



# Mapping seismic risk in Rangpur Division, Bangladesh: an integrated geospatial approach

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## Abstract

Rangpur Division in Bangladesh lies near the active Dauki Fault, yet few studies have fully assessed its earthquake risk. Most research focuses separately on hazard or vulnerability, often ignoring mitigation and detailed spatial analysis. This study fills that gap by using a geospatial multi-criteria approach that integrates hazard, vulnerability, and mitigation indicators into one risk assessment model. Employing Geographic Information Systems (GIS), Analytic Hierarchy Process (AHP), and Multi-Criteria Decision Analysis (MCDA) in Python, nine hazard criteria, seven vulnerability indicators, and five mitigation factors were modeled as weighted raster layers. These layers were combined to produce high-resolution maps and a seismic risk map with five risk levels from very high to very low. Model validation showed strong predictive ability (AUC=0.857) and consistency (CR<0.1). Results reveal that 21.43% of Rangpur is at very high risk, mainly due to proximity to fault lines and dense population, while only 10.62% shows strong mitigation capacity. This highlights the urgent need for better disaster preparedness, infrastructure improvement, and public awareness. The spatial outputs provide valuable guidance for policymakers on urban planning, risk reduction, and resilience-building in the region.

**Keywords** Earthquake hazards · Multi-Criteria decision analysis (MCDA) · Remote sensing · Seismic risk assessment · Spatial analysis

## 1 Introduction

Seismic hazards represent one of the most significant natural threats globally, often ranking among the top hazards depending on the regional context. Earthquakes are among the most devastating natural phenomena due to their sudden and destructive nature. While seismic shaking is experienced worldwide, certain regions are particularly

vulnerable due to their proximity to tectonic plate boundaries [1, 2]. Earthquakes can also trigger secondary hazards such as landslides, soil liquefaction, and tsunamis [3, 4]. The severity of these hazards is often influenced by geotechnical changes during seismic events [5]. According to the National Earthquake Information Center (NEIC), 12,000 to 14,000 earthquakes are recorded globally each year. The most powerful earthquake ever recorded was the 1960 Great Chilean Earthquake (Mw 9.5). Countries frequently affected by major seismic activity include China, India, Japan, Indonesia, the Philippines, and Iran [6].

Bangladesh ranks as the fifth most disaster-prone country globally [7]. Situated at the convergence of the Indo-Burma tectonic plates, it lies near active faults such as the Shillong Plateau Fault, Chaman Fault, and Main Himalayan Thrust [8, 9]. The 2015 Gorkha earthquake in Nepal (Mw 7.8), which caused nearly 9000 deaths, highlighted the region's seismic vulnerability. Proximity to faults like the Dauki Fault further increases Bangladesh's earthquake risk [2]. Historically, major earthquakes strike the country about once every 100 years [10]. In 2016, a 6.7 magnitude quake in Manipur, India, caused fatalities and structural damage

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in parts of Bangladesh. Rangpur Division is particularly active—experiencing nine earthquakes in 2023, the strongest at Mw 5.3. A Mw 7.0 or greater earthquake is expected every 150 years [11]. Dense population and weak infrastructure further elevate seismic risk [12], with Rangpur—home to 10.9% of the population—potentially facing economic losses of \$150–400 million in a major event.

The geomorphological evolution of Rangpur is closely tied to tectonic processes such as fault-controlled uplift, subsidence, and drainage reorganization. Ghosh and Kundu [13] note that features like channel deflection and fluvial offset often signal active deformation in Himalayan foothill zones. Similar geomorphic patterns likely exist in Rangpur, where tectonics influence sedimentation and terrain gradients. When integrated with seismic data, these indicators enhance the spatial accuracy of risk mapping and support more informed hazard assessments.

Mitigating earthquake impacts is a crucial part of disaster risk management. It requires accurate assessments of seismic risk through data on infrastructure, hazard-prone areas, and factors contributing to vulnerability. Risk assessments enable hazard mapping, exposure evaluation, and resource planning for risk reduction [14]. Ground shaking and structural collapse pose serious threats to lives, infrastructure, and ecosystems. Vulnerability is shaped by exposure factors such as population density and asset concentration [5]. Mitigation capacity includes structural and non-structural measures, such as earthquake-resistant buildings, early warning systems, and emergency shelters [15–17]. Risk maps and spatial data play critical roles in guiding disaster preparedness and decision-making.

In Rangpur Division, several studies have examined seismic hazards and vulnerabilities at the local level, often focusing on socio-economic factors and public perceptions [18, 19]. Reliable risk assessments require selecting appropriate criteria—hazard, exposure, vulnerability, and mitigation capacity—and considering the spatial scale of analysis [15]. The chosen scale, whether municipal or regional, greatly affects result accuracy and applicability. Localized data is essential for identifying risk zones and planning effective mitigation [20]. A major challenge lies in selecting appropriate indicators, as seismic risk depends on the interaction of hazard, exposure, and vulnerability [12]. Evaluating a region's adaptive capacity is also important to understand its readiness for future earthquakes [21]. Despite their relevance, integrated spatial and remote sensing approaches remain limited at the regional scale. This highlights the need for more comprehensive, locally relevant assessments to improve seismic resilience planning.

Various models have been used to assess seismic risk through multi-criteria approaches, such as Analytical Hierarchy Process (AHP), Probabilistic Seismic Hazard

Assessment (PSHA), TOPSIS, and machine learning techniques like Support Vector Machine (SVM) and Random Forest. Tools like the Spatial Multi-Criteria Analysis and Ranking Tool (SMART), map algebra, and neighborhood analysis have also contributed to risk modeling [12, 22, 23]. Remote sensing offers valuable spatial and temporal data for identifying high-risk zones [24, 25]. Incorporating socio-economic and physical variables enhances model accuracy. AHP effectively integrates expert judgment and multi-source data for prioritizing risk factors [5, 15, 26]. In seismic hazard assessment, AHP and MCDM approaches are widely used to evaluate the interplay between vulnerability and exposure.

This study presents a novel geospatial methodology that integrates AHP and MCDA with high-resolution spatial and tectonic datasets to develop a comprehensive seismic risk model for Rangpur Division. The model is distinct in its inclusion of hazard, exposure, mitigation, and geomorphic variables within a unified decision-making structure. Model validation using AUC-ROC analysis supports the robustness of this integrative approach. This study offers an innovative, scalable AHP–MCDA framework that integrates diverse seismic risk indicators, moving beyond site-specific analysis. Its design allows for replication in other data-limited, high-risk regions, underscoring its broader applicability and policy relevance.

## 2 Materials and methods

### 2.1 Overview

This study employs a methodological framework that integrates Geographic Information Systems (GIS), Multi-Criteria Decision Analysis (MCDA), and the Analytic Hierarchy Process (AHP) for seismic risk assessment. The criteria were identified through a review of relevant scientific literature and expert consultation to ensure accuracy and applicability in seismic risk mapping.

### 2.2 Study area

The study area is located in northern Bangladesh, covering approximately 16,320 km<sup>2</sup> between latitudes 25°13'N to 26°38'N and longitudes 88° 54' E to 89° 53' E Fig. 1. Rangpur Division has a population of around 17 million, with approximately 23% living in urban areas and a population density of 1041 people per km<sup>2</sup>. The literacy rate stands at 63%. The majority of the population is Bengali, along with smaller indigenous groups such as the Santal and Oraon [27]. Agriculture is the dominant livelihood, supported by

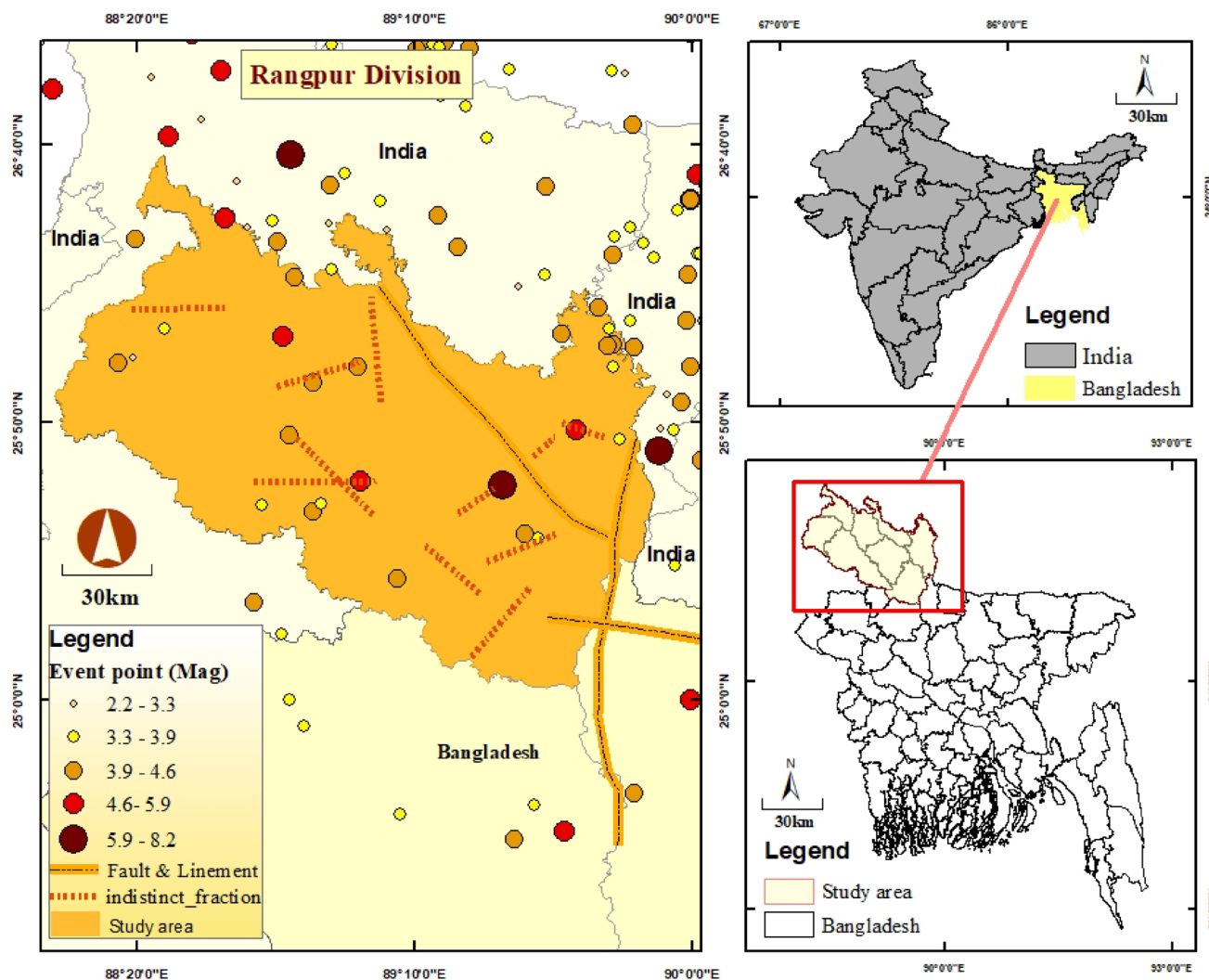


Fig. 1 Study area, Rangpur Division

the region’s fertile plains, followed by trade, services, and non-agricultural labor.

