Tempa and Yuden
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RESEARCH

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Multi-hazard zoning for national scale population risk mapping: a pilot study in Bhutan Himalaya

Karma Tempa* and Kezang Yuden

Abstract

Landslides, floods, fires, windstorms, hailstorms, and earthquakes are major dangers in Bhutan due to historical events and their potential damage. At present, systematic collection of data is scarce and no multi-hazard zoning is reported in the existing literature for Bhutan. In addition, for proper disaster management, recognizing the existence of the hazards and identifying the vulnerable areas are the first important tasks for any multi-hazard risk studies. To fill the gap, the main objective of this study is to prepare the multi-hazard zoning and assess the multi-hazard population risk for Bhutan on seven historical hazard events. To achieve this, we first collected data on the historical events of different periods based on the data availability and created a district-level database. A total of 1224 hazard events were retrieved. We then calculated the weighted score for individual hazards based on the number of occurrences and the degree of impact through a multi-criteria decision analysis model (MCDA) using the analytic hierarchy process (AHP). The district-wise individual hazard scores are then obtained using the weighted scores. The total hazard score (THS) was aggregated and normalized to obtain the district-wise multi-hazard scores. A multi-hazard zoning map was created in the open-source software QGIS, highlighting 70% of districts with moderate to severe multi-hazard vulnerability. Considering the population distribution in each district at the local levels, the multi-hazard score is integrated and the multi-hazard population risk is mapped.

Keywords Multi-hazard, Analytic hierarchy process (AHP), Geographic information system (GIS), Population risk, Bhutan

Introduction

Multi-hazard indicates the simultaneous or cumulative occurrence of disasters and their potential interactive impacts on the ecosystem (Gautam et al. 2021). Expanding human needs and sustainability efforts remain complex and coupled phenomena, leading to unbalanced adaptation, in contrast to expanding exposure and vulnerabilities. The impacts of climate change and man-made activities are also showing similar impacts, resulting in multiple hazards. Extreme catastrophic events have also been experienced frequently in connection with climate change and have gained importance in recent years. Natural disasters that affect land, ocean, and atmosphere are widely recognized around the world (Siddique and Schwarz 2015), and their severity and impact can transform perspectives and preparedness to achieve the Sustainable Development Goals (SDGs) (UN 2016). In Bhutan, the Department of Disaster Management (DDM) is solely responsible for all disaster-related activities, which was only introduced in 2005. With the introduction of the Disaster Management Act 2013 (DDM 2013), DDM has now constituted a national disaster management agency and disaster management committees in all 20 districts.

*Correspondence:
Karma Tempa
karmatempa.cst@rub.edu.bt
Civil Engineering Department, College of Science and Technology, Royal University of Bhutan, Phuentsholing, Bhutan

Bhutan (Fig. 1) faces a variety of threats and remains highly vulnerable to multiple hazards. Extreme weather events have led to major disasters in the form of storms, floods, and landslides, which have caused enormous socio-economic damage (Tempa et al. 2021a, b). In recent years, the occurrence of these hazardous events has become recurrent every monsoon. At the same time, due to the high vulnerability, there is still a risk of fire and the effects of earthquakes. Also, unusual hailstorm events are observed which are likely to increase the associated threats. According to the United Nation's (UN) report (UN 2018): The 2009 Cyclone Aila brought unprecedented rain and flooding to 17 districts killing 15 people and causing Nu. 718 million losses; April 2011 windstorm affected 17 districts, killed one person, and damaged roofs of 2589 buildings; The 1994 Punakha flood caused by glacial lake outburst flood (GLOF), killed 17 people, affected 91 households, and damaged more than 1781 acres of land. The M_w 6.1 Mongar earthquake of September 2009 killed 12 people, damaged 5,967 buildings, and caused economic losses of Nu. 2501 million with similar impacts by the September 2011 Sikkim earthquake of M_w 6.9 that damaged 7965 buildings (Chettri et al. 2021).

The combined effect of multiple hazards in Bhutan has yet to be studied. However, investigating the multi-hazard is more difficult due to the lack of proper long-term historical data. Although recent efforts are being made to collide geospatial-based digital platforms, multi-hazard risk assessment for Bhutan is long overdue. In addition, monitoring and detection of multi-hazard disasters using new technologies (e.g., IoT, satellite imagery, and UAV) is lacking, which is important for maintaining connectivity of various disaster scenarios (Khan et al. 2020). Remote Sensing (RS) and GIS-based applications are still rare,

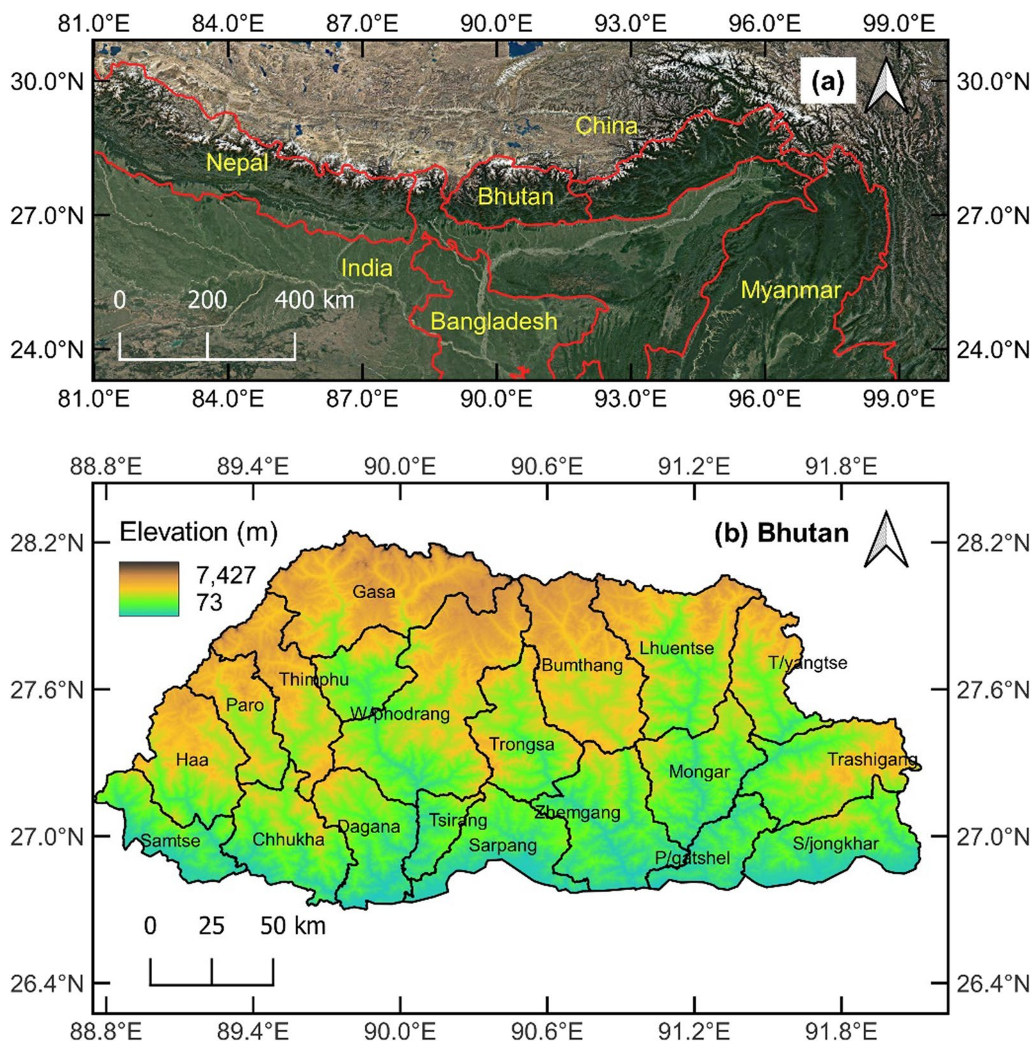

Fig. 1 Study area. **a** The geographical location of Bhutan, **b** district-level administrative units of Bhutan

