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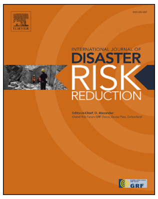

Risk perception and vulnerability of communities in Nepal to transboundary glacial lake outburst floods from Tibet, China

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ABSTRACT

Transboundary glacial lake outburst floods (GLOFs) pose severe risks to downstream communities and infrastructure across international borders. However, previous GLOF research has largely overlooked the transboundary aspects of national and sub-national level GLOFs, focusing instead mostly on inventorying glacial lakes and assessing their hazards. The lack of cross-border coordination could have dire consequences for vulnerable communities and potential disaster preparedness. Assessing risk perception and vulnerability among downstream populations exposed to GLOFs is crucial for effective disaster risk reduction and management. This study examined the risk perception and vulnerabilities of Nepali communities in Bhotekoshi/Sunkoshi (Poiqu in Tibet) and Trishuli (Gyirong in Tibet) river basins, exposed to transboundary GLOFs originating from Tibetan basins. Household-level data were collected from 90 respondents in the villages along those two basins. The findings highlight high risk perception in the Bhotekoshi basin and medium perception in the Trishuli basin, along with corresponding vulnerability levels. Key factors influencing risk perception and vulnerability are explored, emphasizing the need for public awareness and policy formulation at national and regional levels. To reduce vulnerability to transboundary GLOFs, extending early warning systems, enhancing cross-border cooperation, supporting socioeconomically disadvantaged populations, and ensuring resilient infrastructure are essential.

1. Introduction

Glaciers in the Himalayan region are retreating and losing mass in response to ongoing climate change [1,2]. Such responses have resulted in the formation of thousands of glacial lakes over the Himalayas [3–5]. Glacial lakes are dammed by unstable materials such as ice, debris and moraines, making them susceptible to failure from any internal or external triggering factors, such as melting of dead ice inside the dam, piping, avalanches, earthquakes, and heavy precipitation [6,7]. Sudden flooding from these glacial lakes, widely known as glacial lake outburst floods (GLOFs), is often unpredictable and devastating to life, livelihoods, and infrastructure in the downhill settlements. Many past GLOFs were high magnitude hyper concentrated debris flow with run-out distances spanning tens of kilometers, exacerbating the impacts [8,9]. There are more than 21,000 glacial lakes over the Tibetan Plateau including Himalayas [10,11], among them, ~1500 glacial lakes are formed in the headwaters of Tibetan basins that flow into Nepal [12]. These glacial lakes have experienced exponential growth in recent decades [13–16]. The communities in Nepal are immediately exposed to

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probable hazard from transboundary GLOFs [17,18]. Hence, understanding the transboundary aspects of GLOFs including community risk perception, adaptive capacity and sensitivity to the hazard is critical for policy formulation and disaster risk management.

GLOF is a complex phenomenon because of its interaction with the physical and social environments in the context of ongoing climate change. The integrated GLOF risk in an area is defined as the function of probability of hazard, exposure, vulnerability and adaptability [19]. It is important to note that local people's perception, socio-economic and cultural factors play a complex role in how communities respond to the risk posed by GLOF events [20,21], and that this mostly varies between across different communities of the Himalayas. For example, the communities below a dangerous glacial lake, Tsho Rolpa in Nepal have low GLOF risk perception [22] while communities in Ghizer District of Pakistan fear possible GLOF [23]. Nevertheless, it is well established that perceptions of risks can influence people's decision-making [24,25], and the way people perceive and act on risk can be highly contextual and often influenced by the local affective environments [26].

Assessing risk perception and social vulnerability has consequently emerged as paramount in research and policy development, especially concerning disaster risk reduction. Risk perception encompasses how individuals and communities perceive and comprehend the risks they face. It significantly influences their attitudes, behaviors, and decision-making processes concerning risk [20,23,25]. By comprehending risk perception and social vulnerability, researchers and practitioners can gain insights into how communities perceive and respond to risks. This knowledge can inform the development of targeted interventions that account for the unique needs and challenges faced by different communities. Ultimately, this can contribute to the establishment of more resilient communities that are better equipped to cope with and recover from disasters [21,27–31].

Within climate change and disaster risk reduction research, the concept of vulnerability has evolved with time, and its interpretation varies [29,32,33]. Historically, vulnerability was primarily defined as the extent to which a community or elements may be exposed to climate change or associated hazards [34–36]. It was regarded as a measure of the potential impact that these hazards could have on a community. However, this definition failed to encompass the intricate socio-economic and institutional factors that shape a community's capacity to respond and adapt to these risks [29,30,37,38]. In the context of disaster risk reduction, vulnerability is now understood as the ability of individuals or communities to respond differentially to risks based on their social, economic, and institutional contexts [38]. This shift is an acknowledgement that vulnerability is not solely determined by the magnitude of the hazard, but also by the resources, capabilities, and structures that exist within a community. In other words, vulnerability is not merely a function of exposure, but rather a reflection of a community's preparedness and ability to mitigate the impacts of a hazard [39,40]. Two communities living in the same GLOF-prone area might face identical levels of GLOF exposure, while their vulnerability levels may markedly differ if they have differences in financial structure, access to response and rescue support, and overall capacity to confront the hazard [39]. For example, migrant communities exhibited higher vulnerability to potential GLOF compared to non-migrant communities inhabiting the same GLOF hazard zone in Sikkim, India [27]. This disparity was attributed to limited resources, lesser knowledge about the hazard, and weaker social networks within migrant communities, hindering their ability to effectively respond during times of crisis.

Risk perceptions and vulnerability exhibit variations among communities at both the intra-national and cross-national levels [25]. Particularly, transboundary GLOF threat has received substantial attention as it poses a regional threat to communities across international borders [17,18,41–43]. This is exceptionally true for Nepal, a central Himalayan country, which has witnessed at least 10 transboundary GLOF events from Tibet, China, some of which were highly devastating, most often destroying China-Nepal highways, hydropower plants and settlements [44]. The most notable events are the 1981 GLOF from Cirenmaco, which killed nearly 200 people [16,45], and the 2016 Gongbatongshaco GLOF, that caused severe impacts in Nepal [9,46]. Moreover, future GLOFs are predicted to cause greater losses due to rapid expansion of infrastructure and settlements in these areas [47]. Notably, global [48,49] and regional [41,42] studies mark transboundary areas as a potential high-risk zone threatening settlements and infrastructure, highlighting the need for focused and integrated study in these areas.