Rangpur has approximately 720,180 households, with 13.9% located in urban areas [27]. Around 30% of the buildings are permanent (pucca), while the remaining 70% are temporary (kaccha), particularly in rural regions where economic constraints limit construction quality. Reinforced pucca buildings demonstrate high resilience over 85% against moderate seismic events, whereas non-reinforced pucca structures show moderate resilience, ranging from 60 to 80%. In contrast, kaccha buildings exhibit low resilience, between 20 and 40%, making them highly vulnerable to seismic and environmental stresses. These statistics highlight the urgent need for improved building codes and safer construction practices in the region [26]. Geologically, Rangpur is located on the northern foreland shelf and is influenced by major structural features such as the Dauki Fault and Disang Thrust. The southern part of the region

includes the Bogra Shelf, while the eastern boundary connects with the Shillong Massif. All these features lie within the Indian tectonic plate. According to the seismic zoning map, Rangpur falls within Seismic Zone 3 ( $Z=0.28$ ), while its eastern parts extend into Zone 4 ( $Z=0.36$ ), indicating a relatively higher seismic risk [28].

### 2.3 Data acquisition and preparation

Figure 2 illustrates the research methodology applied in this study. A significant amount of regional attribute and numerical data was required to conduct a comprehensive seismic risk assessment. The development of hazard, vulnerability, and mitigation maps involved detailed analysis of selected criteria to ensure accuracy and reliability. Indicators were carefully chosen to represent key aspects of the study area. The risk assessment was structured based on these selected factors. A variety of datasets Table 1 were collected from

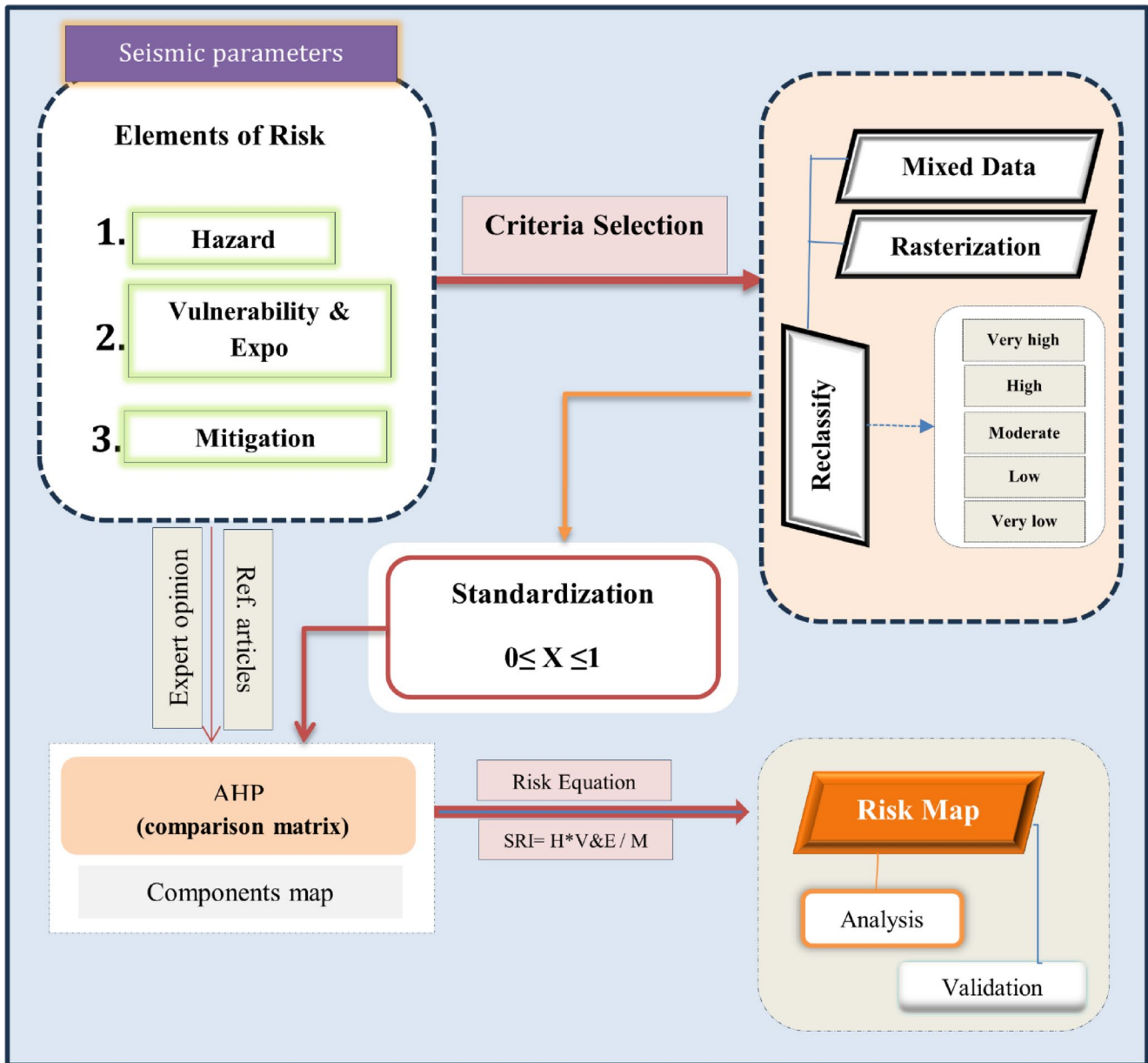


Fig. 2 A comprehensive framework of this risk study

multiple sources, guided by an extensive review of relevant literature and authoritative references [26, 29]. Historical seismic data spanning the last 80 years were obtained from both national and international sources. Some of the criteria layers, such as land use, land cover, and settlement distribution, were dynamic in nature. These layers were updated using Google Earth Engine to enhance the accuracy of the analysis.

Python code was executed on Google Colab to download shapefiles from the United States Geological Survey (USGS), the International Seismological Centre (ISC), and other sources listed in Table 1. For graphical representation, Power BI and Python were used. Technical analyses and

map generation were conducted using ArcGIS 10.8, incorporating spatial data processing and Earth observation technologies. Some raster layer data were categorized using the natural breaks (Jenks) classification technique, which optimally groups values by minimizing variance within classes and maximizing variance between classes—ensuring statistically meaningful classifications in the spatial analysis.

This study utilized 21 criteria layers, each standardized to a spatial resolution of  $10 \times 10$  m. Where applicable, the layers were classified into five classes using the natural breaks method. For some layers, integer distance values were used with a multiple ring buffer approach, based on reference

**Table 1** Dataset and sources of this risk assessment

SI	Dataset	Data types	Source	Layout
1	Events	Vector data	ISC, USGS, BGS	Mag and depth map
2	Faults and others tectonic	Vector data	Reference Article, USGS, GEM	Distance from fault, linement and refraction map
3	Geology	Vector data	FAO, ISRIC, GEE	Lithology and soil map
4	DEM	Raster data	Google earth Pro	Aspect, slope, roughness map
5	PGA	CVS	Peer ground database, world PGA map-2018	PGA zonal map
6	Building data	Vector data	Open building code	Confidence level map
7	Building footprint	Vector data	OSM using GEE	Density of building
8	Population census	Numeric	National population census	Population density map, literacy map
9	Land use	raster	World view-2023, GEE	LULC map
10	Important infrastructure	Vector data	Open street map (OSM)	Distance from infrastructure
11	Economic spot	Raster data	VIIRS night-time lights	Economic hotspot map
12	Fire and civil defence station	Point data	MoDMR, BCDFS-BD	Civil defence map
13	Road network	Vector data	LGED, OSM	Distance from road

articles. The following sections describe the significance of each criterion and the mapping methodologies applied.

## 2.4 Multi-Criteria Decision-Making (MCDM) approach

Multi-Criteria Decision-Making (MCDM) methods are valued for their ability to integrate diverse data types while maintaining a balance between ease of use and the inclusion of comprehensive decision factors [25, 30, 31]. This balance is especially important for effective decision-making in sustainable hazard preparedness and risk reduction, particularly in resource-limited urban areas of developing countries facing high-risk environments [5]. A well-structured risk assessment framework, including a clearly defined risk equation and its components, significantly improves the accuracy of risk evaluations [15]. In this study, based on a comprehensive review of the literature, the Seismic Risk Index (SRI) (Eq. 1) is found to have a positive correlation with hazard, vulnerability, and exposure, and a negative correlation with emergency response and mitigation capacity.

## Seismic risk index

$$= \frac{\text{Hazard} \times \text{Vulnerability and Exposure}}{\text{Mitigation capacity}} \quad (1)$$

The Analytic Hierarchy Process (AHP) and Weighted Overlay (WO) are among the most commonly used multi-criteria decision-making (MCDM) methods in disaster risk assessment [15, 30]. Accordingly, this study employs both AHP and WO techniques to assess seismic risk in the Rangpur Division.

