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Research Paper

Assessing and mapping the vulnerability index of Bangladesh to natural and climate-induced disasters: A spatial analysis at the subdistrict level

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ABSTRACT

This study assesses and maps the vulnerability index of Bangladesh at the subdistrict level to a range of natural and climate-induced disasters. Four vulnerability index maps are created using principal component analysis and categorized into five risk levels: (1) no/very low risk, (2) low risk, (3) moderate risk, (4) high risk and (5) very high risk for each sub-district. The results reveal that the south east region is highly vulnerable to cyclones, Haor region stands out as the most vulnerable area for flash floods, with numerous subdistricts facing very high to high risk levels; northern and north-eastern regions are prone to cold waves, while the western part of Bangladesh is highly vulnerable to heat waves. This comprehensive spatial analysis provides critical information for disaster risk reduction and adaptation strategies, assisting decision-makers in identifying the most vulnerable areas and prioritizing interventions. The findings of this study might be useful for policymakers as well as planners.

***Keywords*:** Vulnerability index, Climate change, Natural disasters, Principal component analysis, Heat wave, Flash flood

Climate change is one of the current issues that severely impact all climate-sensitive sectors, like agriculture. The manifestations of climate change, such as rising temperatures, increasingly erratic rainfall, and more frequent and severe floods and droughts, have grave consequences for the livelihood security of smallholder farming communities, making them more vulnerable. Agriculture plays a great role in the livelihood of rural communities in many Asian countries. Most such countries are, however, predicted to be among the globe's most vulnerable to climatic changes (Samson *et al.,* 2011; Morand *et al.,* 2012). Scientists noted that the negative consequences of climate change are anticipated overall for Asia, where most of the small farmers subsist on rain-fed agriculture. In Bangladesh, agriculture is the dominant sector, contributing around 13% of the gross domestic product (GDP) and 43% of total employment and livelihoods. Crop production is mainly done by small-scale subsistence farmers who practice more traditional farming. The most vulnerable households are those with assets and livelihoods exposed to and sensitive to climatic risks and who have weak risk management capacity (Heltberg *et al.,* 2009).

Assessment and mapping of the vulnerability index to climate change are the basis for the development of site-specific adaptation options that reduce the risks associated with climate change. Several researchers have noted that vulnerability mapping, including exposure, sensitivity, and adaptive capacity, has become a central tool for communicating with policymakers and local stakeholders as well as visualizing climate change impacts on the landscape to more effectively support risk management and spatial planning (Eakin and Luers, 2006; Preston *et al.,* 2011). Vulnerability assessment describes a diverse set of methods used to systematically integrate and examine interactions between humans and their physical and social surroundings. The level of

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vulnerability of different areas to climate change is determined by both socioeconomic and environmental factors. The socioeconomic factors include the level of technological development, infrastructure, and institutional linkage (Chadha *et al.,* 2022; Singh *et al*., 2019), while the environmental attributes are climatic conditions, quality of soil, and availability of water for irrigation (O'Brien *et al.,* 2004). The variations of these socioeconomic and environmental factors across different social groups are responsible for the differences in their levels of vulnerability and coping capacities to climate change. The climate, altitude, agricultural output, cultural customs, and other socioeconomic aspects are not uniform throughout Bangladesh. As a result, different locations and farming practices have varying degrees of susceptibility.

Disaster vulnerability lies in the circumstances affecting the social and economic structures of society (Morrow, 1999; de Chazal *et al.,* 2008). Natural and climate-induced disasters are considered the coincidences between hazardous events (such as cyclones, floods, droughts, and sea-level rise), elements at risk (such as environmental, financial, and political systems), and the conditions of vulnerability of any system (Birkmann, 2011). The susceptibility to the risk of any disaster invariably becomes higher when one or more natural hazards occur in a vulnerable region (Wisner and Luce, 1993). The theoretical conceptualization of vulnerability assessments to identify disaster risk zones have often been used as the basis for pre-impact studies and mitigation planning strategies (Brooks, 2003; Cutter *et al.,* 2008). Various sectors, such as agriculture, forests, water resources, and coastal regions, have been projected to have several catastrophic impacts due to natural and climate-induced disasters. The intensity of these impacts is exacerbated further by any region's present sensitivity, from single stressors (hazards) to many stressors (global change) (Van Aalst, 2006). In Bangladesh, the socioeconomic vulnerability index (Ahsan and Warner, 2014) has been prepared for 7 unions of Koyra sub-district in the southwestern coastal region through a household survey and reported that the southern and south-eastern unions are relatively more vulnerable. All studies emphasized only the southern part of Bangladesh, not the whole Bangladesh. However, index-based vulnerability assessment on a regional scale in Bangladesh is apparently rare.

