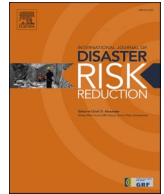




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Public warning and evacuation experiences during recent GLOF events (2019 and 2023) and recommendations for future preparedness: Insights from Lunana, Bhutan

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ABSTRACT

Early warning systems (EWS) are essential for reducing loss of life during the event of glacial lake outburst floods (GLOFs). However, the efficacy of EWS is contingent on factors including warning dissemination and community response. Despite the crucial role of EWS, there remains a paucity of studies examining community experiences with GLOF EWS, which are imperative for improving existing systems. Using surveys, key informant interviews and focus groups, this study offers insights into warning dissemination (including sources and channels of communication) and evacuation during recent (in 2019 and 2023) GLOF events in Lunana, Bhutan. Our analysis showed that environmental cues, such as unusually loud river sounds and ground vibrations, were the main sources of initial warning during past GLOF events. Mobile phone calls from friends and family also emerged as common channels for disseminating both initial and subsequent warning messages. Participants described evacuation during recent events as challenging and uncoordinated, with some people lacking pre-prepared essential items and facing difficult conditions at evacuation sites, including exposure to extreme cold and limited shelter. We first recommend strengthening existing GLOF EWS, making it more community-based, and diversifying communication response channels and sources, particularly through resilient mobile phone-based communication. Second, we recommend enhancing people's resilience to future GLOFs by expanding existing advocacy programmes toward building people's response capability, including regular mock drills, evacuation preparedness training, and fit-for-purpose, co-designed shelters at evacuation sites.

1. Introduction

Glacial lake outburst floods (GLOFs) pose a substantial threat to mountain communities across the world. Globally, ~3153 GLOF events since 850 AD have been documented, causing ~12,529 human death and extensive damage to infrastructure such as hydro-power stations and roads [1]. In High Mountain Asia (Tibetan Plateau and surrounding mountain regions) alone, the human death toll from GLOFs is 7036, accounting for over 50% of global GLOF-associated deaths [2], although 80% of this figure is associated with the 2013 Chorabari, India GLOF event [3]. A notable recent example is the 2023 GLOF from South Lhonak Lake in the Indian State of

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Sikkim, which left 55 people dead, while 74 remained missing. This event damaged approximately ~25,900 buildings, ~276 km² of agricultural land, 31 major concrete bridges, ~18.5 km of road and four hydropower dams. Notably, most building damage from this event was recorded within 200 and 385 km downstream of the lake and affected buildings constructed after 2010, indicating the significant influence of increasing downstream exposure on the impacts of such devastating events [4].

Amidst increasing GLOF hazards [5], effective early warning system (EWS) is an essential component for building people's response capability and reducing losses during events [6]. According to the Sendai framework for disaster risk reduction (SFDRR) 2015–2030, the effective people-centred and end-to-end EWS comprise four interrelated components: “(1) disaster risk knowledge based on the systematic collection of data and disaster risk assessments; (2) detection, monitoring, analysis and forecasting of the hazards and possible consequences; (3) dissemination and communication, by an official source, of authoritative, timely, accurate and actionable

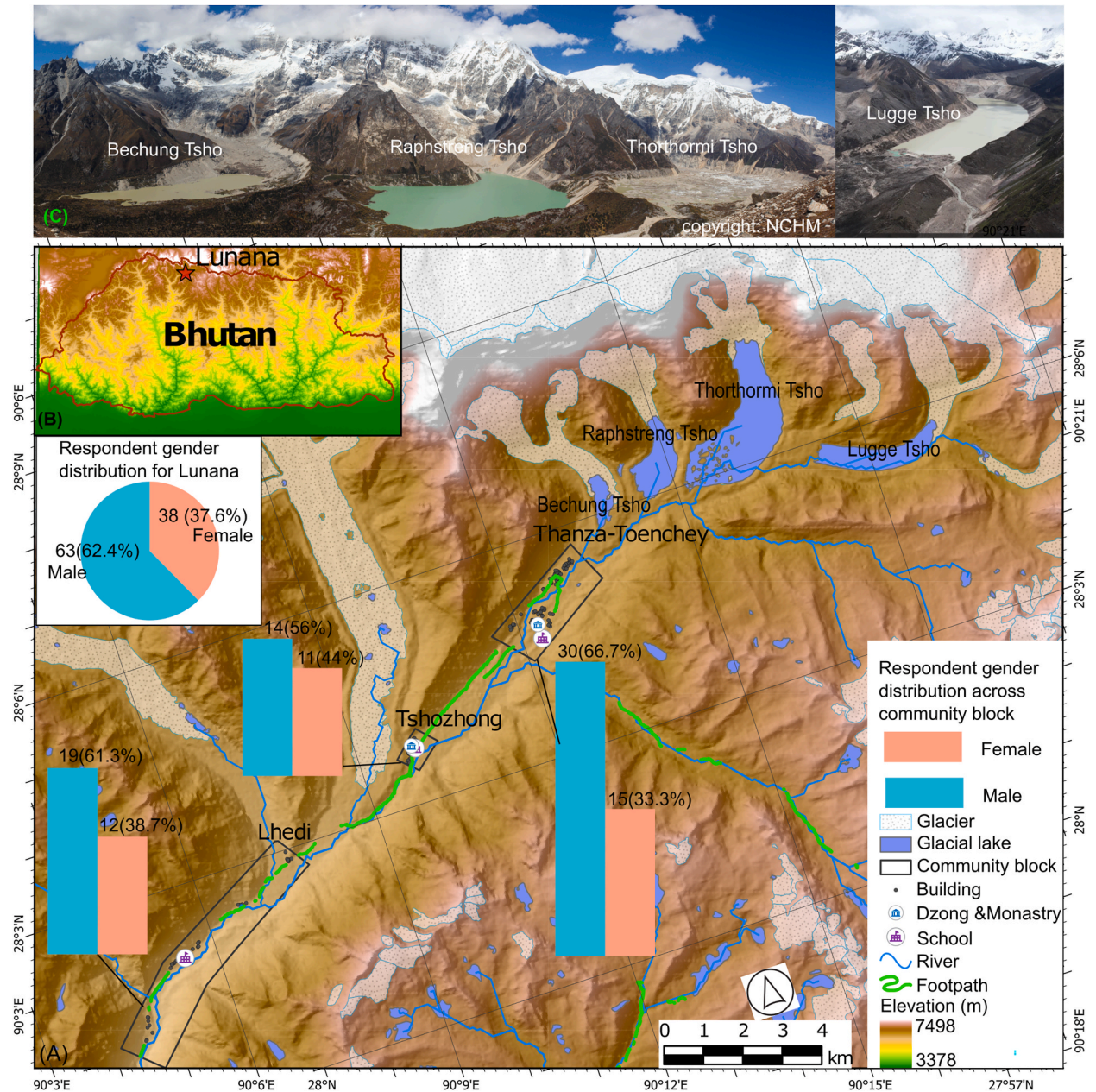


Fig. 1. Map of Lunana, Bhutan. (A) Map of Lunana, showing three community blocks, locally known as Chiwogs, with building distribution shown as points. The boundaries represent different communities solely for this study and do not represent administrative boundaries. Inset (B) shows Bhutan with a star marking Lunana. The inset pie chart shows the proportion of male and female respondents for the entire Lunana, and the bar shows the proportions of male and female for the respective community blocks. Upper panel (C) shows photographs of four glacial lakes that are located upstream of Lunana village.

warnings and associated information on likelihood and impact; and (4) preparedness at all levels to respond to the warnings received" [7]. As well as monitoring and accurately detecting physical hazards, the efficacy of EWS is contingent on how warnings are disseminated and how communities respond. When and how people receive the first warning message, and the protective action they take, all influence the eventual consequences of a GLOF [8,9].