which is one of the powerful tools to perform multitemporal hazard assessment (Fernández et al. 2021). Some of the recent single hazard studies carried out in Bhutan include earthquakes (Tempa et al. 2020; Stevens et al. 2020; Chettri et al. 2021; Tempa et al. 2021a, b) and landslides (Dikshit et al. 2019, 2020; Sarkar and Dorji 2019). The history of hazard cascades (hazard inventories) and impacts on populations, settlements, and infrastructures are directly linked to hazard risk, which typically results in fatalities, damages, and losses. Such datasets are limited for some extreme events, e.g., (RGOB 2009; ADRC 2015; UN 2018; ADPC-UNDRR 2020).

The cascading interaction between the multi-hazard threats is exposed in many regions, resulting in high venerability-level multi-risk (Liu et al. 2015). Many studies are still grounded with single hazard isolation which has shown shortcomings in considering the interactive association of the multi-hazard risk. To overcome some of these limitations, nowadays, multi-hazard studies are receiving growing scientific attention (Arosio et al. 2020). Many researchers considered multi-hazard zoning in multiple countries, taking administrative boundaries into account (Siddique & Schwarz 2015; Durlević et al. 2021; Rusk et al. 2022). Globally, some researchers have developed different approaches to address risk assessment of multi-hazard and applied the concepts in different geographical locations (Johnson et al. 2016; Zharikova and Sherstjuk 2020; Liu et al. 2021). Due to the difficulty of accounting for coupled effects, multi-hazard studies largely rely on a semi-quantitative approach, despite some multi-hazard models (Dunant 2021). Weighted factor or index-based approaches are also widely used for single hazard isolation and multi-hazard assessment frameworks (e.g., Anderson et al. 2019; Papathoma-Köhle et al. 2019; Garschagen et al. 2021)). Some studies also demonstrated the interaction of geo-environmental factors for multi-hazard risk and susceptibility assessment using the analytic hierarchy process (AHP) (Khatakho et al. 2021; Rehman et al. 2022). In contrast to the individual hazard assessment, the investigation of multiple hazards brings with it several additional challenges due to the different characteristics of the processes. After different approaches and challenges have been mentioned, a comparability of the individual hazard results is strongly recommended to select equivalent approaches to assess the overall hazards. Therefore, the first approach to conducting multi-hazard studies is to understand a spatially oriented data scenario and then present a thematic definition that encompasses all hazards (Kappes et al. 2012). Studies also emphasized priority on identifying the areas where the hazards are probable and considered multi-hazard zoning as the first and foremost task for disaster management programs (Barua et al. 2016).

Multi-hazard zoning is an approach that considers more than one hazard at a given location (ideally considering all known hazards) and the interrelationships between those hazards. Multi-hazard zoning is recognized worldwide as a notable area of research to represent comparable hazard levels at different administrative boundaries. As multiple hazards threaten and their damage is enormous, maps with multiple hazard zones can provide important insights before natural hazards occur, so that effective countermeasures and preparedness can be designed and implemented. To the best of the author's knowledge, historical events are poorly recorded over the past decades that are scattered across the organization, presenting greater challenges. The literature review carried out showed that the studies on multi-hazard in Bhutan are still missing. Therefore, the main objective of the study is to prepare a district-wise inventory of seven hazards and implement an indicator-based weighted score of each hazard for the 20 districts and develop a district-level multi-hazard zonation map of Bhutan. Although the delineation of demographic and social datasets for advanced risk assessment studies in Bhutan is long overdue, this study attempts to spatially capture population distribution at the local scale and map population risk to multiple hazards.

Material and method

Study area

Bhutan (Fig. 1a) is located in the eastern part of the Himalayas and borders China's Tibetan plateau to the north and east and India to the south and west. The digital elevation model (DEM) shown in Fig. 1b depicts Bhutan's elevation ranging from 73 m in the southern foothills to more than 7400 m towards the greater Himalayas in the extreme north. Bhutan is a small developing country. The population of Bhutan is estimated at 735,553 in 20 districts and 205 local government units with 163,001 households (NSB 2018). The study area extends up to 38,394 km^2 with an average population density of 19.5 in 2020 (NSB 2020). The hazard vulnerability exists due to inhabitants settled in many pocketed areas in the Himalayan mountains that are not adapted to withstand exposure levels of varying magnitudes. Related to multi-hazards, the demographic scenarios also show significant relative vulnerability to multi-hazards, for example, the rural population is 62.2%, and building categories like masonry, adobe, and wooden structures and makeshift houses are as high as 67.7% with 34.7% who has not attended school, and 36.7% economically inactive, apart from significant contribution from other characteristics (NSB 2018). The topographical features and the fragile geological conditions coupled with the effects of climate change increase the threat of natural hazards and the impending risks.

Data

Most of the data used in the study come from Kuensel, a daily print media that also covers hazard bulletins and provides a rich source of data for the researchers. Data collection and analysis is an important parts of any research. The present study focused on capturing the time series of hazard events and collected information on impacts such as fatalities, damage to infrastructure, affected population, and economic losses. As the newscasts are first-hand information, the economic damage data is not available, but rather descriptive information is usually provided. In particular, there is currently little data on the economic assessment of damage losses, as few have been conducted for some extreme disasters, making it difficult to conduct multi-hazard risk studies. To fill this gap, this study attempted to populate and compile available historical event data sets for 20 districts (Fig. 1b) from different sources. The summary of the data sets and data sources is presented in Table 1. The historical flood inventory was obtained from the National Center for Hydrology and Meteorology (NCHM). The United Nations Development Policy Committee (CDP) document provided the historical earthquake data and the DDM's 2015 country report was also used. The social media alerts maintained by the Department of Roads (DOR) provided a landslide inventory for 2021. Therefore, a total of 1224 hazard events were retrieved and the summary is provided in Table 2. To sort the hazards, we have classified the number of events by windstorm, hailstorm, forest fire, fire-building, flood, landslide, and earthquake. The pre-processing of the data mainly involved data de-clustering in time-series format with the corresponding frequency of occurrence for each of the districts. The data was also split to project the total historical events using the cumulative sum. The geographic coordinates of some hazard events are also marked to provide a comprehensive inventory for future work (e.g., landslide and flood hazards).