With the aim of examining disasters under the concept of vulnerability, this study is an attempt to map the 487 sub-districts in Bangladesh that are vulnerable to natural and climate-induced disasters. The paper is structured to detail the methodology and data collection process, including the computation of vulnerability indices, the application of Principal Component Analysis (PCA), the calculation of unbiased weights for indicators, as well as the utilization of the Standardized Precipitation Index (SPI). Ultimately, this study aims to provide valuable insights into the spatial distribution of different vulnerability, aiding in more effective disaster management and mitigation strategies for agriculture in the country.

MATERIAL AND METHODS

Data collection

The daily gridded precipitation data from the APHRODITE project (Asian Precipitation-Highly-Resolved Observational Data Integration Towards Evaluation) was obtained from their website during the period 1981-2015. The rainfall data for each of the 487 sub-districts in Bangladesh, based on their latitude and longitude coordinates, was extracted from the website data. The indicators were chosen from various sources, such as Bangladesh Meteorological Department (BMD), Bangladesh Bureau of Statistics (BBS), Center for Environmental and Geographic Information Services (CEGIS), Institute of Water Modelling (IWM), and Bangladesh Water Development Board (BWDB).

Based on the availability of secondary data from the Bangladesh Statistical Yearbook (BBS, 2013), the socio-economic drivers/indicators (density of population, male-female ratio, literacy rate, poverty-below poverty line, embankment road, embankment road, cyclone shelter, flood shelter, un-metalled road, irrigation by power pump, production of rice) in this study were chosen. These facts include socioeconomic conditions and span the gamut of sensitivity and adaptability. It gives a succinct description of the selected socioeconomic metrics and their relationship to vulnerability. The same kind of data for natural indicators (Storm surge inundation (m), Inundation due to riverine flood (m), Shoreline erosion (m/year), Shoreline accretion (m/year), Coastal elevation(cm)) under current climatic scenarios is collected from different sources. Since each location's unique variables must be taken into account, classifying signs is a challenging undertaking. It is to be noted that classification of indicators is a difficult task since their categorization is highly dependent on the prevailing local conditions and therefore need a comprehensive understanding of the same. Therefore, this study analyzes the rationale behind the classification of vulnerability indicators and variables as exposure, sensitivity, or adaptive capability.

Methodology

The natural system indicators were chosen from a literature review and expert opinion, as well as from the regular natural hazards occurring in the sub-district areas. The methodology describes how the concepts of exposure, sensitivity, adaptive capacity, and vulnerability were translated into numerical indices, what variables were used, and how variables were aggregated into sub-indices and sub-indices into a composite vulnerability index. This study has been carried out through the determination of the vulnerability index of 487 sub-districts in Bangladesh in terms of both natural systems and climate-induced disasters. This vulnerability index was calculated for the present situation. In the present situation, climate-induced disaster analysis and natural system vulnerability for 487 sub-districts are determined by 4 (four) climate-induced disaster indicators. After identification of the indicators, a period of assessment, data collection, cleaning, and quality checking was done. All the steps of assessing the vulnerability index for both natural system indicators and climate-induced disaster indicators, as well as for the composite system, are shown in Fig. 1.