Past studies have mainly focused on reconstructing the physical processes and mechanisms involved in GLOFs and other glacial hazards [10]. By contrast, people's experiences of responding to past GLOF events have received limited study, even for recent and well-documented events [4]. Understanding these experiences is critical, as losses and damages during GLOF events are not only caused by the physical hazard itself but are also influenced by how affected people conduct emergency response operations during a crisis [11]. Emergency response failures often stem from warning misinterpretation, inefficient coordination among stakeholders, and a lack of resources, knowledge, or contingency plans, all of which can impede successful evacuation, which is critical for saving lives during crises such as GLOFs [12]. The limited understanding of community-level GLOF evacuation experiences and perspectives is, therefore, a crucial deficiency that prevents the development of robust, effective EWS, as part of a comprehensive emergency response preparedness plan.

The community of Lunana is located approximately nine days' walk from the nearest road point in Bhutan. This remoteness makes Lunana one of the country's most vulnerable communities. The village is surrounded by numerous glacial lakes, including Thorthormi Tsho, the most dangerous glacial lake in Bhutan [13] (Fig. 1). Lunana is located in a basin identified as the fourth highest risk basin in the world [14] and is among the most at risk communities within Bhutan [15]. People in Lunana have experienced four GLOFs since 1994 from lakes located upstream of their community and therefore have first-hand experience of evacuation procedures [16–18]. GLOF hazard and risk reduction in Lunana has been a sustained focus of government mitigation programmes since the first major GLOF sourced from Lugge Tsho in 1994 [16]. This combination of repeated GLOF experience, long-standing risk-mitigation efforts, and the community's active involvement in operating the EWS provides a unique opportunity to document detailed lived experiences and local insights.

To this end, this study presents the first comprehensive documentation of public warning dissemination and evacuation during the past GLOF events in Lunana in 2019 and 2023, people's risk awareness and preparedness relative to the EWS in place, and the impacts of GLOFs on livelihoods using a mixed-methods research design. We conclude by providing practical recommendations for improving existing GLOF EWS and wider GLOF risk mitigation efforts applicable to mountain communities elsewhere, informed by our findings, field expertise, local knowledge and wider literature in disaster risk reduction.

2. Study area and rationale

The present study focuses on Lunana gewog (located at 28°3'0"N, 90°10'0"E), within Gasa District in Bhutan. Lunana village is divided into three Chiwogs (local sub-administrative units), namely Thanza-Toenchey, Tshozhong and Lhedi. According to the Bhutan 2017 Population and Housing Census, Lunana has a population of 699 (348 males and 351 females) living in 177 households [19] (Fig. 1), spread along the river valley that routes GLOFs from numerous upstream glacial lakes.

The Punatsangchu basin is equipped with a GLOF EWS consisting of a network of 10 automatic water level sensors and 18 warning sirens placed across the basin [20]. Of these, five automatic water level sensors and three warning sirens are placed in Lunana to monitor the four glacial lakes in Lunana and provide warnings to the people in the event of a future GLOF. This GLOF EWS operates as a semi-automatic system in which automatic water level sensors transmit signals of any abnormal water level change to the control room, where a technician evaluates the information and sends a warning in accordance with established standard operating procedures [20].

The Lunana community has experienced four recorded GLOF events in the recent past, three within the last decade, with the latest occurring in 2023 [17]. The most devastating, the 1994 Lugge Tsho GLOF killed 23 people and damaged ~100 structures, including Punakha Dzong, then Bhutan's administrative capital [16]. On 20 June 2019, a recent GLOF unfolded in Lunana due to the rapid breaching of a small subsidiary lake located on the frontal moraine of Thorthormi Tsho [18]. Likewise, another small GLOF was unleashed from Thorthormi Tsho on 4 October 2023 [17]. On both recent occasions, community members residing in the flood exposed areas evacuated because of the fear of flooding, although there is no indication that they received an official warning from an authoritative source. Furthermore, forward-looking studies have identified Lunana as one of the most at risk communities in Bhutan (See previous section for more detail) [15].

The Himalayan region has experienced multiple episodic and devastating GLOF events, for example, the 2023 outburst flood from South Lhonak Lake in the Indian State of Sikkim [4] and the 2020 event of Jinwu Co in the Southeastern Tibetan Plateau [21]). However, post event accounts of GLOF EWS operation and performance to reduce harm during these events are extremely rare. Notably, both the 2019 and 2023 events have reports on early warning and evacuation operations conducted during the events, but these have not been studied in depth from a social science perspective. Because Lunana is relatively small, almost everyone who experienced the GLOF EWS can be surveyed, enabling us to get first-hand experiential data [17,22]. Also, the 2019 and 2023 events did not cause significant damage, and people were not displaced, meaning that members of the community who received warnings and underwent evacuation were readily available to provide us with information for this study. During fieldwork, the public informed us that they also had evacuated on other occasions, sometimes due to false alarms from the siren. These experiences of false warnings further allowed us to gather information about perception, and in future warning sources.

3. Methods

3.1. Sampling and preparation

We selected all households at GLOF risk in Lunana [23] for the survey. Accordingly, all households in Thanza-Toenchey and Tshozhong were included, and about half of the households in Lhedi Chiwog. Villages including Wachey, Thango and Threlkha were not included because they are located at high elevations above the river, are not at risk from GLOFs and residents would not have direct experience of GLOF response, which might skew our results. However, we acknowledge that people living in these high-elevation villages might also be exposed to GLOFs when they visit downstream exposed areas. Oral or written consent was obtained from each participant before collecting data: oral consent was required in some cases due to low literacy. Ethical approval for the study was obtained from the Faculty of Humanities and Social Sciences Ethics Committee, Newcastle University. The study was also approved by the Gasa district administration, the Department of Forest and Park Services under the Ministry of Agriculture and Forestry, Bhutan, and the local government of Lunana gewog.

The data were collected using both quantitative and qualitative tools. Survey and interview items were prepared based on existing body of literature related to community disaster risk perception and preparedness, and experience [9]. Enumerators were trained in translating items in the questionnaire into the local language, rapport building, and social and cultural sensitivity during the data collection. The research lead accompanied the enumerators throughout the survey to ensure data collection consistency and compliance with ethical procedures, while qualitative data were collected solely by the research lead.

3.2. Survey: quantitative data

For quantitative data collection, we attempted to survey all the households within our focus villages. However, some households were empty during our visit. Ultimately, the survey covered 101 households, with one participant from each household (Thanza-Toenchey: 45, Lhedi: 31, Tshozhong: 25), representing 74% of the total GLOF at-risk households in Lunana. All respondents completed the survey, so the response rate was 100%. Some respondents were not present during either the 2019 or 2023 flood events, the GLOF events of interest; therefore, complete event-experience data were obtained from 71 respondents.

The quantitative survey was conducted mainly to collect information about the experiences of and responses to public alerts and warnings received during past GLOF events and people's preparedness to respond to future events. The questionnaire was adopted from Sorensen, Mileti, Richards and Pope [9], which was designed to collect information on public warning diffusion and response during the February 2017 Oroville Dam spillway event, which prompted mass evacuation. The same questionnaire was used to generate warning issuance, diffusion and protective action initiation delay curves in HEC-LifeSim [24], the agent-based model that simulates warning, evacuation, and consequences (loss and damage) during dam break and other types of floods. The questionnaire of Sorensen, Mileti, Richards and Pope [9] was modified to make it suitable for the Bhutanese context and applicable to the GLOF events in Lunana using our local knowledge and field expertise. Accordingly, we deleted or added alternative options under certain items when necessary (see [Supplementary Material 1](#)). For example, we added 'environmental cues' under the item 'source of first warning' and deleted options such as 'local police', which are not relevant to the context of Lunana.

The questionnaire consisted of 47 items and was divided into five sections and one open-ended question, enabling us to collect detailed information about people's past GLOF evacuation experiences and their preparedness to respond to future GLOF hazards: (1) personal attributes, such as gender and level of education of the respondent (Q1 to Q8); (2) source, channel and people's understanding of the first warning message (Q10 to Q21). We also included questions to determine the point in time at which people received the first warning message. The respondents were given a range of options to choose the channels or sources of communication through which they received early warning messages during past GLOF events. A Likert-type rating scale was presented to assess their understanding and perception of the warning message; (3) people's behaviour and actions before evacuation (Q22 to Q27). Here, we provided respondents with structured options to assess their actions after receiving the first early warning message. Specific questions included information about the follow-up messages and extra information, and the action taken before evacuating; (4) how people evacuated or adopted protective measures (Q28 to Q35), including evacuation timing, mode of evacuation and evacuation destination; and (5) perception and preparedness to respond to future GLOF events (Q36 to Q47), including respondents' future willingness to evacuate, existing evacuation plans, preparedness to respond to GLOF hazards, perceptions of warning sources and communication channels and intended pre-evacuation actions.