Method

District level multi-hazard zonation is not reported in the existing literature for Bhutan. To fulfil the gap, this study analyses the historical events of seven natural hazards. The weights are assigned a priority index by AHP, based on the number of hazard events and the severity of a particular hazard. The final normalized scores are categorized to distinguish multi-hazard levels for each district. Index-based/weight-based approaches with simple statistical parameters are also used to perform multi-hazard zoning based on the occurrence of a specific hazard level in the area of interest (Gautam et al. 2021). The index-based approach is widely used for hazard zoning in different parts of the world (Siddique and Schwarz 2015). These approaches take into account a higher level of hazard, which is directly associated with a higher number of hazards, as well as impacts associated with each hazard. However, some of these methods require a large amount of empirical data, which is not always available, and the actual impact is difficult to predict, e.g., claims of damages are usually presented in a descriptive manner and it is often not possible to determine the actual monetary value (direct or indirect) given the large population of data sets. The losses discussed include damages to the agricultural land, forest cover, road infrastructure, damage to crops and livestock, loss of personal belongings, etc. Therefore, we strive for a qualitative approach to solve this problem by classifying the economic losses with the available information and the extent of the damage. A qualitative rating scale of 1 to 5 (very low, low, moderate, high, very high) is used for the missing data based on the available information. Therefore, to account for both incident frequency and impact anomalies, a multi-criteria decision analysis is proposed using

Table 1 Data sets and data source details

Data sets	Sources	Period range	Data type
Flood	NCHM, (Tempa 2022)	1968–2016	Compendium/Journal
	Kuensel	2009–2021	Archive
Earthquake	Kuensel	2008–2021	Archive
	United Nation (UN)	1897–2016	Reports
	DDM	2009	Reports
Windstorm, hailstorm and fire hazard	Kuensel	2009–2020	Archives
	DDM	2009–2020	Reports
Landslide	DOR	2021	Alerts
	Kuensel	2008–2021	Archive

Table 2 Summary of number of hazard events in 20 districts of Bhutan

District	Windstorm	Hailstorm	Fire-building	Forest fire	Flood	Landslide	Earthquake
Bumthang	1	0	12	0	2	5	3
Chhukha/Phuentsholing	3	3	5	1	17	74	5
Dagana	4	2	0	1	2	17	3
Gasa	2	0	0	0	6	7	3
Haa	1	0	4	1	5	6	1
Lhuentse	2	0	1	0	9	6	3
Mongar	8	2	6	14	6	78	6
Paro	4	0	3	4	3	2	2
Pemagatshel	9	1	3	0	3	15	3
Punakha	3	2	1	4	6	5	4
Samdrupjongkhar	4	1	5	1	8	45	4
Samtse	2	2	3	1	12	12	1
Sarpang	6	1	4	0	17	68	5
Thimphu	0	0	19	33	5	7	6
Trashigang	5	3	3	20	13	24	7
Trongsa	1	1	3	0	2	35	3
Tsirang	3	0	0	1	2	8	2
Wangdiphodrang	3	4	4	13	6	16	5
Trashi Yangtse	2	2	2	2	11	11	5
Zhemgang	9	0	1	0	4	60	3

the AHP model and derived weights of the seven indicators which can be applied to determine the multi-hazard scores. The implementation of the method is shown in Fig. 2.

The multi-criteria decision analysis with AHP represents a common technique used to evaluate complex decision-making processes considering the attributes as an indicator. Multi-objective AHP, developed by Saaty (1990), uses a pairwise comparison process to efficiently evaluate the decision model by constructing the evaluation matrix with the absolute number scale 1–9 (Table 3). AHP uses hierarchical structures to represent a problem and then prioritizes alternatives based on the user's judgment (Saaty 1977). The AHP model delivers a pairwise matrix, eigenvalue, and weighting coefficient and allows a priority ranking check by calculating the consistency ratio (CR). The Consistency Indices (CI) and CR of a given choice are calculated using Eqs. 1 and 2.

$$\mathrm{CI} = \left(\frac{\lambda_{\max} - \mathrm{n}}{\mathrm{n} - 1}\right) \tag{1}$$

$$\mathrm{CR} = \mathrm{CI}\left(\frac{1}{\mathrm{RI}}\right) \tag{2}$$

where $\lambda_{\max}$ is the maximum eigenvalue of the pair-wise comparison vector and n is the number of attributes and the random index (RI) is as shown in Table 4.

Data collected from different sources is de-clustered and separated to fit the scope of the research. This data is then entered into the database, which is designed to meet multi-hazard mapping criteria. A brief procedure is presented as follows:

(a) Formulate the total number of hazard events in each district from the resolved raw data collected
(b) Analyze the severity of each hazard and assign weight factors based on fatalities, losses, affected population, etc.,
(c) Calculate total hazard score (THS):

$$\mathrm{THS} = \sum_{i=1}^{n} W_i N_i$$

where W indicates the weighting factor and N is the number of natural hazard events considered in the study
(d) Normalize the total hazard score as follows:

$$\text{Normalized THS} = \frac{\text{THS of a particular district}}{\text{Maximum THS among 20 districts}}$$

(e) Prepare a multi-hazard zoning map at the district level
(f) Project population distribution under each district for various local administrative boundaries

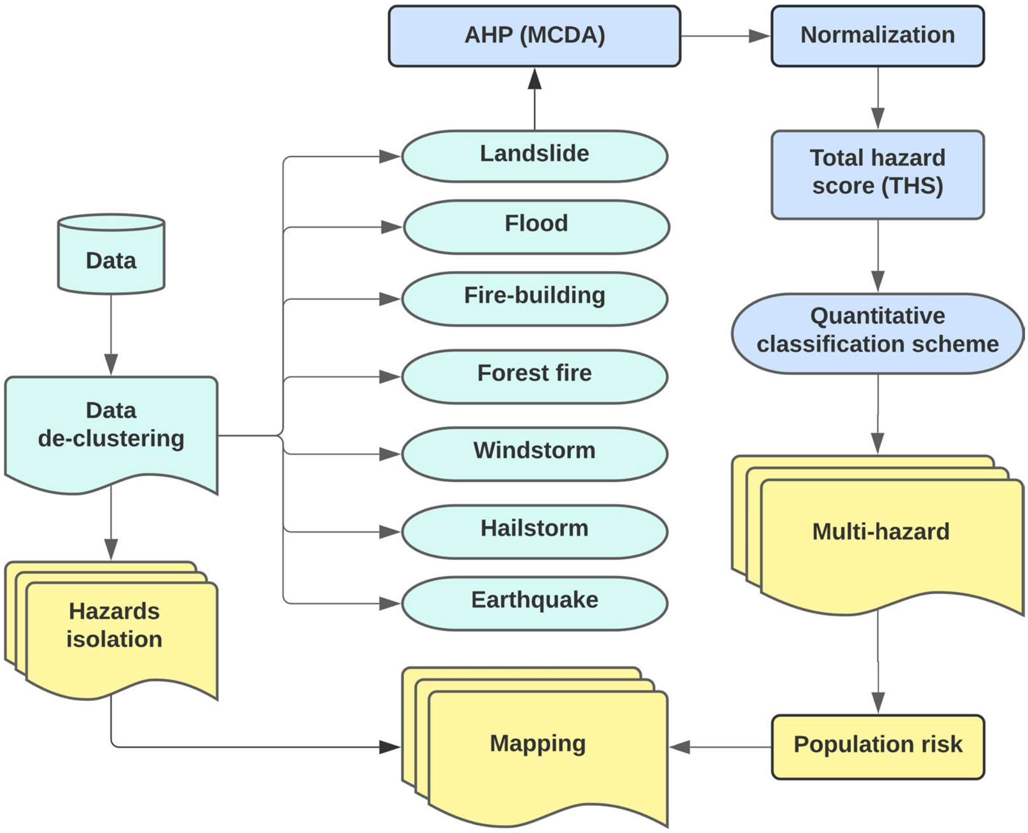

Fig. 2 Implementation of the methodology

Table 3 The fundamental scale of various compared elements

Scale	Judgment of preference	Description
1	Equally important	Two factors contribute equally to the objective
3	Moderately important	Experience and judgment slightly favour one over the other
5	Important	Experience and judgment strongly important favour one over the other
7	Very strongly important	Experience and judgment strongly important favour one over the other
9	Extremely important	The evidence favouring one over the other is of the highest possible validity
2, 4, 6, 8	Intermediate preference between adjacent scales	When compromised is needed

Table 4 Random consistency index

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

(g) Develop a population risk map at the local level for multi-hazard scenarios based on a simplified approach (Risk = Hazard × Population vulnerability).