Majority of the past GLOF studies in Himalayas account for hazard assessments while risk perceptions and vulnerability assessments are still unexplored areas [50] that are necessary, especially in developing nations like Nepal where the socio-economic risk of GLOF is usually greatest [8]. Risk perception is increasingly recognized as a crucial part of disaster science, as it anticipates the public or community reactions and judgements about an event, and is sometimes incorporated into vulnerability assessments [31]. Thus, it facilitates policy formation and disaster preparedness [51]. For example, a community having high risk perception towards an event has high chances to co-operate in emergency rescue and disaster risk reduction activities and *vice-versa* [22,23]. Few studies have considered vulnerability in their comprehensive GLOF risk assessments. Wang et al. [19] have combinedly used hazard score of glacial lakes, impact exposure, vulnerability of exposed elements, and adaptive capacity to calculate the integrated GLOF risk over Qinghai-Tibetan Plateau. Similarly, Taylor et al. [49] used three proxy metrics, i.e. Corruption Perception Index, Human Development Index, national-scale Social Vulnerability Index to measure the vulnerability and integrated it with lake conditions and population exposure to find the GLOF danger at a basin scale globally. Moreover, Rinzin et al. [52] comprehensively assessed the risk of potentially dangerous lakes, integrating GLOF simulation results with local administrative exposure and national statistics-based vulnerability in the Bhutanese Himalayas. As such different national and sub-national level proxies and parameters are used to assess the vulnerability overall, understanding the vulnerability of immediately exposed population to GLOF at a community or a local scale is also crucial for appropriate disaster management [30]. For example, Samui and Sethi [27] have accessed the community level social vulnerability of Chungtang town against probable GLOF from South Lonak lake in Sikkim Himalayas, indicating the differential vulnerabilities among migrated and permanent population.

In the context of above background, the main aim of this study is to assess the risk perception and vulnerability of communities in Nepal that are immediately exposed to transboundary GLOFs from Tibet, China. Furthermore, the study explores their recognition of past GLOF events to establish the connection between these events and the key issues raised from communities and stakeholders, aiming to foster robust integrated disaster management. Here, we selected two China-Nepal transboundary areas, i.e., Gyirong-Trishuli and Poiqu-Bhotekoshi basins and used a bottom-up approach (local-scenario) based on household participatory process [30] to determine the risk perceptions and vulnerability using index based scoring [23,53]. This study will be useful to understand the nature, behavior and vulnerability of locals towards the imminent disaster, and how it shapes their overall resilience, response and preparedness against GLOFs.

2. Study area and its significance

This study primarily focuses on two China-Nepal transboundary basins, namely Poiqu-Bhotekoshi and Gyirong-Trishuli, located in the central Himalayas, which have witnessed multiple devastating past GLOF events (Fig. 1), including the recent Gongbatongshaco GLOF of 2016 [54]. The basins are named after the rivers that flow through them. The same Poiqu river in upstream China is called Bhotekoshi in downstream Nepal (Fig. 1). Further, downstream of Bahrabise, after its confluence with Sunkoshi stream, it is called Sunkoshi River [18]. Similarly, the upstream Giyrong river is called Trishuli in Nepal. The Poiqu-Bhotekoshi river is steeper compared to the Gyirong-Trishuli river, with alluvial and diluvial valleys, ranging with width from 20 to 200 m [55]. Both basins are delimited by the South Tibetan Detachment System (STDS) and the Main Central Thrust, as well as the northern Himalayan Tethyan sedimentary rock belt and the high Himalayan, low Himalayan, and other tectonic units [16,55]. Under such geological conditions, both basins are tectonically active, and earthquake-related landslides and rockfalls are prevalent [56,57]. The climate of the study area is dominated by south Asian monsoon in summer and westerlies in the winter, and the temperature gradually decreases from south to north [58]. The climatology of the area reveals that 80 % of the precipitation occurs in summer seasons (JJAS) [55,59]. The transboundary area is home to numerous glaciers and glacial lakes that feed to the Nepalese river [12]. According to Shrestha et al. [54], this region has witnessed at least 14 GLOF events from 12 glacial lakes since 1900, with major GLOF incidents occurring in Poiqu-Bhotekoshi basin (Table S1).

These areas are of great importance because transnational highways pass through these basins (Fig. 1), which determines the entire trade and tourism from local to national level, so they can also be regarded as transportation corridors. Among the two, Friend-

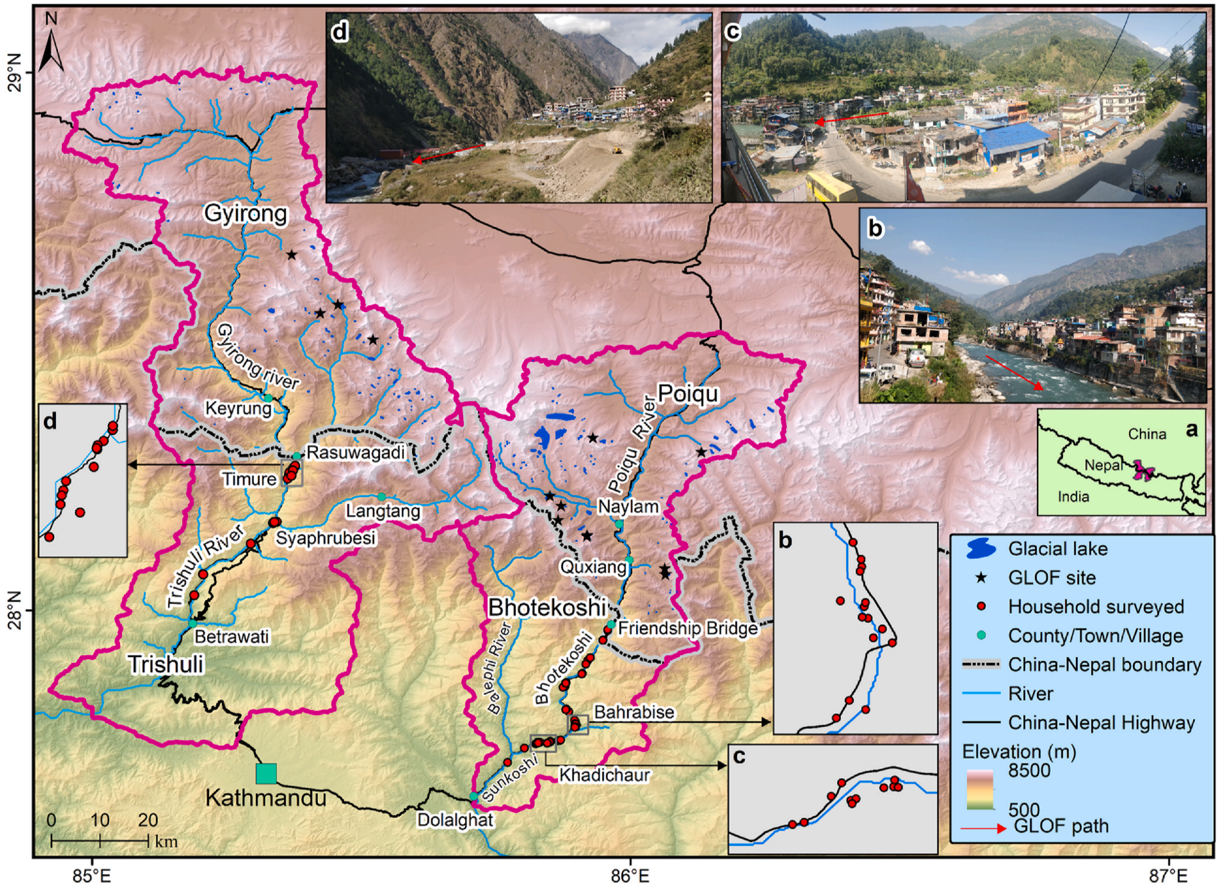


Fig. 1. Study area showing two transboundary basins, i.e. Gyirong-Trishuli and Poiqu-Bhotekoshi basins between China and Nepal. The inset (a) shows the position of the study area at regional level. The red circles show the location of household surveys conducted along two transboundary rivers and the main settlements along them, b) Bahrabise, c) Khadichaur and d) Timure. The red arrows indicate GLOF path. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