3.3. Qualitative data

We asked one open-ended question at the end of the survey to allow participants to share any additional information that was not covered by the questionnaire items. Responses to this question (Q47) were recorded verbatim in Dzongkha, then translated and transcribed into English. When analysing these responses, we found that some community members shared additional insights about the challenges they faced during evacuation and their broader concerns about GLOF hazards in Lunana, which were not explicitly captured by the questionnaire items. Thus, follow-up fieldwork was conducted in May 2025 to further examine in-depth experiences of early warning operations, response, and risk perception. During this fieldwork, we conducted three focus groups (FGs) and nine key informant interviews (KIIs) using structured guidelines focused on the following themes: (1) evacuation experience and challenges, (2) long-term post-GLOF impacts and (3) risk perception and preparedness. The FG and KII participants (n = 21) represented a diverse demographic range, including farmers, senior citizens, monks and public servants in Lunana (see [Supplementary Material 2](#)).

4. Results

4.1. Personal attributes of the respondents

Of the total respondents, 62% were male, while 38% were female. Respondents' ages ranged between 18 and 75 years, with the majority (37%) falling between 25 and 44 years. At least 5% of respondents were 75 years or older. With 55% of the respondents not having attended any form of education, most were illiterate. Approximately 30% of respondents had attended non-formal (15%) and monastic education (15%). The average annual income range of respondents was mostly between \$3500 and \$4999 (30%), and \$5000 to \$7499 (30%). For comparison, the average annual household income in Bhutan is \$4,546, according to the 2022 Bhutan Living Standard Survey [25]. This suggests that people in Lunana earn an income level broadly comparable to the national average. However, we noted that for most households, this income does not represent regular annual earnings but rather income earned during high-yield *Cordyceps sinensis*, which may occur only once every few years. *Cordyceps sinensis* is a rare and highly valued parasitic fungus that grows in Himalayan meadows. Nearly all respondents were self-employed, with the majority (90%) working in farming. Only two respondents were unemployed due to disability and old age.

4.2. Dominant role of informal warning systems during the past GLOF events

Of the total surveyed households (n = 101), most (70%) reported experiencing early warning and evacuation operations during either the 2019 or 2023 Thorthormi GLOF event; the remaining respondents were not in Lunana village for various reasons, including herding cattle and bringing rations. Our questionnaire included questions about the point in time at which respondents received a warning. However, respondents could not remember the timing accurately and at times, were confused between the multiple evacuation experiences over the last few years. We removed these timing questions from the analysis.

During the 2019 and 2023 Thorthormi GLOF events, informal communication channels and sources such as environmental cues (prolonged roaring sounds from the river and ground vibration) (~36.6%) and mobile phone calls (~32.3%) from friends (~25%) and family members (~28%) served as the primary means of disseminating initial alerts for the Lunana community (Table 1). Environmental cues were cited as the dominant (50%) channel and source of communication by people in Thanza-Toenchey, which is the community nearest to the glacial lakes in Lunana. Although the siren was not activated during either the 2019 or 2023 GLOF events, at least five people cited the sound from the siren as their channel of communication. This may reflect the experience of evacuation during events other than the 2019 and 2023 GLOFs, as people in Lunana have experienced several evacuations.

Key informant interviews (KIIs) and focus groups (FGs) revealed that local environmental knowledge enabled communities to distinguish floods from small regular avalanches: avalanche sounds are described as short-lived (lasting ~10 s), while GLOF noises persist for minutes (KII-2, KII-3, KII-4). Information from relatives and friends was the dominant source of first alerts for communities further downstream, where mobile phone calls served as the primary channel of communication. Nearly half of the respondents in Lhedi and Tshozhong reported receiving warnings through phone calls. People's experiences, shared through KIIs and FGs, further corroborated the critical role of mobile phones in relaying information during GLOFs. For example, Lu-63 from Tshozhong recalled, "My nieces and nephews in Thanza, upstream, called me immediately when they noticed signs of flooding, so I evacuated. Now I always keep my phone fully charged." Overall, insights from FGs, KIIs and surveys all indicated that first people detected GLOF threats through environmental cues, such as ground vibration and prolonged roaring sounds, before relaying information to others via mobile phone calls. As Lu-84 noted: "A loud noise came from the river. Stronger members went to inspect the river for a flood. Some of us informed downstream residents in Lhedi using WeChat group chat."

Table 1

Channel and source of the first alert/warning message during the Thorthormi GLOF of 2019 and 2023.

Channel of communication		Number of channels/sources				
		Place				
		Lhedi-Shangsa	Thanza-Toenchey	Tshozhong	Total	Percentage of the total
Environmental cues	Informal channel	3	19	4	26	36.6
Mobile phone call		6	8	9	23	32.3
Face-to-face from friends and family	Traditional	3	5	4	12	16.9%
Face-to-face from the authority		1	2	0	3	4.2%
Outdoor siren		0	2	3	5	7.0%
Social media	Modern	2	0	2	4	5.6%
Total		13	38	20	71	
Source of first warning						
Family members		6	7	5	18	25.0
Friends and neighbours		3	8	6	20	28.2
Local official		0	2	0	2	2.8
National weather centre		0	2	3	6	7.0
Environmental cues		3	19	6	26	36.6
Total		13	38	20	71	

We asked respondents how they felt about receiving a warning. Ideally, this set of questions was designed to assess respondents' understanding of the content of the warning message when detailed information about the hazard and safety action is provided. However, we believe that this was not relevant to the warning messages people received in Lunana during the 2019 and 2023 GLOF events, as their warning messages were mainly about the impending flood hazard and contained limited details; instead, responses to these questions were influenced by people's prior cognitive orientation towards GLOFs. Overall, respondents demonstrated awareness of the threat and consequences of GLOFs, as their responses to indicators such as willingness to evacuate, perceived risk of mortality or injury, and perceived flooding threat were all consistently high (4.53/6). At the community level, communities nearer to the glacial lakes showed a slightly higher agreement, with Thanza-Toenchey (4.75) being the highest, followed by Tshozhong (4.53) and Lhedi (4.46) (Fig. 2).

4.3. Pre-evacuation information and protective actions

Our survey results revealed that the majority (~57.7%) of respondents did not receive any additional messages after the first alert message. This may be because people were worried about the fast-approaching flood and tended to evacuate immediately. For the ~40% who received extra messages, these messages were primarily sourced from friends and neighbours (32.4%), and relatives (22.5%), and were communicated through mobile phone calls (19.7%), social media (18.3%), and face-to-face communication from friends and family (12.7%) (Table 2). Approximately 52% of residents communicated with others and sought additional information from friends and relatives about the flood before evacuating. Again, mobile phone calls emerged as the primary channel of communication (19%). Before evacuating, many people alerted others (27%) and helped others to evacuate (21%). At least 17% managed to pack some items before evacuating, while over 21% managed to secure their homes. Approximately 11% the respondents recalled that they did not undertake any of the pre-evacuation activities listed in the questionnaire before evacuation (Fig. 3).