Calculation of vulnerability index

The aim of this study was to assess and map the vulnerability of sub-districts in Bangladesh to natural and climate-induced disasters. A composite vulnerability index approach was

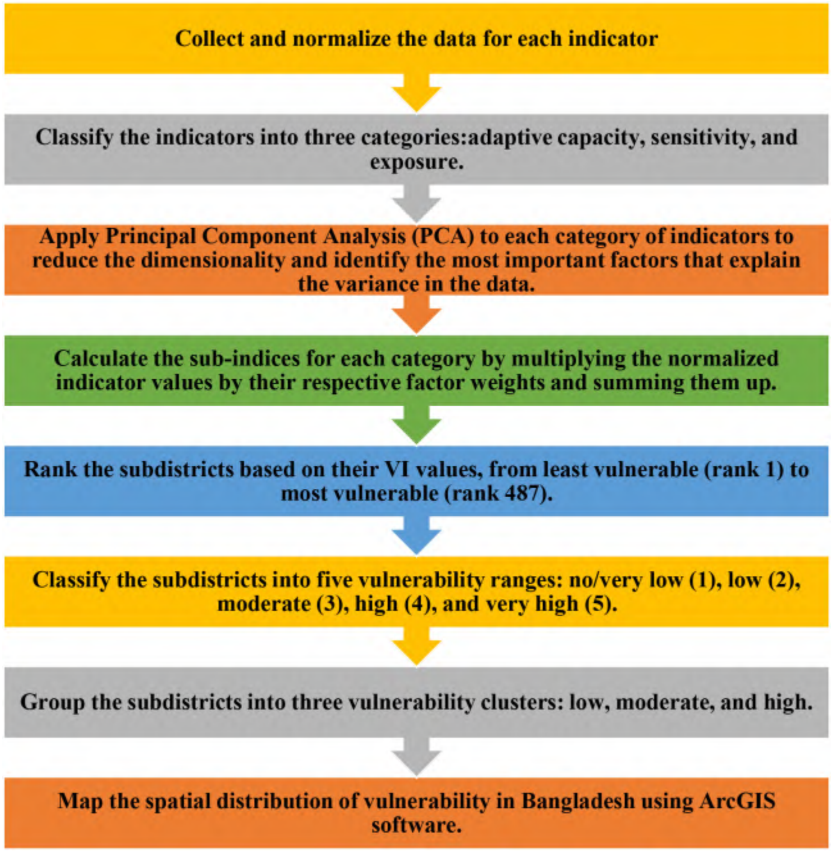

Fig. 1: Steps of assessing vulnerability index

used to measure the vulnerability of each sub-district based on three elements: exposure, sensitivity, and adaptive capacity. The indicators selected for each element were based on the best available proxies of disastrous events, such as floods, cyclones, cold wave, heat wave, landslides, etc., which shows the indicators and their sources for each element of vulnerability (Sullivan and Meigh, 2005). The data for each indicator were obtained from the respective sources and processed by checking for missing values, outliers, errors, and inconsistencies. The data were normalized by using the following equation:

$$\text{Index} = \frac{X_a - X_{min}}{X_{max} - X_{min}}$$

where Index is the normalized value of an indicator, X_a is the actual value of the same indicator, and X_{min} and X_{max} are the minimum and maximum values, respectively, of the same indicator.

Three indices for sensitivity, exposure, and adaptive capacity were constructed by obtaining a weighted mean of the indicators identified. The weights were assigned based on their contribution to the variance of the data using principal component analysis (PCA). The formula used to calculate each index was:

$$Index = \sum_{i=1}^{n} w_i X_i$$

Where Index is the value of sensitivity, exposure, or adaptive capacity index; w_i is the weight of indicator i; X_i is the normalized value of indicator i; and n is the number of indicators. The vulnerability index was obtained by averaging the three indices with differential weights based on their relative importance. The weights were determined using the Analytic Hierarchy Process (AHP). The formula used to calculate the vulnerability index was:

$$\text{Vulnerability index} = Ws\ S + We\ E + Wa\ A$$

Where Vulnerability idex is the value of vulnerability index; W_s, W_e, and W_a are the weights of sensitivity, exposure, and adaptive capacity indices, respectively; and S, E, and A are the values of sensitivity, exposure, and adaptive capacity indices, respectively (Ahsan and Warner, 2014). The vulnerability index was mapped for each sub-district using ArcGIS software. Higher values of the vulnerability index indicate higher vulnerability, and lower values indicate lower vulnerability. The map was used to identify and categorize the highest and lowest vulnerable regions in Bangladesh at the sub-district level (Alam *et al.,* 2020; Cogswell *et al.,* 2018).