ship (Araniko) Highway through Poiqu-Bhotekoshi is the oldest highway connecting China and Nepal, built in the 1960s. The total trade between China and Nepal from these two ports was more than 1000 million USD in 2014/15 [60]. The construction of China-Nepal highways along the rivers has led to the rapid development of settlements [43], particularly in the Trishuli basin during recent years (Fig. S1), consequently increasing their exposure to transboundary GLOF [42]. The main towns/villages in the Bhotekoshi basin are Barabhise, Lamosaghu and Khadichaur, with several houses and settlements along the highway (Fig. 1). Timure and Syaphrubesi are the main villages in the Trishuli basin along the river course and downstream of Syaphrubesi, the river is mostly steep and uninhabited.

3. Materials and methods

3.1. Household sampling and questionnaire

Previous studies related to GLOF risk perception [23] and vulnerability [27] were conducted at a specified place using purposive sampling method. Here, sampling was to be conducted in downstream areas along the river course from the border region of China-Nepal. Thus, we followed a series of steps to determine the sampling size and households (or settlements) to be sampled, reducing subjectiveness. First, as GLOF follows the river path, we roughly estimated the probable impact area as 200 m buffer distance on both sides of the river. Secondly, Open Street Map (OSM) was used to extract the total number of buildings (type = ‘houses’ or ‘residential’; considered as households, $n = 194$ for Bhotekoshi and $n = 95$ for Trishuli) intersecting the impact area. OSM data has been widely used in GLOF risk assessment [41,42] and it's completeness is greater than 80 % in Nepal [61]. Thirdly, the sample size was determined using a standard formula at 95 % z-score and 10 % margin of error, excluding the office and non-residential buildings. At last, sample households were randomly selected and plotted in topographic maps and Google Earth to know the settlements to be surveyed. A sample size of 61 households were surveyed for Bhotekoshi and 29 households for Trishuli basins at different locations along the river course. The surveyed sample size is slightly less in Trishuli basin because study was limited to upper areas as impact of GLOF would largely attenuate downstream [41] and due to time and resources. The field study was conducted in those selected places in October and November 2023 (Fig. S2). The questions were interviewed in semi-structure form and each interview lasted for about 30–40 min (Refer Supplementary file for questionnaire). In addition to questions on basic information, risk perception and vulnerability, few other questions were presented in interviews and group discussions (Fig. S3), which were used to link with the key results and couple them for risk management.

3.2. GLOF risk perception

Risk perception is primarily subjective and qualitative in nature [25], however, several indices are being used to quantify it [62]. Risk perception varies across the globe, from one country to another, within the country, communities and individuals [25,63]. Here, we used four GLOF risk perception indicators (Table 1) to quantify overall GLOF perception. It is worthy to note that since GLOF is an unusual but high magnitude event, perceived risk is largely influenced by the geographic and temporal dimensions of GLOF (refer Section 5.1) [20,22], and specific set of indicators to quantify it may differ geographically. All indicators were questioned on a Likert-scale, from the lowest (1) value to the highest value (5) to determine the level of risk perception. Risk perception of each indicator was obtained as a weighted average, i.e., the product of Likert-scale value and its total responses in each category and then averaging the obtained total value by number of respondents. The overall GLOF risk perception was calculated as the average of total values of each GLOF risk perception indicator (Equation (1)) [23].

$$\text{Overall GLOF risk perception (GRP)} = [\text{GRP}_1 + \text{GRP}_2 + \text{GRP}_3 + (5\text{-GRP}_4)]/4 \ldots \ldots \ldots \quad (1)$$

Here, GRP_4 is used in a reversed scale, since it has a negative relationship with risk perception.

3.3. Selection of vulnerability indicators

As compared to the number of studies on social vulnerabilities of floods, landslides and other disasters [64], assessing vulnerability of GLOFs is relatively an unexplored area. Selecting appropriate vulnerability indicators for GLOFs is currently crucial and in a developing stage, considering that GLOFs are rare but high-magnitude events. According to IPCC [40] framework, exposure is defined as the presence of people, livelihood, infrastructure and other tangible assets in a place that could be adversely affected. Vulnerability, on the other hand, encompasses various ideas and elements, including susceptibility or sensitivity to harm, and lacking the ability to adapt and cope with adverse effects. Here, we define composite vulnerability as the function of exposure, susceptibility and adaptive capacity (Equation (2)) [65]. Exposure and susceptibility increase the vulnerability, while adaptive capacity decreases the vulnerability. Therefore, we reviewed the indicators used by previous studies [27,28] for social vulnerability assessment of flood and GLOF, and then adopted them with modifications according to the nature of our study area through expert consultations. A total of 13

Table 1
Indicators used for transboundary GLOF risk perception. Modified after Aslam et al. [23].

GLOF risk perception indicators	Indicator questions
GRP_1: Perceived future occurrences	What are the chances of future GLOF occurrences?
GRP_2: Perceived afraid/worry	How much are you afraid of probable transboundary GLOFs?
GRP_3: Perceived transboundary threat	What are chances that future transboundary GLOF can damage your house and property?
GRP_4: Perceived level of coping capacity	How much do you think your local government can cope with transboundary GLOF?

indicators were used to assess the vulnerability (Table 2). These indicators are considered to be both practically and unbiasedly accessible from respondents. Furthermore, they are consistent, interpretable, robust and highly relevant within the context of the study area [66].

$$\text{Composite Vulnerability} = \text{f [exposure, susceptibility, adaptive capacity]} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \tag{2}$$

In Exposure vulnerability component, besides lateral distance and house height from river level [27], we added the distance from China-Nepal border as an indicator (Table 2) because GLOF intensity (depth and flow) attenuates and GLOF travel time increases with distance [67,69], directly influencing the impact and evacuation time. Thus, households closer to the border are considered more vulnerable to transboundary GLOF than at a far distance. This will be representative when we consider the GLOF case from any lake since there are many dangerous lakes located in different places in Tibet (Fig. 2) [42]. Houses with non-concrete structures, number of disables and dependents, illiteracy rate and proportion of female population were considered as susceptible indicators to GLOF following previous studies [27,65].