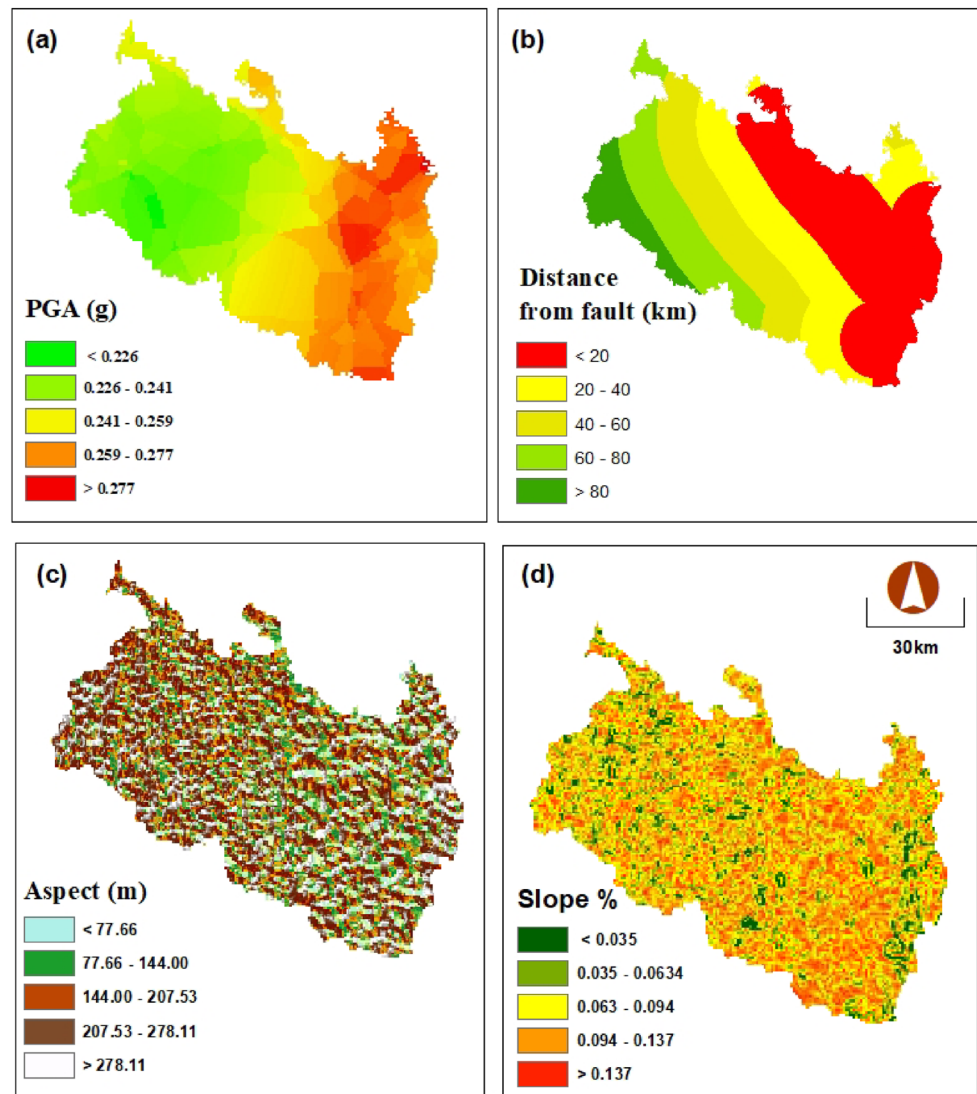
## 2.5 Criteria for seismic hazard mapping

Seismic hazard assessment involves several key indicators, including Peak Ground Acceleration (PGA, proximity to fault lines, seismic intensity, earthquake frequency, lithological composition, and soil classification each contributing to the overall hazard level [12]. In this study, nine criteria were selected to evaluate seismic hazard within the study area. Digital Elevation Model (DEM) data was utilized to derive aspect and slope maps (Fig. 3c and d), which are critical for assessing how topographical features influence seismic impacts. The aspect map helps predict the directional behavior of land movement during seismic events, while the slope map identifies areas susceptible to instability due to steep terrain. These geomorphological parameters provide valuable insights into how the landscape may respond to seismic forces and help pinpoint high-risk zones [3].

Lithology and soil classification play a vital role in determining ground shaking intensity and the risk of liquefaction. Softer soils, such as clay and unconsolidated sediments, tend to amplify seismic waves, whereas harder rock formations help reduce ground motion (Fig. 4g and h). These factors are essential in seismic risk assessment and the development of mitigation strategies [12, 32]. Proximity to fault lines is another critical parameter in seismic hazard modeling, as it helps identify high-risk zones and supports informed decision-making for earthquake preparedness, structural retrofitting, and building code development. Lineaments linear features in the landscape often indicate subsurface faults or fractures and may contribute to increased seismic hazard [33]. Areas located closer to fault lines, as illustrated in (Fig. 3b), are more likely to experience frequent and intense ground shaking. This layer highlights regional vulnerability based on proximity to faults, with nearer areas being at greater risk [23].

Refraction in seismic hazards refers to the bending of seismic waves as they pass through layers of varying density within the Earth's crust. This process can either amplify or diminish ground shaking, depending on the underlying geological structure. Understanding seismic wave refraction

**Fig. 3** Criteria layer for hazard, **a** PGA (g); **b** Distance from fault; **c** Aspect; **d** Slope



(Fig. 4f) is essential for improving hazard assessments, particularly in high-risk areas.

Peak Ground Acceleration (PGA) represents the intensity of ground shaking during an earthquake and is a crucial parameter for assessing seismic risk [20]. The PGA map (Fig. 3a), uses darker red shades to indicate areas with stronger ground motion. PGA is influenced by subsurface conditions and is closely related to refraction lines (Fig. 4h) as different soil and rock types respond differently to seismic waves [34]. Higher PGA values indicate a greater likelihood of damage to buildings and infrastructure during seismic events [35].

Magnitude and depth are critical factors in assessing earthquake risk, as they directly influence the intensity of ground shaking. Historical earthquake magnitudes (Fig. 4e) provide insight into the severity of past seismic events. Depth (Fig. 4e), offer insights into the severity of past seismic events. Event depth (Fig. 4i) is also important, as deeper

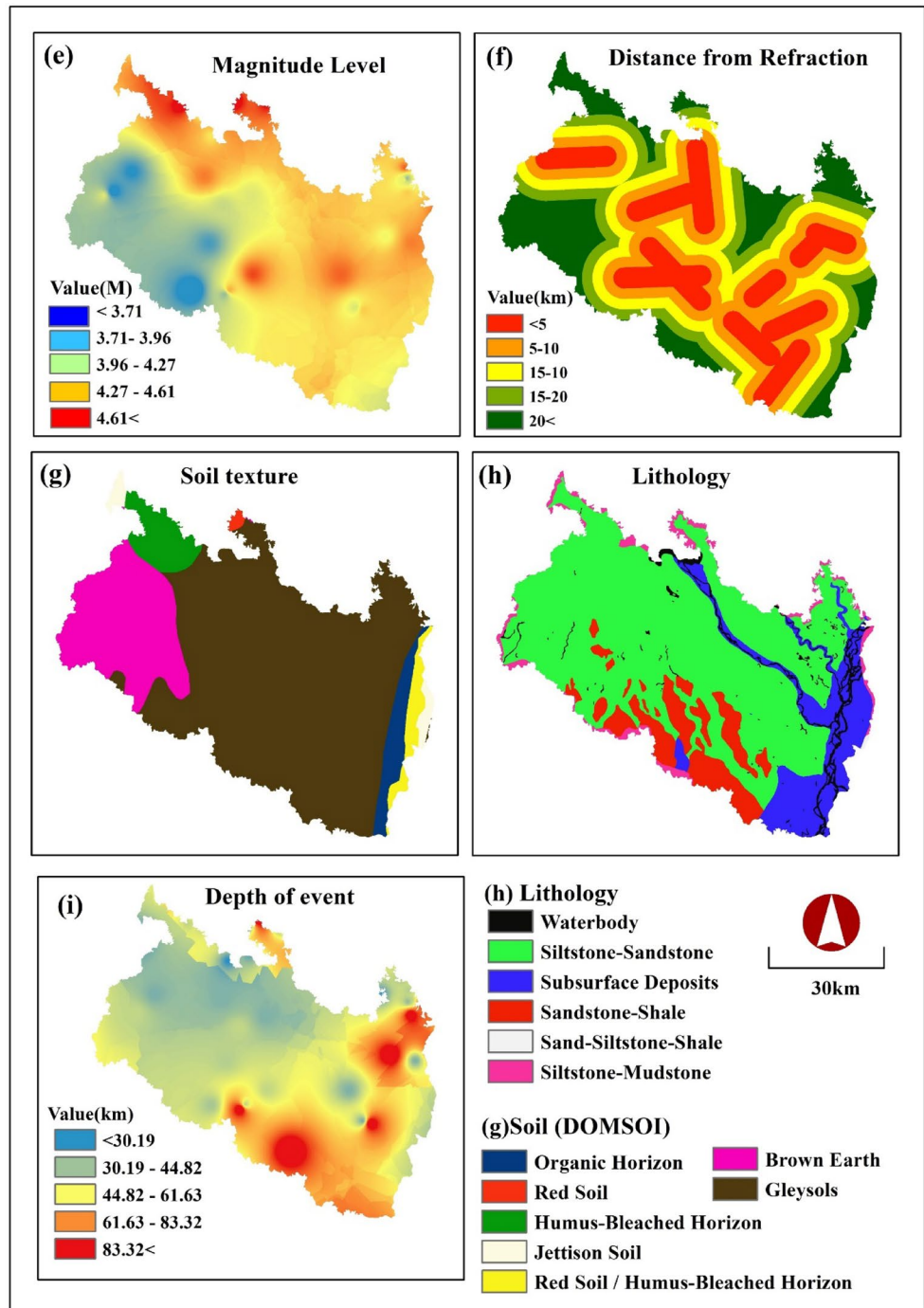
earthquakes typically result in less intense surface shaking compared to shallower ones. In this study, historical data indicate that earthquakes with magnitudes above 4.7 and depths exceeding 83 km warrant particular concern [24].

## 2.6 Criteria for vulnerability and exposure mapping

Vulnerability and exposure are key concepts in assessing earthquake risk, referring to how susceptible individuals, buildings, and infrastructure are to earthquake impacts [36]. Factors such as building density, construction quality, and population density influence this susceptibility. Seven criteria were used to identify vulnerability and exposure, including population density, education rate, building density, building quality, economic zone, land use, and infrastructure.