Results and discussion

Hazard statistics

A total of 1224 hazard events were populated. The hazard events are dominated by the risk of landslides, followed

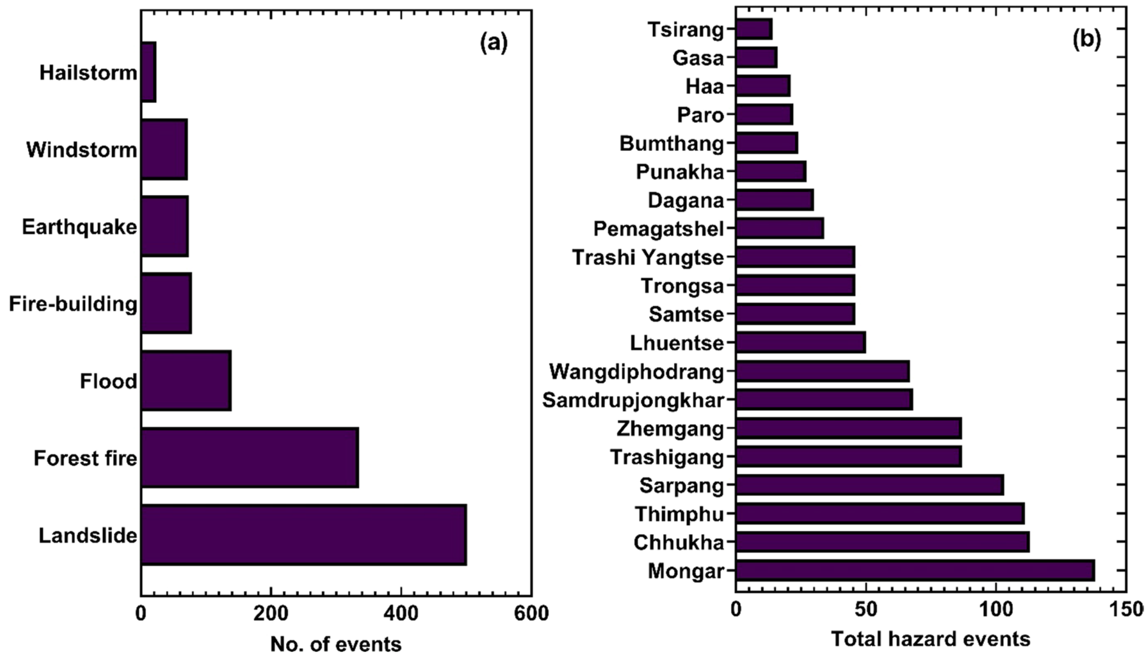

Fig. 3 Multi-hazard records in Bhutan, **a** number of incidents of each hazard, **b** number of incidents under each district

by forest fires, floods, fire-building, earthquakes, storms, and hail (Fig. 3a). The highest event was recorded for landslides with 501 events, and the lowest event with 24 for hail. Fire hazards were classified into two categories: forest fires and building fires, and 335 and 79 fire incidents were recorded, respectively. The total cumulative hazards for each district are shown in Fig. 3b. Mongar was highest with 138 hazards, followed by Chhukha Thimphu and Sarpang with 113, 111, and 103 events, respectively. Tsirang, Gasa, Paro, Haa, Bumthang, Punakha, Dagana, and Pemagatshel recorded the fewest hazard events between 14 and 26, and the rest of the district experienced a moderate number of hazard events.

Basic statistical analysis is also performed on the de-clustered datasets. The hazard and the corresponding frequency of occurrence are shown in the box and whisker plots (Fig. 4). A box-and-whisker plot (or boxplot) is a convenient way to visually represent the distribution of data across their quartiles. As shown in Fig. 4, the boxplot represents the distribution of each hazard event across the 20 districts, providing the mathematical function or expression of the probability of the hazard system that will assume a particular value or set of values. The median and mean for windstorm, hailstorm, building fire, flood, and earthquake are between 1–6 and 1–17, respectively. The median and mean values for a landslide are 14 and 25, respectively. We speculate on a similar future development (1 decade) of the median and mean values as well as a possible increase in the frequency of occurrence of the events in the respective districts. The boxplot also depicts outliers in the hazard events (e.g., building fire, forest fire, and landslide). In terms of hazards, in particular, these outliers show significant importance for the frequency of occurrence in some districts (e.g., fire hazards in Thimphu and landslides in Chhukha) and provide crucial valuable information.

