and Gongbatongsha Co lake in 2013 in the Indian Himalaya (Cook et al., 2018). Thus, the likelihood of producing a GLOF from any glacial lake is subject to inevitable uncertainties. Most importantly, ~~PDGLs~~ focusing just on this likelihood,~~defined solely based on the GLOF likelihood of the lake overlooks how~~ how the hydrodynamic properties of a possible GLOF interact with downstream exposure and vulnerability. If a glacial lake generates an exceptionally large flood, but the downstream community is unaffected, we can consider the ~~danger~~ risk from the glacial lake as low, whereas even a small flood that impacts a large number of people should be classified as a high ~~danger~~risk. Typically, this is neglected in favour of classifications of ~~danger~~ PGDL~~based~~ only on lake/trigger conditions, and not downstream impacts (Taylor et al., 2023a).

In recent decades, the amount of infrastructure, buildings and farmland exposed to potential GLOFs in HMA has increased (Nie et al., 2023). For example, critical and high-cost infrastructure, such as hydroelectric power plants are~~, is~~ being developed closer to glacial lakes due to growing energy demand in HMA regions (Nie et al., 2021; Schwanghart et al., 2016). In HMA, the population in GLOF-exposed areas increased by 31% (7.0 million to 9.2 million) between 2000 and 2020 and may therefore have contributed significantly more towards rising GLOF ~~danger~~ risk than (debatably) increasing potential GLOF magnitude due to lake expansion (Taylor et al., 2023b). Thus, changing downstream exposure and vulnerability can play a greater role in shaping contemporary and near-future GLOF risk than the glacial lake and surrounding properties, making the inclusion of the former in the identification of ~~dangerous~~ high hazard lakes a crucial, but often overlooked, factor both in the HMA and other high GLOF risk regions globally, such as the Andes (Cook et al., 2016; Colavitto et al., 2024).

To identify ~~PDGLs~~ GLOF risk with greater confidence and to implement effective management, mitigation and/or emergency response, we need to consider the interaction between GLOFs and~~,~~ downstream exposure and vulnerability. Taylor et al. (2023a) used the downstream population within a 1 km buffer of the river through which a GLOF would flow, to a maximum runout of 50 km from each glacial lake~~,~~ to calculate global-scale GLOF ~~danger~~risk/danger. However, the coarse resolution of data and crude assumption of GLOF flow path without hydrodynamic modelling introduces substantial uncertainties due to factors such as detailed local topography, especially where even populations very close in plain view distance to a GLOF flow routeway are in reality disconnected from the river by, for example, high river terraces - ~~, which are~~ common in high-mountain regions such as Bhutan. GLOF risk assessments at the HMA scale have been ~~done~~ undertaken by combining hydrodynamic modelling and open-source downstream data, such as OpenStreetMap (Zhang et al., 2023b),~~.~~ ~~Yet, they conducted~~but the flood mapping component was only for ~~the~~ glacial lakes that ~~that~~ they deemed very high or high ~~danger~~ hazard through prior GLOF susceptibility assessment. Fl~~This means that fl~~ood mapping for some ~~of the~~ lakes that can directly impact ~~the~~ downstream communities in ~~case of the~~ future GLOF events ~~from these lakes~~ ha~~ve~~s not been carried out despite huge deviations and inconsistencies between the previous susceptibility assessments (Zheng et al., 2021b; Zhang et al., 2023b; Rinzin et al., 2021; National Centre for Hydrology and Meteorology [~~National Centre for Hydrology and Meteorology~~NCHM], 2019)~~(Zheng et al., 2021b; Zhang et al., 2023b; Rinzin et al., 2021; National Centre for Hydrology and Meteorology [NCHM], 2019)~~. Moreover, since such studies are focused on a global to continental scale, they do not provide adequate granularity at the national and basin scale for bespoke risk reduction activities and planning.

This study presents a new GLOF ~~danger~~ risk assessment approach for Bhutan,~~,~~ which combines robust flood mapping (through hydrodynamic modelling) and downstream exposure and vulnerability data. For this, we selected all glacial lakes with an area of 0.05 $km^2$ (n=278) within the Bhutan Himalaya and conducted hydrodynamic simulations for all these lakes using HEC-RAS (U.S. Army Corps of Engineers, 2021). We then combined the flood map generated through hydrodynamic modelling with downstream data on exposure and vulnerability derived from OpenStreetMap, land-use and land cover maps, and population and housing 2017 census data (National Statistics Bureau of Bhutan [NSB], 2018). As a result, 1) we produced a flood map ~~for each~~for all study glacial lakes in Bhutan ~~above 0.05 km$^2$~~; 2) mapped all downstream exposed elements; and 3) provided a new, updated ranking of glacial lakes in Bhutan, based on the ~~danger~~ hazard they pose to downstream settlement(s). We have developed a publicly available web portal that hosts the glacial lake dataset, GLOF inundation maps and downstream GLOF ~~dangers~~ risk across local administrative units in Bhutan.

## 2 Study area

Bhutan's landscape is characterised by high mountains, rugged topography and steep terrain with elevations ranging between 200 m a.s.l. in the south to over 7,000 m a.s.l. in the north. Bhutan's northern regions consist of the G~~g~~reater Himalaya mountains, which contain ~1,487 $km^2$ of glacier ice, of which 64% (951 $km^2$) are debris-covered glaciers (Nagai et al., 2016) (Fig. 1). Between 2000 and 2020, Bhutanese glaciers lost mass at a rate of 0.47 m w.e. $yr^{-1}$, which exceeds the neighbouring eastern Himalayan (~0.33 m w.e. $yr^{-1}$) and Nyainqêntanglha (~0.46 m w.e. $yr^{-1}$) regions (Hugonnet et al., 2021). It is projected that Bhutanese glaciers will undergo continuous and accelerated melting in the future in response to the current climate warming trend (Rupper et al., 2012). As of 2020, there were 2,574 (156.63 ± 7.95 $km^2$) glacial lakes in Bhutan, which was an increase of 17.7% in number and 20.3% in area from the 1960s (Rinzin et al., 2021) (Fig. 1). While these glacial lakes are predominantly present in basins such as Phochu (28.18% of the total lake area) and Kurichu (26.35 % of the total area), they are widespread across the Bhutan Himalaya and drainage from these lakes flows ~~across~~through most of the major towns and settlements in Bhutan (Fig. 1). Sixty-four (64) glacial lakes greater than 0.05 $km^2$ were identified as highly or very highly susceptible to producing GLOF in the future based on geomorphological conditions such as topographical potential for avalanching into the lake (Rinzin et al., 2021). Likewise, using similar criteria, the ~~National Centre for Hydrology and Meteorology~~NCHM ~~(NCHM)~~ has identified 17 high hazard lakes (~~known as~~ termed '~~PDGLs~~ potentially dangerous' in their report) (~~National Centre for Hydrology and Meteorology~~NCHM, 2019),~~NCHM (2019)~~ based on the earlier assessment by ICIMOD (Mool et al., 2001). Of these high hazard~~dangerous~~ glacial lakes, the majority (n=9) are located within the Phochu basins, the headwaters of Punatsangchu (where 'Chu' translates to river/stream).

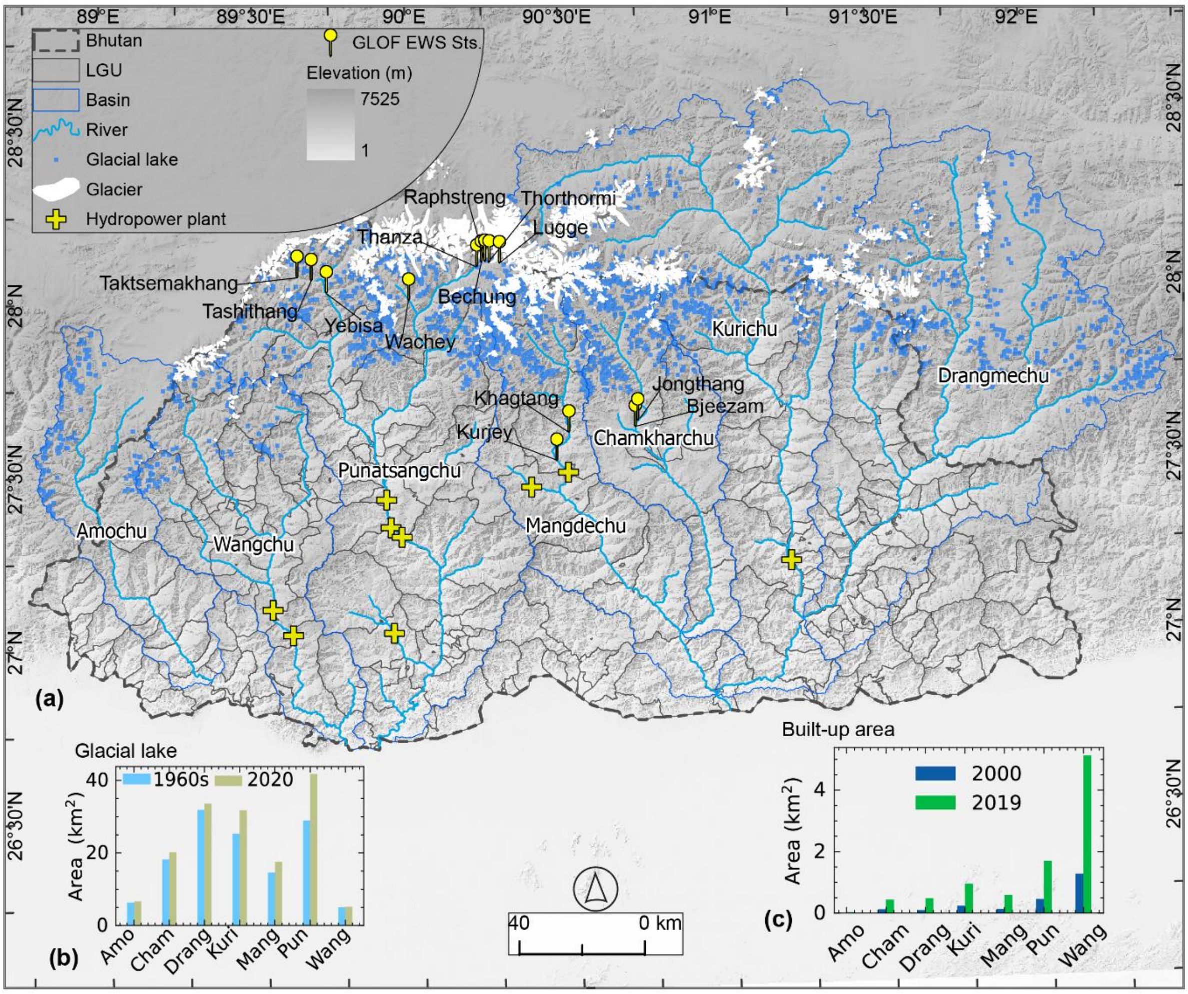


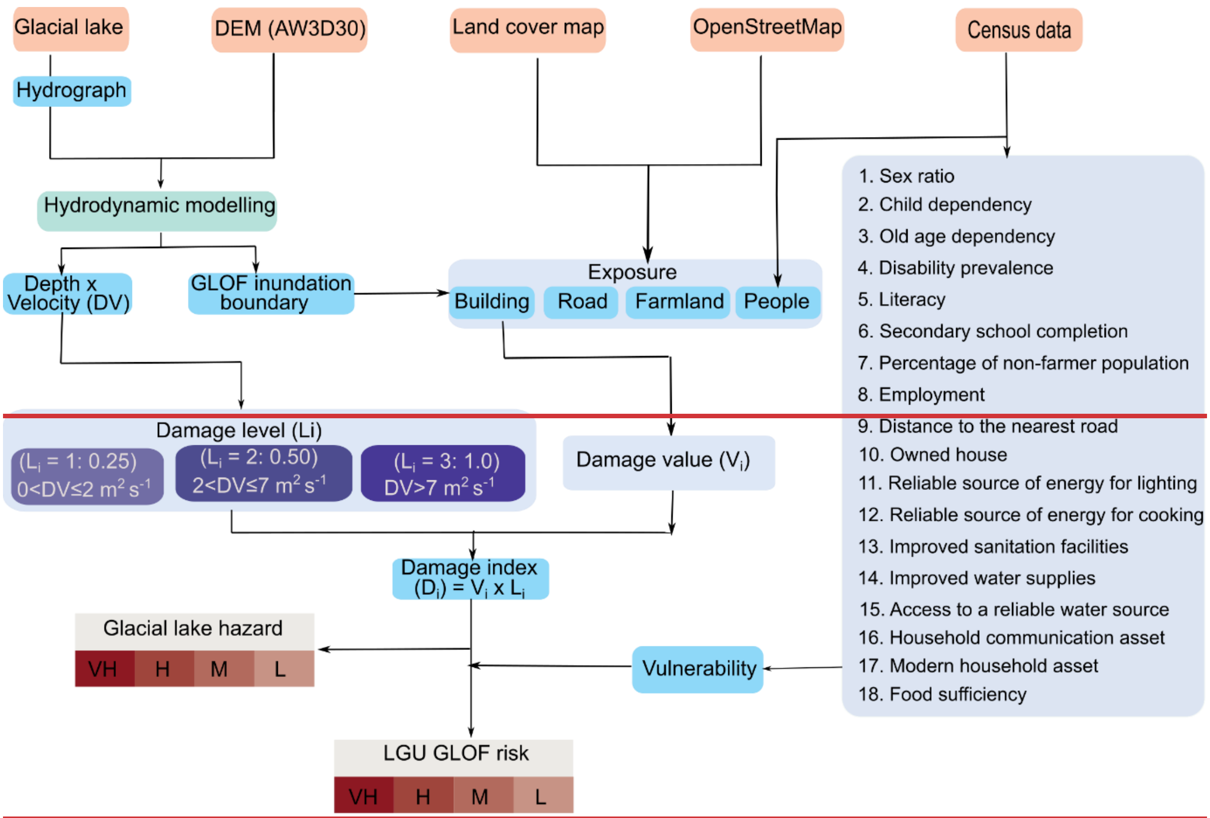

**Figure 1**. The map (a) depicts Bhutan and the glaciated basins from which the rivers flow into inland Bhutan. It also shows the distribution of glacial lakes, glaciers, GLOF early warning monitoring stations (with the names of the places where they are located), and hydropower plants. The inset bar charts illustrate (b) the glacial lake area in the 1960s and 2020 (Rinzin et al., 2021) and (c) built-up area changes between 2000 and 2021 as per the land-use and land cover map of ICIMOD (Uddin et al., 2021). The basin names are presented in abbreviated form on x-tick labels for both bar charts.