In adaptive capacity vulnerability, Samui and Sethi [27] employed multiple income sources and employment as different indicators, however, we used only multiple income sources to remove the collinearity as multiple income sources inherently captures multiple employment. We introduced an additional indicator, whether households possess land beyond the immediate vicinity. Ownership of land outside the probable GLOF impact zone offers these households alternative resettlement options, thereby enhancing their adaptability. Further, household ownership of vehicles was also considered as an indicator in the adaptive capacity assessment, as it indicates the wealth of a household in underdeveloped countries like Nepal and, most importantly, eases evacuation during an event, thereby increasing the adaptability [39]. In addition, government agencies in Nepal receive advance information from Tibet, China, when there is extreme rainfall and probability of extreme events. Such information is disseminated among communities through miking by police forces, so that people move to a safe place. Households that receive such information flow are less vulnerable, so, we included this as an indicator of adaptive capacity. In this way, we choose 3 indicators for exposure vulnerability assessment, 5 indicators for sensitivity vulnerability and 6 indicators for adaptive capacity vulnerability. The details of these indicators with explanations are given in Table 2.

Table 2
Components and their indicators used for vulnerability assessment.

Components	Indicators	Explanation	Sources
Exposure Vulnerability Index (EVI)	Lateral distance of house with river (<100 and < 70 m for Bhotekoshi and Trishuli basins, respectively)	Household close to river are more vulnerable	[27,53]
	Height of house from river level (<25 and < 20 m for Bhotekoshi and Trishuli basins, respectively)	Lower the ratio of house height to river level, higher the vulnerability	[27]
	Distance from China-Nepal border (<35 and < 15 km for Bhotekoshi and Trishuli basins, respectively)	Households closer to border are more vulnerable as travel time and impact of transboundary GLOF will be high and GLOF attenuates with distance	This study. It is used since this is longitudinal study.
Sensitivity/Susceptibility Vulnerability Index (SVI)	Type of House	House made with weak materials such as mud-stone and non-brick are more vulnerable	[27,28]
	Disabled person	Family members with physically or psychologically disabled are more vulnerable as it retards escape during emergency	[27,53]
	Dependents	High numbers of dependents children and old (<16 years and >65 years) are more vulnerable as it retards escape during emergency	[27,70]
	Illiteracy	Households with a greater number of illiterate people have low information and access to communication, increases vulnerability	[28]
	Female population	Female are more vulnerable to climate change and related disasters in a male dominated society	[39,65]
Adaptive Capacity Vulnerability Index (ACVI)	Multiple Income Sources including employment in any private/government sector and foreign countries and others	Households with multiple income sources, multiple employment, receiving remittance are less vulnerable as they can replace the loss of one income source with other	[28,53]
	Having land outside GLOF impact zone	Households having land outside the GLOF risk area have alternatives to settle, decreasing the vulnerability	This study
	Access to TV and internet	Households access with TV and internet can get information before-hand and can be safe, are less vulnerable	[39,65]
	Life insurance coverage	Households having life insurance of at least one member of the family (especially children and old) can compensate the loss in case of death due to an event, are less vulnerable	[27,70]
	Household ownership of vehicles	Households having vehicles help in escaping during the event, are less vulnerable	[39,65]
	Flow of information prior to any probable extreme events, such as GLOF	Households getting prior information about extreme events from Tibet by any means, such as from securities forces (army/police), hydropower sirens and local government are less vulnerable	This study, [28]

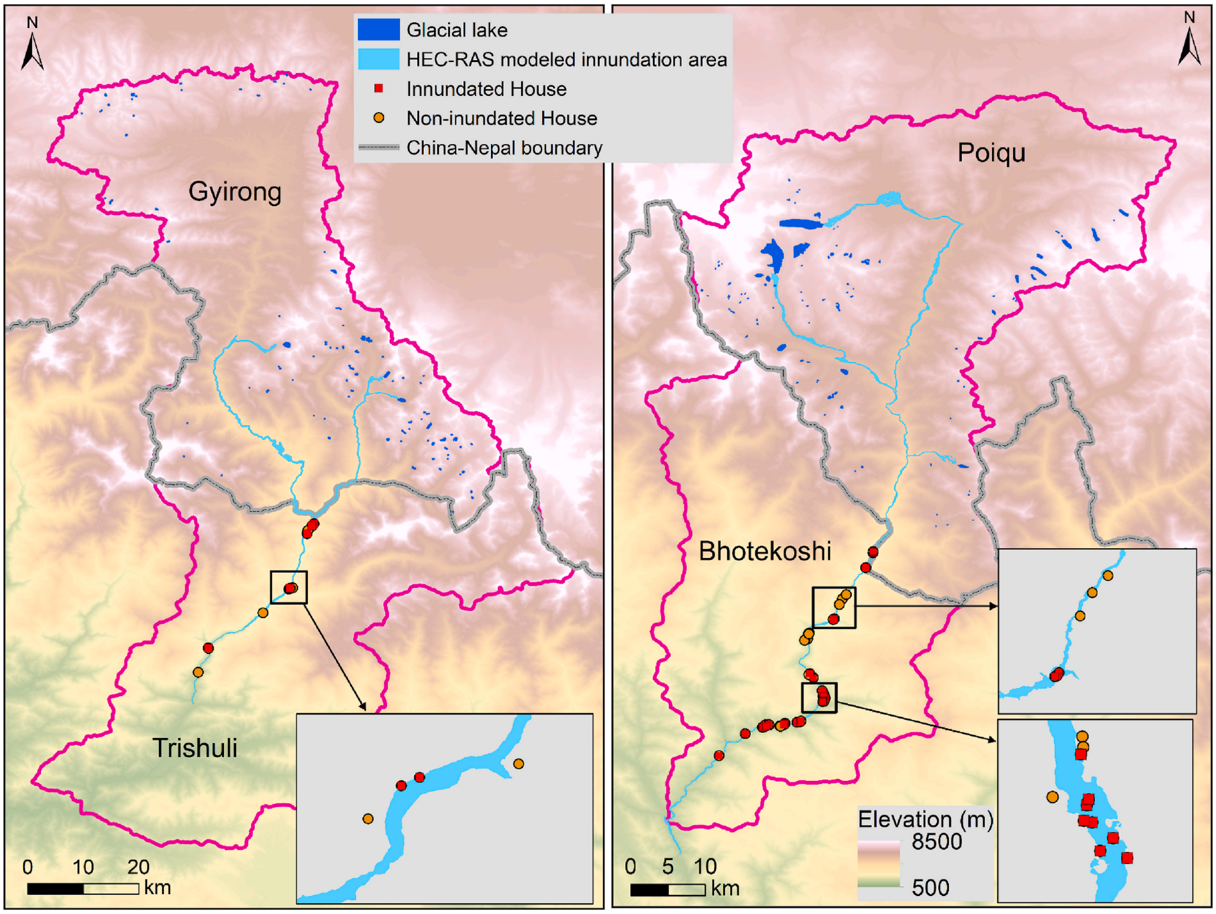


Fig. 2. Visualization of inundated (red) and non-inundated (brown) houses from transboundary glacial lake outburst floods in two transboundary basins. The inundation area was obtained from Zhang et al. [41], which was created using HEC-RAS model. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

For assessing exposure vulnerability, we used <30 m (<20 m) for assessing height of house from river level and <100 m (<70 m) as lateral distance of house from river for Bhotekoshi basin (Trishuli basin). These thresholds represent maximum worst-case values and were selected based on the data of previous 1981 GLOF [68] in Poiqu-Bhotekoshi basin and modelling studies of large dangerous glacial lakes in Tibet [41,45,47,69]. These values might (or might not) exceed in some places according to the topography of the basin, however are considerable for approximate first order exposure assessment. Furthermore, inundation maps obtained from recent modeling works [41] were used for validation to ascertain the exposure (Fig. 2).