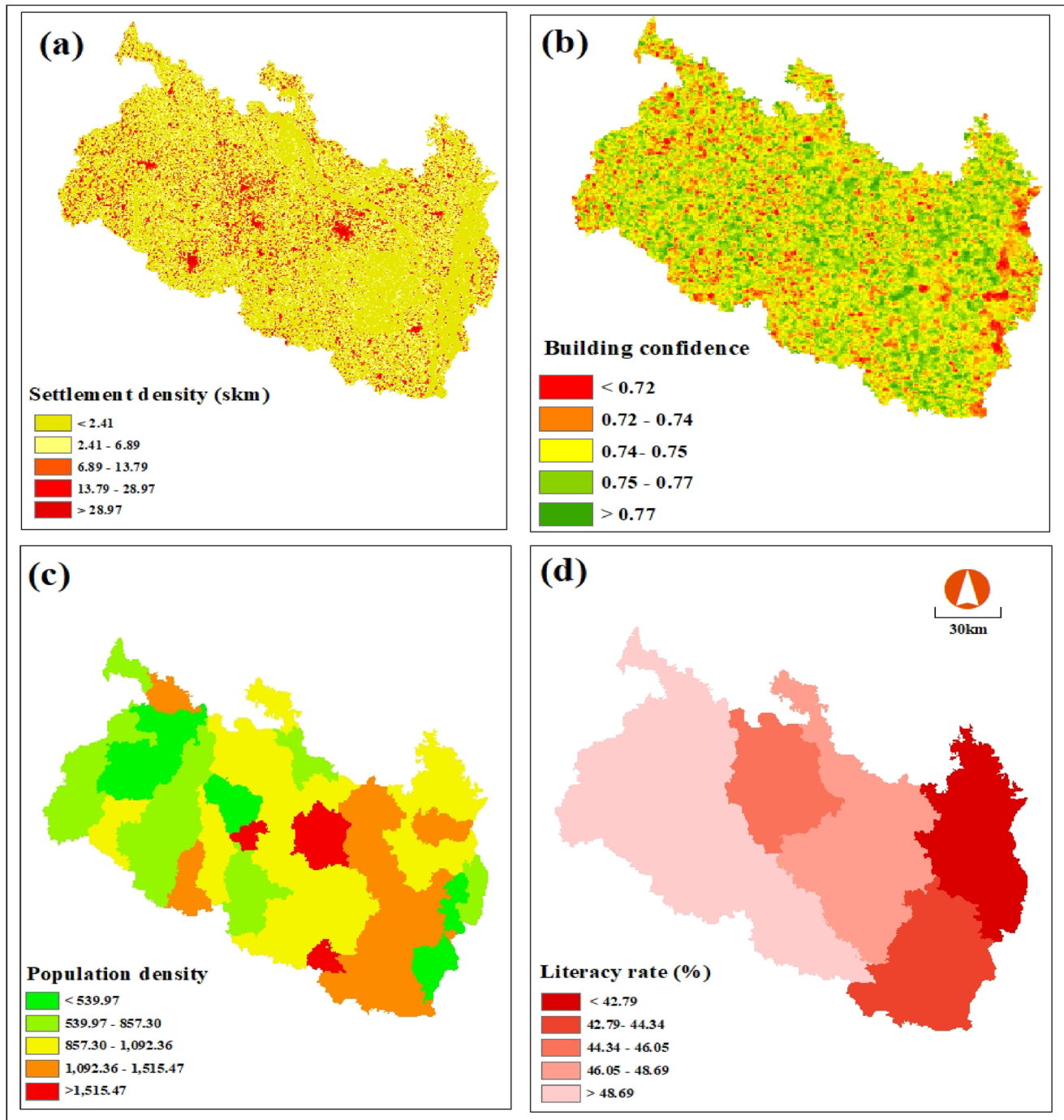
The relationship between settlements and earthquake vulnerability is crucial, as the development and density of a

**Fig. 4** Criteria layer for hazard e Event magnitude; f Refraction; g Soil; h Lithology; i Depth of event



settlement significantly affect its risk. In densely populated urban areas, earthquakes can cause widespread destruction due to the high concentration of buildings, infrastructure, and people. Poorly planned settlements with weak building codes and substandard construction are especially vulnerable [26]. Settlements near fault lines (Fig. 6a) or in earthquake-prone areas face heightened risks. High population density (Fig. 5c) in small areas is particularly susceptible to severe damage. In addition to buildings, infrastructure

such as markets, bridges, power lines, and water supply systems are also at risk. Infrastructure near fault lines can suffer extreme damage, and poorly designed or outdated infrastructure (Fig. 6e) may collapse during an earthquake, triggering secondary hazards such as fires, flooding, and power outages [37]. Building resilience involves both individual preparedness and community-wide efforts. Confidence can be strengthened through education on earthquake risks, safety protocols, and regular drills [26]. Map (Fig. 5b)



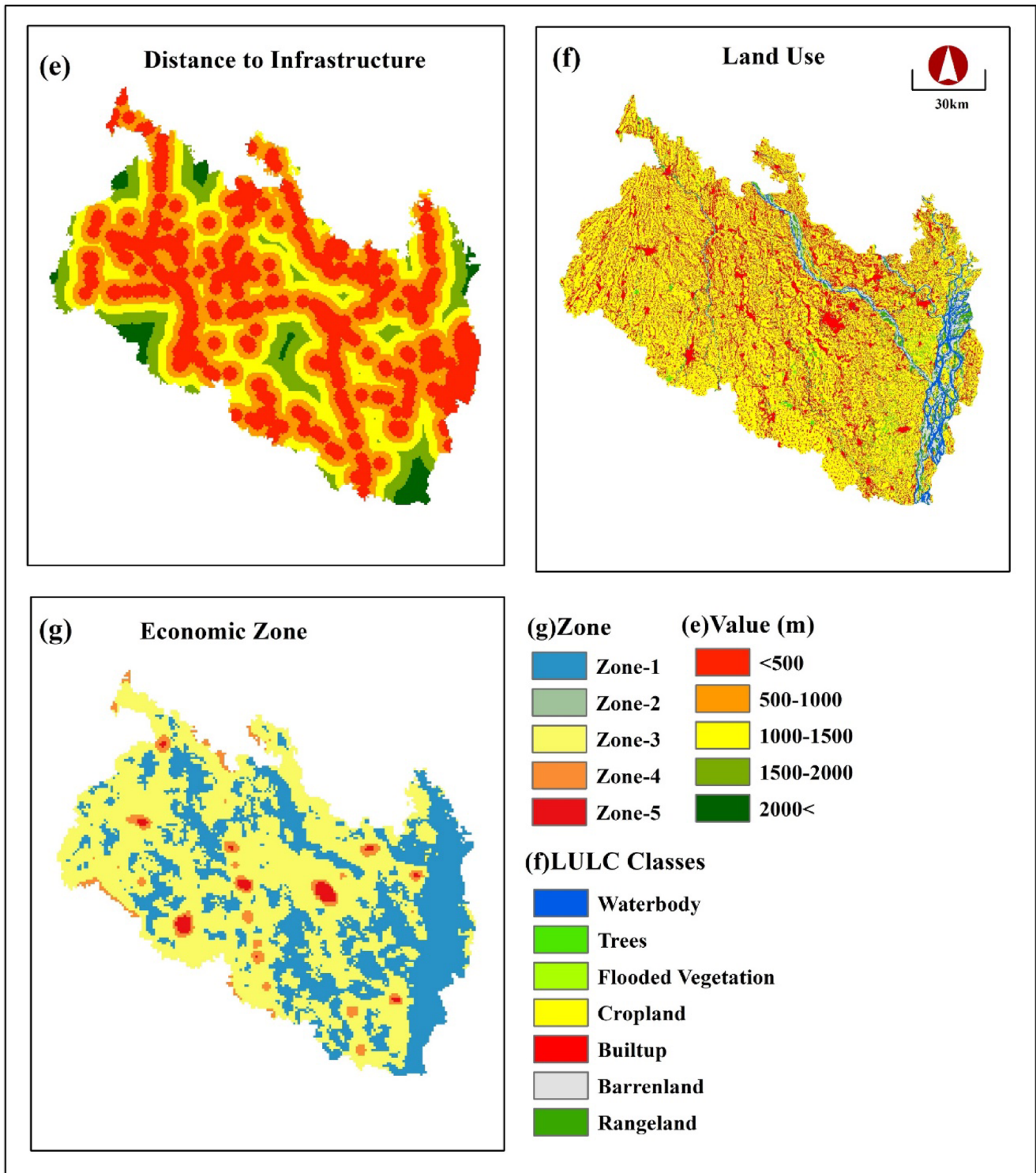
**Fig. 5** Vulnerability and exposure criteria layers. **a** Settlement density; **b** Building confidence; **c** Population density; **d** Literacy rate

shows areas with varying levels of confidence, with values above 0.7 indicating greater resilience to seismic risks.

Population density plays a significant role in determining building density, as higher population levels demand more settlements and infrastructure, which can increase vulnerability to seismic hazards [38]. In densely populated areas, the concentration of people, buildings, and essential infrastructure heightens the risk of damage and casualties

during earthquakes [39]. Rapid urbanization often leads to overcrowded housing and poorly constructed buildings, further amplifying vulnerability. Population density (Fig. 5c) is measured in persons per square kilometer and classified into five categories.

The literacy rate (Fig. 6d) plays a crucial role in a population's ability to respond effectively to earthquakes. Higher literacy levels are associated with better understanding of



**Fig. 6** Vulnerability and exposure criteria layers. e Infrastructure proximity; f LULC; g Economic zones

earthquake risks and preparedness measures. Literate individuals are more likely to engage with disaster awareness programs, adopt earthquake-resistant construction practices, and follow safety guidelines. In contrast, low literacy can hinder access to vital information, increasing vulnerability.

Therefore, improving literacy is essential for enhancing earthquake preparedness and community resilience.

Land Use and Land Cover (LULC) data (Fig. 6f) provides valuable insights into how land is utilized, which directly influences the extent of damage during seismic events.

**Table 2** Land use and land cover feature classes

Land use/land cover type	Description
Water	Rivers, lakes, canals, ponds, and permanent open water bodies
Trees	Forest areas including deciduous and ever-green trees, plantations, and homestead forests
Flooded vegetation	Wetlands, swamps, and areas where vegetation is seasonally or permanently submerged
Crop Land	Agricultural areas, crop fields, vegetable lands, and orchards
Built-up	Urban and rural settlements, roads, buildings, bridges, and other man-made structures
Bare land	Exposed soil, fallow land, sand dunes, and areas with little or no vegetation cover
Range land	Grasslands, pasturelands, and areas primarily used for grazing

Effective land management, guided by LULC analysis, can play a crucial role in reducing earthquake-related risks. The 2023 LULC dataset, which categorizes various land cover types (Table 2), is instrumental in assessing regional vulnerability. Built-up areas are particularly at risk due to high population density and the presence of poorly constructed infrastructure, which is more likely to collapse during an earthquake. In contrast, water bodies and flooded vegetation may be susceptible to secondary hazards such as liquefaction and landslides [40]. Tree-covered areas and rangelands are generally less affected directly, though they may experience shifts in terrain stability (Table 2).

Economic zones are particularly vulnerable to earthquakes due to the concentration of industries, infrastructure, and investments. These areas typically include factories, warehouses, and commercial hubs that play a vital role in the national economy. Any disruption caused by seismic activity can result in substantial financial losses [36]. Damage to critical infrastructure such as transportation networks and utility services can halt production, disrupt supply chains, and affect employment. The combined cost of repairs, reconstruction, and business interruptions can place a heavy burden on both local and national economies [7]. In earthquake-prone regions (Fig. 6g) it is essential to enforce strict building codes, adopt earthquake-resistant designs, and develop comprehensive disaster management plans. Strengthening infrastructure and ensuring business continuity are key strategies to reduce economic impacts and enable faster recovery [41].