Calculation of unbiased weights

The selection of weights for each indicator is a challenging issue in the development of an aggregated index, especially when the indicators are diverse and heterogeneous. To avoid the uncertainty of equal weighting, the Principal Component Analysis (PCA) method was used to assign different weights to the indicators based on their contribution to the variance of the data.

Table: Drought intensity classification as per standardized precipitation index (SPI) values

SPI value	Drought intensity
-2.0 or less	Extremely dry/extreme drought
-1.5 to -1.99	Severely dry/severe drought
-1.0 to -1.49	Moderately dry/moderate drought
-0.99 to 0.99	Near normal
1.0 to 1.49	Moderately wet
1.5 to 1.99	Very wet
2.0 or more	Extremely wet

Standardized precipitation index (SPI) calculation

The Standardized Precipitation Index (SPI), which is based on the likelihood of rainfall over a specific time period and is quite easy to calculate (McKee *et al.,* 1993). The time scale reflects the impact of drought on different water resources, such as soil moisture, groundwater, stream flow, and reservoir storage. A long series of rainfall data for the desired period was used to calculate the SPI for each of the 487 sub-districts in Bangladesh. A gamma probability distribution was fitted to the rainfall data, which was then transformed into a standardized normal distribution so that the mean SPI for the sub-district and period was zero. Positive SPI values indicated greater than median rainfall, and negative values indicated less than median rainfall. The classification of drought intensities based on the SPI value was proposed by McKee *et al.,* (1993), as shown in Table 1.

The gamma probability distribution function (pdf) is given as

$$f(x)= \frac{1}{b^{a}\Gamma(a)} x^{a-1} e^{-x/b}$$

For $x > 0$, where $a > 0$ and $b > 0$ were the shape and scale parameters, respectively, $x > 0$ was the rainfall and $\Gamma(a)$ was the gamma function. The parameters a and b were estimated by using the maximum likelihood method. The pdf was integrated with respect to x, and the estimated values of a and b were inserted to obtain the gamma cumulative distribution function (CDF) at each value of x. The CDF was transformed into the standard normal distribution to obtain the SPI.

RESULT AND DISCUSSION

Vulnerability maps

In this section, we present the vulnerability maps for four natural and climate-induced hazards that affect the different regions of Bangladesh. These hazards are cyclones, flash flood inundation, cold waves, and heat waves. To calculate the vulnerability index using principal component analysis (PCA) for each hazard based on various indicators and data sources, the vulnerability maps show the spatial distribution of the risk levels for each upazila in Bangladesh under the present scenario. The risk levels are categorized into five groups: (1) no/very low risk, (2) low risk, (3) moderate risk, (4) high risk, and (5) very high risk. The criteria for each risk category are presented in Table 1. The vulnerability maps are displayed in Fig. 2 and 3. These maps can help identify the most vulnerable areas for each hazard and inform the decision-making process for disaster risk reduction and adaptation strategies.

Cyclone vulnerability map

Cyclones are one of the major natural hazards that affect the coastal regions of Bangladesh almost every year. They generally occur in the early summer (April–May) or late rainy season (October–November) and originate from low atmospheric pressures over the Bay of Bengal. In this sub-section, we present a cyclone vulnerability map that shows the risk levels of different upazilas in Bangladesh based on the vulnerability index calculated using principal component analysis (PCs). Fig. 2 (a) shows the cyclone vulnerability map for Bangladesh. This map shows that the Chittagong-Feni coast is the most vulnerable area for cyclone landfall, with 15 upazilas having very high-risk levels as shown in the Fig 2(a) as red colour. The Barishal and Lakshmipur coasts have moderate risk levels for cyclones. On the other hand, the Satkhira-Khulna/Sundarban and Cox's Bazar coasts are relatively less vulnerable to cyclones compared to the other coasts (Hoque *et al.,* 2021).