The glaciers in the northern mountains feed seven major river systems in Bhutan, namely (West-East): Amochu, Wangchu, Punatsangchu, Mangdechu, Chamkharchu, Kurichu and Drangmechu (Fig. 1). The hydropower generated from these river systems accounts for about 40% of Bhutan's national revenue, ~~a~~, as the majority of energy is being exported to India, valued at 0.27 billion USD (Ministry of Economic Affairs, 2021)~~, as the majority of energy is being exported to India~~. All seven currently operational hydropower plants and two nearly commissioned hydropower plants (Punatsangchu-I and Punatsangchu-II) are located along these glacier-fed rivers (Fig.1). The agriculture sector, which is also heavily dependent on these river systems, employs about 60% of the total population (786,385) (~~National Statistics Bureau of Bhutan~~NSB, 2018). The built-up areas within the 1 km buffer of these glacier-fed rivers have increased by 200% (2.3 to 9.3 km$^2$) within ~19 years from 2000 to 2019 (Fig.1) (Uddin et al., 2021). Thus, infrastructure and crucial economic activity have grown rapidly in areas downstream of glacial lakes in recent decades in Bhutan, making it vital to quantify the risk~~danger~~ posed by GLOFs in these basins.

# 3 Datasets and Methods

## 3.1 GLOF modelling hydrodynamic parameters

We used the glacial lake inventory by Rinzin et al. (2021), which has been developed specifically for Bhutan, ~~and which~~and offers greater robustness and accuracy for Bhutan compared to~~ the~~ other datasets available at the Pan-HMA scale (Zhang et al., 2023b; Zheng et al., 2021b). Rinzin et al. (2021) mapped 2,574 glacial lakes in 2020, located within 10 km of glacier termini and with a minimum lake area threshold of 0.003 km². This dataset includes 85 transboundary glacial lakes, located in the Indian and Chinese territories of the Himalaya, whose drainage flows into the inland regions of Bhutan. Previous records indicate that GLOF originating from a relatively small lake (as small as 0.001 km²) can cause substantial damage in downstream communities, although such cases are rare (Sattar et al., 2025a). For instance, across the HMA region, the median area of glacial lakes with known pre-outburst extents is approximately 0.189 km² (Shrestha et al., 2023). In Bhutan specifically, the smallest glacial lake with a documented outburst history has a present-day area of 0.0506 km² (Rinzin et al., 2021; Komori et al., 2012). Including all glacial lakes for detailed hydraulic modelling would substantially increase the computational demands, whereas resorting to simplified GIS-based approaches (Allen et al., 2019; Zheng et al., 2021b) to cover all lakes would significantly compromise the robustness and accuracy of the resulting flood maps. Therefore, based on the trade-off between model complexity and result reliability, we focused on glacial lakes that (i) are at least 0.05 km² in area and (ii) are located within 1 km of glacier termini. This approach ensures a balance between computational feasibility and the production of reliable flood maps, while still capturing a substantial number of high hazard~~potentially dangerous~~ lakes. Based on these criteria, we identified 278 glacial lakes in Bhutan for flood inundation mapping using hydrodynamic modelling (Fig. S1).



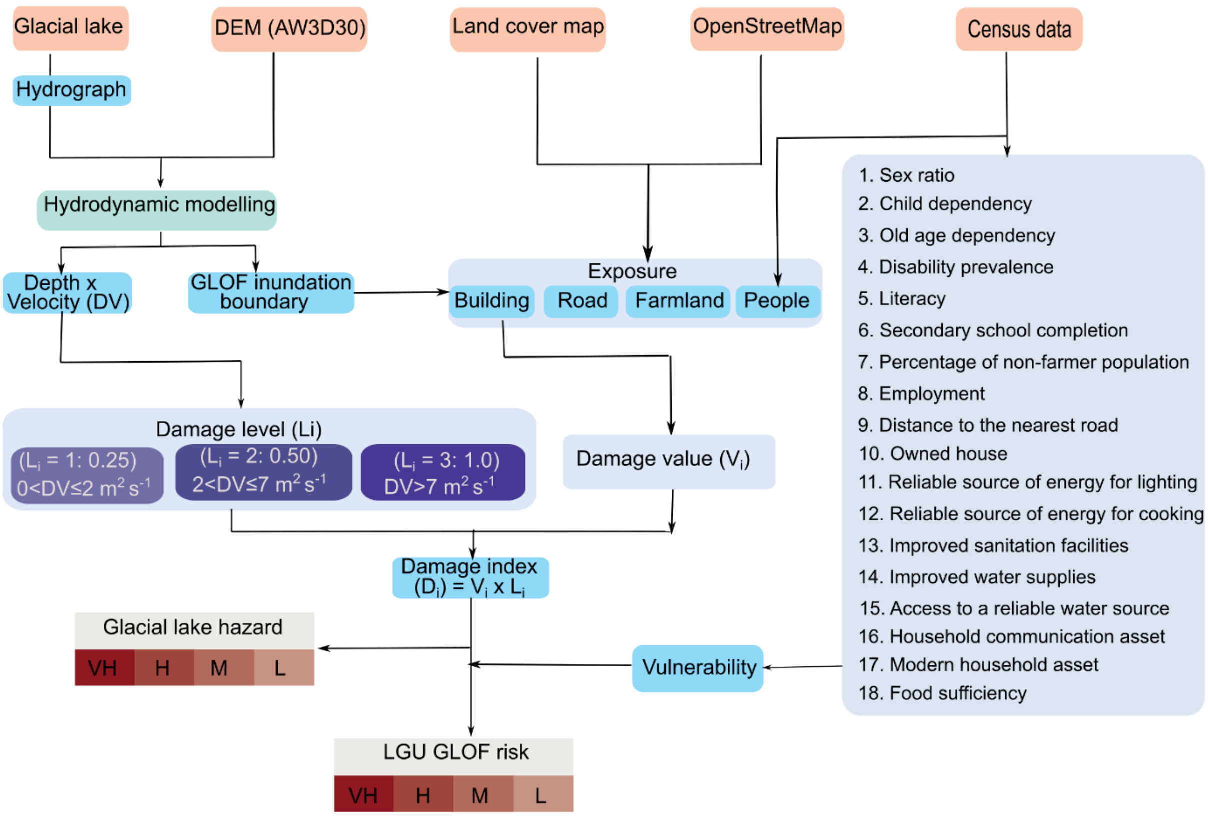




**Figure 2.** Flow chart showing an overview of the methodology we used for assessing GLOF riskdanger in this study. Here GLOF damage index ($D_i$) for each esposedexposed building was calculated as a function of damage value ($V_i$) and damage and level ($L_i$). The damaglacial

lake hazard was calculated as the sum of the $D_i$ across the GLOF inundation boundary of the respective lake. ge index for theThe GLOF risk at the local administrative unit ($LGU_{di}$) is was calculated by by further multiplying the sum of $D_i$ across the respective LGU boundary by the vulnerability index ($VL_i$). AW3D30 is the abbreviated form for Advanced Land Observing Satellite (ALOS) Global Digital Surface Model – 30m.

$$V = 42.95 \times A^{1.408} \qquad \text{(i)}$$

Where $V$ is the volume in $10^6$ $m^3$, and $A$ is the area in $km^2$

Accurate glacial lake volume data is crucial as one of the key determinants of modelled GLOF hydrodynamic characteristics such as flow depth and velocity. However, field-based bathymetric measurement for multiple lakes is costly and not currently possible for some glacial lakes due to their remote location. In the absence of in-situ bathymetric data to determine volume, we calculated the volume of each glacial lake using the area-volume scaling relationship (equation (i)) proposed by Zhang et al. (2023a) based on the area of each glacial lake as mapped in 2020 (Rinzin et al., 2021) (See table S1). This area-volume scaling relationship (maintaining an error margin of ±15% in the eastern Himalaya), based on recent bathymetric data from the Greater Himalayan region, including 13 representative lakes from Bhutan, is well-suited to approximate Bhutanese glacial lake volumes (Zhang et al., 2023a). However, the lake area is an essential parameter in our study, as we used it as a proxy for calculating volume and peak discharge as follows. Therefore, we examined the sensitivity of model output (depth-velocity) by varying lake size between 0.01 and 5 $km^2$ (see supplementary text for details).

It is important to note that not all lakes drain entirely during a GLOF (Maurer et al., 2020; Nie et al., 2018; Zhang et al., 2024). The amount of water drained during a GLOF event depends on numerous factors, such as dam geometry and composition, lake bedbathymetry topography, and potentialGLOF triggers.- for example, seepage--induced versus landslide--triggered wave overtopping. -While consideration of all these factors is crucial for a detailed impact assessment of a particular glacial lake, constraining the drained volume based on these detailed attributes is highly challenging for a study involving numerous glacial lakes. Previous data indicate that smaller lakes are more likely to drain completely during a GLOF event than larger lakes. Here, we used data from Zhang et al. (2023b) documenting the drainage volumes of 64 lakes in the HMA regions. Among these 64 lakes, the median percentage of drainage volume was 98% for lakes with an area < 0.1 $km^2$, 62% for lakes with an area of 0.1 to 1 $km^2$ and 33% for lakes with an area >1 $km^2$. We used these observed drainage percentages as the basis to calculate the flood volume generated by each lake. For simplicity and recognizing recognising that these median drainage values lie within the uncertainty bounds of established area-volume scaling relationships, we adopted the following assumptions: 100% drainage for lakes < 0.1 km², 60% drainage for lakes between 0.1 and 1 km², and 30% drainage for lakes > 1 km². Subsequently, we used Evans's empirical equation (ii) for moraine-dammed lakes to calculate the possible peak discharge of each lake (Evans, 1986). See supplementary Figure S1 for the distribution of volume and peak flow calculated for each glacial lake in Bhutan (see Table S1).

$$Q_{max} = 0.72V^{0.53} \quad \text{(ii)}$$

$Q_{max}$ is peak discharge, and $V$ is the total volume of the lake calculated using equation (i)

### 3.2 HEC-RAS model set-up

Most GLOFs from moraine-dammed lakes start from dam breaching, which is frequently triggered by large mass movement(s) entering the lake from the surrounding terrain hillslopes (Shrestha et al., 2023). However, conducting a dam breach simulation for each lake is challenging due to complexities and uncertainties in constraining the appropriate value for a large range of input parameters (U.S. Army Corps of Engineers, 2021). To simplify this, we conducted a flood simulation resulting fromfor each lake by using an input hydrograph as an upstream boundary condition. For each lake, we generated an input hydrograph by fitting the peak flow of each lake to thea log-normal distribution curve with a standard deviation (sigma) value of 0.75 and a mean of 0, adapting the approach used by the earlier studies (Carr et al., 2024; Kropáček et al., 2015). For example, for lake1, the peak flow was 1,110 $m^3$ $s^{-1}$,; thus, we constructed a log-normally distributed hydrograph with a peak flow of 1,110 $m^3$ $s^{-1}$ and gradually decreasingsed the flow after reaching this peak flow. With this assumption, we generated the hydrograph so that the flow rises to its peak rapidly and progressively decreases after attaining the peak, which is consistent with the hydrograph of many previous GLOF events (Maurer et al., 2020; Nie et al., 2020; Zheng et al., 2021a) (see supplementary Figure S2 for a representative hydrograph). The flow duration of the hydrograph of each lake was subsequently adjusted to account for the complete drainage of the estimated drainage volume calculated for each lake. For example, for lake1, the required drainage volume was calculated at 1.036 × $10^6$ $m^3$, and so, the flow duration for this lake was adjusted so that the cumulative flow through the GLOF event was equal to this volume (Table S1).

We used the ALOS Global Digital Surface Model (AW3D30) with ~30 m ground resolution as a source of terrain information for the model setup (Japan Aerospace Exploration Agency, 2021). The DSM was hydrologically corrected by removing spurious depressions and burning in artificial flow paths in locations where deep gorges were incorrectly represented as floodplains (Rinzin et al., 2023). We chose AW3D30 because ~~various~~ previous studies (Rinzin et al., 2025) have indicated that it has higher vertical and horizontal accuracy compared to other freely available DEMs ~~over~~for our study area with similar spatial resolution, such as SRTM GL1 (for example, Liu et al. (2019). We assigned an *n* value of 0.06, which has been used in GLOF modelling in Bhutan previously (Maurer et al., 2020). However, *n* is one of the most sensitive input parameters in hydraulic modelling. Therefore, we conducted sensitivity analysis by varying *n* between 0.040 and 0.070, the value range suggested by Chow (1959) ~~suggested Manning's Coefficient (*n*) between 0.040 to 0.070~~ for ~~the~~ river channel beds with large boulders and cobbles, which ~~closely~~ characterise ~~the~~ river channels in the Bhutan Himalaya (see supplementary text for details). ~~WeThus assigned *n* value of 0.06 which haves been used in GLOF modelling in Bhutan previously (Maurer et al., 2020).~~

We created one HEC-RAS project for each major river basin so that a total of seven project files correspond to the seven glaciated basins in Bhutan. For each project, the model domain was established by creating a 1,000 m buffer on either side of the centre line of the river originating from each lake. Within this model domain, a computational mesh with a grid resolution equal to the native resolution of AW3D30 (30 × 30 m) was generated. An upstream boundary condition for each lake was defined at the frontal terminus of each lake. W~~However,~~ ~~w~~e used the same downstream boundary condition for all lakes in the basin, which ~~were~~was defined at the furthest end at the international border between Bhutan and India (for example, Fig. S2). U~~Likewise, u~~nique flow data was created for each lake, where we imposed flow hydrographs as the upstream boundary condition for the respective lake and downstream boundary conditions defined by normal depth with an energy slope of 0.01 (U.S. Army Corps of Engineers, 2021). Finally, one unsteady flow analysis plan for each lake with corresponding unsteady flow data and boundary conditions was developed. For example, in the Phochu basin, which contains 67 glacial lakes considered for this study, one project file was established. This project file included a single model domain, a downstream boundary condition, 67 upstream boundary conditions and 67 flow datasets~~. Accordingly, we created 67 individual plans, each featuring the respective upstream boundary, uniform downstream boundary condition and flow data that contains the specific hydrograph for each lake~~ (Fig. S2).

We computed all the simulations using the full momentum shallow water equations since they better represent GLOF rheology (although with a clear water assumption) than the diffusion wave equation (Sattar et al., 2023; Sattar et al., 2021). Considering that this study is mainly aimed at providing a GLOF risk~~danger~~ overview ~~at the~~in Bhutan~~ scale~~, all other computational parameters were maintained at the default setting. At a mesh size of 30 m, each model was run stably with a computational time step of 3 seconds ~~within~~ with a Courant number well below 2 (U.S. Army Corps of Engineers, 2021). The simulations were executed simultaneously across 15 computers at the Geospatial Laboratory in Newcastle University. We maintained 10 hours of simulation time for each model setup, which took 2 to 4 hours depending on the lake's size. The Ooutput for each project plan was carefully examined and any models exhibiting instability (e.g., a Courant number above 2 or failed before complete execution) were re-executed by adjusting the position of upstream boundary condition, changing the timesteps, orand adding additional features like refinement regions within the 2D model domains to ensure stable model run and reliable results (U.S. Army Corps of Engineers, 2021).