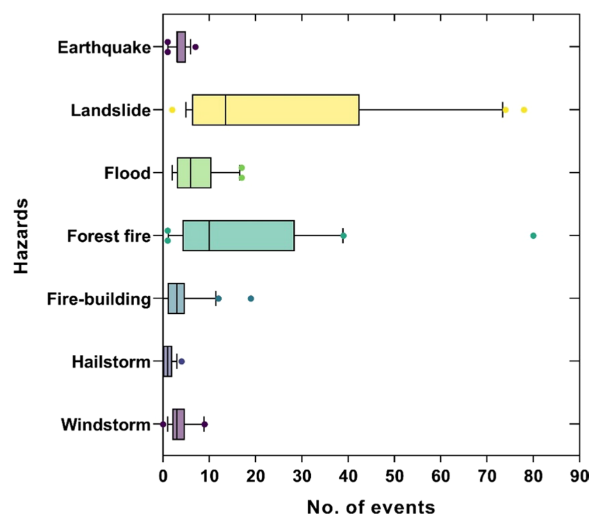

Fig. 4 Statistical hazard distribution with boxplot

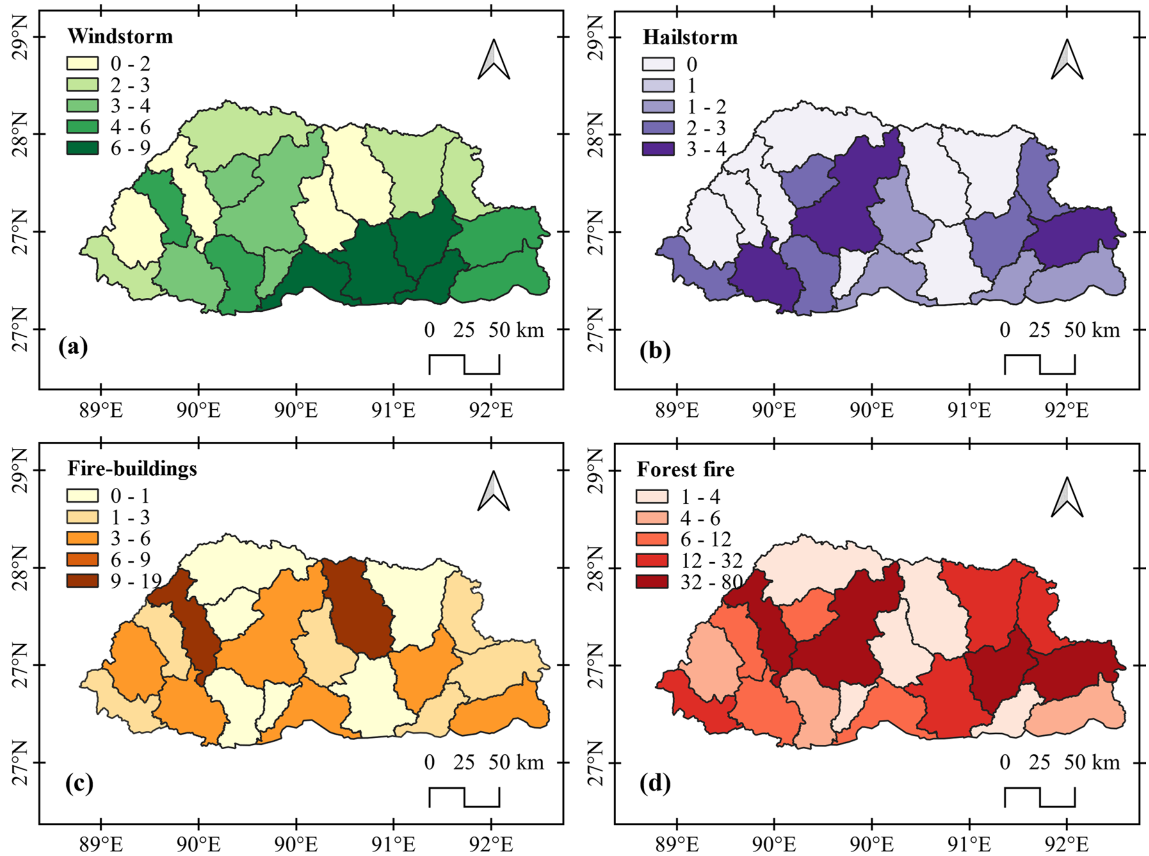

Fig. 5 District level hazard zonation of Bhutan (2008–2021). **a** Windstorm, **b** hailstorm, **c** fire-building, **d** forest fire

Hazard zonation

On the account of the multi-hazard scenario, first, we considered district-level zoning for individual hazards. Figure 5a presents the occurrence of windstorm hazards at the district level in Bhutan with a total of 72 incidents. Storm hazards are particularly catastrophic in spring (March to May) and fall (September to November), often accompanied by torrential rain. The most affected building typology is the traditional buildings with masonry structures with rare cases in the modern buildings. In most cases, the timber truss, the roof, and the main walls of the buildings are completely damaged. The severity of the storm threat is more in the southern belt of the country and some parts of central Bhutan. Mongar, Pemagatshel, Sarpang, and Zhemgang are the hardest-hit districts with the greatest impact on households followed by Dagana, Samdrupjongkhar, Thimphu, and Trashigang. Similarly, hailstorm events in Bhutan are shown in Fig. 5b. Hail events are particularly concentrated in a few districts in the south, centre, and east, such as Chhukha, Trashigang, and Wangdiphodrang. Most of the impacts are on agricultural land, causing major damage to crops, usually in spring and autumn. The 12-years record shows a total of 24 hail events.

With the onset of the dry season, Bhutan is facing multiple wildfires across the country. Fire on buildings remains unpredictable. Fire hazard is divided into two categories based on the nature of the impact. A total of 414 fire incidents were recorded. The impact of the building fire is intense and direct, resulting in deaths and loss of livelihood. The building fire zoning in Fig. 5c shows 3 districts with the highest number of hazards. The capital Thimphu recorded the highest number of building fires, followed by Bumthang and Mongar, indicating that most building fires were concentrated in densely populated urban areas. Traditional buildings are highly vulnerable and suffered the most from the effects. Forest fires (Fig. 5d) have so far not caused any fatalities or major damage to infrastructure. However, land cover degradation is enormous that poses a potential threat to the pristine environment and natural resources. Again, the capital Thimphu recorded the most forest fires, followed by Trashigang, Mongar, and Wangdiphodrang.

Historical flood hazards date back to 1968. So far, a total of 139 major flood events are registered. Figure 6a

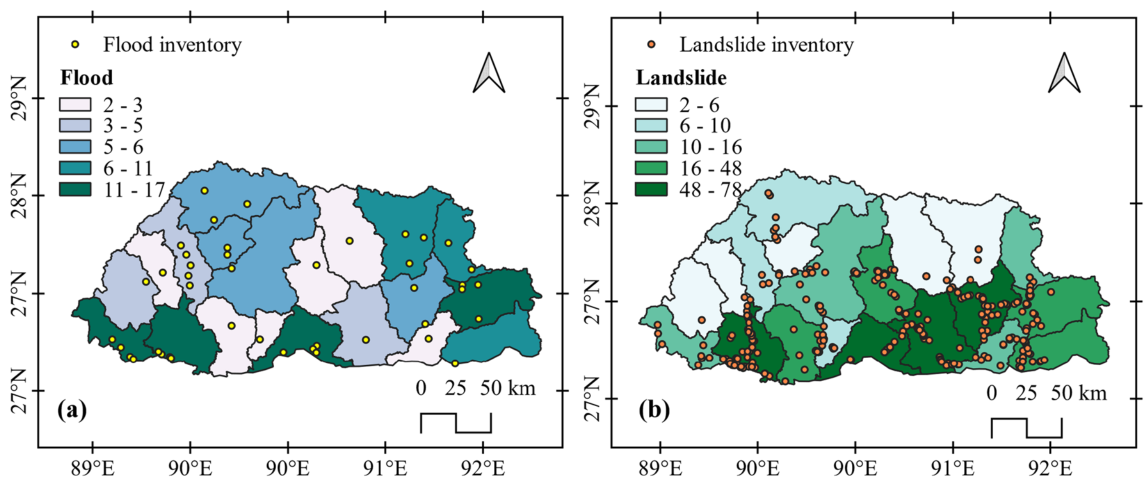

Fig. 6 District-level hazard zonation of Bhutan. **a** Floods, **b** landslides

shows the zoning and inventory map of flood hazards in Bhutan. Floods are one of the most destructive natural hazards in Bhutan. The frequency of flooding in the southern regions of the country shows a similar trend due to heavy rainfall in the region. Chhukha and Sarpang are the hardest hit by the flood disaster, followed by Samtse, Trashigang, Trashi Yangtse, and Lhuentse. Moderately few flooding events were observed in other districts, except for the Punakha district, which was hit by three major Glacial Lake Outburst Floods (GLOF) events. According to a study by Gurung et al. (2017), Punakha remains highly vulnerable to GLOF due to the active Lemthang Tsho and its association with climate change impact. In Chhukha, a major flood disaster occurred in Pasakha in 1996 when the Barsakchu River flooded. The flood damaged more than 25 residential buildings causing more than Nu. 30 million losses. Similarly, the city of Phuentsholing in the same district was devastated by the Dhuti Khola flood in 2000 and the Amochu flood in 2016. The extreme Himalayan region in Gasa and parts of Wangdiphodrang also recently experienced a major flood disaster. The 2021 Gasa flood devastated the hot spring facility and caused huge economic losses.