## 2.7 Criteria for seismic mitigation capacity mapping

Mitigation capacity plays a vital role in natural hazard studies, reflecting the ability of communities, governments, and organizations to reduce the impact of disasters through proactive planning and preparedness [12, 15]. Assessing this

**Fig. 7** Mitigation capacity criteria layers. **a** Distance from road; **b** Hospital proximity; **c** Distance from terminal; **d** Distance from playground and park; **e** Civil defense and fire station proximity

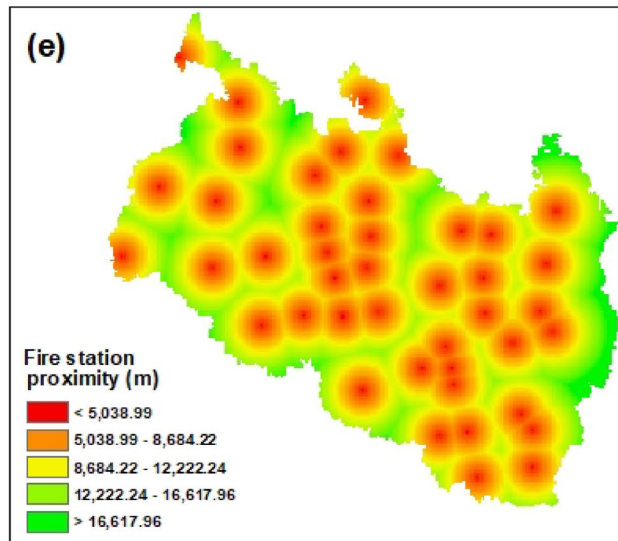
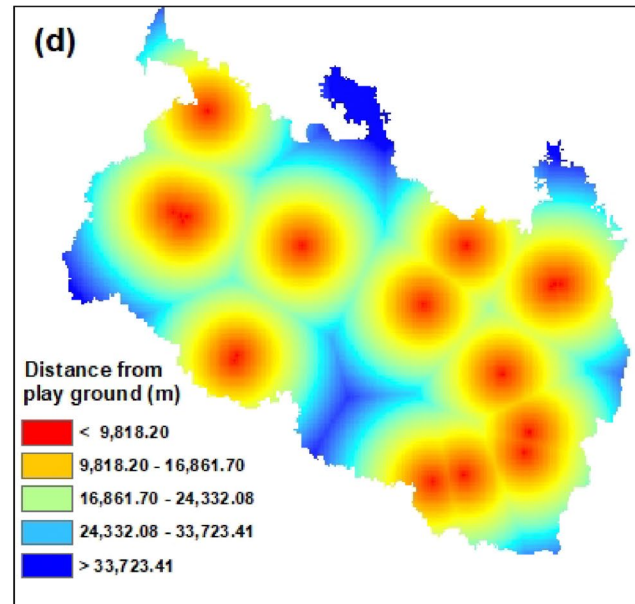
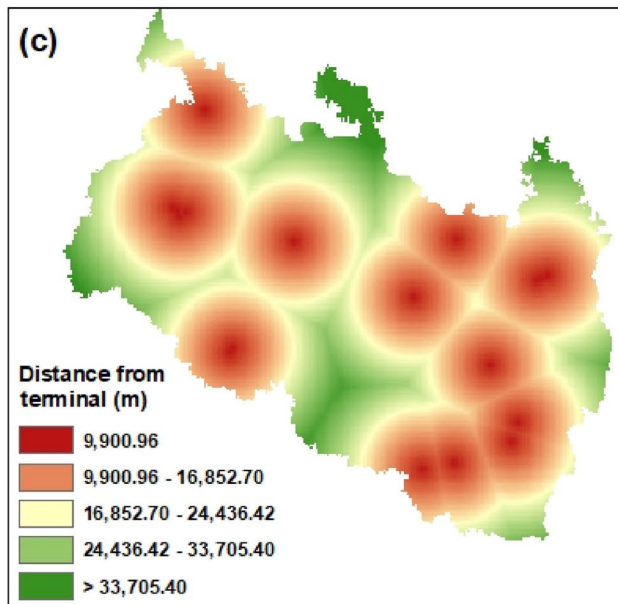
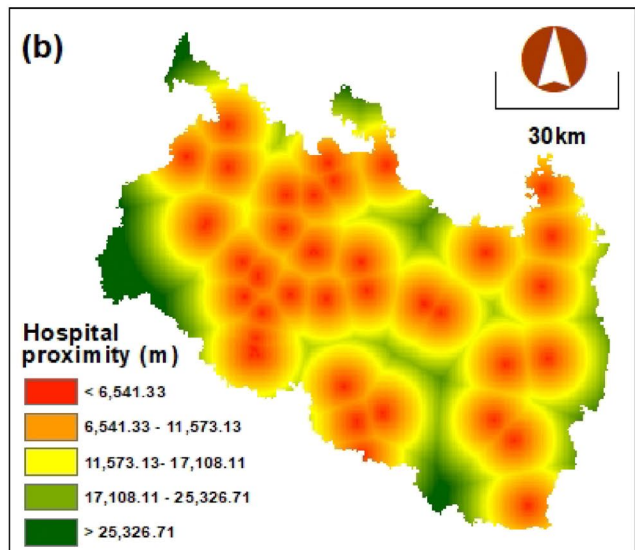
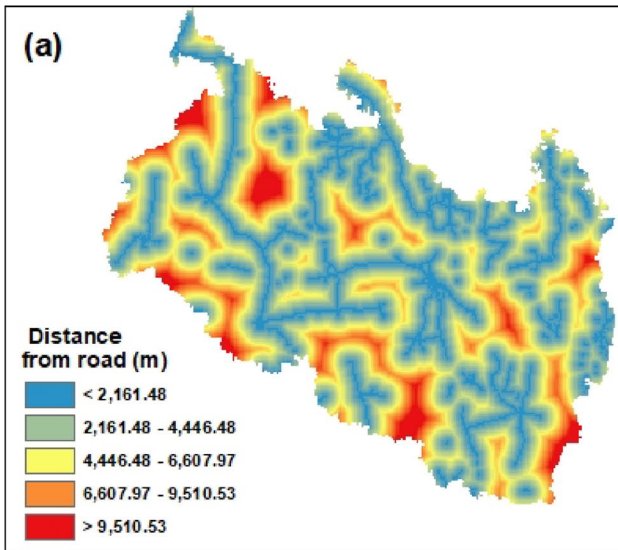
capacity helps identify vulnerabilities in infrastructure, population distribution, and emergency response systems, enabling targeted strategies to minimize potential damage and loss of life. Key mitigation measures such as enforcing building codes, enhancing early warning systems, and promoting public awareness significantly improve resilience to earthquakes. Strengthening mitigation capacity also ensures more efficient resource allocation, particularly in high-risk areas, and supports long-term recovery and sustainable development [38].

This assessment incorporates five mitigation factors to demonstrate strategies for reducing losses and saving lives during earthquakes. Research highlights the importance of proximity to hospitals, roads, civil defense and fire stations, transport terminals, and open spaces such as playgrounds in earthquake risk mitigation. Among these, distance from roads (Fig. 7a) is particularly critical, as it affects emergency access for rescue and evacuation operations. Following an earthquake, roads serve as vital routes for delivering aid and medical supplies to affected areas [7]. Buildings and infrastructure located far from major roads may face delays in evacuation and emergency response, increasing the risk of casualties and damage. Conversely, areas near roads benefit from preparedness measures such as marked evacuation routes and designated shelter points [12]. Effective urban planning that ensures accessible road networks enhances emergency response and supports disaster resilience [31].

Proximity to hospitals (Fig. 7b) plays a critical role in earthquake mitigation, as it directly affects access to emergency medical care. Timely treatment is essential for reducing injuries and fatalities during seismic events. Areas located far from healthcare facilities may experience delays in medical response, leading to higher morbidity and mortality rates. Enhancing transportation infrastructure and establishing temporary medical units can significantly improve emergency response during such disasters [23].

The distance from civil defense and fire stations (Fig. 7e) is a critical factor, as it directly affects the speed and effectiveness of emergency response. These facilities are essential for rescue operations and disaster management. Areas located farther from such services are likely to face delays in assistance, increasing the risk of casualties. Therefore, urban planning should prioritize establishing fire and civil defense stations near densely populated and high-risk zones.

Proximity to transportation terminals (Fig. 7c) such as airports and bus stations, and open spaces like playgrounds (Fig. 7d), also plays a vital role in disaster preparedness. Terminals enable the swift movement of people and resources, improving evacuation efficiency. Similarly, playgrounds



can serve as safe gathering points and temporary shelters following an earthquake. When these facilities are located too far from residential areas, the safety and coordination of response efforts may be compromised [12]. Incorporating terminals and open spaces into disaster preparedness planning enhances community resilience and supports rapid, organized emergency response.

### 2.8 Alternative ranking and standardization criteria layer

Each spatial criterion was classified into five risk levels, where rank 1 indicates very high risk and rank 5 indicates very low risk (Table 3). Each spatial criterion was categorized into five risk levels reflecting its contribution to seismic risk, using a combination of spatial analysis, expert knowledge, literature review, and Jenks natural breaks statistical classification.

To facilitate raster-based weighted sum analysis, all map layers were converted into 10-meter resolution raster format.

The alternatives were then ranked based on their risk contribution using the Analytic Hierarchy Process (AHP).

The spatial criteria raster layers were standardized to a common scale of 0 to 1 using a linear scaling transformation (Eq. 2). This method ensured that all criteria were expressed in consistent units, enabling effective multi-criteria decision-making.

$$Z = \frac{(n - \min)}{(max - \min)} \tag{2}$$

Where Z represents the standardized score, n denotes the value of the individual raster cell, and min and max refer to the minimum and maximum values of the respective dataset. Each spatial criterion was classified into five risk levels based on its contribution to seismic risk, using a combination of spatial analysis, expert knowledge, literature, and statistical classification (Jenks). The standardized layers ensured consistent inputs for AHP-based multi-criteria analysis. The classification thresholds and value ranges

**Table 3** The alternatives are ranked based on their contribution to seismic risk

Components	Criteria layers	Risk ranking				
		Very low	Low	Moderate	High	Very high
Hazard	Distance from fault line (km)	<20	20–40	40–60	60–80	>80
	PGA (g)	<0.226	0.221–0.241	0.241–0.259	0.259–0.277	>0.277
	Event magnitude (M)	<3.71	3.71–3.96	3.96–4.27	4.27–4.61	>4.61
	Aspect (m)	<77.66	77.66–144.00	144.00–207.53	207.53–278.11	>278.11
	Slope (%)	<0.035	0.035–0.063	0.063–0.094	0.094–0.137	>0.137
	Lithology	Siltstone-mudstone/water body	Subsurface deposits	Sandstone-shale	Siltstone-sandstone	Sand-siltstone-shale
	Soil (DOMSOIL)	Gleysols/regosol soil	Brown earth	Jettison soil	Red soil/humus-bleached horizon	Organic horizon
	Refraction (km)	<5	5–10	10–15	15–20	>20
	Event depth (km)	>83.32	61.63–83.32	44.83–61.63	30.19–44.83	<30.19
	Vulnerability And Exposure	Settlement density (skm)	<2.41	2.41–6.89	6.89–13.79	13.79–28.97
Building confidence		>0.77	0.77–0.75	0.75–0.74	0.74–0.72	<0.72
Population density (skm)		<539.97	539.97–857.30	857.30–1092.36	1092.36–1515.47	>1515.47
Literacy rate (%)		>48.69	48.69–46.05	46.05–44.34	44.34–42.79	<42.79
Distance from infrastructure(m)		>2000	2000–1500	1500–1000	1000–500	<500
Economic zone		Zone-1	Zone-2	Zone-3	Zone-4	Zone-5
Land use and land cover		Water	Trees	Crops/ Rangeland	Barrenland/ Flooded Vegetation	Built Area
Mitigation Capacity		Distance from fire station and civil service(m)	>16617.96	16617.96–12222.24	12222.24–8684.22	8684.22–5038.99
	Distance from hospital (m)	>25316.71	25316.71–17108.11	17108.11–11573.13	11573.13–6541.33	<6541.33
	Distance from road network (m)	>9510.54	9510.54–6607.97	6607.97–4446.48	4446.48–2161.48	<2161.48
	Distance from terminal (m)	>33705.11	33705.11–24436.42	24236.42–16852.77	16852.77–9900.96	<9900.96
	Distance from play ground (m)	>33723.41	33723.41–24332.08	24332.08–16161.70	16161.70–98018.21	<98018.21