### 3.3 GLOF impact and exposure

We collated the GLOF inundation boundary for each lake generated through the HEC-RAS modelling and calculated the area and length of each inundation. We mapped all buildings, roads, bridges, farmland, and hydropower plants within the GLOF inundation area to identify downstream elements at risk. The OpenStreetMap (updated as of 30-04-2025) was used to map buildings, roads and bridges, which we. We manually verified the OpenStreetMap data using Google Earth high-resolution imagery. This resulted in and updates ofd 41 km of missing roads, 152 buildings and 20 bridges using the Google Earth imagery within the flood inundation plain. The local government administrative unit (LGU) boundary map was then used to map these elements at risk in each LGU. However,As there is no population data with sufficient granularity to map exposed people directly,. wWe therefore used exposed buildings as a proxy for exposed people, assuming that the distribution of people usually corresponds to the location of buildings. Specifically, we divided the total population of each LGU by its total number of buildings, using the 2017 Bhutan population and census data (National Statistics Bureau of BhutanNSB, 2018) and OpenStreetMap building data. The number of people exposed to GLOF in each LGU was then calculated by multiplying the population per building by the total number of exposed buildings. The ICIMOD's Landsat-based land-use and land cover map of 2023 was used to map farmland (Uddin, 2021) since it is of better quality at the HKH scale than other open-access land cover data, such as Esri Sentinel-2 land cover data (Karra et al., 2021). We considered buildings the most important downstream exposed element because they are the primary space where people live. Thus, we used exposed buildings to calculate the GLOF damage index (Fig. 2), and our risk assessment is biased towards loss of life based on building counts over, for example, asset monetary value where hydropower losses may dominate.

### 3.4 GLOF damage and hazarddanger

In this study, we defined a GLOF hazarddanger based on the downstream damage (calculated here as damage index ($D_i$)) resulting from each GLOF event (Fig. 2). The term 'danger' is

~~adopted in this study instead of 'hazard' and 'risk' as our assessment does not account a probability component of hazard following the convention used in the earlier studies (Taylor et al., 2023a; Allen et al., 2019).~~ The ~~danger~~ hazard in this study refers to damage/destruction to buildings that could result~~s~~ from future potential GLOF. We assume that any of our study glacial lakes has the potential to generate a GLOF in the future, and the resulting damage will determine the ~~how danger~~level of hazard that the glacial lake would ~~be~~ pose to those downstream communities. The $D_i$ for each element (grid cell) resulting from any GLOF event was calculated as a function of the value of the exposed element ($V_i$) and the level of damage ($L_i$) following the approach proposed by Petrucci (2012) (equation (ii)) (Fig. 2). Qualitative data such as construction type, occupancy type, and value of the content of the building inside the house are essential to obtain the appropriate value of structure and content. However, such qualitative attributes are incomplete in the existing OpenStreetMap and introduce substantial uncertainties when estimated using other open-access data. In this study, our focus is on providing a relative quantitative comparison of GLOF impacts across different communities instead of determining exact damage values resulting from each GLOF event. Therefore, we considered each building as one unit of $V_i$ uniformly applied across the study domain (Fig. 2).

GLOFs with higher ~~water~~ flow velocity can cause more damage to ~~the downstream~~exposed elements than ~~slow-flowing water~~low flow velocity (Federal Emergency Management Agency, 2004). Therefore, we calculated the $L_i$ associated with each GLOF event as a function of both velocity and depth, which was accomplished by calculating the depth × velocity ($DV$) from the HEC-RAS output layer. The level of damage a building suffers also depends on its structural integrity, which in turn is a function of the construction type of the building. The 2017 Bhutan Population and Housing Census reported that the construction type of most Bhutanese buildings is masonry ~~(National Statistics Bureau of Bhutan, 2018)~~NSB, 2018). Clausen and Clark (1990) have ~~categorized~~ categorised three damage levels to masonry buildings based on $DV$ as follows: inundation ($DV \leq 2$ m$^2$ s$^{-1}$), partial damage (2 m$^2$ s$^{-1}$ < $DV \leq 7$ m$^2$ s$^{-1}$) and complete damage ($DV > 7$ m$^2$ s$^{-1}$). Accordingly, we used these $DV$ value ranges to classify three levels of damage and assigned $L_i$ following Petrucci (2012) as follows: Level 1 ($L_i$ = 0.25), Level 2 ($L_i$ = 0.5), and Level 3 ($L_i$ = 1) (Fig. 2).

Finally, the sum of $D_i$ for all damaged ~~grid~~ buildings ~~cells~~ located within the GLOF inundation boundary of each lake ~~were~~ was summed to derive a~~n~~ ~~danger~~ hazard value (~~$D_g$~~$H_g$) associated with each lake (equation (iii)). The ~~$D_g$~~ $H_g$ was then ~~normalized~~ normalised between 0 and 1, and lakes were ranked based on this metric. Additionally, for the classification purpose, using ~~normalized~~ normalised ~~$D_g$~~$H_g$, we ~~categorized~~ categorised glacial lakes into four ~~danger~~ hazard levels: very high~~ danger~~, high~~ danger~~, moderate~~ danger~~, and low ~~danger~~ hazard using the Natural Jenks classification system in ArcGIS.

$$H_g \, \bcancel{D_g} = \sum_{i \in g} D_i = \sum_{i \in g} V_i L_i \qquad \text{(iii)}$$

$$R_g = H_g \times Vl_g \qquad \text{(iv)}$$

Where $D_i$ is the damage index for exposed element $i$, $V_i$ is the value of each downstream element, and $L_i$ is the damage level for each element. $H_g$~~$D_g$~~ is the aggregated damage index for geographical unit $g$ (LGU or inundation boundary of the respective lake). $R_g$ is the risk index for geographical unit $g$ (LGU). $Vl_g$ is the vulnerability of the geographical unit $g$~~)~~

**Table 1.** Socio-economic indicators are used to calculate LGUs' vulnerability to the future GLOF. The indicators were extracted from Bhutan's 2017 population and housing census. Details on how data for each indicator are collected are provided in the ~~National Statistics Bureau of Bhutan (2018)~~NSB (2018). The calculated values were inverted so that they contribute positively to vulnerability for the indicators other than child dependency, old age dependency, and disability prevalence rate.

| Indicator | Definition |
|---|---|
| Sex ratio | Number of males ~~to~~ for every 100 females |
| Child dependency | The ratio of the number of children aged 0 to 14 years to the population aged 15 to 64 |
| Old age dependency | The ratio of persons 65 years and above to the population aged 15 to 64 years |
| Disability prevalence | The proportion of the population with a disability |
| Literacy | The ratio of the literate population (read and write in Dzongkha and English) aged 6 years and above to the total population of the same age group. |
| Secondary school completion | The ratio of persons aged 6 years and above who have completed secondary education (grade XII) to the population of the same age group, expressed as a percentage. |
| Percentage of non-farmer population | Percentage of people aged 15 years and above who are employed in sectors other than farming. |
| Employment | Percentage of persons aged 15 years and above who are employed. |
| Distance to the nearest road | Proportion of households within a 30-minute walk of the nearest road point. |
| Owned house | Proportion of households living in an owned house. |
| Reliable source of energy for lighting | Proportion of households with a main source of energy for lighting as electricity. |
| Reliable source of energy for cooking | Proportion of households with a main source of energy for cooking as electricity. |
| Improved sanitation facilities | Proportion of households with improved sanitation facilities. |

| | |
|---|---|
| Improved water supply | Proportion of households with water supplies inside the dwelling. |
| Access to a reliable water source | Proportion of households with ~~a~~ water available at least during the critical times (5:00–8:00, 11:00–14:00 and 17:00–21:00), adequate for washing and cooking. |
| Household communication asset | Proportion of households owning communication and media facilities. |
| Modern household asset | Proportion of households with modern household assets. |
| Food sufficiency | Proportion of households having sufficient food to feed all the household members during the last 12 months. |

## 3.5 Downstream ~~exposure and danger~~GLOF risk

We conducted ~~-~~GLOF ~~damage~~ risk assessment ($R_g$) for downstream settlements at various geographical scales: 20 districts and 274 local government administrative units (LGUs) (including 205 gewogs [sub-district blocks] and 69 towns). We aggregated the $D_i$ of each damage grid located within the respective LGU boundary to calculate $HD_g$ for each LGU using equation (iii). In cases where downstream elements were affected by GLOFs originating from multiple lakes, the combined $HD_g$ from each contributing lake was considered in the analysis to account for their exposure to multiple possible GLOFs (Fig. 2).

As well as the magnitude of GLOF and the presence of downstream elements along the flow path, downstream GLOF ~~danger~~ risk is also determined by the community's capacity to prepare, respond and recover from a GLOF event (Cutter et al., 2008; Zhou et al., 2009). Lack of this capacity, referred to as vulnerability, is influenced by wide-ranging socio-economic factors, including but not limited to the standard of living and the age and gender composition of the community (Cutter and Finch, 2008). Across the world, developed countries were found to be more disaster resilient than developing countries, while disaster-related death and damage have largely spiked in low-income countries (Rahmani et al., 2022). However, identifying specific socio-economic variables that are most relevant to GLOF damage remains a significant challenge, particularly because social data from past events are either unknown or, at times, overlooked. Past studies have used variables such as gross domestic product, population density (Carrivick and Tweed, 2016), human development index, corruption index and social vulnerability index at the national scale (Taylor et al., 2023a). While such data represent a broad overview of the country's socio-economic condition and thus vulnerability to disaster, they do not represent the regional and community-level disparity within the country that influences their ability to respond and recover from the disaster. To address this, drawing upon our local understanding and following earlier studies (Allen et al., 2016; Rinzin et al., 2023), we calculated the relative vulnerability index ($VI_g$) using a total of 18 socio-economic indicators from the 2017 Bhutan population and housing census ~~(National Statistics Bureau of Bhutan, 2018)~~NSB, 2018) (Table 1). This census data, which is updated every 10 years, represents the most comprehensive and detailed dataset currently available, offering spatial granularity at the individual LGU level. These indicators are essential for evaluating a community's preparedness and response capacity to disasters from hazards like GLOF (Cutter and Finch, 2008). For example, in Bhutan's traditionally gendered societal structure, men often assume more prominent roles in disaster response efforts. The $VI_i$ ~~vulnerability index~~ for each LGU was calculated as the normalised value across these 18 socio-economic indicators (Fig. 2). The definitions and approaches used for calculating each indicator are ~~summarized~~ summarised in Table 1. Assuming that the LGUs with higher $VI_i$ ~~vulnerability index~~ are less able to respond to and recover from a future GLOF, $HD_g$ for each LGU was multiplied by $VI_g$ to calculated associated GLOF risk ($R_g$) (equation iv)~~vulnerability index~~.

## 3.6 GLOF arrival time and GLOF early warning system

Building damage from a GLOF is a function of hydrodynamic factors such as depth and velocity, and the structural integrity of the buildings. On the other hand, human casualties and injuries also depend on the warning/response time, making it essential to consider flood arrival time in GLOF risk~~danger~~ assessment. Thus, GLOF arrival time needs to be considered separately from the $D_i$ we computed earlier. Accordingly, we determined the flow arrival time of the earliest arriving GLOF for each LGU to determine the amount of response time the people living in the particular LGU will get in case of a future GLOF.

The NCHM, ~~(NCHM),~~ Bhutan, monitors several lakes in Bhutan identified as high hazard~~dangerous~~ (~~National Centre for Hydrology and Meteorology~~NCHM, 2019).~~(NCHM, 2019).~~ Currently, they have a GLOF early warning system covering Punatsangchu, Mangdechu and Chamkharchu basins, which consists of 23 monitoring stations (Fig. 1). We ~~utilized~~ utilised monitoring station location data from NCHM to evaluate the relationship between Bhutan's existing early warning system, modelled GLOF scenarios originating from these glacial lakes and affected downstream communities. To achieve this, we first overlaid all monitoring stations in Bhutan ~~using ArcGIS~~in a GIS and counted how many of our catalogue of possible GLOFs in the region are covered by the existing early warning system based on their hydrological relationship (~~National Centre for Hydrology and Meteorology~~NCHM, 2021).~~(NCHM, 2021).~~ We assumed that if a GLOF flow intersects any of the existing EWS monitoring stations, then the event would be monitored by the existing EWS in Bhutan. Similarly, if an LGU is affected by a GLOF that passes through one or more of these stations, the LGU is regarded as being monitored by the existing EWS.

## ~~3.7 Sensitivity analysis~~

~~Hydraulic modelling is complex, relying on numerous input parameters, some of which are difficult to constrain even with novel field observation data. However, conducting sensitivity~~

analysis for every parameter is highly challenging and deemed unnecessary within the scope of this study, given the scale of GLOF modelling conducted in this study. Here, we therefore focused on Manning's coefficient value and the area of glacial lakes for the sensitivity analysis. *n* is a well-established sensitive parameter in hydraulic modelling with HEC-RAS 2D, and the area of the lake is essential in our study, as we used it as a proxy for calculating volume and peak discharge using an empirical equation. We examined the interaction impact of *n* and area of glacial lake variation by modelling 20 scenarios of GLOF, combining four different *n* (0.04, 0.05, 0.06, 0.07 as suggested by Chow (1959) for cobble beds with large boulderboulders for mountain streams) and five different scenarios of glacial lake area (0.01, 0.05, 0.1, 1, 5 km$^2$). We assessed how these interactions affect *DV*, the main hydraulic metric we used for assessing downstream damage from the future potential GLOF.