The landslide hazard zoning map of Bhutan is shown in Fig. 6b. Among the hazards considered, landslides have the most significant impact events. A total of 501 landslide events were verified. The recent trend shows an increase in the occurrence of landslides with frequent and recurring phenomena throughout most of the year. The majority of landslides are triggered by heavy and sustained rainfall from April to September with few cases of co-seismic landslides. In addition, the topographic and fragile geological environment makes the Bhutan Himalaya highly prone to landslides and conditions are at their worst during extreme meteorological events. The majority of landslide sites are concentrated in the central and southern belts. Geologically, the lower lesser Himalayan region falling in the southern belt consists of weak formations such as the Buxa Group (Phuentsholing Formation, Pangshari Formation, and Manas Formation), the Daling-Shumar Group (Daling Formation, Shumar Formation, and Orthogneiss), and the Jaishidanda Formation. The lithological features in these formations are predominantly heavily weathered dark grey to black shale and phyllite, limestone strata, cream dolomite, and fractured quartzite. The upper lesser Himalayas dominate the central belt inheriting orthogneiss and lower metasedimentary units. The majority of these two belts are dominated by multiple shear zones, thrusts, strikes, and dips of foliation and bedding, confirming high susceptibility to landslide activity.

The latest landslides statistics show the most landslides in July and August. In 2021 alone, the highest record of 158 landslide events was registered. The data population indicates the majority of landslides along the road corridor. Landslide hazards included landslides from natural slopes, debris, mudslides, falling rocks, and boulders. Boxcut, 15 km from Gelephu along the Gelephu-Trongsa primary national highway (PNH) under Sarpang registered the highest landslides, followed by Namling on Simtokha-Trashigang PNH. Landslides are also common throughout the year in Kurizampa-Nganglam PNH and Tingtibi-Panbang PNH under Pemagatshel and Zhemgang districts, respectively. The district-level landslide hazard zoning in Fig. 6b shows the highest landslide events in Mongar, followed by Chhukha, Sarpang, and Zhemgang with 78, 74, 68, and 60 landslide events, respectively. Paro, Haa, Punakha, Bumthang, and Lhuentse registered relatively low landslide hazards. 361 landslide locations are geo-referenced.

The history of earthquake impacts in Bhutan dates back to the eighteenth century Great 1987 Assam earthquake 8.15 < Mw < 8.358 which struck on a south-dipping fault near the northern edge of the Shillong Plateau, India (England and Bilham 2015). Bhutan Himalaya is considered one of the most seismically active regions in the world due to active seismic-tectonic activities, however, in particular, Bhutan has not faced an extreme earthquake (Mw > 6.5) for the past 6 decades (Tempa et al. 2020). In most of the cases, the earthquake impacts were felt due to earthquakes in the neighboring regions. The Himalayan range has experienced many large earthquakes, including the 1950 Mw 8.7 Assam event, which ruptured within ~ 200 km east of Bhutan. 2015, Mw 7.8, Gorkha Nepal earthquake, and the 2005 Mw 7.6, Kashmir India earthquake, are some of the recent events that also caused multiple deaths and destruction (Stevens et al. 2020). 2009, the Mongar earthquake (Mw 6.1) with the epicenter situated 180 km east of the capital Thimphu, in Mongar district at a depth of 14 km affected six nearby districts. The earthquake caused 12 deaths and 47 injuries. The earthquake affected 4,950 households, 25 basic health units, 91 school buildings, more than 800 cultural/religious heritage structures, 22 renewable natural resource offices, and 27 government and public office buildings (ADRC 2015). The 2011 Sikkim-Nepal bordar earthquake (Mw 6.9) that struck at a focal depth of ~ 35 km also damaged 7,965 buildings in all the 20 districts of Bhutan (Chettri et al. 2021). According to personal communication with the DDM, the Mw 6.4 Assam earthquake 2021 reported major damages to 2,500 buildings in 16 districts of Bhutan. The majority of the damages were observed in cultural heritage buildings and masonry structures. The earthquake events in this study accounted for the number of events that caused significant damage to infrastructures. Mongar, Trashigang, and Thimphu recorded the highest infrastructure damages (Fig. 7).

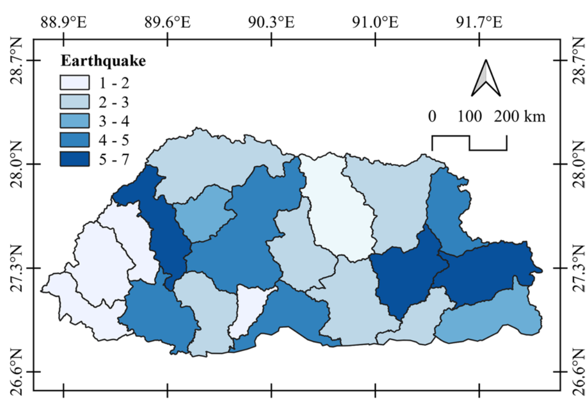

Fig. 7 District-level earthquake hazard zonation of Bhutan (1987–2021)

Multi-hazard zonation

The cascading hazard events are widespread across the country with different impact patterns and numbers of occurrences. The individual hazard zoning established in the previous section may be very conservative to provide adequate insight into the overall hazard level. In the context of this argument, resource allocation or pre-disaster planning may not be as efficient. In particular, a different association pattern was observed between the frequency of hazards and impact in different administrative units. The correlation between these two themes is essential to substantiate and validate the multi-hazard scenario for a given region. Moreover, for some hazards, the quantitative assessment of indicators remains a challenge due to a lack of sufficient empirical data (e.g., the population affected by landslide hazards and economic losses). A possible solution to this difficult problem could involve the use of a multi-criteria decision analysis model and by index-based weighted approach. Therefore, indicator-based weighted multi-hazard zoning is performed on the district administrative scale. To achieve this, we used AHP on the indicator attributes available in Table 5 and initiated 21 pairwise comparisons. A further prioritization was performed to derive the weights of the indicators (Table 6). The results of the priority ranking

Table 5 Summary of reported cumulative hazard impacts

	Fatalities	Affected population	Building damage	Economic loss
Landslide	28	Very high (5)	20	Very high (5)
Fire-building	9	818	281	Moderate (3)
Forest fire	0	4	49	Low (2)
Windstorm	1	8096	5365	High (4)
Hailstorm	1	1972	0	Moderate (3)
Floods	196	797	660	Nu. 2012.8 million
Earthquake	13	7290	13,578	Nu. 1239.63 million

Table 6 Pairwise comparisons of indicators using AHP (CR = 6.2%)

	Landslide	Fire-building	Forest fire	Windstorm	Hailstorm	Flood	Earthquake
Landslide	1	8	6	4	8	2	3
Fire-building	1/8	1	2	1	2	1/9	1/7
Forest fire	1/6	1/2	1	1/2	1/3	1/9	1/8
Windstorm	1/4	1	2	1	2	1/5	1/7
Hailstorm	1/8	1/2	3	1/2	1	1/8	1/8
Flood	1/2	9	9	5	8	1	2
Earthquake	1/3	7	8	7	8	1/2	1
Priority (%)	34.30	4.40	2.70	5.30	3.60	27.70	22.00

Table 7 Normalized priority ranking and corresponding weights

	Landslide	Fire-building	Forest fire	Windstorm	Hailstorm	Flood	Earthquake	Weights
Landslide	0.40	0.30	0.19	0.21	0.27	0.50	0.46	0.39
Fire-building	0.05	0.04	0.06	0.05	0.07	0.03	0.02	0.05
Forest fire	0.07	0.02	0.03	0.03	0.01	0.03	0.02	0.03
Windstorm	0.10	0.04	0.06	0.05	0.07	0.05	0.02	0.07
Hailstorm	0.05	0.02	0.10	0.03	0.03	0.03	0.02	0.05
Flood	0.20	0.33	0.29	0.26	0.27	0.25	0.31	0.32
Earthquake	0.13	0.26	0.26	0.37	0.27	0.12	0.15	0.26