Flash flood vulnerability map

Flash floods are another major natural hazard that affects the low-lying areas of Bangladesh during the pre-monsoon season (March–April). Excessive rainfall in their upstream regions creates the major rivers that flow through Bangladesh. In this sub-section, we present a flash flood vulnerability map that shows the risk levels of different upazilas in Bangladesh based on the vulnerability index calculated using PCA. Fig. 2(b) shows the flash flood vulnerability map for Bangladesh. The map shows that the Haor region is the most vulnerable area for flash floods as red colour, with 37 (north-eastern region) upazilas having very high to high risk levels.

The Haor region is a large wetland ecosystem in northeastern Bangladesh that supports rich biodiversity and provides livelihoods for millions of people. However, it is also prone to flash floods due to its low elevation and proximity to the Meghna River basin. Another high-risk area for flash floods is found in some upazilas in Madaripur, Shariatpur, Rajbari, Faridpur, Manikganj, Jamalpur, and Gaibandha districts. These districts are in Bangladesh's north and center, and the Ganges and Brahmaputra River basins frequently experience flash floods. The rest of the districts are comparatively less vulnerable to flash floods than the above-mentioned districts, which was found by Hoque *et al.,* (2021).

Cold wave vulnerability map

They are caused by cold air masses from the Himalayas that lower the temperature below 10°C. In this sub-section, we present a cold wave vulnerability map that shows the risk levels of different upazilas in Bangladesh based on the vulnerability index calculated using PCA. Fig. 3(a) shows the cold wave vulnerability map for Bangladesh. The map shows that the upazilas under Rajshahi and Rangpur divisions are the most vulnerable areas for cold waves, with 8 (eight) districts having very high-risk levels as shown in Fig. 3(a) as red colour. The Rajshahi division located in north-western Bangladesh and is close to the Himalayas. The rest of the locations (upazilas and districts) are found to be low to moderately vulnerable areas in Bangladesh.