**Table 2.** GLOF exposed elements: people, buildings, roads, bridges and farmland distributed across the top 20 GLOF LGUs. The total value in the last row represents the total exposed elements across all LGUs in Bhutan.

| Gewog/Town | District | Building (count) | Population (count) | Road (km) | Bridge (count) | Farmland (km$^2$) | Rank |
|---|---|---|---|---|---|---|---|
| Chhoekhor | Bumthang | 192 | 321 | 41.69 | 36 | 0.28 | 1 |
| Punakha Town | Punakha | 272 | 1635 | 10.84 | 4 | 1.14 | 2 |
| Lunana | Gasa | 121 | 232 | 39.97 | 30 | 0.00 | 3 |
| Thedtsho | Wangdue Phodrang | 165 | 705 | 3.59 | 6 | 0.90 | 4 |
| Bumthang Town | Bumthang | 283 | 864 | 13.27 | 2 | 2.32 | 5 |
| Khatoed | Gasa | 17 | 16 | 0.42 | 4 | 0.00 | 6 |
| Toedwang | Punakha | 60 | 98 | 4.97 | 8 | 1.08 | 7 |
| Nubi | Trongsa | 29 | 53 | 1.95 | 8 | 0.30 | 8 |
| Lamgong | Paro | 195 | 541 | 7.86 | 6 | 0.85 | 9 |
| Paro Town | Paro | 262 | 1748 | 13.23 | 12 | 1.14 | 10 |
| Darkar | Wangdue Phodrang | 85 | 1936 | 3.22 | 16 | 0.31 | 11 |
| Lingmukha | Punakha | 65 | 90 | 5.74 | 2 | 0.19 | 12 |
| Dzomi | Punakha | 53 | 134 | 6.22 | 6 | 1.22 | 13 |
| Wangdue Phodrang Town | Wangdue Phodrang | 109 | 1059 | 1.19 | 0 | 0.25 | 14 |
| Sharpa | Paro | 120 | 370 | 3.75 | 8 | 0.94 | 15 |
| Toedtsho | Yangtse | 13 | 20 | 0.39 | 0 | 0.09 | 16 |
| Athang | Wangdue Phodrang | 38 | 54 | 2.04 | 10 | 0.42 | 17 |
| Khoma | Lhuentse | 42 | 87 | 6.68 | 8 | 0.04 | 18 |
| Gase Tshogongm | Wangdue Phodrang | 37 | 156 | 3.76 | 8 | 0.26 | 19 |
| Langthil | Trongsa | 11 | 38 | 1.26 | 8 | 0.82 | 20 |

| | | | | | |
|---|---|---|---|---|---|
| Total | **2,613** | 11,322 | 264 | 362 | 19 |

# 4 Results

## 4.1 Flood volume and peak discharge

Of the 278 glacial lakes selected for GLOF modelling and downstream risk~~danger~~ assessment in this study, the majority (n= 91) of them were in the Punatsangchu basin, followed by the Kurichu basin (n=64). By contrast, Wangchu (n = 2) and Amochu (n=5) had the minimum number of lakes meeting our selection criteria (Fig. 3). ~~The t~~The~~total~~ volumes of the selected glacial lakes ranged between 0.64 × $10^6$ $m^3$ ~~to~~and 344.1 × $10^6$ $m^3$, with a median volume of 2 × $10^6$ $m^3$. Based on these total volumes, minimum, median and maximum drainage volumes were 0.64 × $10^6$ $m^3$, 1.4 × $10^6$ $m^3$ and 103.2 × $10^6$ $m^3$, respectively. Furthermore, the empirical-based estimation showed that these glacial lakes can produce GLOFs with peak discharges of up to 24,085 $m^3$ $m^{-1}$, while the median peak discharge is 1,552 $m^3$ $m^{-1}$ (Fig. S3).

## 4.2 GLOF impact and exposure

Our study revealed that GLOFs from individual glacial lakes can travel as far as 167 km downstream and can inundate a maximum area of 30 $km^2$. The modelled GLOFs exhibit a median travel distance of 40 km and an inundation area of 2.9 $km^2$ (Fig. S3). Collectively, about 2% (781 $km^2$) of Bhutan's total land area is exposed to GLOF. The mean flow depth and velocity were 3.3 m and 3.4 m $s^{-1}$, respectively (Fig. S4). The shortest arrival time to the nearest building was 8 minutes, and the longest was 10 hours (Fig. S3). As a result, a total of 11,322 people, 2,613 buildings, 270 km of road, 402 bridges, 19 $km^2$ of farmland and 4 hydropower dams are exposed to GLOFs in Bhutan (Table 2). Of the total modelled GLOF events, 71% (n = 197) affect roads, 42% (n = 116) affect buildings, and 28% (n = 77) affect farmland.~~ The rest of the GLOFs do not affect any downstream entities. ~~ A GLOF ~~from Bhutan's most dangerous lake, ~~Thorthormi Tsho~~,~~ could impact 1,119 buildings, 72 km of roads, and 4.2 $km^2$ of farmland, making it the most consequential event ~~for ~~reaching elements at risk. It is followed by lake278, located in the Wangchu basin and Chubdha Tsho in the Chamkharchu basin, both of which are classified as high hazard~~danger~~ glacial lakes by this study (Table S1).

Out of 278 glacial lakes selected for flood mapping for this study, 85 (30.6%) are within catchments that cross the boundaries of India and China and drain into Bhutan inland. GLOFs from these transboundary lakes also affect a substantial number of downstream elements located in Bhutan, including 20 buildings, 0.6 $km^2$ of farmland, and 2 km of roads in Bhutan. All these exposed elements are situated within the Kurichu and Drangmechu basins.

The exposed elements are distributed across 17 districts and 88 local government administrative units (LGUs). Bumthang, Paro, Punakha, Wangdue Phodrang and Gasa districts are most affected by the GLOFs. For example, Paro itself has 673 GLOF exposed buildings, 32 km of road and 64 bridges (Table 2). Among the LGUs, ~~the m~~the maximum number of exposed buildings ~~are~~is~~is~~ in Bumthang town (n= 283), followed by Punakha town (n= 272) and Paro town (n=262). The greatest road (roads, footpaths, tracks) inundation occurs in Chhoekhor, followed by Lunana and Saephu, while most farmland is impacted in LGUs such as Bumthang town (2.3 $km^2$), Dzomi Gewog (1.2 $km^2$) and Paro town (1.1 $km^2$) (Table S2).

### 4.3 GLOF hazards~~Potentially dangerous glacial lakes~~

We defined the ~~glacial lake danger~~GLOF hazard~~ in Bhutan~~ based on the total damage associated with each lake. Of the total lakes studied here (278), 164 had zero damage index as the GLOF from these lakes does not impact any buildings. Among other lakes, with the highest $D_g$, Thorthormi Tsho in the Punatsangchu basin emerged as the very high PDGL in Bhutan (Fig. 3). Five other lakes are identified as high ~~PDGL~~hazard, which are distributed across the Wangchu (2), Chamkharchu (2), and Punatsangchu (1) basins. Twenty-two of the glacial lakes were in the moderate hazard~~danger~~ category: seven in Punatsangchu, five in Mangechu basin, four in Drangmechu basin, three in Chamkharchu, two in Kurichu and one in Wangchu basins (Fig. 3). The remaining (250) were classified as low hazard~~danger~~. None of the high or very high hazard~~danger~~ glacial lakes were located within the Chinese and Indian sides of the basins, which drain into Bhutan (Fig. 3).

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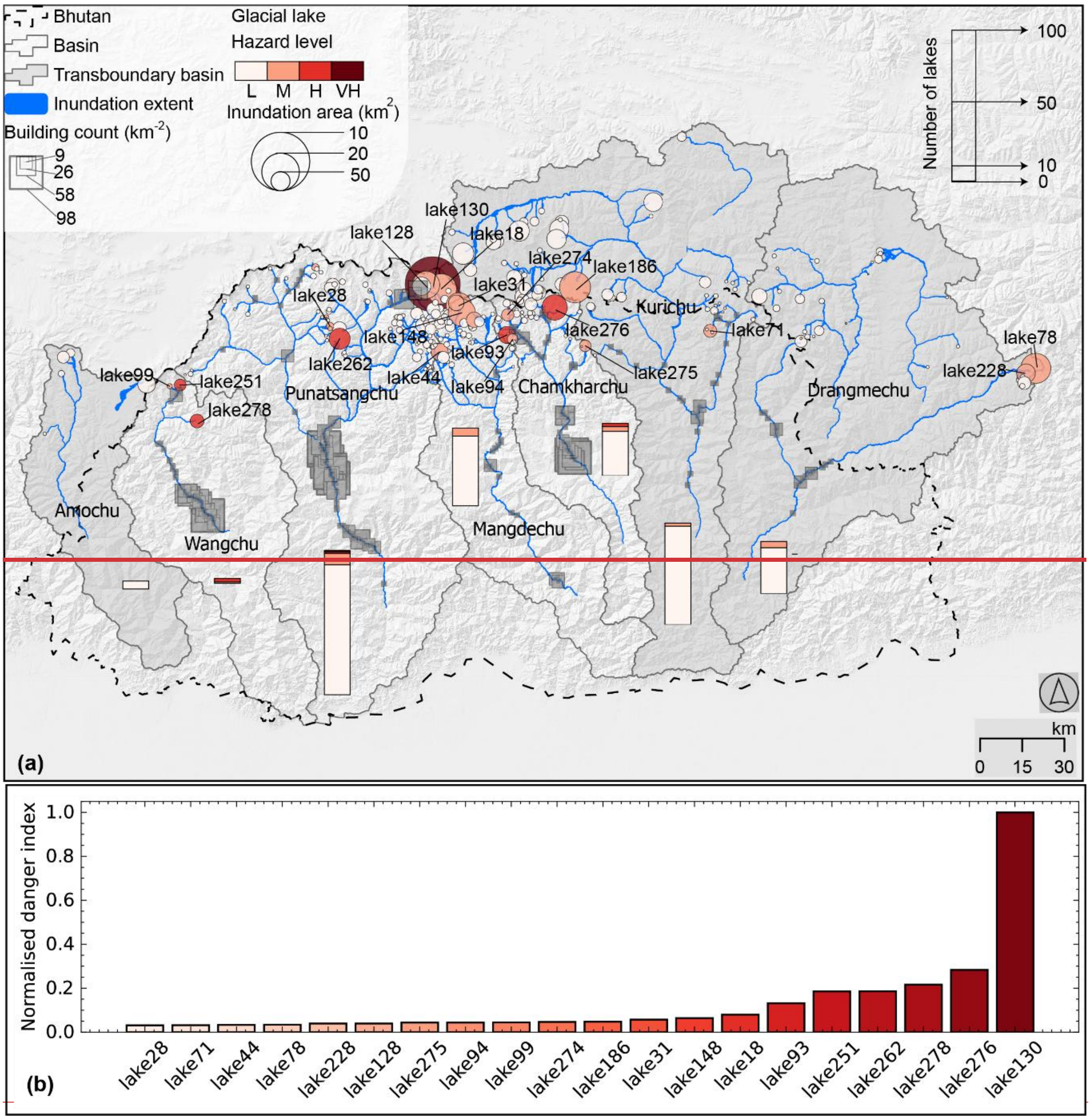


Bhutan
Basin
Transboundary basin
Inundation extent
Building count (km-2)
9
26
58
98
Glacial lake
Hazard level
L M H VH
Inundation area (km2)
10
20
50
Number of lakes
100
50
10
0
lake130
lake128
lake18
lake274
lake186
lake28
lake31
Kurichu
lake148
lake262
lake93
lake276
lake71
lake78
lake99
lake251
lake44
lake94
lake275
lake228
Punatsangchu
Chamkharchu
Drangmechu
lake278
Amochu
Wangchu
Mangdechu
km
0 15 30
(a)
Normalised danger index
1.0
0.8
0.6
0.4
0.2
0.0
lake28
lake71
lake44
lake78
lake228
lake128
lake275
lake94
lake99
lake274
lake186
lake31
lake148
lake18
lake93
lake251
lake262
lake278
lake276
lake130
(b)

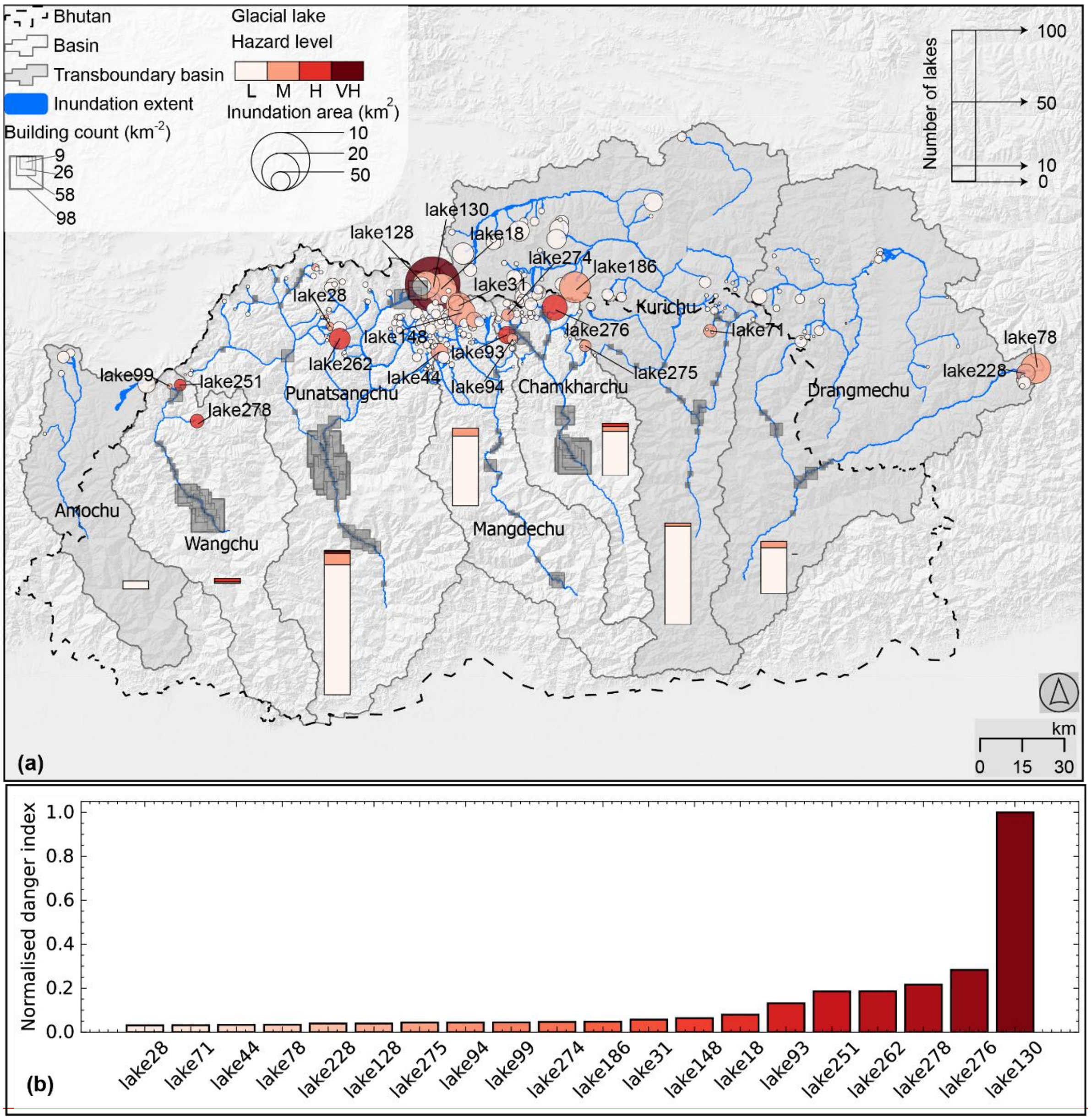
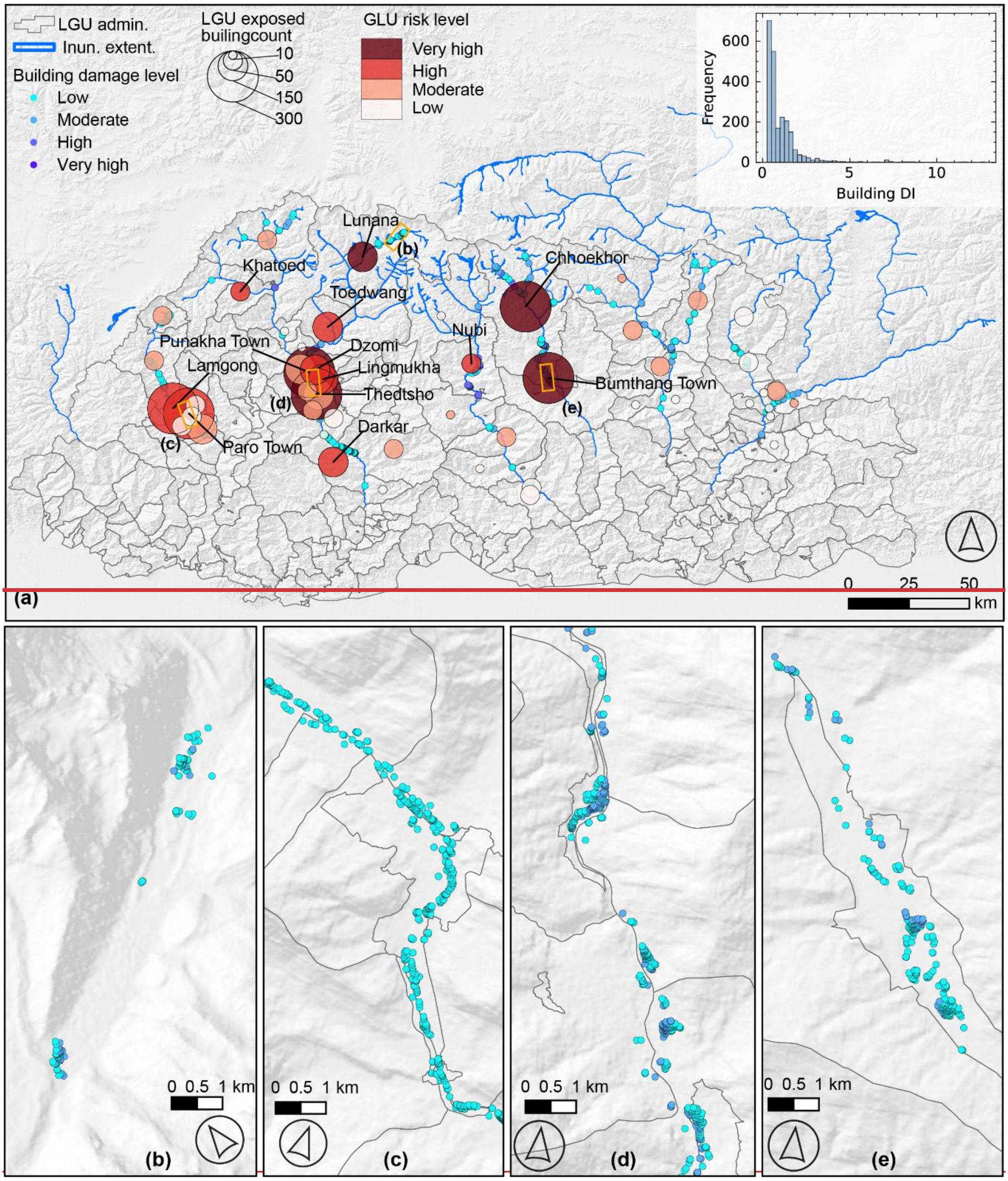