Table 8 Implementation of weights, hazard score aggregation and multi-hazard level rating

Districts	Landslide	Fire-building	Forest fire	Windstorm	Hailstorm	Flood	Earthquake	Hazard rating
Bumthang	1.60	0.40	0.26	0.39	0.00	0.09	0.78	0.11
Chhukha	23.61	0.17	0.72	1.16	0.16	0.77	1.31	0.85
Dagana	5.42	0.00	0.33	1.55	0.11	0.09	0.78	0.25
Gasa	2.23	0.00	0.07	0.78	0.00	0.27	0.78	0.13
Haa	1.91	0.13	0.33	0.39	0.00	0.23	0.26	0.10
Lhuentse	1.91	0.03	2.10	0.78	0.00	0.41	0.78	0.18
Mongar	24.89	0.20	2.49	3.11	0.11	0.27	1.57	1.00
Paro	0.64	0.10	0.66	1.55	0.00	0.14	0.52	0.11
Pemagatshel	4.79	0.10	0.20	3.49	0.05	0.14	0.78	0.29
Punakha	1.60	0.03	0.66	1.16	0.11	0.27	1.05	0.15
Samdrupjongkhar	14.36	0.17	0.33	1.55	0.05	0.36	1.05	0.55
Samtse	3.83	0.10	0.98	0.78	0.11	0.54	0.26	0.20
Sarpang	21.70	0.13	0.46	2.33	0.05	0.77	1.31	0.82
Thimphu	2.23	0.64	5.25	0.00	0.00	0.23	1.57	0.30
Trashigang	7.66	0.10	2.56	1.94	0.16	0.59	1.83	0.45
Trongsa	11.17	0.10	0.26	0.39	0.05	0.09	0.78	0.39
Tsirang	2.55	0.00	0.07	1.16	0.00	0.09	0.52	0.13
Wangdiphodrang	5.11	0.13	2.23	1.16	0.21	0.27	1.31	0.32
Trashi Yangtse	3.51	0.07	1.18	0.78	0.11	0.50	1.31	0.23
Zhemgang	19.15	0.03	0.85	3.49	0.00	0.18	0.78	0.75

generated by the AHP model are normalized to get the final scores (Table 7). Implementation of the AHP scores into the corresponding hazards for each district resulted in the aggregation of the weighted score (THS). In the end, the THS of the district's weighted score divided by the highest weighted score yielded the district-level multi-hazard ratings (Table 8).

The multi-hazard zoning at the district level is shown in Fig. 8. As shown in Fig. 8, the southern part of the country is more prone to multi-hazard than the western parts, mainly because natural hazards are most common in the southern regions. These regional districts include Chhukha, Mongar, Sarpang, and Zhemgang, which have a very high multi-hazard level. The central region in Trongsa and Wangdiphodrang, Thimphu in the west, and the far east in Pemagatshel, Trashigang, and Samdrupjongkhar fall under a high multi-hazard level.

A summary of the multi-hazard levels is shown in Table 9. Four districts are categorized under very high multi-hazard levels and three each in the low and very low levels. Two districts fall under moderate multi-hazard level. The highest of the six districts are under high multi-hazard levels. Thus, it is clear that more than 70% of districts in Bhutan are vulnerable to depict moderate to severe multi-hazard levels.

Population risk mapping

According to the National Statistics Bureau (www.nsb.gov.bt), the projected population in 2022 is estimated at 763,249 people spread across 205 local government units

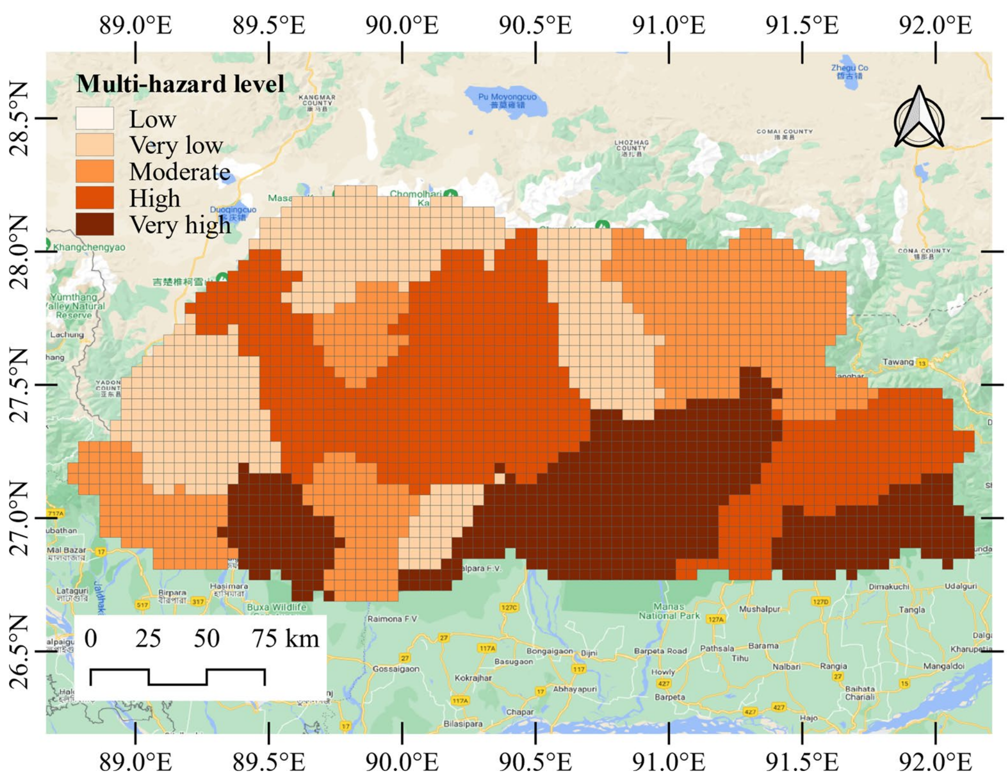

Fig. 8 District-level multi-hazard zonation of Bhutan

Table 9 Summary of multi-hazard levels

Multi-hazard score	Multi-hazard levels	No. of districts	Districts
0	Very low	0	None
0–0.13	Low	6	Bumthang, Gasa, Haa, Paro, Punakha, Tsirang
0.13–0.26	Moderate	4	Dagana, Lhuentse, Samtse, Trashi Yangtse
0.26–0.45	High	5	Pemagatshel, Thimphu, Trashigang, Trongsa, Wangdiphodrang
0.45–1	Very high	5	Chhukha, Mongar, Sarpang, Samdrupjongkhar, Zhemgang