4.4. Evacuation response patterns and community coping strategies

Our study shows that nearly all people (95%) who were present in Lunana during either the 2019 or 2023 Thorthormi GLOF events evacuated. The remaining residents did not evacuate because their houses are located at higher elevations with minimal risk of flooding. Almost all residents evacuated to higher elevations, although they were uncertain about the point in time they evacuated or

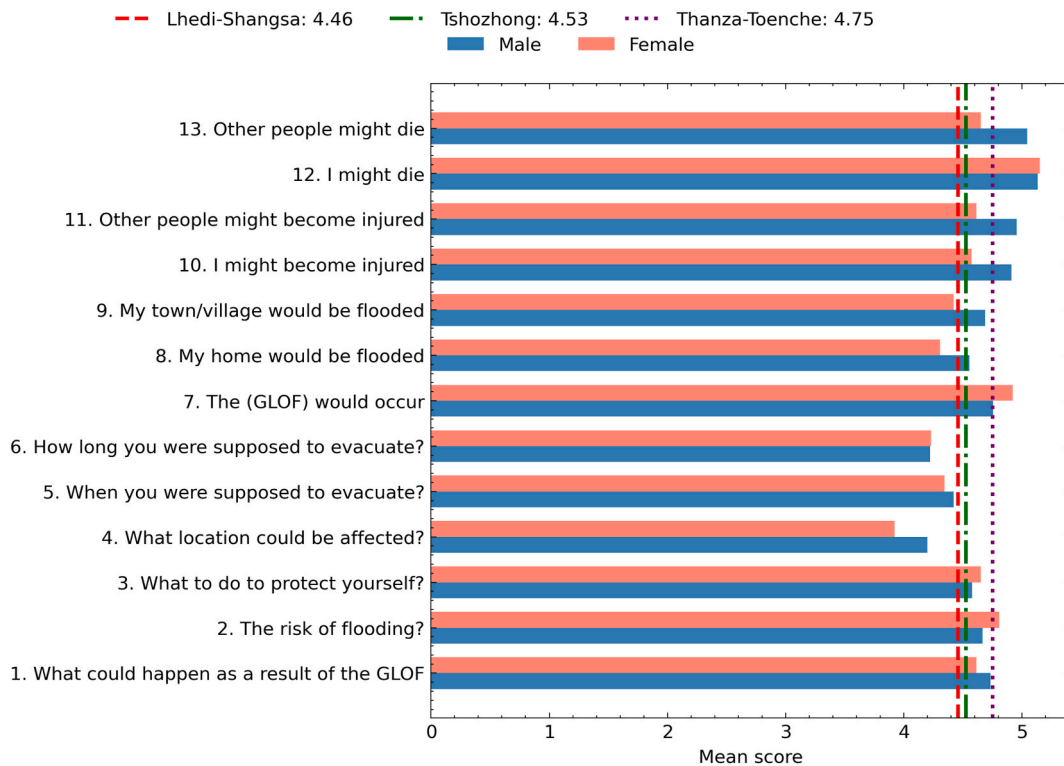


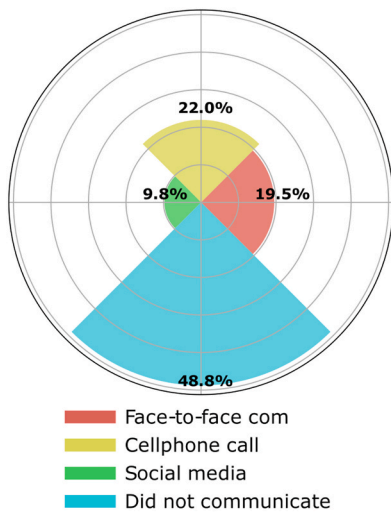
Fig. 2. GLOF threat perception. The bars show respondents' perceptions across three dimensions: understanding vs. not understanding (items 1–6), believability vs. unbelievability (items 7–9), and likelihood vs. unlikely (items 10–13). Scores range from 1 to 6, where 1 indicates a strongly negative perception, and 6 indicates a strongly positive perception. For example, for items 1–6, a score of 1 represents “not understood at all,” whereas a score of 6 represents “fully understood.” The dashed lines represent the average scores for the three communities: Lhedi, Tshozhong, and Thanza-Toenchey.

Table 2
Channel and source of the subsequent message during the 2019 and 2023 Thorthormi GLOF events in Lunana.

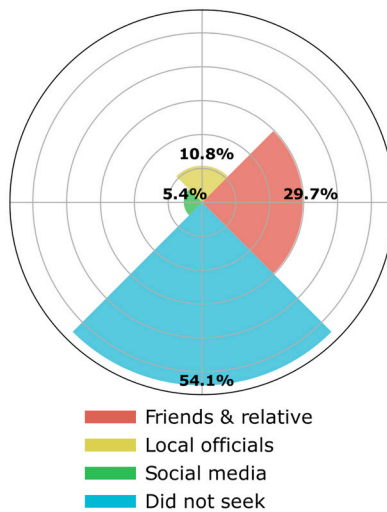
Channel	Number of respondents				Percentage (%) of total respondents
	Lhedi	Tshozhong	Thanza-Toenchey	Total	
Social media	5	4	4	13	18.3
Face-to-face from the authority	1	4	3	8	11.3
Mobile phone call	5	7	2	14	19.7
Face-to-face from friends and family	3	2	4	9	12.7
I did not receive any extra message	4	9	28	41	57.7

Source	Number of respondents				Percentage (%) of total respondents
	Lhedi	Tshozhong	Thanza-Toenchey	Total	
Government official	0	1	1	2	2.8
Local official	1	5	1	7	9.9
Family members	6	4	6	16	22.5
Neighbours and friends	7	9	7	23	32.4

(A) Com. with others



(B) Sought add. info



(C) Act. before eva.

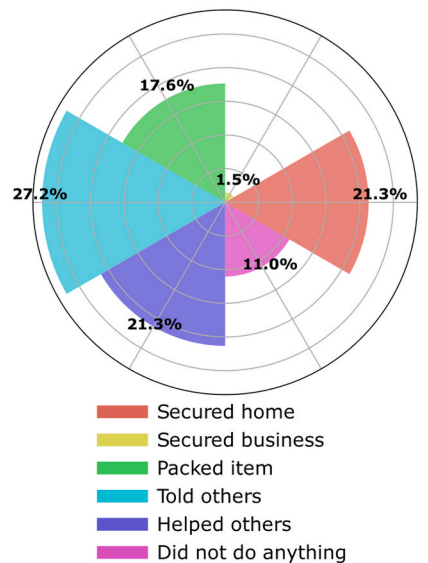


Fig. 3. Actions taken between receiving the first alert/warning message and starting evacuation: (a) communication with others, (b) seeking additional information, and (c) actions performed before evacuation. The size of each radial bar corresponds to the proportion of the respondent population.

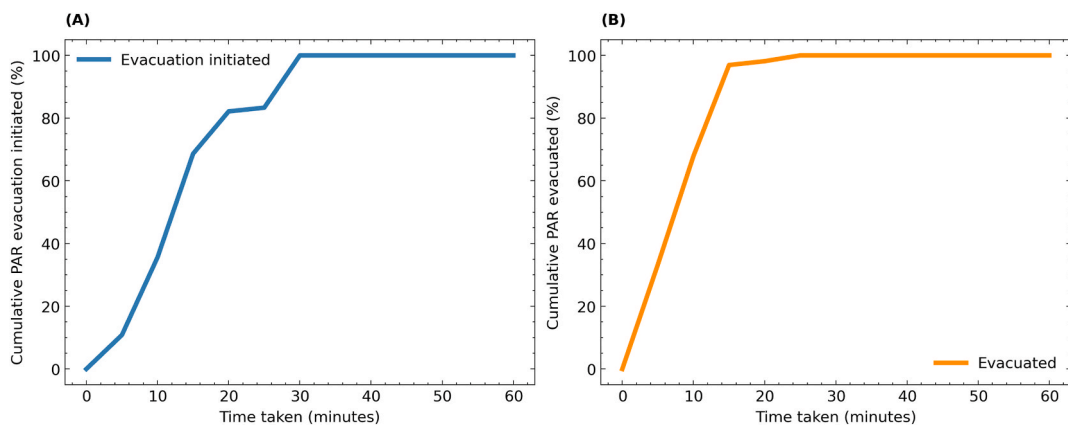


Fig. 4. Protective action initiation curve. Cumulative percentage of evacuating people at risk (PAR): observed for the 2019 and 2023 Thorthormi events in Lunana.

the exact time taken to begin evacuation after receiving the first warning message. Their recollections suggest that the interval between receiving the warning and starting evacuation ranges from 5 to 20 min, with the majority taking 15 min. Residents either walked or ran to the evacuation site, with most taking ~10 min to arrive at the destination (Fig. 4).