3.4. Calculation of vulnerability

The primary data obtained from households were expressed as percentage, thereby obviating the need for a normalization process. Here, we do not use a weighting scheme for calculating indicator vulnerability index (IVI) in an apparent effort to avoid subjectivity. Thus, IVI of each indicator was obtained directly as the value (%) obtained from household data. The vulnerability score for each component, i.e., EVI, SVI and ACVI was obtained by averaging all IVIs related to that component. We opted for a different approach to calculate the composite vulnerability index (CVI) than the one employed in previous studies (see Section 5.2.2), since we did not use a weighting scheme [27,28,53]. It was calculated as the average value of EVI, SVI and ACVI, similar to the GLOF risk perception equation.

$$\text{Compositive Vulnerability Index (CVI)} = [\text{EVI} + \text{SVI}+(1\text{-ACVI})]/3 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \tag{3}$$

In Eq. (3), ACVI is used in reversed scale, since it has a negative relationship with vulnerability [65]. We used Eq. (3) to calculate the CVI as it is simple, straightforward and can be explained, such as increase in EVI and SVI increases the CVI and *vice-versa*, while increase in ACVI decreases the CVI and *vice-versa*, keeping the resultant values between 0 and 1. For interpreting final scores of vulnerability index, four designations were used, i.e., low (<0.25), medium (0.25–0.5), high (0.5–0.75) and very high (>0.75), as described by earlier study of Balica et al. [53].

4. Results

4.1. Demography of the respondents

Out of total respondents, 17 were male (58.62 %) and 12 (41.37 %) were female in Trishuli basin while 45 were male (73.77 %) and 16 were female (26.22 %) in Bhotekoshi basin. Among them, 90 % and 64 % were head of households in Trishuli and Bhotekoshi basins, respectively. The average age of the sampled respondents was 44 ($\sigma = 11.54$) and 49 ($\sigma = 16.36$) years in Trishuli and Bhotekoshi basins, respectively, with the majority falling in the range of 35–65 years. The main religion practiced by the respondents is Buddhism in Trishuli area and Hinduism in Bhotekoshi area (Table 3). Data analysis shows that the average household size is the same for both study sites, i.e. 6.4 person per household, which is higher than the 2021-Nepal's average household size (4.37 persons per household) [71]. The education level of respondents in both study sites was very low, i.e., about 36 % of total respondents received no formal education while 42 % received formal education but below secondary level (grade 10). About 4 % of the respondents had a university degree (Bachelors) while none had post-graduate degree (Master's). Although Nepal being an agriculture country, majority (~51 %) of the respondents were engaged in business (at-least registered within local government) while only 11 % had agriculture as the main occupation. Remaining respondents were engaged in private (14 %) and government (2 %) jobs and 7 %, 6.25 % and 8.75 % were housewives, students and retired/no-occupation, respectively.

4.2. Evaluation of risk perception

In Bhotekoshi basin, 89 % of the respondents were familiar with the concept of glacial lake and glacial lake outburst floods. Remaining 11 % of respondents became aware and recognized it after explanation, as they were not familiar with the specific terms "glacial lakes" and "GLOF". Thus, to reduce biasness, we only included 89 % of the total sample (89 % of 61 = 54) for further risk perception. Among them, 6 % were unaware that transboundary GLOF from Tibet could cause damage to Nepal and their household.

In Trishuli basin, 97 % of the respondents were familiar about glacial lake and outburst flood. This rate is slightly high due to the well-recognized glacial lakes considered as religious in the region [72]. Among them, 37 % were unaware that transboundary GLOF from Tibet could cause damage to Nepal and their hometown, higher rate than Bhotekoshi basin.

Overall, the risk perception indicator shows that people's risk perception is high in Bhotekoshi basin (GRP = 3.69) and medium in Trishuli basin (GRP = 2.92). This is because the people in Bhotekoshi basin are more worried or more concerned about transboundary GLOF (GRP2 = 4.16 vs 3.1) and its likely threat (GRP3 = 4.14 vs 2.75) than in Trishuli basin. The perceived future occurrence of GLOF for two basins fell into the same high category (Fig. 3). People of both basins believe that their local government does not have a high coping capacity for transboundary GLOF and seek the central government role in such extreme cases.

4.3. Recognition of 1981 and 2016 GLOFs in Bhotekoshi basin: Implication for policy making

In Bhotekoshi, 88 % of the respondents recognized about the recent 2016 GLOF from a small Gongbatongshaco glacial lake in Tibet. Further, they provided a detailed explanation of the impacts noting the severe effects were confined to the border region of China-Nepal, as well as to the upper Bhotekoshi hydropower project. This is true in light of the actual impacts reported by scientific studies [9,46,73]. Further, when interviewed with older generation (>60 years), almost all respondents recognized the severe flood of 1981 and its impact. Additionally, they accurately identified that the origin of GLOF was not from Nyalam town but rather up-

Table 3
Demography of the respondents

Study area/Variables	Sub-category	Trishuli				Bhotekoshi			
		N	%	Mean	SD (σ)	N	%	Mean	SD (σ)
Age		29		44	11.54	61		49	16.36
Gender	Male	17	58.62			45	73.77		
	Female	12	41.37			16	26.22		
Household head	Yes	26	89.66			39	36.07		
	No	3	10.34			22	63.93		
Religion	Hindu	3	10.34			42	68.85		
	Buddhist	26	89.66			16	26.23		
	Others	–				3	4.92		
Residency	Permanent	23	79.31			59	96.72		
	Temporary	6	20.69			2	3.28		
Family type	Joint	8	27.59			17	27.87		
	Nuclear	21	72.41			44	72.13		
Household size	Joint	83	44.15	10.4		169	43.11	11.53	
	Nuclear	105	55.85	5		223	56.89	5.07	
	Total	188	100	6.48	3.7	392	100	6.43	3.31
Education	No formal	11	37.93			21	34.43		
	Below Secondary	12	41.38			26	42.62		
	Secondary level	2	6.90			7	11.48		
	Higher Secondary	3	10.34			5	8.20		
	Graduate	1	3.45			2	3.28		