**Figure 3. Distribution of ~~dangerous~~ glacial lakes** of various hazard types.~~.~~ The ~~(a)~~ size of the bubble in map (a) ~~map~~ shows the distribution of glacial lakes with associated GLOF ~~danger~~ hazard levels (D. level) across the eight glaciated basins in Bhutan: very high (VH), high (H), moderate (M) and low ~~dangers~~hazards. The size of the bubble corresponds to the area of GLOF inundation corresponding to each lake.~~.~~ The bar charts within the map show the number of glacial lakes (where the height of the bar corresponds to the number of lakes in each basin, referenced to the inset bar) with various hazard~~danger~~ levels in each basin. The boxes along the flood path show the number of buildings per km². The (b) bar chart shows the damage index (~~normalized~~ normalised between 0 ~~to~~ and 1) associated with the top 20 lakes arranged in ascending order (left to right). The lake ID on the x-tick label correspond to the ID on the map.

### 4.4 Downstream GLOF risk~~danger~~

In this section, we present the GLOF risk~~danger~~ ranking and level associated with downstream communities, encompassing 20 districts and 274 LGUs. ~~. Based on the damage index for respective LGUs, which accounts for both damage from GLOF and people's vulnerability (Fig. S5),~~ Punakha is identified as the district that would suffer from the highest GLOF damage in the future, followed by Bumthang and Wangdue Phodrang districts.


LGU admin.
Inun. extent.
Building damage level
Low
Moderate
High
Very high
LGU exposed builingcount
10
50
150
300
GLU risk level
Very high
High
Moderate
Low
Frequency
600
400
200
0
0
5
10
Building DI
Lunana
(b)
Khatoed
Toedwang
Chhoekhor
Punakha Town
Dzomi
Lingmukha
Thedtsho
Lamgong
(d)
(c)
Paro Town
Darkar
Nubi
Bumthang Town
(e)
(a)
0 25 50
km
0 0.5 1 km
(b)
(c)
(d)
(e)

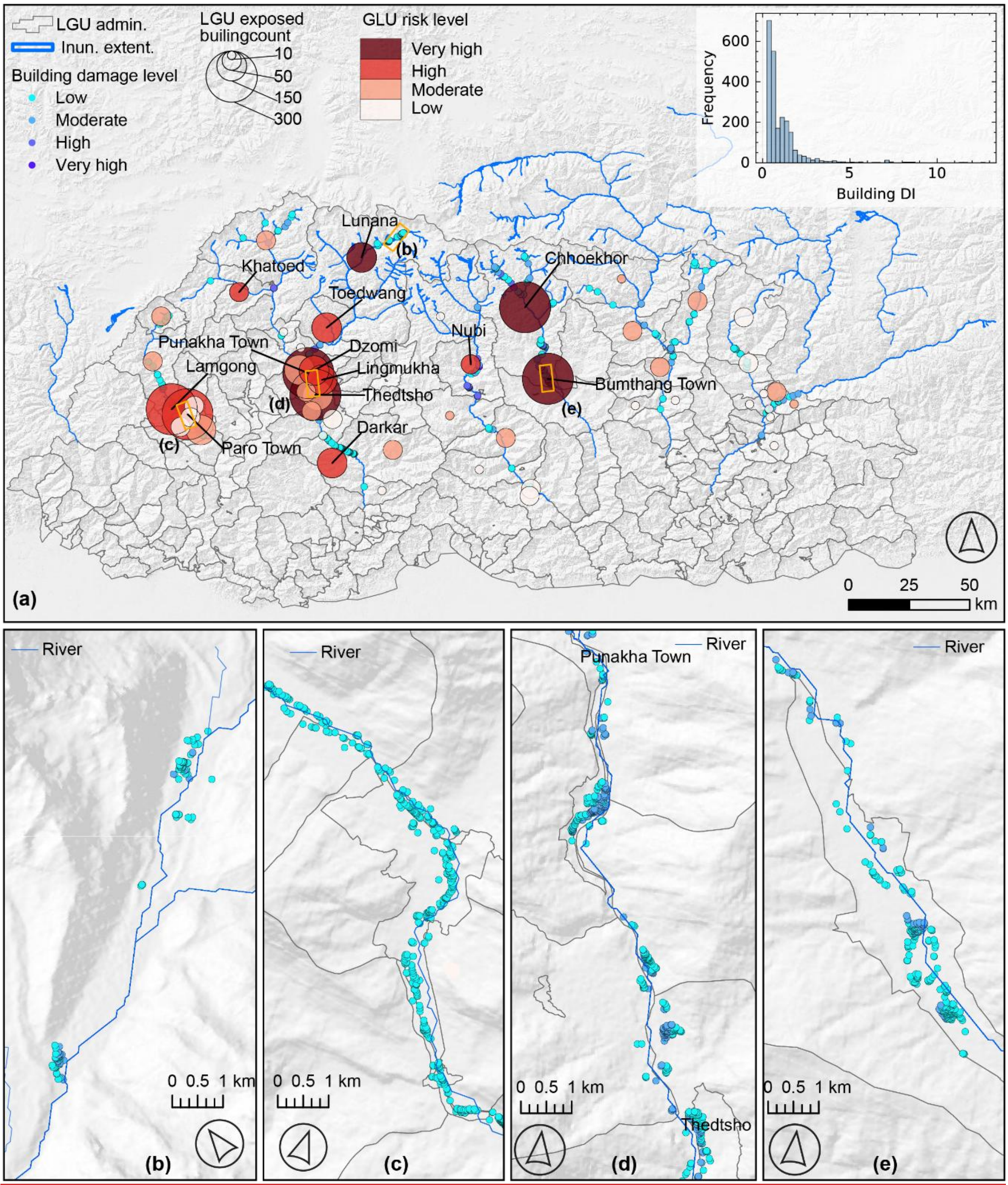



**Figure 4. Downstream GLOF risk~~danger~~.** GLOF risk level across (a) LGUs and GLOF inundation extent (innun. extent). The inset bar graph in (a) shows distribution of damage index (Di) across exposed building. The lower panels (b–e) are the zoomed-in~~GLOF danger level across (a) LGUs and GLOF inundation extent (innun. extent). Inset bar graph in (a) shows the number of buildings in Bhutan impacted by the modelled GLOF and associated damage level: very high (VH), high (H), moderate (M) and low (L). The lower panels (c–f) are the zoomed-in maps from panel (a) which shows the damage level associated with individual buildings~~.

~~Among the LGUs, f~~Five~~five~~ of the LGUs~~them~~ were classified as having very high GLOF risk~~danger~~, including: Chhoekhor, Punakha town, Lunana, Thedtsho, and Bumthang town (Fig. 4). Further, eight others were associated with high GLOF risk~~danger~~. Likewise, 18 LGUs were associated with moderate GLOF risk~~danger~~, while the rest were identified as low risk~~danger~~ LGUs (Fig. 4).

### 4.5 Flow arrival time

We also ranked the LGUs based on the flow arrival time of the GLOF scenario that would impact the first buildings in the LGU. Results showed that, for the seven gewogs including Soe, Khoma, Chhoekhor, Lunana, Laya, Saephu, and Kurtoed, the fastest GLOF can impact some of their buildings within 30 minutes. Some buildings in Khatoed, Tsento, Toedwang and Nubi could be affected within one hour. Nine gewogs can be affected within 2 to 4 hours, another nine within 4-6 hours, while the fastest GLOF could take more than 6 hours to affect buildings in other LGUs (Fig. 5).

In the LGUs such as Soe and Laya, the first buildings affected by the GLOF are typically isolated and located very close to glacial lakes. Despite their proximity, the GLOF risk~~danger~~ ranking for these LGUs remains relatively low due to the limited number of exposed buildings in these LGUs (Fig. 5). Therefore, we compared the $Di$ and the arrival time of the fastest-arriving GLOF within each LGU. This analysis identified Lunana and Chhoekhor as LGUs with very high GLOF risk~~danger~~ levels, and the fastest GLOF can arrive in as little as 15 minutes. On the other hand, the fastest GLOF impacting buildings takes up to three hours for other LGUs with very high GLOF risk~~danger~~, such as Punakha town and Bumthang town (Fig. 5).

### 4.6 Early Warning System and GLOF

We ~~analyzed~~ analysed the distribution of the existing GLOF early warning system in Bhutan with respect to ~~PDGLs~~ high hazard lakes and downstream communities associated with GLOF risk~~danger~~. Currently, Bhutan has a GLOF early warning system in three basins: Punatsangchu, Mangdechu, and Chamkharchu. Across these basins, the system is equipped with 13 monitoring stations placed at various locations (Fig.1). Assuming that GLOFs from a lake may be monitored if an EWS monitoring station is located downstream of the glacial lake, our study shows that the existing EWS currently tracks 51 out of the 278 glacial lakes we investigated here. Among these monitored lakes, the network includes the very high hazard~~most dangerous~~ glacial lake, Thorthormi Tsho, as well as two of the five high hazard~~danger~~ glacial lakes and five of the six moderate hazard~~danger~~ glacial lakes. The remaining monitored lakes are classified as low or very low hazard~~danger~~. Notably, the high hazard~~danger~~ glacial lakes newly identified here, including lake251, lake262 and lake278, are not monitored by ~~the~~ existing early warning systems.

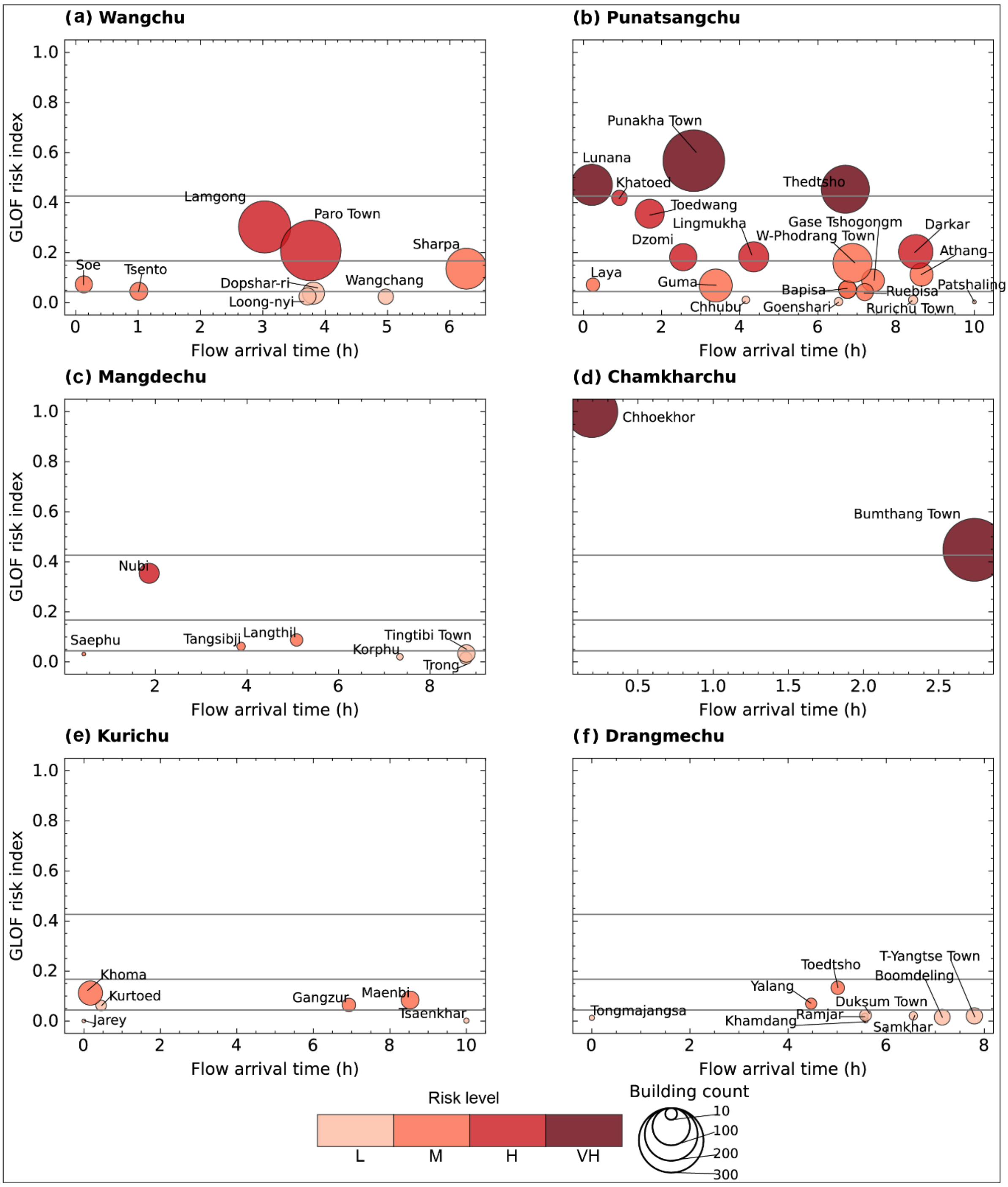



**Figure 5.** The damage index and flow arrival time of the fastest arriving GLOF for each local administrative unit (LGUs) in impacted basins: (a) Wangchu, (b) Punatsangchu, (c) Mangdechu, (d) Chamkharchu, (e) Kurichu and (f) Drangmechu. The horizontal grey lines ~~categorize~~ categorise LGUs into various GLOF risk~~danger~~ levels based on the damage index (low hazard~~danger~~ level to very high hazard~~danger~~ level).