Previous experience of the deadly 1994 floods [26], indigenous knowledge, government advocacy programmes and scientific outreach all motivated respondents to evacuate during the 2019 and 2023 Thorthormi GLOF events. For example, KII-7 noted that ‘although the flood in 2023 was small, it is likely that such small floods could be followed by bigger ones, so we all evacuated to higher ground’. The majority of respondents knew the location of designated safe sites (usually higher elevation) which were identified by government officials (e.g., KII-2 noted “official told us the evacuation point is safe from flooding”) and often learnt through community memory reinforced by the devastating 1994 Lugge Tsho GLOF (e.g., KII-6 noted “my parents told me they had evacuated to that same place during the 1994 flood”). However, a lack of preparedness to evacuate despite high awareness was evident. People described the panic after receiving warnings, making evacuation chaotic and disorganized, with many forgetting necessities such as footwear and blankets (Lu-6, Lu-11, Lu-76, Lu-148). This also reveals that people usually do not have a prepared “go-bag” instead resorting to hastily picking up essential items (warm clothes, blankets and jackets) and valuable items (such as cash, *Cordyceps* and phones) during chaotic departures. Their strong sense of community and attachment to family members motivated them to help vulnerable individuals, including the elderly and people living with disabilities, during evacuations and to alert neighbours about hazards and evacuation through phone calls and face-to-face communication (KII-1, FG-2).

Residents usually spent a night at the evacuation site, lighting fires and using blankets to stay warm. Residents also used local environmental knowledge to decide when it was safe to return homes, as they did not have an official procedure in place. Many of the residents stated that they physically inspected the river and only returned home once they observed that the flood had visibly receded (KII-1, Lu-76). KII-2 noted, “after confirming that the flood had subsided, we returned to our homes,” and KII-9 recollected “, later, we inspected the river and found the flood had subsided, so we returned home to collect our clothes”.

4.5. GLOF perception and future response preparation

Nearly all respondents (95%), irrespective of age, gender and other demographics, perceived the GLOF as the primary type of

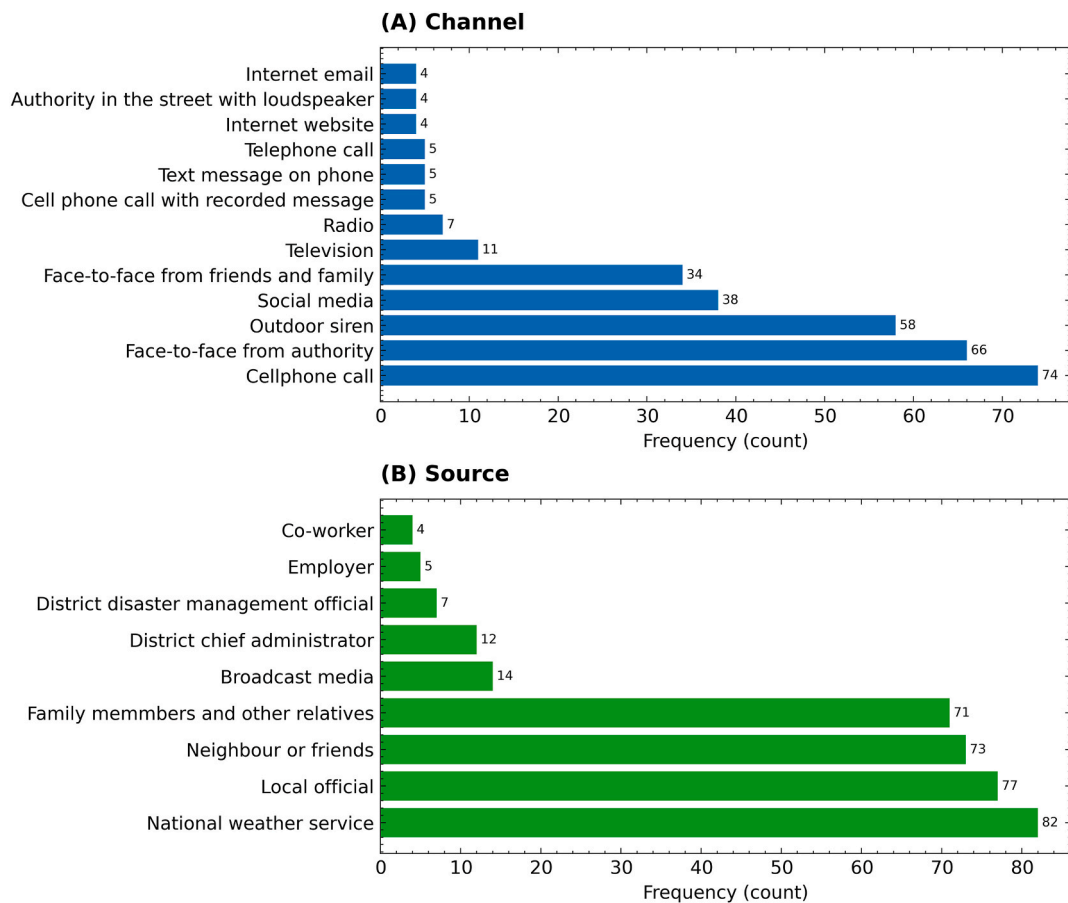


Fig. 5. Perceived reliable source and channel of information in case of a future GLOF event. The size of the bar corresponds to the number of respondents.

disaster threatening their community. Likewise, residents consistently identified GLOF as the primary natural hazard threatening their community during interviews (KII-2, -5, -6, -7). They attributed the GLOF threat to rapid glacial retreat (e.g., Thorthormi transforming from a debris-covered glacier to a water-filled lake), exacerbated by erratic weather events (KII-9, KII-8, KII-2). Residents were also worried about large-scale floods due to cascading flood events between the two largest lakes (Raphstreng and Thorthormi) located above their community (for example, Lu-16 noted that “Raphstreng and Thorthormi are now metres apart”).

In the case of a hypothetical future GLOF event, most respondents (81%) perceived information originating from the National Centre for Hydrology and Meteorology (NCHM) as the most reliable, while people also associated a high level of trust with other sources, including local officials (75%), neighbours and friends (72%), and relatives (70%). Regarding communication channels, mobile phone calls emerged as the most trusted channel (72%), followed by face-to-face communication from authorities (47%) and warning sirens (39%) (Fig. 5). Some key informant interviewees stated that they would trust the existing GLOF EWS over informal means of communication such as mobile phone calls and social media, despite a few false alarms and absence of siren activation during the last two GLOFs, if the systems were regularly maintained and community members were regularly updated about its condition (KII-2). People's trust in mobile phone calls was also highlighted by the KIIs (Lu-63, Lu-48, Lu-74). For example, Lu-48 from Lhedi stated: “I always keep my phone fully charged, ... my wife or I place our phones near the door at night to ensure we can get their calls in case of a flood.”

Our survey questionnaires also assessed measures people are willing to undertake to reduce loss and damage in the case of a future GLOF event in Lunana. Responses revealed that all residents in Lunana have building insurance, which also covers damage from floods, including GLOFs. However, this building insurance is part of the government-subsidised rural insurance scheme, which is provided to all households in Bhutan. Residents expressed concern that the sum assured under this scheme is far lower than the actual cost of constructing a house, leaving them financially vulnerable in the event of damage. Furthermore, they do not have insurance covering the contents of the building, animals or crops. Nearly all people (93%) also know where to evacuate during or before a GLOF arrival. Over half of respondents (51%) reported that they have planned items to move to higher ground, and 59% shared that they have decided what important items to carry with them when evacuating. Further inquiry through KIIs and FGs revealed that these items are usually limited to valuables such as money and jewellery. Over half (56%) also claimed that they have prepared emergency kits for evacuation, although these kits are largely limited to a torch (in most cases substituted by a mobile phone flashlight) and readily available warm clothes (Fig. 6).

Community insights also revealed that while people are aware of evacuation sites and routes in the case of future GLOFs, practical readiness remains low. Most residents know where to go (“Everyone knows the evacuation site ... we don't even need to talk about it,” KII-22) but lack practical preparation for events: There was consistent advocacy about flood threats, but no respondents reported participating in mock drills (“We've never done a mock drill once,” KII-2). Household-level mitigation efforts, such as sandbags, are seen as ineffective against the expected flood magnitude (“No use of building barriers ... the flood will be too large for such a small barrier,” KII-1).