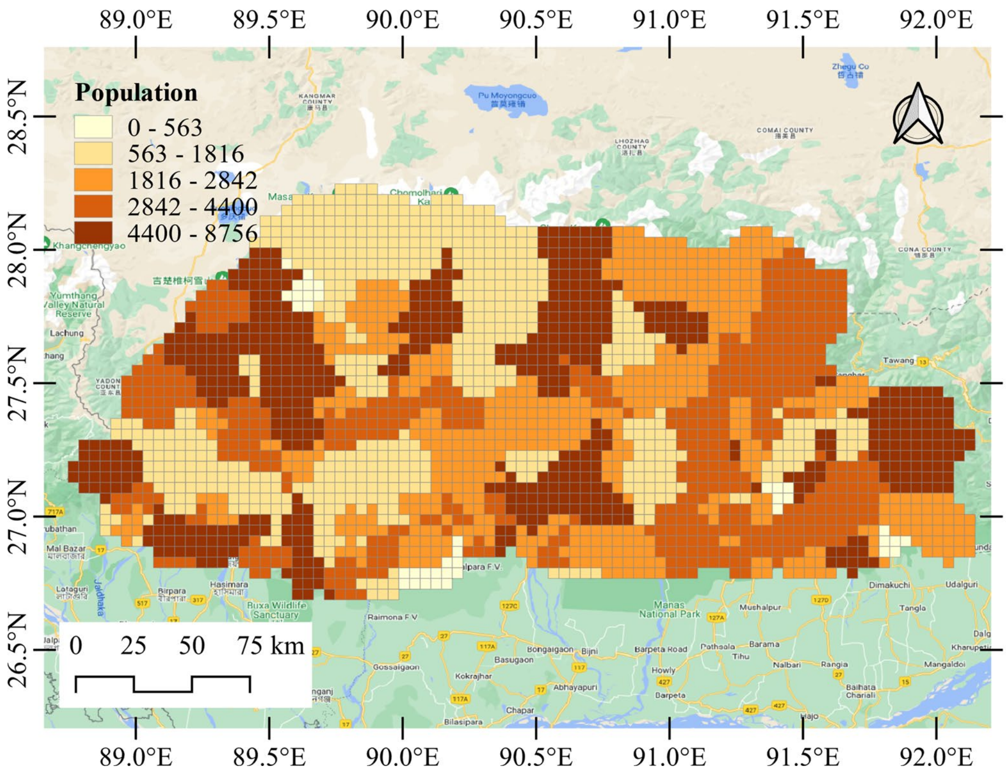

Fig. 9 Local-level population distribution of Bhutan

as shown in Fig. 9. The 2017 country-level census tract, the latest population, and housing census were used in the current study to map the spatial distribution of vulnerability of the Bhutanese population to multi-hazard risks. Estimates of population exposure are important to define the severity of a region's hazard risk from hazard disasters e.g., landslide (Dikshit et al. 2020), flood (Tate et al. 2021), and earthquake (Stevens et al. 2020). Occasionally, several catastrophic events have claimed lives each year and the dangerous scenario is imminent.

To overcome some of the impending multi-hazard risks, the multi-hazard population risk assignment in the local government units is calculated by multiplying the population vulnerability distribution by the multi-hazard exposure rating relative to the district-level boundary. The multi-hazard population risk map is created to demonstrate the multi-hazard risk level as shown in Fig. 10. The risk assessment of the population includes one of the most important goals of the United Nations for sustainable development (SDGs), e.g., sustainable cities and communities, climate action, and life on land (Jatana and Currie 2020). In addition, the existence of residents in different geographical locations is attributed to hunger, good health and well-being, quality education, and socio-economic activities linked to infrastructure and its resilience to climate protection. Most catastrophic events are related to climate change leading to torrential rains and storms causing floods, storms, landslides, and even hailstorms. Hazard risk assessment studies are carried out extensively to improve communities' coping capacities for natural and man-made hazards. The end goal of such studies is to first identify the vulnerable areas and integrate multi-hazard scenarios. This enables planners, developers, and policymakers to implement appropriate mitigation plans and strategies, as well as long-term resource allocations in delivering climate mitigation actions for resilient infrastructure.

Conclusion

In this study, district-wise multi-hazard inventory was created and multi-hazard zoning performed to map population risk with multiple hazards. In Bhutan, there are no systematic hazard and geospatial data are scare. A total of 1224 events consisting of seven hazards were retrieved from various sources through this study. Geodata were created for the landslide (361 locations) and flood hazards (43 locations). Floods, landslides, and earthquakes have caused the most destructive impacts followed by fire hazards and windstorms. Multi-hazard zoning shows that 70% of the 20 districts are vulnerable to moderate to severe multi-hazard. Chhukha, Mongar, Sarpang, and Zhemgang suffer the most

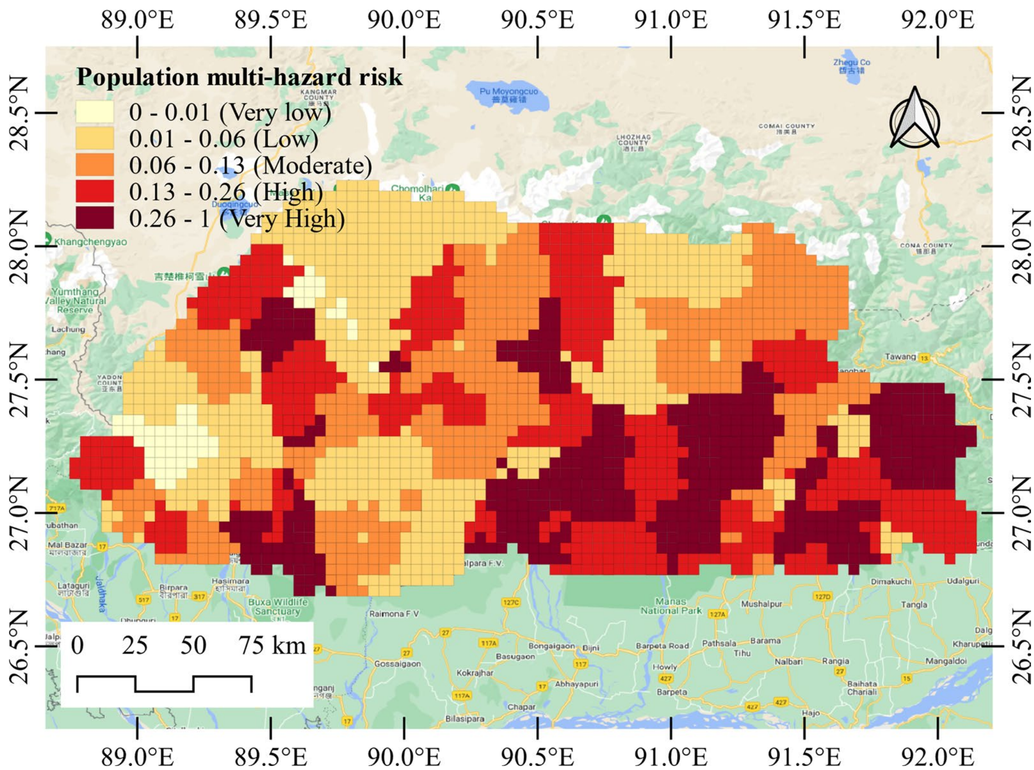

Fig. 10 Population risk map to multi-hazard for Bhutan at the local level

from the effects of multi-hazards. A multi-hazard risk assessment is long overdue in Bhutan. In this study, an attempt was made to map the population risk to the multi-hazard risk, taking into account the distribution of the population in the local government units. Local government units under Chhukha, Mongar, Trashigang, Samdrupjongkhar, and Zhemgang districts report very high population risk for multiple hazards.

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Author contributions
KT contributed to the study's conception and design. KY and KT carried out data collection. Analysis was performed by KT. The first draft of the manuscript was written by KT and all authors edited and commented on previous versions of the manuscript. All authors also read, revised, provided inputs, and approved the final manuscript.

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Availability of data and materials
All data generated or analysed during this study are included in this published article.

Declarations

Competing interests
The authors declare that they have no competing interests.

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