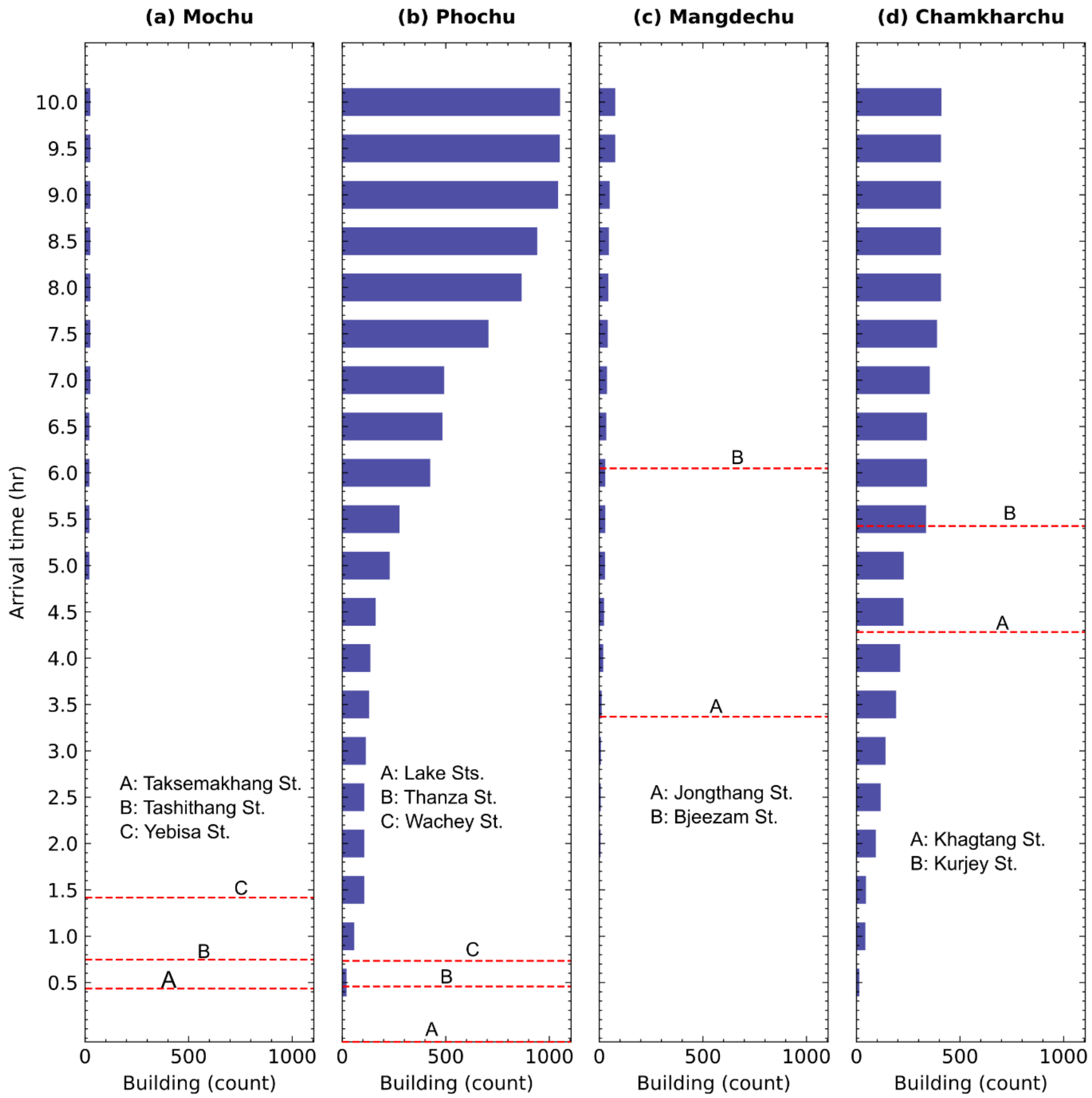



**Figure 6.** Bar plots showing the number of buildings located downstream of GLOF early warning monitoring stations in Punatsangchu basin [(a) Mochu, (b) Phochu], (c) Mangdechu, and (d) Chamkharchu basins. Red dashed lines represent the location of EWS monitoring stations relative to the average flow arrival time of all GLOFs detected by each EWS monitoring station. The names and location of each EWS monitoring station are indicated with a letter (A to C) within the respective panel. The monitoring stations located at the lakes, including Bechung, Raphstreng, Thorthormi and Lugge Tsho in Phochu basin, are marked as "Lake Sts." in panel (b).

We further examined how many residents within GLOF exposed buildings could receive early warnings based on their hydrological relationship to the existing EWS monitoring stations. Assuming that the buildings located downstream of the EWS monitoring stations can receive an early warning, our study revealed that the existing GLOF monitoring stations can provide early warning to the people living in 1,549 buildings, of which about 75% are in the Punatsangchu basin. Of these, residents in 268 buildings are estimated to have less than 30 minutes to evacuate after receiving a warning from the EWS monitoring stations located in their respective communities (Fig. 6).

Conversely, people living in 1,050 exposed buildings, that is, at least 41% of ~~them~~exposed buildings, do not have access to early warning coverage. Approximately half of these unserved buildings are clustered in downstream LGUs with high GLOF risk~~danger~~, including Lamgong and Paro Town in Paro districts. Although EWS is in place in the Chamkharchu basin, a cluster of about 82 buildings in Chhoekhor in Bumthang is not covered by EWS. This is because the flood waves from the potential GLOF can arrive at these buildings before activating the monitoring stations at Khagtang and Kurjey (Fig. 6).

## ~~5.0 Sensitivity analysis~~

~~The sensitivity analysis revealed that the mean *DV* increases proportionately in response to the increased in lake area. For example, when the area of lake increased by 2 orders of magnitude (0.01 to 5 km) the resulting DV also increases by the same order of magnitude. The variation of Manning's roughness coefficient (*n*) between 0.04 and 0.07 results to linear increase *DV* ($R^2$ > 0.88) across all area categories (0.01, 0.05, 0.1, 1, and 5 km$^2$). To evaluate how lake size modulates this sensitivity, we compared the slope ($\beta_1$) of all regression equations, which represents the expected change in *DV* for one unit increase in *n*. The result indicates that the influence of *n* on *DV* becomes progressively more pronounced with increasing lake area. Specifically, when the area was increased from 0.01 to 5 km$^2$, the value of $\beta_1$ increased by one order of magnitude: from 1.23 to 58.7 m$^2$ s$^{-1}$. Intermediate values show a consistent upward trend: $\beta_1$ = 4.7 m$^2$ s$^{-1}$ at 0.05 km$^2$ and 48.7 m$^2$ s$^{-1}$ at 1 km$^2$, indicating that larger lakes amplify the hydraulic sensitivity to roughness variations (Fig. S6).~~

# ~~7~~5 Discussion

## ~~7.1~~5.1 ~~Redefined potentially dangerous glacial lake~~Improved GLOF risk understanding

Some of the most damaging historical GLOF events in the world have occurred from seemingly inconspicuous glacial lakes (Allen et al., 2015; Petrakov et al., 2020), whilst some large-magnitude GLOF events have caused minimal or no downstream damage (Shrestha et al., 2023; Lützow et al., 2023). This is because the GLOF magnitude alone does not determine downstream damage caused by the GLOF event; instead, it is the interaction between GLOF magnitude and the downstream exposed elements that determines the extent of damage

(Taylor et al., 2023a). For example, the greatest number of ~~structural~~ building damages associated with the 2023 South Lhoknak Lake GLOF event in the Indian state of Sikkim occurred between 200 and 385 km downstream of the glacial lake, with 59% of these impacted structures constructed within the past decade (Sattar et al., 2025b). This highlights the escalating exposure and so the risk due to infrastructure expansion and settlement growth in GLOF-exposed areas (Nie et al., 2023) and underscores the importance of considering exposure data in GLOF risk~~danger~~ assessment. To address this in Bhutan, we ~~redefined~~ improved our understanding of ~~potentially dangerous glacial lakes~~GLOF risk by coupling flood characteristic modelling of individual lakes and downstream exposure data. Accordingly, we have produced flood mapping and GLOF hazard~~danger~~ ranking for 278 glacial lakes, along with comprehensive GLOF risk~~danger~~ assessments for 274 local government administrative units (LGUs). As a result, we classified lake130 (Thorthormi Tsho) as a very high hazard~~danger~~ glacial lake in Bhutan, five lakes (lake93, lake251, lake262, lake276 and lake278) as high hazard~~danger~~ and 20 other lakes as moderate hazard~~danger~~. Likewise, five downstream LGUs were associated with very high GLOF risk~~danger~~, while eight others were associated with high GLOF risk~~danger~~.

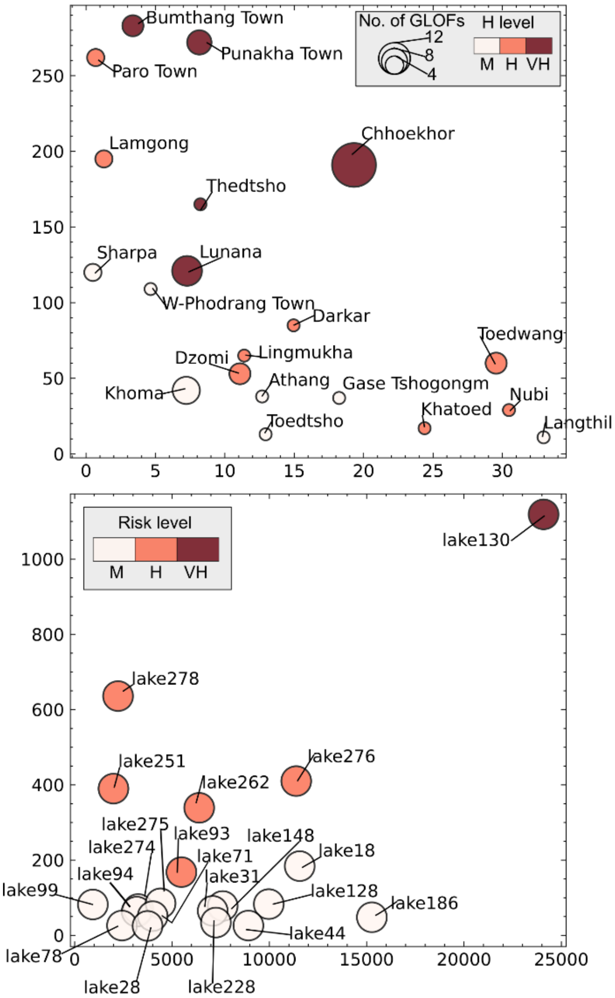
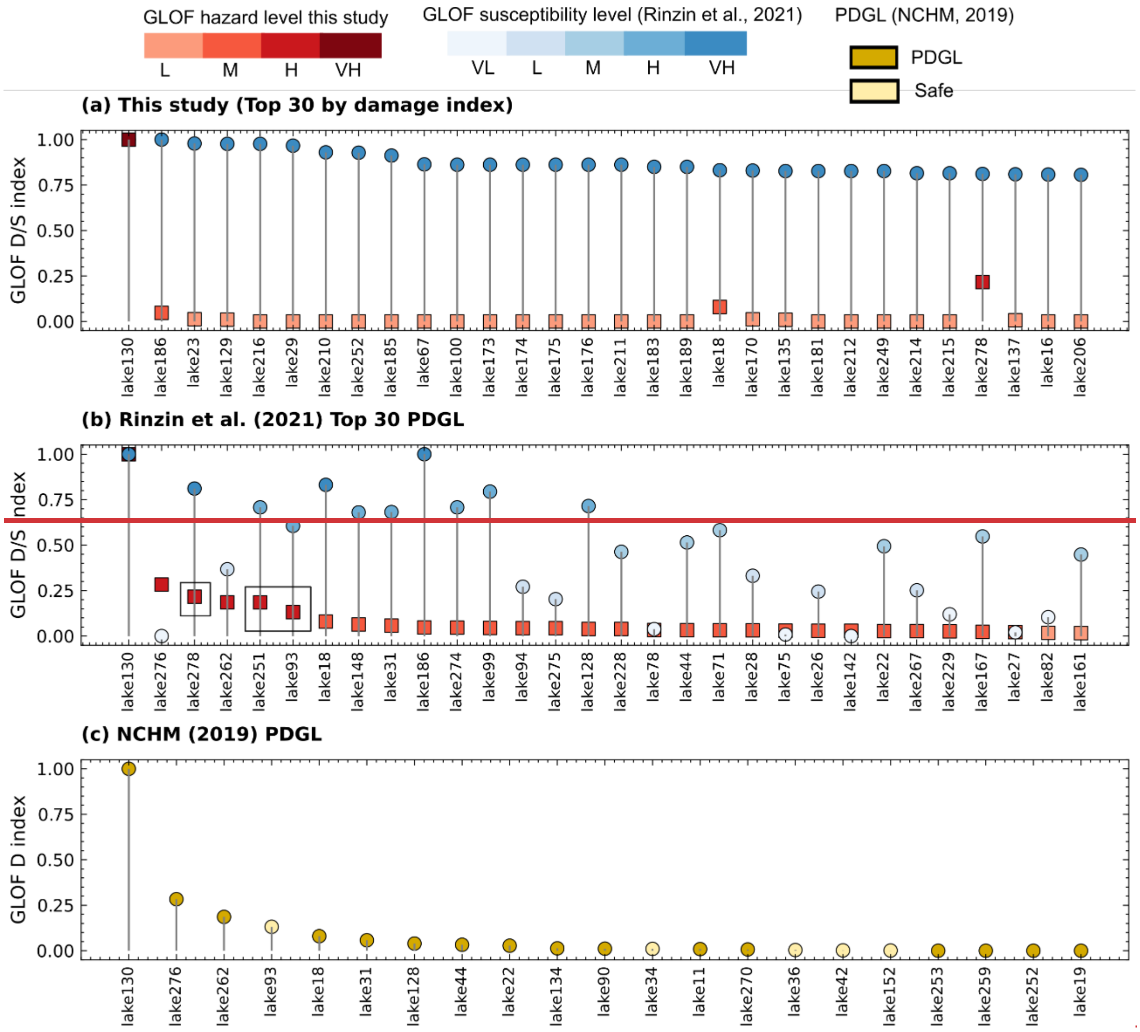


**Figure 7.** Dot plot illustrating the influence of GLOF magnitude and downstream exposure on risk~~danger~~ level computed in this study for (a) downstream LGUs and (b) individual lakes. In panel (a), the GLOF magnitude is based on median depth-velocity across all the GLOFs that strike at least one building in the LGU. In panel (b), we considered peak discharge (Qp) as a proxy for GLOF magnitude. In both panels, the colour associated with each dot indicates the GLOF hazard and risk~~danger~~ (d) level associated with each ~~LGU or~~ lake and LGU, respectively.~~.~~ The size of the dots in panel (a) corresponds to the number of GLOFs from various glacial lakes that impact the respective community. For better ~~visualization~~visualisation, only the top 15 high hazard lakes ~~PDGLs~~ and ~~the top~~ 15 high risk LGUs ~~with GLOF danger~~ are displayed here.