4.6. Long-term consequences

The Royal Government of Bhutan has relocated two communities (Thanza-Toenchey) in 2023, which constitute over 80 households, due to previous GLOF experiences and the threat of future events. One school (Thanza-Toenchey community school) has already been relocated to a temporary shed, and another (Lhedi Primary School) is planned for relocation, with construction of a new campus currently underway. The 1994 Lugge Tsho GLOF completely damaged grazing land for the Dotag community under the Thanza-

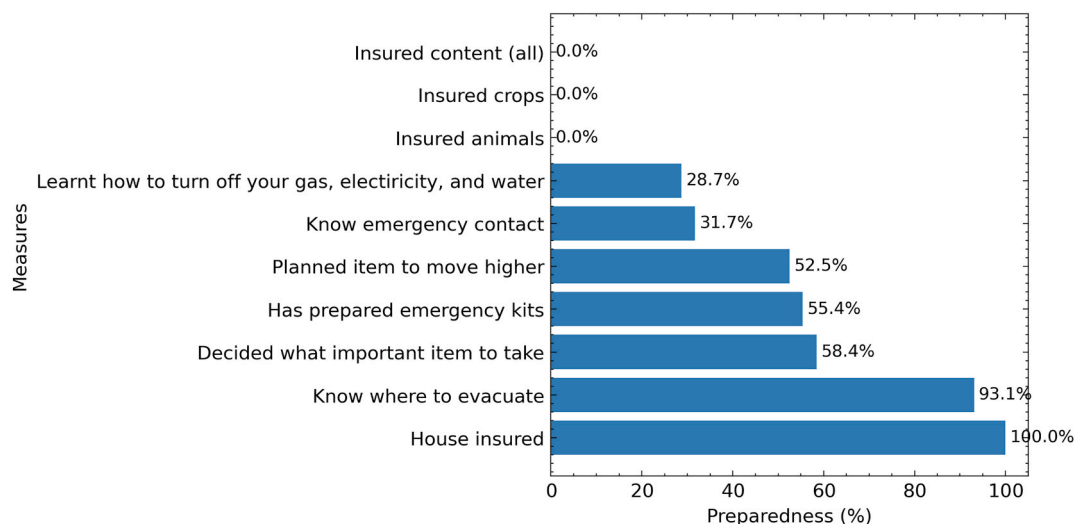


Fig. 6. Preparedness among the people of Lunana to respond to the future potential GLOF event.

Toenchey Chiwog. However, residents have not made significant adjustments to their livelihoods, such as construction practices, farming methods or livestock rearing, partly due to limited alternatives. Instead, residents prioritise safeguarding valuables by storing cash in banks and keeping valuable items in houses owned by neighbours at higher elevations (KII-7). Many respondents expressed worry about property and livelihood loss, with some deliberately avoiding home improvements due to flood risk (KII-2, FG-2). For example, KII-2 noted "some avoid painting new houses, fearing they will be washed away."

4.7. Cultural beliefs

The interview responses revealed a clear distinction between how cultural beliefs influence local people's perceptions of different aspects of disaster response. Spiritual beliefs tied to glacial lakes, such as the idea that a yogi's blessing and offerings to the local deity can protect against floods, do not seem to deter people from evacuating in the event of a GLOF (KII-1, KII-7). This coexistence of cultural beliefs with scientific understanding, rather than the former overriding the latter, has also been documented among Himalayan communities such as the Sherpas in Nepal [27]. Residents have acted pragmatically during past events, trusting warnings or signs of flooding and evacuating almost immediately (KII-2, KII-7). However, when it comes to long-term adaptation strategies such as reallocation to safer areas, cultural and religious attachments to land have become significant barriers as noted in a previous similar study [28]. The fear of offending local deities by abandoning or dismantling homes, along with generational emotional connections to ancestral homes, makes relocation emotionally and spiritually difficult, even when the risks of staying are understood (KII-9, KII-2, KII-8). One participant recalled a tragic outcome that was believed to have resulted from displeasing a deity by dismantling their house (KII-8) which contributed to doubts about moving an ancestral home to the newly reallocated safer place, although residents also associated these challenges with financial and resource constraints. This suggests that while traditional beliefs may not hinder emergency responses, they may have to be considered as critical matters when it comes to long term measures like permanent relocation.

4.8. Perceived challenges and anticipated future improvements

Residents of Lunana do not have shelters at current evacuation sites, which is a critical deficiency given that evacuees often endure freezing temperatures overnight with only blankets and fires for warmth. Moreover, this lack of shelter disproportionately affects vulnerable populations, particularly the elderly and children, according to residents. For example, KII-7 "having proper shelters would be very useful ... It would especially help elderly people who cannot tolerate the cold." Many respondents emphasised the need for weather-resistant structures that could not only shelter them but also store emergency rations and warm clothing.

Many residents thought that completely draining the lake water with heavy machinery would be the most effective mitigation strategy (Lu-64, KII-8, KII-2). Residents articulated multiple benefits of this approach: immediate flood risk reduction (so that they do not have to relocate), protection of downstream infrastructure (including culturally significant sites like Punakha Dzong and critical hydropower plants), and secondary advantages like improved local access through accompanying road construction (Lu-46, KII-2).

While residents recognised the importance of the existing siren-based GLOF EWS, insights from KIIs also highlighted opportunities to further strengthen its effectiveness and community confidence. Participants noted that the sirens are a valuable for saving lives, particularly if they are regularly maintained, improved for accuracy, and supported by continued community awareness activities (KII-9, KII-4, KII-6). Survey respondents and KII participants also suggested that clearer public guidance on how the siren system works, including how to distinguish routine tests or false alarms from real flood warnings, would further improve trust and response. For example, KII-9 noted that although sirens had been installed, additional explanation on their operation would be useful for the community.

Community members believed that EWS would save their lives, but not their livelihoods (e.g., yaks and horses) or houses and household property (KII-1, FG-1). There was some consensus around the need for insurance mechanisms to protect property, livestock, and assets that represent generations of family investment, but residents were not aware of any such insurance policies (KII-8). The KIIs also revealed how GLOF risks intersect with broader livelihood challenges and social vulnerability due to the remoteness of the community, absence of basic modern facilities such as roads and environmental conditions that constrain agricultural productivity and basic infrastructure development (KII-7). Because of these environmental conditions, residents must buy food supplies in advance, enough for either six months or up to one year, and store them in their houses, which also risk being damaged in the event of a GLOF.

5. Discussion

Numerous studies have documented the physical processes and mechanisms of past GLOF events across High Mountain Asia in recent decades to constrain parameter values for forward-looking GLOF hazard and risk assessments [4,10]. Although a few studies have examined efforts to build community capacity to respond to disasters such as GLOFs [29,30], to our knowledge, none has focused specifically on people's early warning and evacuation experiences. Physical processes and mechanisms involved in GLOFs are dynamic, uncertain and difficult to predict because every event is influenced by various local geomorphological conditions and situational factors. Our study, therefore, focuses on people's lived experiences and their first-hand perspectives, which are less likely to change, unlike physical parameters, and present a crucial alternative insight for improving our GLOF risk understanding at the local community level and can thus be used to strengthen risk mitigation activities. In the following sections, we discuss the significance and implications of our findings.

5.1. Dominant role of informal channels and sources of early warning messages

Residents of Lunana reported that during past GLOF events, they primarily received warnings through informal channels, despite the presence of a siren-based GLOF EWS. Mobile phone calls from friends and relatives also played a dominant role in disseminating subsequent messages after residents received the first alert warning message. This was, however, not entirely because the existing GLOF EWS was not functioning. According to the National Centre for Hydrology and Meteorology [18], the Lunana GLOF EWS was not activated during the 2019 Thorthormi GLOF event because the flood magnitude remained below activation thresholds. Further site verification was not possible because the flood occurred at night. Likewise, the GLOF EWS was not activated during the 2023 flood because the automatic water level sensors at Thorthormi Tsho were destroyed by the flood wave [17].