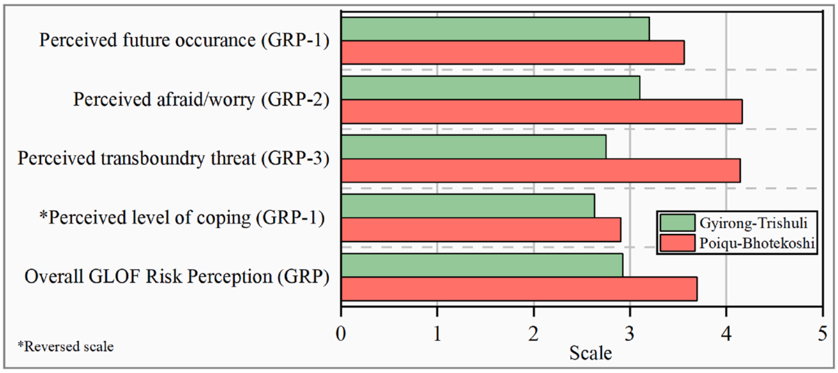


Fig. 3. Values obtained for GLOF risk perception indicators. The scale ranges from very low (0) to very high (5).

stream of Quxiang village, close to Nepal, which aligns with the truth [16]. Such recognition shows that the communities are well-known about the GLOF events which directly eases for any policy making and implementing resilient programs.

4.4. Vulnerability assessment

4.4.1. Exposure vulnerability assessment

The obtained higher EVI value of 0.82 in the Bhotekoshi basin indicates a greater vulnerability to exposure from transboundary GLOF compared to Trishuli basin with EVI values of 0.50. This result was as anticipated given the higher number of settlements and houses in the Bhotekoshi basin, which features the oldest road connecting Nepal with China, constructed in the 1960s. This area is hub for transboundary economic activities. Furthermore, the head waters of the basin in Tibet contain large potentially dangerous glacial lakes, including Cirenmaco, Galangco, Gangxico and Jialongco [19,42]. Downstream, major settlements, such as Bahrabise and Lamosaghu/Khadichaur have developed along-side the river and China-Nepal highway (Fig. 1). This result corroborates with the results of the risk perception, as high-risk perception was observed in the Bhotekoshi basin due to higher perception of transboundary GLOF threat (Fig. 3). However, the Gyirong-Trishuli is relatively new corridor and has comparatively very few numbers of houses along the China-Nepal highway. Moreover, empirical evidence suggest that the people of Bhotekoshi has experienced past GLOF and flooding events, making them highly exposed [74]. Notably, when considering modeled inundation areas (Fig. 2), although obtained EVI values decreased (Table 4), the vulnerability classes for both basins remained unchanged.

4.4.2. Sensitivity vulnerability assessment

The SVI score of Bhotekoshi and Trishuli basins are 0.29 and 0.32, both falling under medium level vulnerability. The SVI score of Trishuli basin is slightly high because the number of non-concrete houses are slightly more in Trishuli basin (Table 4), increasing the

Table 4
Scores of vulnerability indicators and components in Trishuli and Bhotekoshi basins.

Components	Indicators	Trishuli residents		Bhotekoshi residents	
		% value	IVI	% value	IVI
Exposure	E1: Lateral distance of house with river	59.00	0.59	91.07	0.91
	E2: Height of house from river level	20.10	0.20	72.00	0.72
	E3: Distance from China-Nepal border	70.00	0.70	83.90	0.84
EVI		**49.70**	**0.50**	**82.32**	**0.82**
HEC-RAS model-based exposure (inundated houses)		44.44	0.44	79	0.79
Sensitivity	S1: Type of House	47.40	0.47	32.80	0.33
	S2: Disabled person	2.50	0.03	2.10	0.02
	S3: Dependents	24.60	0.25	24.50	0.25
	S4: Illiteracy	35.00	0.35	34.43	0.34
	S5: Female Population	48.5	0.49	51.8	0.52
SVI		**31.60**	**0.32**	**29.13**	**0.29**
Adaptive Capacity	AC1: Multiple Income Sources including employment in any private/government sector and foreign countries	52.63	0.53	55.60	0.56
	AC2: Having land outside GLOF risk zone	70.95	0.71	66.97	0.67
	AC3: Access to TV, internet and social-networking	89.47	0.89	90.44	0.90
	AC4: Life insurance coverage	21.05	0.21	27.70	0.28
	AC5: Household ownership of vehicles	57.89	0.58	49.79	0.50
	AC6: Flow of information prior to any probable extreme events, such as heavy precipitation and GLOF	29.70	0.30	60.42	0.60
ACVI		**52.88**	**0.53**	**58.49**	**0.58**
CVI		**42.81**	**0.43**	**51.91**	**0.52**

overall SVI score. The higher score of SVI increases the total vulnerability of the basin and *vice-versa*. Other indicators, like disabled, dependents and illiteracy rate are similar in both the basins.

4.4.3. Adaptive vulnerability assessment

The AVI score of Gyirong and Bhotekoshi basins falls under the same high adaptive capacity. This is because the high number of households in both basins are engaged in multiple income sources, have land outside the probable GLOF risk zone and have access to TV, internet and social-networks. The flow of information prior to any probable extreme events is high in Bhotekoshi basin when compared to Trishuli basin. Bhotekoshi basin is highly susceptible to disasters such as extreme precipitation [75] and immediate response of authorities in case of disaster play a key role in decreasing the vulnerability. Notably, it was found that the households located in main settlements, like Bahrabise, Khadichaur and Lamosaghu receive immediate response in case of any disasters than households located far from the main settlements. During the interview, it was found that many households from nearby places shifted along the China-Nepal highway for business and economic opportunities. This often leads to high exposure to GLOFs. However, as houses near to roads are often built with concrete and income generation is high through business, eventually increasing the adaptive capacity.

4.4.4. Composite vulnerability assessment

The composite vulnerability assessment shows CVI scores of Bhotekoshi basin is higher (0.52) than Trishuli basin (0.43) (Table 4, Fig. 4). Bhotekoshi basin falls under high vulnerability while Trishuli under medium level vulnerability, according to classification scheme provided by previous study [53]. Moreover, when considering model-based exposure, the CVI value slightly decreased (0.52–0.5 and 0.43 to 0.41), however the vulnerability class in which they fall remained the same. Such results are due to higher EVI scores in Bhotekoshi basin, resulting in higher CVI. The obtained CVI scores indicate that physical and social elements of both basins are vulnerable to floods, however the recovery process varies from several months to years and will be comparably slow in the highly vulnerable Bhotekoshi basin depending upon the amount of investment [53].

5. Discussions

Recent literatures have begun to recognize the importance of analyzing the risk perceptions and vulnerabilities of communities to understand the complex roles in responding to such risks, influencing overall risk and adaptation/mitigation strategies [25]. In this study, both simplified (empirical) and hydrodynamic model-based exposure assessments were incorporated and combined with household-level susceptibility and adaptive capacity to determine the overall composite vulnerability in mountainous regions affected by transboundary GLOF.