**Table 4** Degree of relative significance adapted from [42]

Relative importance	Description
1	Two elements impact equally toward the purpose.
3	Skillset and judgment moderately favor one aspect prioritized over another.
5	Skillset and judgment robustly favor one aspect prioritized over another.
7	One decision factor is heavily prioritized over another, with its dominance clearly demonstrated in practice.
9	The evidence supporting one decision factor over another is of the utmost level of validity.
2, 4, 6, 8	Values that lie between two neighboring judgments, used to reach a compromise when necessary. .

**Table 5** Contribution of criteria factors

Components	Factors	Weight
Hazard Consistency ratio (CR): 0.079	Distance from fault line	0.27
	PGA	0.2
	Event magnitude	0.23
	Aspect	0.1
	Slope	0.05
	Lithology	0.05
	Soil	0.05
	Refraction	0.025
Vulnerability and exposure Consistency ratio (CR): 0.052	Event depth	0.025
	Settlement density	0.3
	Building confidence	0.2
	Population density	0.25
	Literacy rate	0.1
	Distance from infrastructure	0.05
	Land use & land cover	0.05
Mitigation Consistency ratio (CR): 0.060	Economic zone	0.05
	Proximity to fire station	0.23
	Proximity to hospital	0.21
	Distance from road network	0.26
	Distance from terminal	0.16
	Distance from playground	0.14

presented in Table 3 are justified based on the explanations provided for each criterion in the Method section.

### 2.9 Weighting the criteria using AHP

AHP is an effective method for assessing seismic risk [26]. In this study, the AHP method was used to assign weights to the factors of vulnerability, exposure, hazard, and mitigation capacity within the risk assessment framework. The process of evaluating earthquake vulnerability using the AHP model involves first establishing a hierarchy of factors and then creating a reciprocal matrix through pairwise comparisons, based on nine-point scale (Table 4) [42].

Next, the eigenvector and eigenvalue are calculated to determine the factor weights. The consistency of the

judgments is tested using specific equations (Eq. 3) and (Eq. 4). For consistency, the ratio must be below 0.1; otherwise, the process must be repeated. The consistency index and ratio are calculated using formulas provided by Saaty [42].

$$CR = \frac{CI}{RI} \tag{3}$$

$$CI = \frac{(\lambda_{max} - n)}{(n - 1)} \tag{4}$$

In this context, the Random Index (RI) represents the average consistency index generated randomly, while the Consistency Index (CI) is calculated using the formula below. Here,  $\lambda_{max}$  is the highest eigenvalue of the matrix, and  $n$  is the matrix size. The weights assigned to the criteria are derived from paired comparison matrices. The consistency of these comparisons is assessed through a literature review and user input, based on a scale reflecting their relative importance (Table 5).

The Consistency Ratio (CR) values for hazard (0.079), vulnerability and exposure (0.052), and mitigation (0.060) indicate acceptable consistency in the decision-making process. A CR below 0.1 is considered acceptable in AHP, meaning the comparisons between criteria were sufficiently consistent to yield meaningful results [42].

### 2.10 Risk mapping

The final seismic risk index was calculated by integrating hazard, vulnerability, and mitigation layers using a weighted overlay technique. Spatial layers for each risk component were classified into five categories: very low, low, moderate, high, and very high. The risk index was computed by combining hazard, vulnerability, and exposure indices, adjusted for mitigation capacity using Eq. 1 in the raster calculator. These indices were standardized to a 0–1 scale (Eq. 2) and classified into five risk levels. The final risk map highlights areas based on relative seismic risk. Accuracy analysis confirmed the model’s effectiveness in identifying high-risk zones, demonstrating its reliability for seismic risk assessments.

### 2.11 Risk model validation

The validation process for the Rangpur Division seismic risk assessment involved several methods to ensure the model’s accuracy and reliability. The Receiver Operating Characteristic (ROC) curve was used to assess the model’s predictive power, comparing the True Positive Rate to the False Positive Rate. Additionally, the Consistency Ratio (CR) was calculated for all models (Table 5) with values ranging

from 0.01, indicating that the AHP process achieved the desired consistency in judgments. Sensitivity analyses were conducted to examine the influence of input variables on the output, enhancing the model's robustness. Stakeholder reviews were also incorporated to ensure the local context was considered. Overall, this validation process outlines the approach for seismic risk assessments and provides guidance for future evaluations, ensuring more effective disaster response and resource allocation in Bangladesh.

### 3 Result and discussion

#### 3.1 Hazard mapping

Seismic hazard is a crucial component of earthquake risk analysis. In this study, a spatial analysis tool, the weighted sum, is used to create a seismic hazard map. The analysis incorporates nine criteria, with each layer normalized on a scale from 0 to 1. The contributions of these factors are determined based on a thorough review of the relevant literature. The study area is located in the northern region of Bangladesh, near the Meghalaya and Shillong shelf fault lines. Other geological features, such as refraction and lineaments, are also considered significant in the assessment. The seismic hazard classification for earthquake risk analysis follows a five-step process (Fig. 8).

Our analysis categorized the study area into five hazard classes, ranging from moderate to very low risk. A significant portion of the area, however, falls within the high to very high hazard zones. The eastern region, near lineaments and the Dauki Fault, is classified as an extreme hazard zone due to its history of tremors. The high hazard zone covers 18.78%, slightly higher than the 18.16% in the very low hazard zone. Approximately 22.09% and 21.26% of the area were identified as moderate and low hazard zones, respectively. Combined, the high and very high hazard zones make up 36.49% of the study area. High and very high values represent the most hazard-prone areas, indicating that the criteria in this assessment strongly influence seismic event occurrence.

#### 3.2 Vulnerability and exposure mapping

A vulnerability and exposure map for Rangpur Division was developed using the overlay sum method, incorporating socio-economic and physical factors. The criteria considered include literacy rate, population density, building density, building quality, economic zones, land use and land cover (LULC), and proximity to infrastructure. These factors were chosen for their impact on community resilience and exposure to seismic hazards.

The map categorizes the region into five vulnerability zones: very high, high, moderate, low, and very low. The results indicate that 14.14% of the area is classified as very high vulnerability, characterized by dense population, low literacy, poor building quality, and proximity to critical infrastructure. About 21.46% of the region falls into the high vulnerability category, while 25.29% is classified as moderate. In contrast, 23.07% is categorized as low vulnerability, and 16.04% is identified as very low vulnerability, where stronger building codes, better literacy rates, and lower population density reduce seismic risk (Fig. 9).

There is a strong correlation between seismic risk and community vulnerability. Regions with poor construction practices, high population density, and limited access to education and resources are more likely to suffer severe impacts during earthquakes. For instance, areas with low building resilience or dense populations often experience greater casualties and infrastructure damage. The location of critical infrastructure such as hospitals, roads, and economic centers also plays a key role in determining a community's ability to respond to and recover from seismic events. These factors highlight the urgent need for targeted disaster preparedness and mitigation strategies, especially in zones identified as having high or very high vulnerability, such as Rangpur Division.

#### 3.3 Mitigation mapping

In this study, a mitigation map for Rangpur Division was created by incorporating critical factors such as proximity to roads, hospitals, fire stations, terminals, and playgrounds. These factors were combined using the overlay sum method to assess preparedness for seismic hazards. The resulting map (Fig. 10) categorizes the region into five levels of mitigation capacity.

The findings show that 10.62% of the area falls under the very high mitigation category, indicating good infrastructure and services, including road connectivity, emergency response centers, and public spaces for evacuation. Another 20.61% of the area is classified as high mitigation, while 24.92% is rated as moderate, with some infrastructure improvements needed. However, 28.39% of the area falls under low mitigation, and 15.46% is classified as very low, where limited access to essential services increases vulnerability to seismic risks.

The relationship between vulnerability and seismicity is closely tied to mitigation capacity. Areas with low mitigation capacity are more vulnerable to seismic hazards due to limited access to emergency services, transportation, and safe zones. In contrast, regions with higher mitigation capacity are better equipped to manage and recover from seismic events, thanks to stronger infrastructure and