The use of environmental cues for detecting GLOFs by local people and the use of mobile phone calls from friends and relatives to spread warning messages during GLOF events is not unique to Lunana but has also been reported in other parts of the Himalaya. In Nepal, communities have identified impending GLOFs by sensing unusual ground shaking, hearing loud noises, and smelling gunpowder-like scents from rock abrasion within debris flows [31]. Similarly, a recent GLOF event in Gilgit-Baltistan, Pakistan, on 22 August 2025 demonstrated the critical role of environmental cues. Media reports indicated that despite the presence of a formal early warning system, it was local shepherds in Roshan Village who first observed signs of the flood and used mobile phones to alert residents, enabling successful community evacuation before floodwaters arrived [32]. These instances underscore the important role local populations play in disseminating early warnings, in tandem with technological systems and the challenges of deploying and maintaining such systems in high mountain environments. This is consistent with our reported GLOF experiences in Lunana, where community members chose to evacuate based on their own judgment and intuition, even in the absence of an official warning from the designated authoritative source. Monitoring stations designed to provide sufficient lead time are frequently prone to malfunction due to harsh high-altitude environments, as seen in Lunana, or are sometimes destroyed by the GLOF event itself.

Our study revealed that residents attached a high level of trust to warnings from authoritative sources, as recommended by the United Nations Office for Disaster Risk Reduction [7], although they were alerted about the past GLOF events largely by environmental cues and relatives. In the context of Lunana, this is likely because NCHM is the nodal agency administering the GLOF EWS in Bhutan and has been coordinating GLOF risk mitigation in Lunana for over three decades. Similarly, local officials are trusted figures elected by the community through majority vote. We posit that trust in mobile phones as the preferred reliable communication channel is influenced by their established role in daily communication and by the role mobile phones played during the past GLOF events. Although residents have experienced some false alarms, they maintained that warning sirens would still be reliable because they are loud enough to alert the entire community simultaneously, which is also cited as the main advantage of warning sirens in the literature, although sirens cannot provide detailed warning messages [33]. False alarms have neither diminished people's threat perception nor led to a complete loss of trust in the existing EWS, unlike findings reported from a case study in the Nepal Himalaya [34]. Nevertheless, KIIs and FGs further indicated that sirens would be reliable only if the system is regularly maintained and the community members are updated accordingly. Government advocacy programmes have likely played a key role in mitigating the false alarm effect, a finding supported by earlier literature from the USA based on man-made dam breach flood [9]. However, it is important to acknowledge that repeated false warnings could erode public trust in the siren-based system [35]. Therefore, continuous and strengthened community education on the functioning of EWS, including the potential for and meaning of false alarms, is essential to maintain credibility and effectiveness.

5.2. High threat perception but inadequate preparation

The strong community awareness of GLOFs likely reflects a heightened sense of risk accumulated over decades after the 1994 Luge Tsho flood, reinforced by government advocacy and scientific awareness programmes. People's high motivation to evacuate, even in the absence of a mandatory order from an authoritative source, can also be attributed to their higher risk perception developed through previous flood experience and reinforced by government advocacy programmes [36]. This was evident from the insights gained through KIIs and FGs and is also consistent with people's responses during other natural hazards, such as cyclones [36]. In addition, Lunana is a small community where everyone knows each other, and many people are related, fostering a strong sense of solidarity and mutual assistance during crises such as GLOFs. However, people's previous evacuation experiences and future preparedness indicate that they are not fully prepared to evacuate. Some community members described the evacuation as confused and disorganized and reported that they did not have prepared items to take with them. Such deficiencies could potentially delay evacuation in a faster-onset disaster, which is true in the case of Lunana, as a GLOF could arrive within minutes and increase the risk of injury or panic while evacuating, even if the eventual flood causes no direct damage [37]. Furthermore, evacuees who relocate to open spaces without essential clothing and shelter find it highly challenging to remain for an extended period (at least one day, based on their experience), exacerbating the crisis during a GLOF event. This suggests that existing risk knowledge gained through prior experience and government advocacy has raised people's flood threat perception, but future efforts are still needed to improve appropriate response during the event of GLOF events.

5.3. Strengthening the existing early warning system

Early warning systems are defined as "the set of capacities needed to generate and disseminate timely and meaningful warning information to enable those threatened by a hazard to prepare and act appropriately and in sufficient time to reduce the possibility of harm or loss" [7]. The Sendai Framework emphasised that a community-based approach should integrate local people across the entire

EWS process: from system design and risk knowledge gathering to ongoing monitoring, warning dissemination, and building response capabilities [7]. Our observations and interactions with locals through KIIs and FGs reveal that trust in the existing siren-based GLOF EWS can be strengthened by making it more community-based. Advocacy programmes and risk mitigation initiatives led by authorities since the late 1990s have greatly enhanced public understanding of GLOF risks in Lunana. This long-term trust, together with strong community relations, provides an excellent platform to further enhance the siren-based system. Based on interviews, this could be achieved through greater community involvement with the EWS and targeted education, alongside strengthening community warning dissemination through both leaders and wider social networks. Our results demonstrate the feasibility of this approach. Data shows that residents place high trust not only in NCHM but also in information from their own community leaders. Furthermore, the cultural norms and belief systems do not appear to obstruct emergency evacuation. The crucial role of social networks and community vitality in disseminating warnings and facilitating past evacuations provides a strong social foundation for a formalised community-based EWS.

Another key finding from this study is the centrality of mobile communication during past GLOF warnings and evacuations. Residents have developed adaptive strategies, such as keeping phones charged despite limited electricity sourced from solar energy and identifying locations with stable mobile network coverage to ensure they receive warnings, often via neighbours. This demonstrates a clear opportunity to formally integrate mobile-based technologies into the official EWS. Therefore, the existing GLOF EWS can be strengthened by integrating mobile phone-based communication. This is possible because Lunana now has 4G mobile network coverage. Moreover, improved living conditions, particularly from the commercialisation of *Cordyceps sinensis* collection, have further enhanced residents' ability to access and use mobile phones. Mobile phones are also the main devices through which people access social media platforms such as WeChat and Facebook, through which warning messages can be delivered across social networks [38]. Acknowledging network providers such as Bhutan Telecom as integral to GLOF EWS is essential; this practice has been implemented in neighbouring countries such as Nepal [39]. An authoritative source such as NHCM could use mobile networks to broadcast recorded early warning messages with specific details through selected applications or a recorded voice message.

Nevertheless, mobile phone communications are also associated with inherent challenges, especially in remote places such as Lunana. Repairs after network outages due to bad weather events are often delayed for weeks, as Bhutan Telecom do not station technical personnel in Lunana. This might be partly because mobile network communication is perceived as a utility for daily communication rather than an essential lifeline during emergencies. Efforts should be made to develop a resilient mobile network with built-in fallback redundancy to reduce vulnerability to weather-related disruption [40] and reduce repair times in cases of inevitable damage from weather events such as windstorms. Given the vulnerability of mobile networks to occasional failure, other means of communication, such as megaphones and high-frequency radios, should also be adopted to introduce redundancy in the EWS and prevent communication failures during crises that can prove fatal, as evidenced by the 2014 Babai River flood in Nepal, which resulted in over 30 casualties [39].

Finally, while indigenous knowledge has proven invaluable, sole reliance on environmental cues can be dangerous, as evidenced by accounts from KIIs where evacuees manually assessed flood water levels to decide whether to evacuate and later return home. Such reliance on environmental cues introduces uncertainties, as the community must physically see or hear the flood, which would be more challenging at night, which does not guarantee enough time for evacuation, especially at night. According to Lindell and Perry [41], environmental cues are more ambiguous and more likely to be misinterpreted. Moreover, depending on environmental cues to detect GLOFs and then assessing severity of flood in person at the riverbank poses a significant risk, especially during large and rapidly evolving events. People's environmental knowledge and willingness to evacuate should therefore be augmented with technological approaches, for example, using fixed cameras or other sensors to safely observe river conditions and involving residents in operating such equipment through a citizen science approach. Likewise, residents should be encouraged to return home only after the relevant official has ruled out any further flood danger.

5.4. Long-term response capacity building

A well-designed warning from an official source, containing clear, actionable instructions, is essential to enable a smooth and rapid evacuation [9]. This is particularly crucial in Lunana, where the short lead time before a GLOF strikes leaves minimal room for hesitation or misinterpretation. Yet, given the logistical challenges that could disrupt communication immediately before an event, pre-crisis community preparedness is equally vital. Therefore, resilience cannot depend solely on receiving detailed instructions in the moment of crisis. Instead, efforts must focus on pre-informing and training residents on evacuation procedures before a disaster occurs.