Our approach departs from many existing practices of identifying ~~dangerous~~ high hazard glacial lakes, which are primarily based on the susceptibility of lakes to produce GLOF without regarding the characteristics of settlements located downstream of the lakes (Rinzin et al., 2021; ~~National Centre for Hydrology and Meteorology~~NCHM, 2019)~~(Rinzin et al., 2021; NCHM, 2019)~~, in two ways: **1) Incorporation of GLOF Hydrodynamic characteristics**: we considered flow velocity and flow depth, which are both primary components of the GLOF flow that determine damage to the downstream elements (Federal Emergency Management Agency, 2004). **2) Interaction of flow depth and velocity with downstream exposed buildings:** We mapped potential downstream building damage associated with each GLOF event based on the interaction between the depth-velocity and downstream at risk elements. By focusing on the interaction between flood magnitude and downstream exposed buildings, our method classifies glacial lakes as high hazard~~dangerous~~ only when their potential flood poses a threat to downstream elements, making it a more practical and effective strategy for bespoke GLOF risk reduction activities. For example, lake278 and lake251 are small, and they produce relatively small GLOFs with their estimated peak discharge approximately 2000 $m^3 s^{-1}$. However, both were classified as high hazard~~danger~~ as the GLOF from these lakes impacts hundreds of downstream buildings (Fig. 7). Likewise, our approach assigns a higher GLOF risk~~danger~~ ranking to communities that are either affected by GLOFs from multiple lakes, impacted by high-magnitude GLOFs, or have multiple buildings located within the GLOF inundation area, whilst also considering the community's vulnerability. For example, Chhoekhor was identified as having the highest GLOF risk~~danger~~ in Bhutan because at least 191 buildings were potentially impacted by GLOF from as many as 14 lakes in the basin. On the other hand, gewogs such as Toedwang in Punakha are also classified as having very high GLOF risk~~danger~~, despite having a comparatively low number (60) of potentially impacted buildings, because these buildings could be impacted by very high magnitude GLOFs in terms of depth and velocity (Fig. 7).

We classified only one lake (Thorthormi Tsho) as a very high hazard~~danger~~ glacial lake. This is because~~, at about ~4.3 km² in size,~~it is not only the largest glacial lake ~~Thorthormi Tsho is the largest glacial lake, approximately double the size of the next largest glacial lake in Bhutan. Moreover, Thorthormi Tsho~~but is~~-~~ also located in the Punatsangchu basin, which is among Bhutan's most populated basins, resulting in exposure of up to 1,119 buildings, again, an order of magnitude more exposure than the next lake associated with the highest exposure. These findings further highlight the importance of strengthening risk mitigation measures for Thorthormi Tsho and the affected downstream settlements.

Our study complements conventional ~~-~~PDGL assessment approaches by redefining which glacial lakes pose the greatest hazard~~danger~~ to the downstream settlements. As a result, we identified three new high hazard~~danger~~ glacial lakes, including lake93 (Phudung Tsho), lake251, and lake278 (Wonney Tsho), which are not ~~recognized~~ recognised as high hazard or PDGL by any of the previous studies. Also, 53 of the previously identified 64 very highly susceptible to GLOFs lakes (Rinzin et al., 2021) are ~~categorized~~ categorised as low GLOF hazard~~danger~~ lakes. Conversely, 12 lakes classified as low or very low GLOF susceptibility emerge as moderate to high hazard~~danger~~ in our study (Rinzin et al., 2021). Likewise, nine of the high hazard~~dangerous~~ lakes monitored by NCHM (six in Punatsangchu basin, one each in Mangdechu, Chamkharchu and Kurichu basins) (~~National Centre for Hydrology and Meteorology~~NCHM, 2019)~~(NCHM, 2019)~~ are categorized as low hazard~~danger~~ in our study (Fig. 8). These discrepancies arise because we classified lakes as high hazard~~dangerous~~ only if a potential GLOF would affect a significant number of downstream buildings, whereas earlier studies' definitions are motivated by the likelihood of producing GLOF based on characteristics of lake and surrounding terrains (Rinzin et al., 2021; ~~National Centre for Hydrology and Meteorology~~NCHM, 2019)~~(Rinzin et al., 2021; NCHM, 2019)~~ (Fig. 8). For example, lake278 in the Wangchu headwaters is classified as high hazard~~danger~~ in our study because a potential GLOF could impact 636 buildings across seven LGUs in Paro while the earlier studies considered this lake as safe as it does not have geomorphological characteristics and lake condition to qualify as high hazard~~dangerous~~ (Rinzin et al., 2021).



GLOF hazard level this study
L
M
H
VH
GLOF susceptibility level (Rinzin et al., 2021)
VL
L
M
H
VH
PDGL (NCHM, 2019)
PDGL
Safe
(a) This study (Top 30 by damage index)
GLOF D/S index
1.00
0.75
0.50
0.25
0.00
lake130 lake186 lake23 lake129 lake216 lake29 lake210 lake252 lake185 lake67 lake100 lake173 lake174 lake175 lake176 lake211 lake183 lake189 lake18 lake170 lake135 lake181 lake212 lake249 lake214 lake215 lake278 lake137 lake16 lake206
(b) Rinzin et al. (2021) Top 30 PDGL
GLOF D/S index
1.00
0.75
0.50
0.25
0.00
lake130 lake276 lake278 lake262 lake251 lake93 lake18 lake148 lake31 lake186 lake274 lake99 lake94 lake275 lake128 lake228 lake78 lake44 lake71 lake28 lake75 lake26 lake142 lake22 lake267 lake229 lake167 lake27 lake82 lake161
(c) NCHM (2019) PDGL
GLOF D index
1.00
0.75
0.50
0.25
0.00
lake130 lake276 lake262 lake93 lake18 lake31 lake128 lake44 lake22 lake134 lake90 lake34 lake11 lake270 lake36 lake42 lake152 lake253 lake259 lake252 lake19

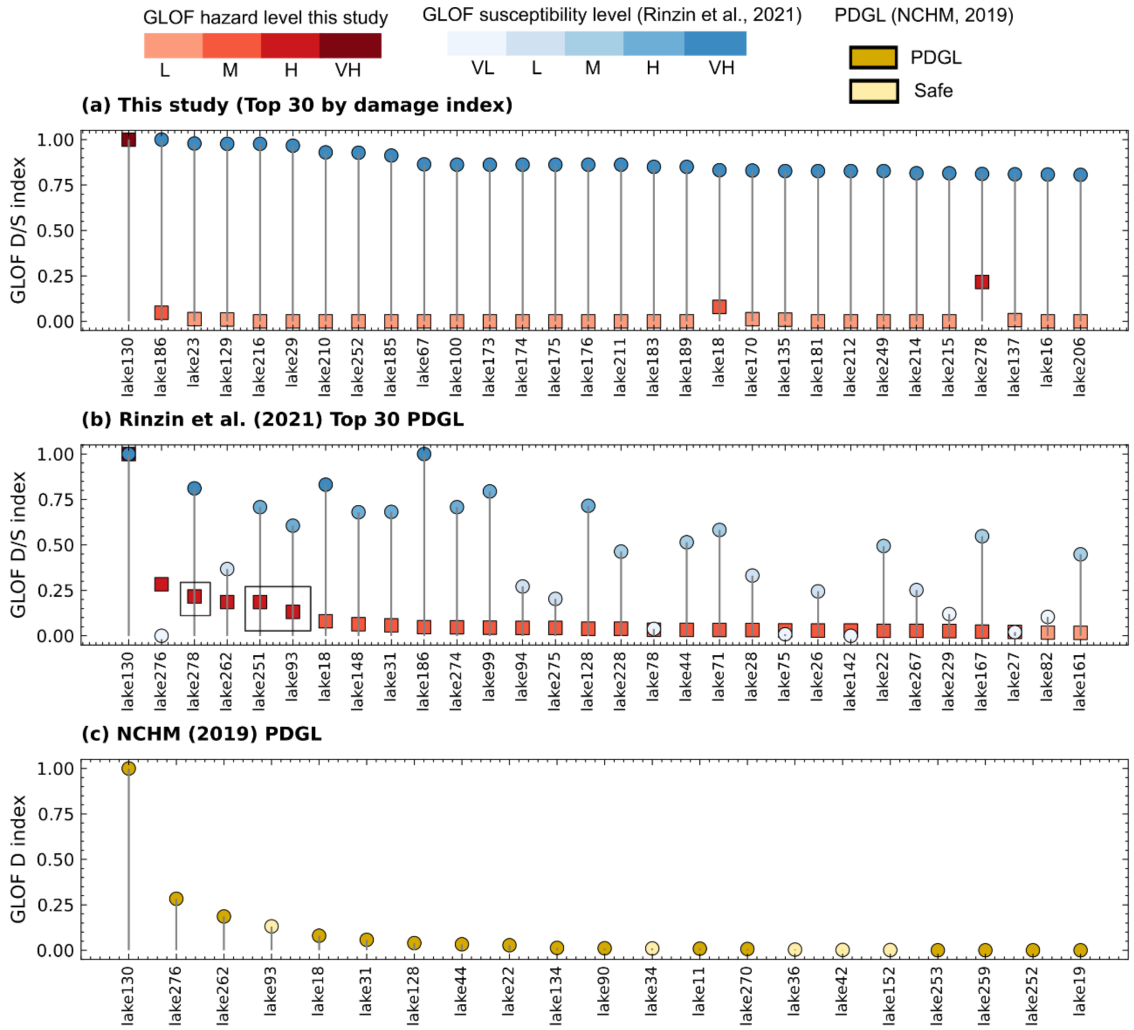



**Figure 8.** Comparison (a, b) GLOF damage index (DI) for the top 30 ~~PDGL~~ high hazard calculated in the current study and GLOF susceptibility score from Rinzin et al. (2021), and (c) damage index (DI) for PDGLs in Bhutan identified by the ~~National Centre for Hydrology and Meteorology~~NCHM (2019). The black bounding box in panel (b) shows the new high hazard lakes identified in this study for the first time.~~, and (c) damage index (DI) for PDGLs in Bhutan identified by the NCHM (2019). The black bounding box in panel (b) shows the new PDGLs identified in this study for the first time.~~

By ranking GLOF risk~~danger~~ for all 274 LGUs, we discovered ~~a~~ potential new GLOF risk hotspots, such as Paro town and Lamgong gewog in Paro and Chhoekhor gewog in Bumthang. GLOF risk~~danger~~ in these places was previously not quantified, and existing GLOF early warning systems in Bhutan currently do not cover these high GLOF risk~~danger~~ LGUs (~~National Centre for Hydrology and Meteorology~~NCHM, 2021).~~(NCHM, 2021).~~ We therefore recommend ~~prioritizing~~ prioritising monitoring of glacial lakes in Bhutan based on all components of risk (hazard, exposure and vulnerability)~~, rather than focusing on lakes selected solely based on geomorphic susceptibility assessments, which takes care of only the~~

~~likelihood of producing GLOF~~. Specifically, Bhutan's glacial lake monitoring and downstream risk mitigation efforts should expand beyond Lunana to include other high GLOF hazard~~danger~~ lakes and vulnerable downstream settlements such as Paro Town and Chhoekhor gewog, while emphasising that higher granularity studies might be needed to guide bespoke risk reduction efforts in these respective areas.

### ~~7.2~~5.2 Transboundary GLOF

None of the transboundary lakes were classified as very high or high hazard~~danger~~ based on potential GLOF impacts in Bhutan. This is because damage was minimal, mainly inundating uninhabited parts of Bhutan, located in deep, inaccessible gorges. However, we identified GLOF from four lakes in the Drangmechu basin (located in Arunachal Pradesh, India) and 11 in the Kurichu basin (located in the Tibetan Autonomous Region, China), which could potentially impact several buildings in Bhutan. Furthermore, GLOF from 20 lakes located in the Indian and Chinese territories of the Himalaya enter Bhutan, although they do not impact any buildings (Fig. 9). The modelled transboundary GLOFs sourced ~~-~~from l~~all l~~akes located within ~~in~~ Bhutan attenuate~~s~~ before ~~it~~they cross ~~es~~ the international border between Bhutan and India. However, we acknowledge that some of the GLOF events in the future can impact settlements along transboundary river floodplains in India, especially under the worst-case scenarios and when their flows are amplified by the addition of material along the flow path, such as from a landslide deposit (Cook et al., 2018) and~~/~~/or hydropower dams (Sattar et al., 2025b). Identifying potential transboundary GLOFs is vital, given their potential destructive power and long ~~run-~~ run-out distances and challenges stemming from the absence of transboundary GLOF risk mitigation mechanisms. For example, a recent GLOF from South Lhoknak Lake in the Indian Himalaya ~~has~~ travelled over 300 km downstream, causing significant damage in Bangladesh (Sattar et al., 2025b). The absence of transboundary cooperation for GLOF risk mitigation (for example, flood magnitude communication, shared hydropower reservoir draw-down management) between Bhutan, China, and India complicates efforts to monitor and manage such risks. Establishing regional cooperation is essential to enhance early warning systems, facilitate data sharing, and implement coordinated risk reduction strategies, such as one proposed by Zhang et al. (2025a)~~Zhang et al. (2025)~~, thereby ~~minimizing~~ minimising the potential damage from future transboundary GLOFs.