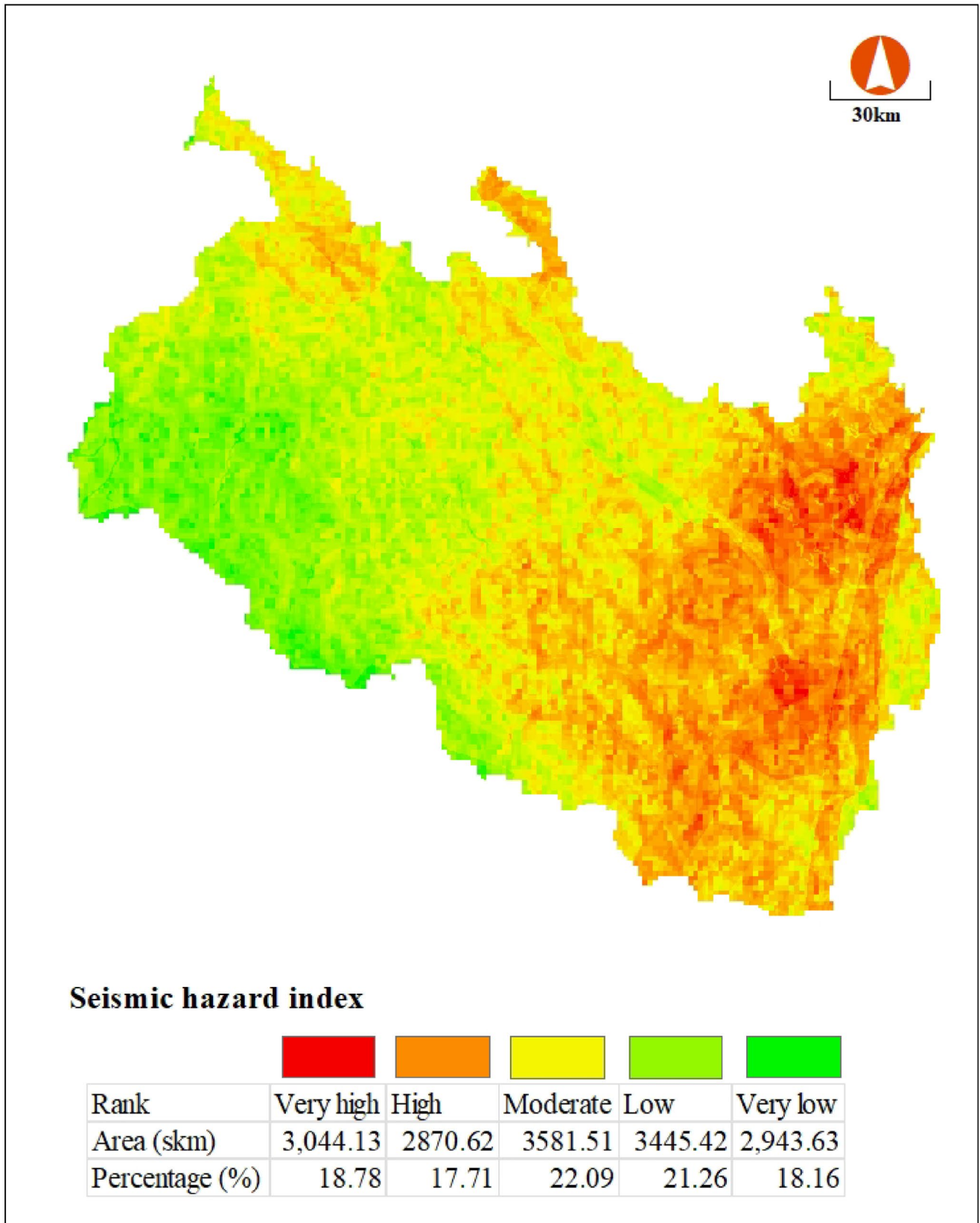
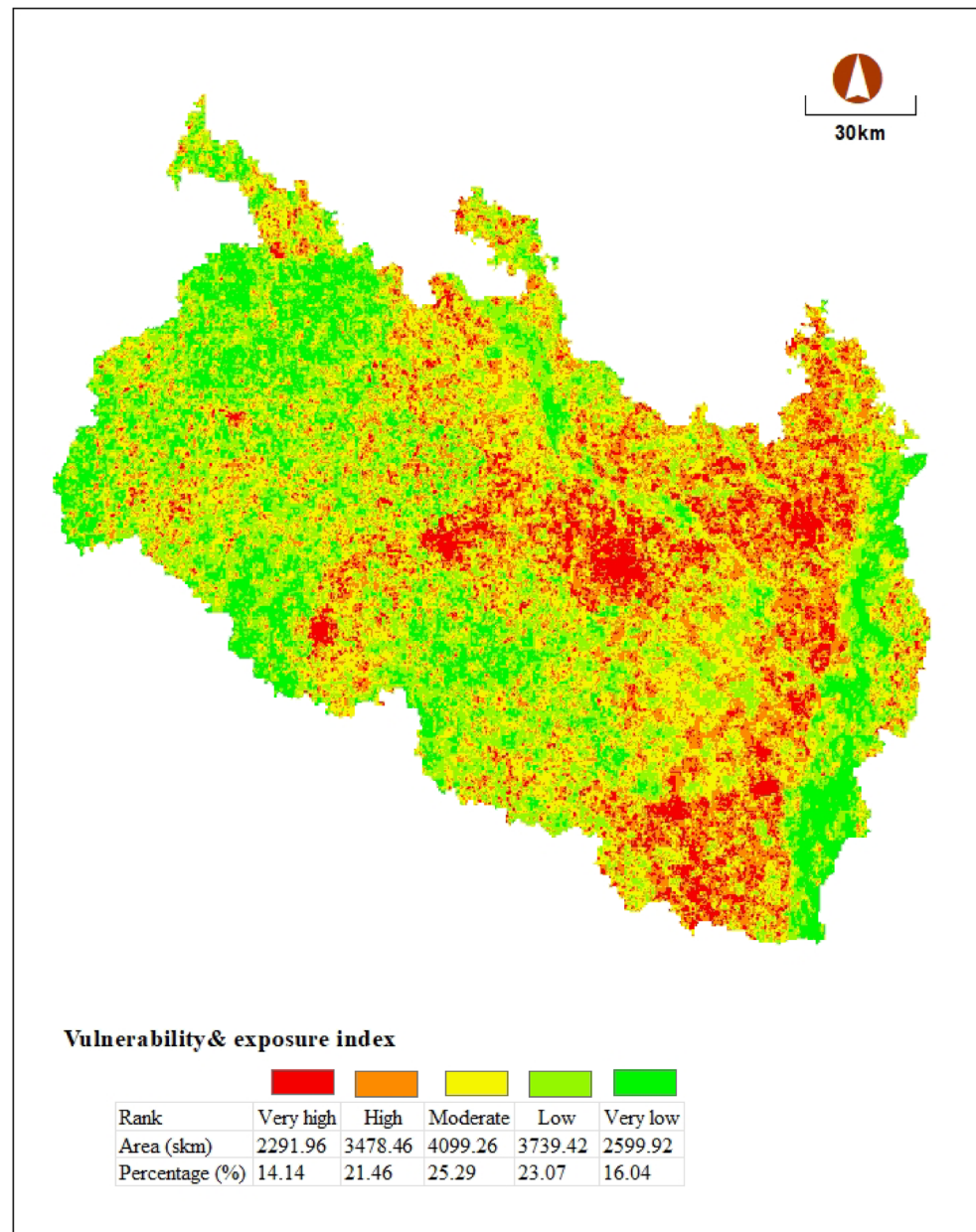


Fig. 8 Hazard map illustrating the spatial distribution and intensity of seismic risk

**Fig. 9** Map of vulnerability and exposure illustrating the spatial distribution and intensity of seismic risk



emergency services [1]. This study emphasizes the need to improve access to critical facilities and infrastructure in high-risk areas. Strengthening these mitigation factors can reduce community vulnerability and enhance resilience to future earthquakes.

### 3.4 Risk mapping

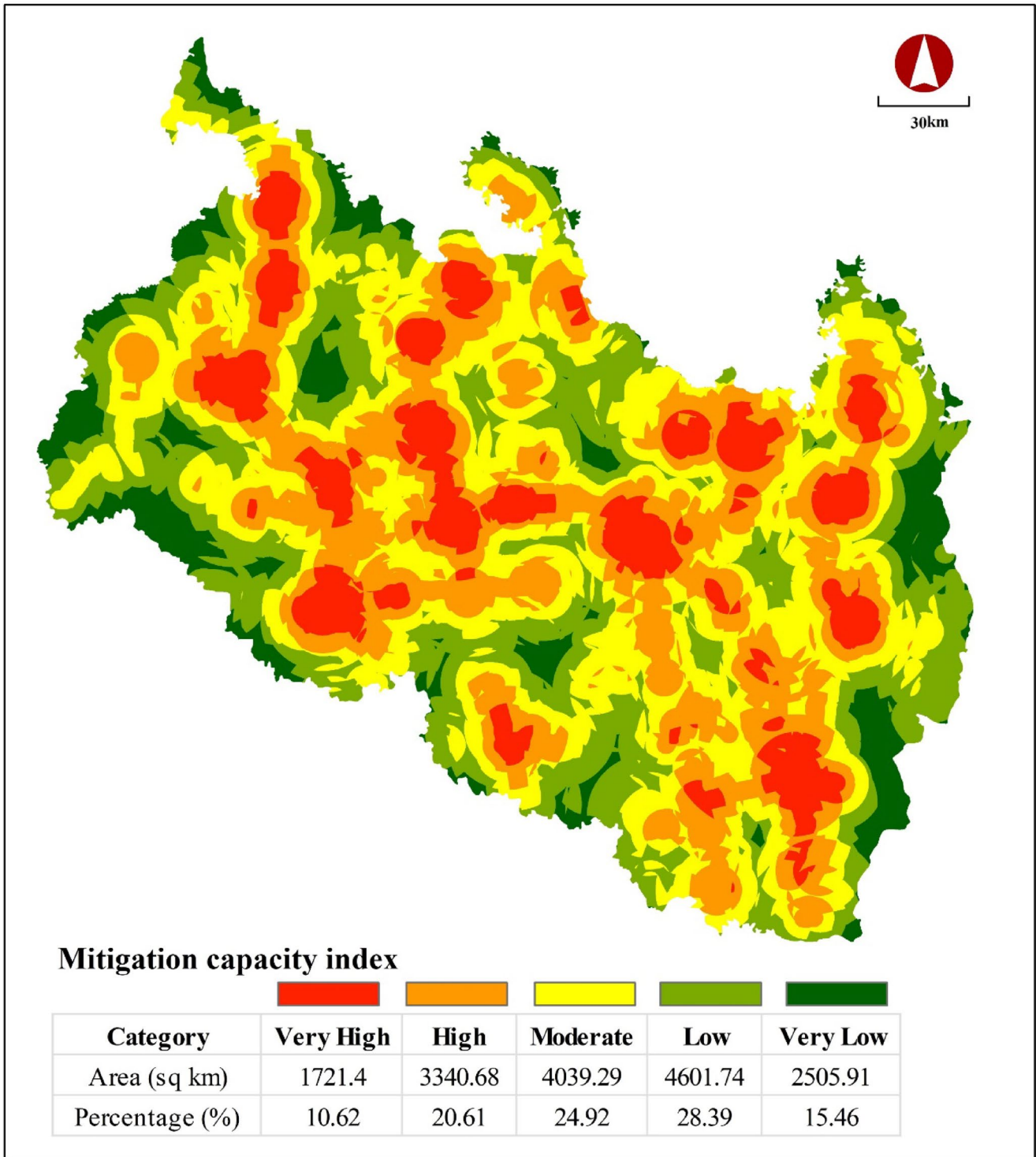
This study presents a seismic risk map (Fig. 11) assessing the vulnerability of Rangpur Division to earthquakes. The assessment categorizes the region into five risk levels using a risk equation that incorporates three key factors.

The very high and high-risk categories identify areas with extreme vulnerability due to factors such as high population

density, proximity to fault lines, and poor building structures. This category covers 47.51% of the total area, highlighting regions most likely to suffer severe consequences in the event of an earthquake. These areas are prioritized for risk mitigation efforts to improve resilience.