Our findings show that people have high risk perception but lack adequate response preparation, indicating that existing flood risk advocacy campaigns should go beyond communicating risk by enhancing the coping capabilities of individuals, as proposed by Ref. [38]. Providing detailed information to people and reinforcing this by involving community leaders to facilitate protective behaviour, e.g. by explaining the types of measures available to limit flood risk, and how they can be implemented [29,38]. For example, a mandatory community-wide mock drill should be implemented at least twice a year [42]. In Lunana, given the logistical challenges, implementing agencies can leverage the expertise of local institutions, such as schools, teachers, and leaders, as expert resource persons to train residents on how to evacuate effectively, as they have experience conducting mock drills in schools. Risk coping strategies can be communicated through various channels, including WeChat (groups), school meetings, community noticeboards and local leaders to reach wider social networks. Here too, schools can be leveraged as community hubs to disseminate key information through educational media such as theatre productions and billboards. While over half of people mentioned that they have emergency kits (55.4%) and had decided which important items to take in the event of a future GLOF (58.4%), further discussion with locals through KIIs and FGs revealed that these preparations are mostly limited to readily available warm clothes, torches (mostly

replaced by mobile phone flashlights) and valuables such as money and jewellery. Further, without mock drills, their experiences revealed that people may not remember to take items with them because of panic and fear during a flood threat. Household preparedness can therefore be enhanced by providing and clearly explaining a “grab-and-go” emergency kit checklist to every family, ensuring that all are prepared to evacuate quickly with essential supplies. This information can be disseminated through social media such as WeChat, which is popular in Lunana, and printed copies distributed to each household.

Residents vividly recalled the extreme hardship of enduring entire nights exposed to extreme cold in open spaces during past evacuations, as designated evacuation sites lack proper shelters. While these conditions have not yet discouraged people from evacuating, they represent a real test of resilience and well-being and present a particular risk to vulnerable groups. Previous evacuation events have been limited to a single night, allowing residents to return to homes the following day. However, a prolonged evacuation scenario would become untenable without access to adequate shelter, food, and essential supplies. This vulnerability is compounded by Lunana’s extreme remoteness; without road connections, aid delivery can take seven to nine days, and helicopter services are entirely dependent on favourable weather conditions as well as being prohibitively expensive. People in Lunana also do not have insurance coverage for livestock, crops or household contents. To address this critical gap, the community strongly advocates for the construction of proper shelters at evacuation sites. These multi-purpose facilities would provide basic protection from the elements during a disaster. Government and local authorities should stock food and other basic supplies, such as blankets, in these shelters to create a vital buffer if the external aid is delayed. The shelters should also be equipped with satellite phones to allow rapid communication, both to warn communities further downstream and to expedite the delivery of assistance. This is particularly important for community perceptions of risk and security, as communities are now concerned more about their livelihoods, believing that the GLOF EWS can save lives but not livelihoods. Furthermore, recognising the immense logistical challenges that hinder district and national-level emergency response, we recommend training local public servants, particularly teachers, who are often permanently stationed in the community, in basic first aid, crisis management, and the distribution of emergency supplies. This strategy of localising capacity and pre-positioning resources is essential for building a resilient and self-reliant community in the face of inevitable future GLOF events and other multi-hazards.

5.5. Challenges and recommendations for future study

While assessing local community experience and perception of GLOF EWS operation for GLOF events in the Himalaya for the first time, we encountered several methodological constraints. First, people could not remember critical points in time, such as when they received a warning message. This deficiency prevented us from constructing warning diffusion curves for the entire community or for specific demographic groups (e.g., gender and age), which are crucial for optimising early warning systems. While respondents were able to roughly recall evacuation delay time, defined as time taken to start evacuation after receiving a warning message, this is subject to substantial uncertainty due to recall error [9], i.e. people may not recall correctly even for events that occurred only a few years ago such as 2019 and 2023 and there was significant confusion between the memories of different, including recent events, the large 1994 event and false alarms. Reported times are also likely affected by anchoring, that is, the tendency to anchor time estimates to cognitively available reference points: such as hours, half hours, 15 min intervals [9]. This was evident in our responses, as people usually mentioned times such as half an hour, 15 min or 10 min. Finally, the responses we received may also have been affected by normative bias [9]. That is, instead of reporting their actual behaviour, some people may have given answers that reflected what they think they should have done. For example, people may have reported evacuating immediately, even if they did not, based on awareness created by government officials. The experiences shared may also be influenced by recent events or heightened consciousness due to subsequent education programmes by government officials. All these limitations arise primarily from the delay in information collection after the GLOF events. Therefore, future efforts should aim to conduct similar studies immediately after GLOF events or early warning and evacuation experiences.

Our results did not show any significant disparities in people’s risk perception and evacuation experience across demographic attributes such as gender and level of education. While this could be partly because nearly all people in Lunana are extremely worried about the well-publicised GLOF threat, we do not discount the potential influence of gender representation bias among our participants. According to the Bhutan 2017 Population and Housing Census, Lunana has a nearly equal proportion of male and female residents [19]. Despite this near equal proportion, our respondents were predominantly male. This was partly because Lunana is a society with gender specific roles; males are usually more extroverted and willing to participate in programmes such as our research, while females tend to be more reserved. While our research provides an overall understanding of GLOF risk perception and evacuation experience, which is adequate for drawing conclusions about a small community such as Lunana, future studies focusing on in-depth analysis of evacuation and GLOF risk perception across demographic characteristics would be useful. We observed that women in Lunana are often reluctant and reserved when interacting with unfamiliar individuals, particularly men, which posed a significant challenge in obtaining female respondents. In future studies, the recruitment of female enumerators and local facilitators may enhance participation, as women are generally more comfortable engaging with female interviewers.

6. Conclusions

Glacial lake outburst floods pose a substantial risk to vulnerable mountain communities across the world. Early warning systems are indispensable for saving lives in the event of a GLOF. While people’s response capability and behaviour form an essential part of the successful execution of an EWS, past studies have largely focused on understanding hazard processes and mechanisms, which remain uncertain because of the difficulty involved in measuring accurate values and the sensitivity of mountain environments to climate

change. Our study, therefore, explores people's early warning and evacuation experiences and their perspectives on GLOF risk for the first time. Our study revealed that environmental cues and mobile phone calls from friends and family served as primary means of communication during past GLOF events in the remote Himalayan community of Lunana, Bhutan. We observed that people in Lunana generally have high GLOF threat perception, which we attribute to the government's efforts to create awareness since Lunana experienced a devastating GLOF event in 1994. However, people's evacuation experiences and future preparation revealed that their response preparation needs to be further strengthened. Based on our findings, we provide the following recommendations.

1. The existing GLOF EWS can be strengthened by enhancing local people's engagement in all processes and components of the system.
2. Existing means of communication during times of emergency can be diversified, particularly by leveraging mobile phone communication, which is accessible to nearly all people in Lunana.
3. The people's environmental knowledge should be combined with modern science and technology, for example, to safely determine if a GLOF is underway after receiving a warning.
4. Training programmes such as mock drills can be organised regularly [at least twice a year]. Given the logistical challenges, implementing agencies can leverage the expertise of local institutions, such as schools and use teachers as resource persons to train and educate residents through various media, including theatre production and billboards.
5. Residents can be provided with a "grab-and-go" emergency kit checklist to ensure all families are prepared to evacuate quickly with essential supplies. This information can also be disseminated through social media such as WeChat (which is popular in Lunana) and printed copies distributed to each household.
6. Construction of proper and permanent shelters at evacuation sites is recommended to provide multi-purpose facilities for basic protection from the elements during a disaster. These shelters could also serve as secure storage units for emergency food and other basic supplies, such as blankets, and could include resilient communication methods, such as satellite phones to warn further downstream and coordinate responses, creating a vital buffer against delayed external aid.

CRedit authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ijdr.2026.106211>.

Data availability

Data will be made available on request.

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