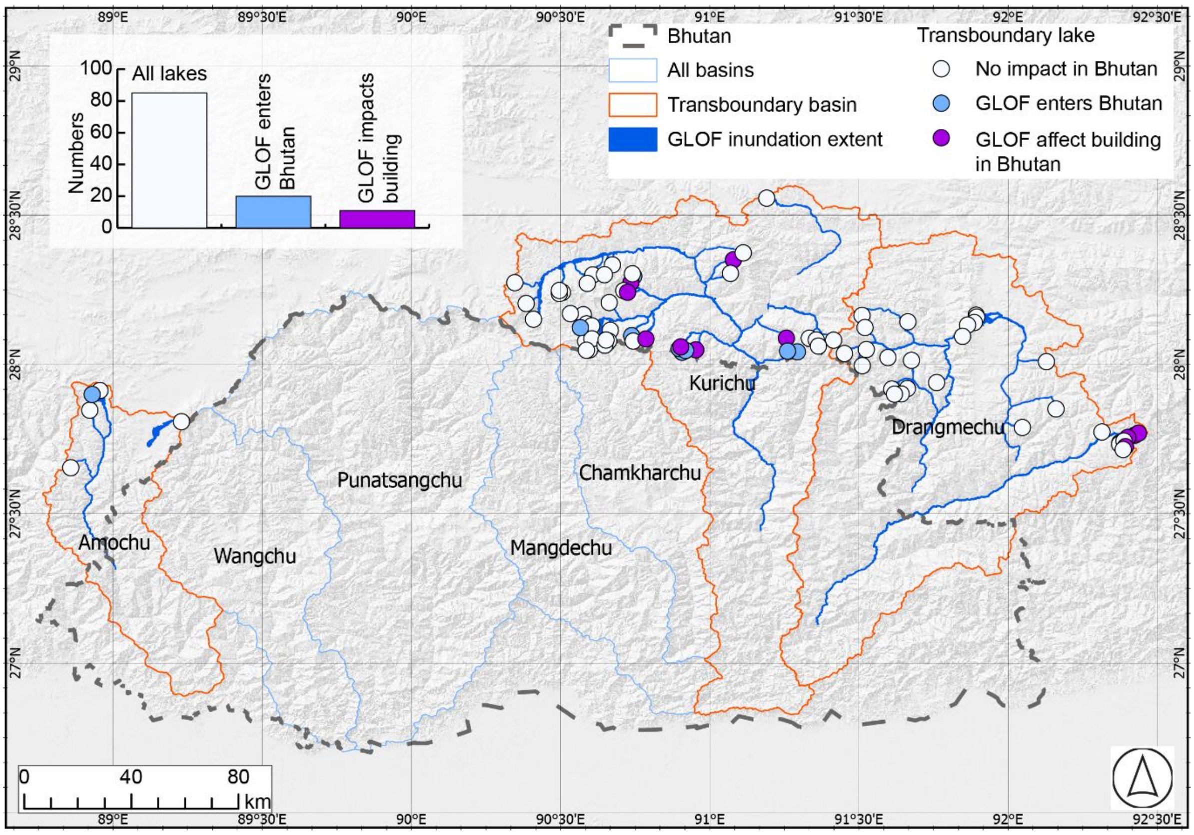



**Figure 9.** The map shows the impact of GLOF in Bhutan, which originates from lakes located on the Chinese and Indian sides of transboundary basins. The inset bar graph shows the total number of lakes, lakes from which GLOFs enter Bhutan and lakes from which GLOF impacts buildings in Bhutan. The lake ID on the x-tick labels corresponds to the ID on the map.

### ~~7.3~~5.3 Significance, limitations and the way forward

#### ~~7.3.1~~5.3.1 Significance

Our approach of GLOF risk~~danger~~ assessment using both flood magnitude and downstream exposure data provides local authorities and relevant stakeholders with valuable information to plan and ~~prioritize~~ prioritise wide-ranging risk mitigation activities. These activities may target either specific glacial lakes or downstream communities based on the damage index and level we have provided, whilst also incorporating practical factors, such as resource availability and logistical constraints. This study is particularly timely, as the Royal Government of Bhutan is planning to ~~modernize~~ modernise and expand its network of flood monitoring and GLOF early warning systems (World Bank, 2024). This initiative, outlined in the roadmap for 2024–2034, aims to develop multi-hazard warning services, aligning closely with the practical applications and insights provided by our research. For example, our flood mapping and flow arrival time data can be used to appropriately locate GLOF monitoring stations for early warning systems (Wang et al., 2022). Likewise, some of the scattered buildings in LGUs such as Soe gewog in Paro could be impacted by GLOFs within as little as 10 minutes. This short lead time means it is ~~practically~~likely not effective to install early warning systems for residents in these rapidly ~~affected~~impacted areas. In ~~such~~this context, our flood extent mapping can effectively guide land-use zoning and support targeted decision-making for future development in these vulnerable locations.

### ~~7.3.2~~5.3.2 Limitations and the way forward

Our work establishes a baseline GLOF mapping and risk assessment in Bhutan. However, we acknowledge that the magnitude of floods from glacial lakes will continue to evolve as glacier retreat drives the expansion of existing lakes within a topographically constrained ~~extent~~basin, and due to the formation of new lakes within the depressions left by ~~the~~ retreating glaciers (Zheng et al., 2021b; Furian et al., 2022). This increasing lake area is expected to amplify GLOF magnitude~~ in terms of hydraulic intensity~~GLOF magnitude, as supported by our sensitivity analysis, which shows that the ~~that~~ *DV* increases approximately by two orders of magnitude when the area increases from 0.01 to 5 km². Concomitantly, the downstream settlements within the GLOF-prone areas are evolving, with population growth and infrastructure development leading to increased GLOF exposure (Nie et al., 2023; Uddin et al., 2021)~~.~~. The interplay of these factors means GLOF risk~~danger~~ will likely increase in the future and highlights the need for dynamic and regularly updated GLOF flood mapping and risk assessments in the future.

We determined the minimum glacial lake area threshold (0.05 km$^2$) for GLOF modelling based on the empirical evidence from the previous inventory (Shrestha et al., 2023; Komori et al., 2012). However, it is important to acknowledge that glacial lakes smaller than 0.05 km$^2$ have also been known to produce GLOFs with a magnitude substantial enough to cause significant downstream damage (Sattar et al., 2025a), particularly when they combine with other floods like meteorological floods (Allen et al., 2015) or when the outburst flow entrains a large amount of debris (Petrakov et al., 2020; Cook et al., 2018). Thus, the future modelling efforts should also consider smaller lakes than the size threshold we considered here and more complex, sediment-laden rheologies and phase changes.

Our drainage volume and peak discharge calculations are based on empirical equations and the previous GLOF events, with ~~scarcely~~incomplete documented ~~detailed~~ characteristics (Shrestha et al., 2023). Employing such proxy parameters is reasonable for this study, as we aimed to provide an overview of GLOF risk~~danger~~ in Bhutan based on the downstream impact. The modelled GLOF scenarios for each lake are directly comparable, enabling an assessment of the overall and relative levels of hazard~~danger~~, and representing a moderate scenario. We ~~recognize~~recognise, however, that this is just one set of scenarios while empirical relationships between the volume and area are associated with significant uncertainty (Schwanghart et al., 2016). Due to time and computational constraints, it was not feasible to simulate all potential variations. Future studies focusing on the detailed impact of specific glacial lakes or on specific downstream communities must be grounded ~~on~~ on site-specific scenarios informed by situational triggering factors and dam composition and geometry. The study should also consider the site-specific worst-case scenario, considering the future climatic conditions.

While we mapped all types of exposed elements located within the GLOF flow inundation extent, our GLOF damage index is calculated solely based on the impact on the number of exposed buildings. This approach is grounded in the rationale that buildings represent the primary places where people reside and are therefore the most direct proxy for population exposure. However, critical infrastructure such as hydropower plants (e.g., in the Punatsangchu basin) and the international airport in Paro (Wangchu basin), which are vital to the national economy, were not included in our risk~~danger~~ calculation. This omission stems from the considerable challenges involved in accurately estimating the economic cost of potential damage to such high-value infrastructure. When ~~the~~ a GLOF intercepts hydropower dams, it can cause overtopping, excessive sedimentation, outages, and equipment damage, leading to significant revenue losses from the hydropower plants (Dunning et al., 2006) as well as cascading impacts on the low-lying settlements (Sattar et al., 2025b). Likewise, damage to the crucial infrastructure, such as Paro international airport, will hinder relief efforts after the GLOF disaster, delaying the recovery and escalating overall loss and damage. Therefore, future studies should also consider absolute economic impact of GLOF to aid relevant stakeholders and policymakers in developing appropriate strategies to mitigate risks to vital infrastructure.

The socio-economic indicators used here are the best available census data at the finest granularity in Bhutan. These indicators represent people's capability to respond to and recover from not only GLOF but also any natural or man-made hazards (Cutter et al., 2003). However, these indicators do not necessarily represent people's specific vulnerability to GLOF, as it also depends on other factors such as prior experience of natural hazards (Lloyd's Register Foundation, 2024). For example, we classified Lunana gewog as the most vulnerable gewog based on these socio-economic indicators (Fig. S5); however, how their prior experience influences their response capability remains beyond the scope of this study. Future studies focusing on specific downstream settlements or impact of a particular glacial lake should also consider the broader implications of vulnerability and resilience.

Looking forward, the glacial lake dataset can be updated using wide-ranging open-access remote sensing imagery. Similarly, platforms such as OpenStreetMap, which leverage crowdsourced data and are frequently updated, present a valuable resource for mapping evolving downstream buildings and other structure data. Likewise, hydrodynamic modelling for multiple glacial lakes with freely available and user-friendly models such as HEC-RAS is increasingly becoming feasible with the recent development in artificial intelligence and cloud-based computing platforms like Flood Platform (https://www.floodplatform.com/), which enable integrating products from varied flood simulations/models into a common framework. We have developed a website, which hosts glacial lake data and flood maps, serving as a valuable resource for periodic updates to flood damage assessments. By integrating up-to-date glacial lake flood magnitude information with evolving downstream exposure data, this platform can provide valuable information for informed decision-making and proactive risk management, such as tailored early warning systems~~ and~~, land use management and development.

## ~~8~~6 Conclusion

Glacial lakes, which are growing in number and area in mountains globally, pose a serious GLOF threat to the communities living downstream of them. However, the destruction and damage caused during the GLOF event are not determined solely by flood magnitude or ~~intensity, but~~intensity but also depend on their interaction with downstream exposed elements. Despite this, traditional approaches to assessing the hazard~~danger~~ posed by glacial lakes have been mainly based on the likelihood and magnitude of a lake to produce GLOF and often disregard the potential downstream impact. To address this gap, this study redefines the hazard classification ~~classification~~ of ~~PDGLs~~ glacial lakes in Bhutan (one of the high GLOF risk countries globally) by combining GLOF hydrodynamic characteristics and downstream exposed buildings.

This study produced GLOF hydrodynamic characteristics for all glacial lakes in Bhutan that are greater than 0.05 km$^2$ and located within 1 km of a glacier terminus. The analysis revealed that over 11,322 people, 2,600 buildings, as well as other infrastructure such as roads, bridges and farmland are exposed to GLOF in Bhutan. A GLOF damage index was developed by combining flood mapping data with downstream exposure metrics, enabling the ranking of glacial lakes based on their potential hazard~~danger~~. Thorthormi Tsho was identified as a very high hazard~~the most dangerous~~ glacial lake in Bhutan. Furthermore, we identified five additional glacial lakes as having high GLOF ~~danger~~hazard. ~~, two of which are in the headwaters of Wangchu, neither included in the previous study nor monitored by the existing early warning system in Bhutan.~~ Among these high hazard~~dangerous~~ glacial lakes, three of them are newly identified ~~(potentially dangerous glacial lakes (~~lake251 and lake~~,~~ 278 in the headwaters of the Wangchu basin and lake93 in the Chamkharchu basin) ~~in the current study~~,

~~neither included in the previous study nor~~and are not monitored by the existing early warning system in Bhutan.~~..~~

For the first time, this study provides GLOF ~~danger~~ risk ranking for 20 districts and 274 local government administrative blocks (gewogs and towns) [LGUs] in Bhutan. In addition to the previously identified high GLOF ~~danger~~ risk gewogs and towns, we have identified six additional LGUs with similarly high GLOF ~~dangers~~risks. These include Chhoekhor and Bumthang town in Bumthang, Paro town and Lamgong in Paro, Nubi in Trongsa and Khoma in Lhuentse districts. Most strikingly, some downstream LGUs such as Paro town and Lamgong gewog in Paro are not covered by the existing Bhutan early warning system, highlighting significant gaps in existing risk mitigation efforts.

This study underscores the criticality of incorporating flood mapping and downstream exposure and vulnerability data when defining ~~PDGLs and assessing downstream~~GLOF risk. For Bhutan, the findings ~~emphasize~~ emphasise the urgent need to expand and strengthen GLOF risk mitigation strategies, including the enhancement of early warning systems and the implementation of targeted interventions in newly identified high-risk areas. These measures are essential to safeguarding vulnerable communities and infrastructure from the escalating threat of GLOFs in the context of ongoing climate change and glacial retreat.


## ~~9~~7 Acknowledgement

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## Code and data availability

The HEC-RAS 2D model we used here for simulating glacial lake outburst modelling can be accessed at: https://www.hec.usace.army.mil/. The AW3D30 DEMS used here can be downloaded from the OpenTopogra~~g~~phy at: OpenTopography - Find Topography Data. Bhutan 2017 housing and census data can be downloaded from the National Statistical Bureau of Bhutan at https://www.nsb.gov.bt/. Landover and landuse data used in this study can be accessed at: https://rds.icimod.org/. The OpenStreetMap data can be assessed at: https://www.openstreetmap.org/relation/184629. GLOF hydraulic data for each glacial lake will be made available through the web portal upon publication of~~-~~ this ar~~i~~ticle.

## Supplement

The supplement related to this article is available online at:

## Author contributions

SR, SD and RC ~~conceptualized~~ conceptualised the study. SR undertook data analysis, visualization and wrote the original draft. SD and RC secured the funding, supervised and contributed equally to the work. SA, AS and SW reviewed and edited the manuscript. All authors contributed to the final manuscript.

## Competing interests

The contact author has declared that none of the authors has any competing interests.

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