Another quarter of the region falls within the high-risk classification. While less vulnerable than very high-risk areas, these regions still face significant threats due to their geographic and structural characteristics. This classification highlights the need for strategic planning to reduce exposure to seismic hazards.

The moderate-risk zone covers 22.53% of the land, comprising areas that are relatively better prepared but still require interventions to strengthen resilience against



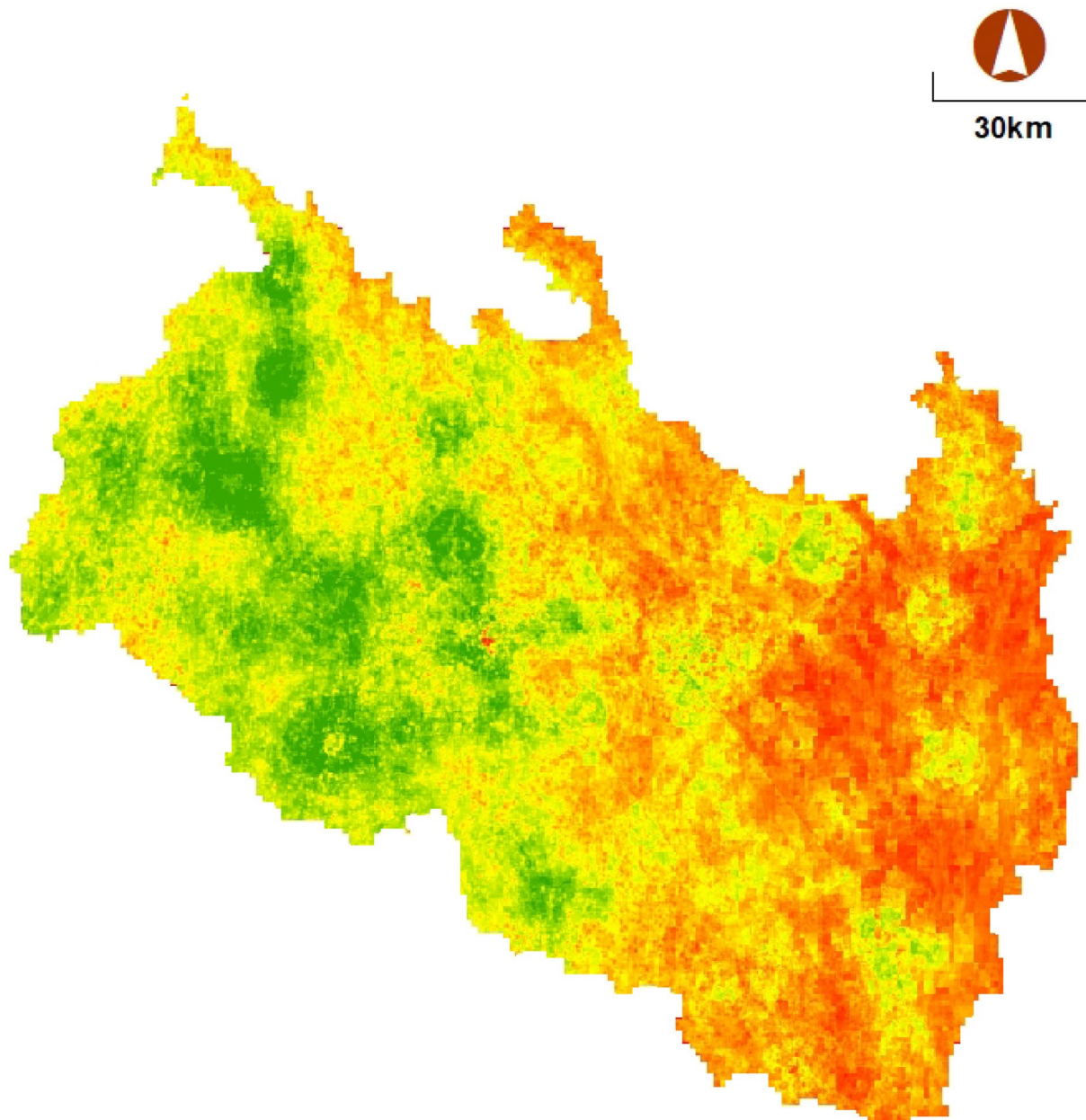
**Fig. 10** Mitigation capacity map illustrates the spatial distribution and degree of mitigation capacity in response to persistent seismic risk threats

potential seismic events. This highlights the need for ongoing assessments and resource allocation to maintain preparedness.

The remaining 29.96% is classified as low and very low risk, with factors such as lower population density, stronger

infrastructure, and greater distances from fault lines contributing to reduced vulnerability.

This analysis underscores the need for targeted disaster preparedness and response strategies, particularly in high-risk areas. By focusing resources on the most vulnerable

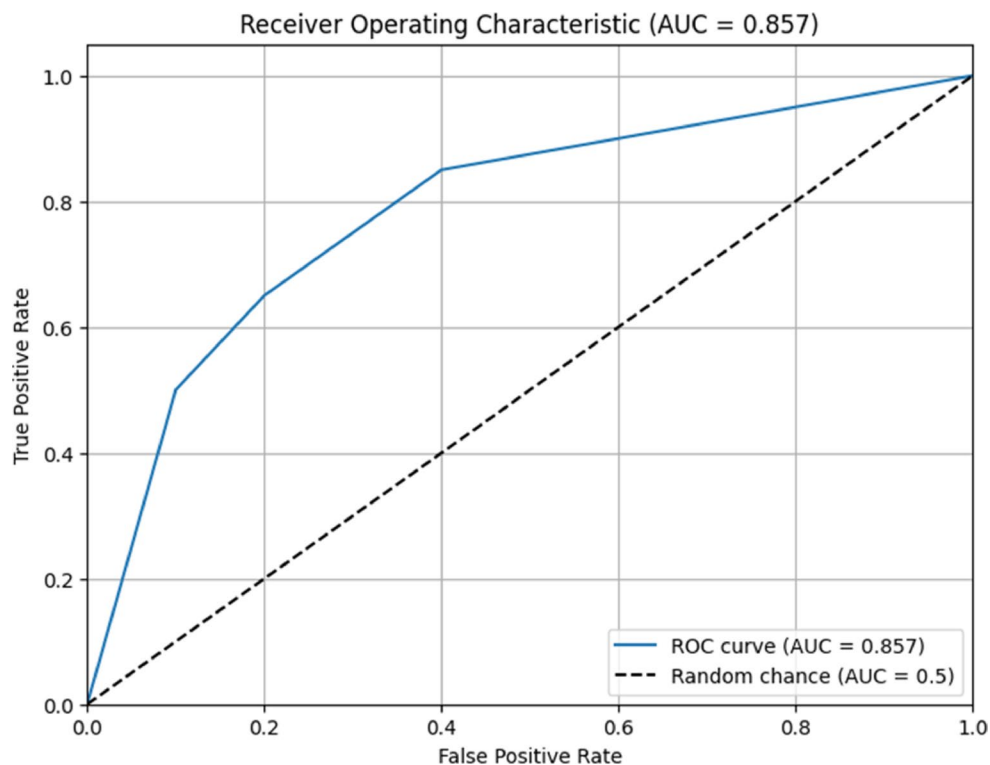


### Seismic risk index

	Very high	High	Moderate	Low	Very low
Rank	Very high	High	Moderate	Low	Very low
Area (skm)	3471.97	4227.3	3651.89	2794.4	2063.79
Percentage (%)	21.42	26.08	22.53	17.24	12.73

**Fig. 11** Seismic risk map illustrating the spatial distribution and degree of risk based on indices of spatial hazard, vulnerability, exposure, and mitigation capacity

**Fig. 12** Analytic Hierarchy Process (AHP) model accuracy



regions, authorities can improve community resilience and reduce the impacts of future seismic events. These efforts are essential for ensuring the safety and security of Rangpur Division's residents during natural disasters.

### 3.5 AHP model accuracy in seismic risk assessment

The Receiver Operating Characteristic (ROC) curve assesses the model's performance in predicting seismic risk. The x-axis represents the False Positive Rate (FPR), while the y-axis shows the True Positive Rate (TPR). The blue curve (Fig. 12) illustrates the trade-off between TPR and FPR, with the black dashed line indicating random guessing (AUC=0.5).

An AUC value of 0.857 indicates strong model performance, correctly distinguishing between high and low-risk areas 85.7% of the time. This accuracy aids in disaster preparedness and risk management by identifying vulnerable areas for infrastructure development.

The use of Multi-Criteria Decision Analysis (MCDA) provides a structured approach for evaluating seismic hazards, vulnerabilities, and mitigation strategies. The Analytic Hierarchy Process (AHP) was applied for factor weighting due to its ability to incorporate expert judgment and ensure consistency ( $CR < 0.1$ ). The integration of spatial data with decision-making tools enhances the methodological robustness. Model validation using the ROC curve confirms strong predictive performance.

## 4 Conclusion

Seismic risk assessment was conducted for Rangpur Division, Bangladesh, by integrating 21 criteria across three core components: hazard, vulnerability and exposure, and mitigation. Using Multi-Criteria Decision Analysis (MCDA) alongside a Pearson correlation matrix, weighted values were assigned to enhance accuracy. The resulting risk map highlights high-risk zones, providing a comprehensive overview of the region's seismic susceptibility to support targeted mitigation efforts.

Applying the Analytic Hierarchy Process (AHP) and MCDA, the study classified 19.96% of the area as very high risk, 27.55% as high risk, 22.53% as moderate risk, and 29.96% as low to very low risk. This distribution illustrates the complex interplay between seismic hazards and exposure. Less than 1% of raster data (10-meter resolution) had missing values, which were corrected to maintain analytical integrity.

The findings emphasize an urgent need for intervention in nearly half of Rangpur Division's high-risk zones, which face significant seismic threats compounded by socio-economic vulnerabilities such as dense populations and inadequate infrastructure. By providing detailed spatial insights, this study enables policymakers and planners to prioritize resources effectively for targeted disaster risk reduction. Key recommendations include promoting earthquake-resistant construction, enhancing infrastructure planning,

strengthening emergency response, and adopting resilient land-use policies. Expanding critical facilities like hospitals, fire stations, and evacuation routes, alongside raising public awareness and implementing early warning systems, are essential to reduce casualties and economic losses.

Despite providing a validated framework for seismic risk assessment, this study acknowledges limitations. The subjective nature of AHP weighting may introduce bias, and the complexity of MCDA could challenge practical policy-making. Raster overlays may oversimplify spatial variability, potentially missing high-risk areas with low mitigation capacity. Additionally, rapidly changing data quality and static model design limit real-time assessment and fail to account for secondary hazards like landslides. Future work should integrate real-time data, machine learning techniques, and community-level inputs to improve the accuracy and applicability of risk analyses.

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## Declarations

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

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