5.1. Actual and perceived risk

Actual risk of GLOF in any basin can be assessed from the frequency and intensity of past GLOF events, the number and potential flood volume of dangerous glacial lakes and the basin's overall danger/risk ranking from past studies. Based on previous studies, Poiqu-Bhotekoshi basin has witnessed a greater number of GLOF events with greater magnitude flooding than Gyirong-Trishuli basin (Table S1). Further, average size of potentially dangerous glacial lakes and overall integrated risk level is much higher in Poiqu basin than Gyirong basin (Table 5). Notably, 1981 catastrophic Cirenmaco GLOF event [16] and a recent 2016 transboundary GLOF [9] has hit Bhotekoshi basin while no major incidents have recently occurred in Gyirong basin. The regional cooperation and information flow from Tibetan authorities to Nepalese authorities and to the local communities in Bhotekoshi basin has helped communities to get indirect early warning. This has raised the awareness, while crucial, has also instilled fear within the communities in Bhotekoshi

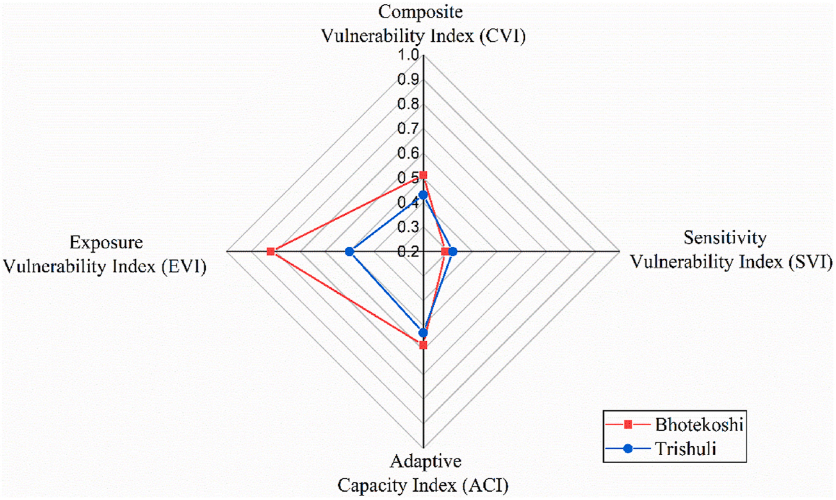


Fig. 4. Comparison of different vulnerability indices of Bhotekoshi and Trishuli basins.

Table 5
GLOF risk interpretation of Poiqu and Gyirong basins.

Basins	Poiqu	Gyirong	Source
No of known GLOF events	13	4	[54]
No of potentially dangerous lakes and their total area	21 (14.07 km^2, 0.67 km^2 per lake)	26 (2.81 km^2, 0.11 km^2 per lake)	[42]
Integrated risk level	Very high	Medium	[19]

basin, especially during monsoon season when monitoring for potential GLOF intensifies. Consequently, residents were sometimes advised to evacuate to safer places. Thus, the high risk (medium risk) perceived by the communities of Bhotekoshi basin (Trishuli basin) align with the actual risk and cases. However, it is worth noting that high/medium risk perception does not necessarily indicate a future risk is of the same level. Instead, the actual risk is highly dependent on GLOF susceptibility and exposure [42], both of which are increasing particularly in the Gyirong-Trishuli basin (Fig. S1).

5.2. *Factors affecting risk perception and GLOF vulnerability*

Vulnerability results are often used as a decision support tool to help guide policy and implementation by directing investments to the most appropriate sectors [53]. The risk perception and vulnerability assessment are highly dependent on the indicators selected and the households sampled. The Spearman's correlation shows that sex, age, education and religion have no influence on the risk perception indicators and hence, overall risk perception (Table 6). Results indicate that the adaptive capacity of locals has risen greatly when compared with the study conducted a decade ago [18], largely because of foreign employment, development of telecommunications [64] and economic opportunities in these transportation corridors. It should be noted that the results of adaptive capacity are particularly related to the set of indicators used. Here, we separated the households whose main source of income was business from those with non-business in an attempt to find the relative difference in vulnerability between these two groups. Further, a simple sensitivity test was applied to check to what degree the obtained CVI results fluctuates for both basins.

5.2.1. *Vulnerabilities difference between business and non-business households*

The results indicated that the business households were among the highest exposure (0.74 vs 0.59) and also with higher adaptive capacity (0.71 vs 0.56) than the non-business households in the Bhotekoshi basin. Counter effectively, this led both business and non-business households to fall in the same level of composite vulnerability as they had similar scores for SVI. The business areas are concentrated along the China-Nepal highway and this highway follows the river path, i.e., a river corridor transportation area, which ultimately increases the exposure to GLOF. Meanwhile, higher income and other well-harnessed opportunities make business households highly adaptive. Thus, the main income source of the household, highly affects the adaptive vulnerability. Moreover, the households engaged in agriculture and with poor socio-economic conditions are most often vulnerable to disasters.

5.2.2. *Sensitivity tests*

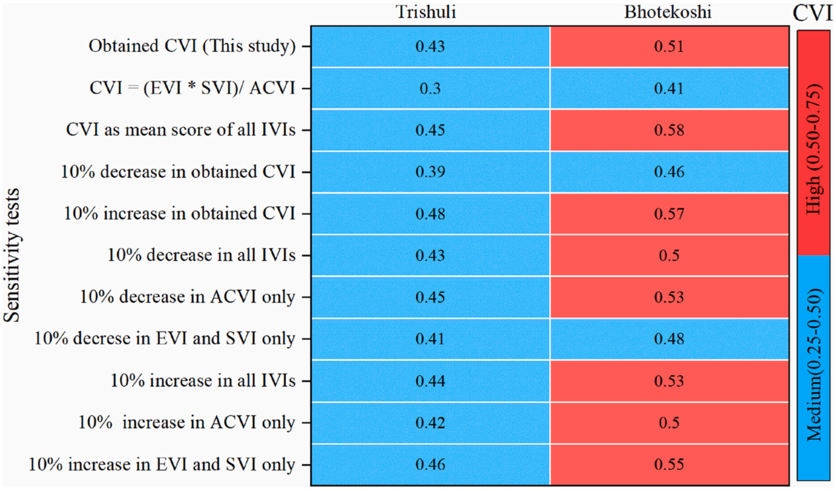
We performed 10 sensitivity tests for CVI utilizing different formulae and altering the component values by ±10 %. The sensitivity tests reveal that final CVI scores vary with different sensitivity tests (Fig. 5). It shows that the vulnerability class of Bhotekoshi basin fluctuated between medium and high class with a maximum score of 0.58, while the vulnerability of Trishuli basin did not change its medium class. Furthermore, an increase of ±10 % in the obtained CVI scores didn't change the class in which both basins fall, while a decrease led the Bhotekoshi to marginally drop into medium level vulnerability. Here, we took a different approach and did not determine CVI as the product of EVI and SVI, and divided by ACVI as done in previous studies [27,28,53], because such calculation can lead to absurd results when any component value equals zero, theoretically. However, utilizing this equation, both basins fall on medium class, without assigning weights to indicators. The final scores of both basins increased when mean scores of all IVIs were used to calculate CVI, yet the classification level of each basin remained unchanged. Thus, we can conclude according to sensitivity tests (Fig. 5), Trishuli basin is medium level vulnerable to transboundary GLOF while Bhotekoshi basin falls in range of medium to high class based on our data and method.

Table 6
Spearman's (nonparametric) correlation coefficient for Likert scale values of GLOF risk perceptions. For definitions of GRP-1, GRP-2, GRP-3 and GRP-4, refer to Table 1.

	GRP-1	GRP-2	GRP-3	GRP-4	Sex	Age	Education	Religion
GRP-1	1.00							
GRP-2	0.325[a]	1.00						
GRP-3	−0.10	0.27	1.00					
GRP-4	0.19	−0.22	−0.28	1.00				
Sex	0.01	−0.427[b]	−0.14	0.323[a]	1.00			
Age	0.28	0.07	−0.18	0.04	0.13	1.00		
Education	0.01	−0.03	0.01	0.04	−0.19	−0.67[b]	1.00	
Religion	0.15	0.25	−0.03	0.10	−0.11	−0.22	0.28	1.00

[a] Correlation is significant at the 0.05 level (2-tailed).

[b] Correlation is significant at the 0.01 level (2-tailed).



Sensitivity tests	Trishuli	Bhotekoshi
Obtained CVI (This study)	0.43	0.51
CVI = (EVI * SVI)/ ACVI	0.3	0.41
CVI as mean score of all IVIs	0.45	0.58
10% decrease in obtained CVI	0.39	0.46
10% increase in obtained CVI	0.48	0.57
10% decrease in all IVIs	0.43	0.5
10% decrease in ACVI only	0.45	0.53
10% decrese in EVI and SVI only	0.41	0.48
10% increase in all IVIs	0.44	0.53
10% increase in ACVI only	0.42	0.5
10% increase in EVI and SVI only	0.46	0.55

Fig. 5. Sensitivity tests of CVI for Trishuli and Bhotekoshi basins.

5.3. *Early warning system in Tibet, China and implication for regional disaster management*

An early warning system (EWS) has been designed and established for a possible GLOF from the dangerous Cirenmaco glacial lake, which is claimed to have benefits for disaster risk information for both China and Nepal [76]. In our survey, 86 % of the respondents had no idea of any kind of early warning system established in Tibet, indicating a clear gap between the scientific works and dissemination among the locals. Remaining respondents responded that they have heard about GLOF risk reduction activities in China, such as siphoning, siren system and lake lowering, which is true as JilongCo, a dangerous lake, was lowered by 16 m [47]. Extending such early warning systems is essential as major towns and settlements are located cross-borders, which require regional cooperation.

6. Conclusions and national-regional policy recommendations

We conducted household level transboundary GLOF risk perception and vulnerability assessment on the Nepalese side of two China-Nepal transboundary basins, identified as past and future GLOF hotspots. The risk perception indicator shows that residents of Bhotekoshi basin have higher GLOF risk perception than Trishuli basin (medium), corroborating with the frequency of past GLOF events. Furthermore, the residents of Bhotekoshi basin have a clear understanding of the origin and impacts of the 1981 and 2016 transboundary GLOF events, which greatly facilitates the implementation of resilient programs. The result of exposure vulnerability assessment indicates that communities in Bhotekoshi basin are more exposed to possible transboundary GLOF than Trishuli basin. Although both basins exhibit similar levels of sensitivity and adaptive capacity, differences in exposure vulnerability leads to a medium vulnerability for the communities in Trishuli basin while the Bhotekoshi basin faces a high level of vulnerability.

Besides household surveys, we conducted two focus group discussions with locals and three key informant interviews with stakeholders at local government (Fig. S3) to perceive their understanding and recommendations with preliminary results of this study. Based on the field discussions and the results of this study, we recommend possible research gaps and five key national to regional level strategies for reducing the vulnerability of communities in Nepal to transboundary GLOFs.

- **Extending early warning systems:** Reducing the susceptibility to transboundary GLOFs from Tibet, China requires the extension of EWS established in Tibet [76] to Nepalese communities. As part of this, monitoring equipment must be installed and maintained, trustworthy communication networks must be established, and local communities must be trained to identify early warning signals and take appropriate action.
- **Strengthening cross-border cooperation:** It was found that at present there is cross borders cooperation between security forces of China and Nepal in informing possible transboundary disasters. Further strengthening by establishing joint committees including local governments for regular coordination, communication and data exchange will benefit both parties in efficient disaster management. Collaborative research projects and efforts to enhance capacity are additional forms of cross-border cooperation.
- **Ensuring resilient infrastructure and land use planning:** Chains of hydropower are being constructed in main rivers of both basins. There are uncertainties whether the dams of such hydropower are resilient to GLOFs and locals fear the destruction of such dams would amplify the impacts. People living at higher elevation than river level feared about the possible bank cutting, subsequent landslides and impacts during GLOF, which is true in the fragile Bhotekoshi basin [73]. These two gaps must be addressed in future studies. Thus, it is imperative to make investments in resilient infrastructure and land use planning. This entails creating protective structures to manage floodwaters, like dams or embankments, and creating suitable zoning laws to limit settlements in high-risk areas.
- **Raising awareness and education:** According to locals and stakeholders, no GLOF awareness programs have been conducted in either of the study sites to date. The significance of community based early warning systems, evacuation plans, and other

preparedness measures can be underscored and disseminated to individuals and communities through awareness campaigns, training programs, and the integration of disaster risk reduction education into school curricula.

- **Developing the capacity of local government and bilateral aid agreements:** Local governments in Nepal are directly responsible for formulating the local policies and uplifting the life of their residents. Strengthening them by guiding on policies, providing enough resources (expertise, budget, equipment) and developing disaster response, recovery and mitigation capacity to cope with GLOF will help in decreasing the vulnerability. Specifically, core programs must be implemented by local governments focusing socio-economically marginalized people to uplift their adaptive capacity. Further, to enable the sharing of resources, knowledge, and support in times of emergency, Nepal and China should collaborate and create mutual aid agreements or frameworks for provision of emergency response teams, tools, and monetary support in the case of a transboundary GLOF.

While the results of this study are representative of the number of sampled households and the set of indicators used, these are also consistent with and are reflective of the general trends of GLOF vulnerability and risk reported in the region. The sample size was determined from the building polygons (type = houses only) obtained from an integrated open street map in QGIS, which may suffer completeness for classifying the types. Further, GLOF impact largely depends upon intensity and magnitude, eventually altering the vulnerability. Notably, identifying and incorporating several indicators and extending the questionnaire to many samples may enhance results which require greater resources and time; however, we believe the main results and conclusions presented here are highly representative and recommendable for policy makers.

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CRediT authorship contribution statement

Nitesh Khadka: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Xiaoqing Chen:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Milan Shrestha:** Writing – review & editing, Conceptualization. **Weiming Liu:** Writing – review & editing, Supervision, Funding acquisition.

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.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

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