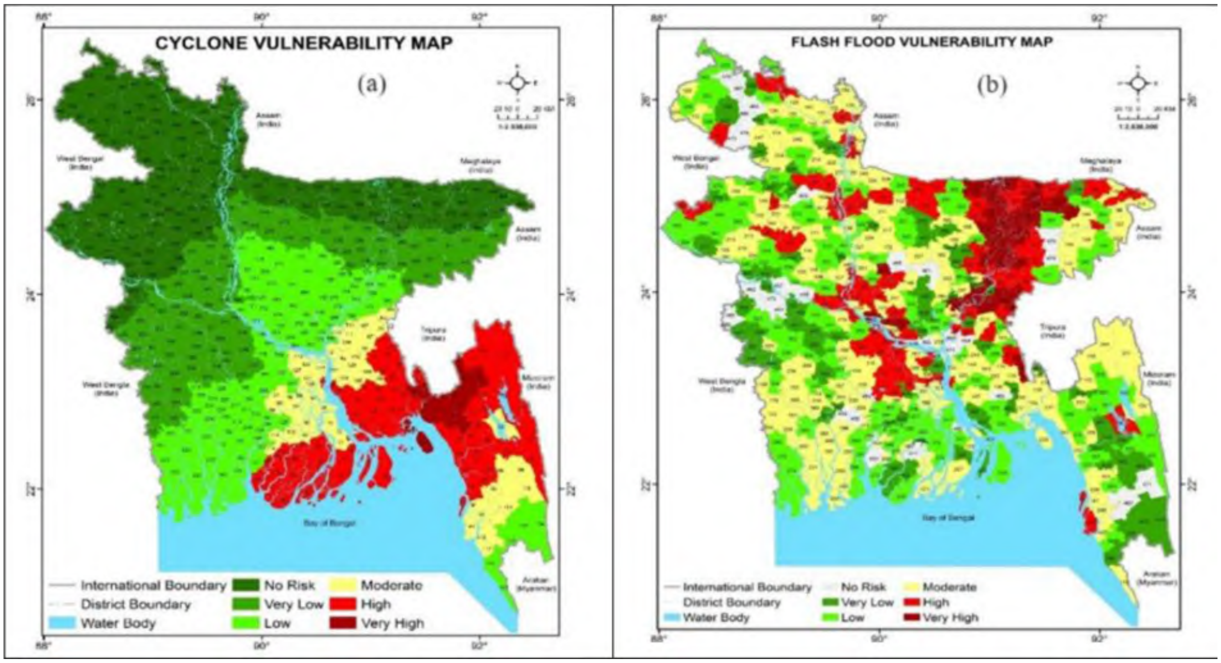

Fig. 2: Vulnerability index map of (a) cyclone and (b) flash flood in Bangladesh

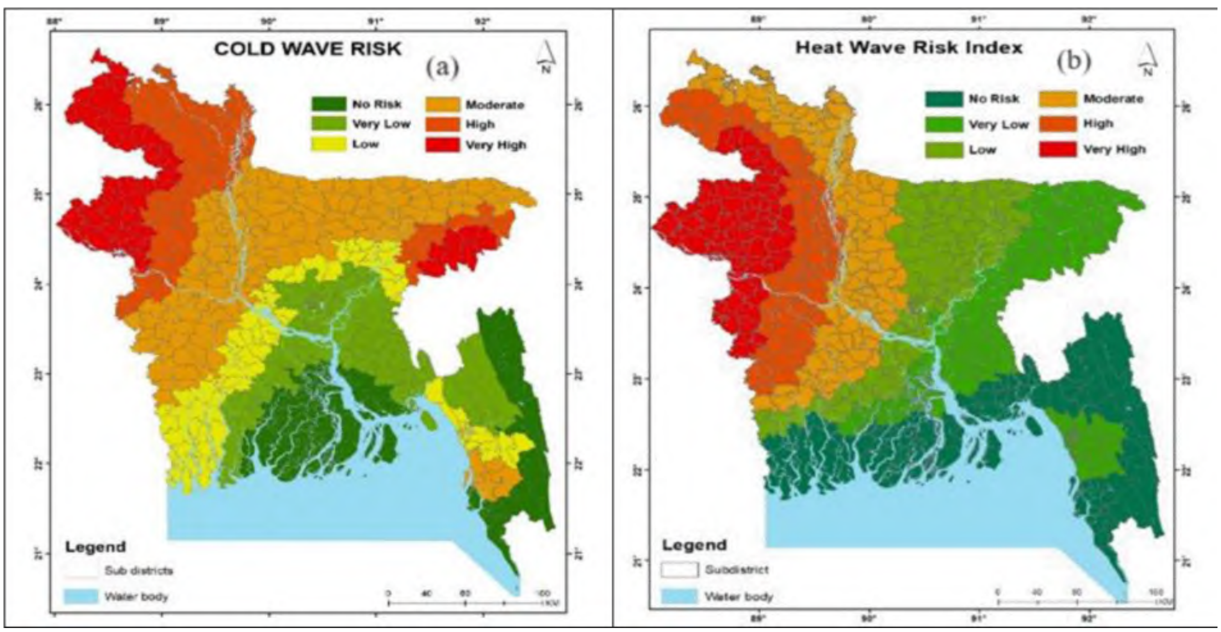

Fig. 3: Vulnerability index map of (a) cold wave and (b) heat wave in Bangladesh.

Heat wave vulnerability map

Heat waves are another major natural hazard that affects the western part of Bangladesh during the summer season (May–June). They are caused by high atmospheric pressure and dry air that increase the temperature above 40°C. In this sub-section, we present a heat wave vulnerability map that shows the risk levels of different upazilas in Bangladesh based on the vulnerability index calculated using PCA. Fig. 3(b) shows the heat wave vulnerability map for Bangladesh. The map shows that the upazilas under western districts are the most vulnerable area for heat waves, with 64 upazilas having very high to high risk levels as shown in Fig. 3(b) as red colour. On the other hand, no heat wave-vulnerable area is noticed over the upazilas of the southern coastal area, as shown in Fig. 3(b). The cooling impact of the Bay of Bengal affects these upazilas, which are situated in southeast Bangladesh.

CONCLUSION

In this study, an extensive assessment and mapping of Bangladesh's vulnerability to various natural and climate-induced disasters at the subdistrict level have been conducted. The study utilized PCA to calculate vulnerability indices for four hazards, including cyclones, flash floods, cold waves, heat waves in Bangladesh. The vulnerability maps provided a comprehensive spatial analysis of risk levels across the country. The major findings of this study reveal that different regions of Bangladesh face varying levels of vulnerability to these hazards. Coastal areas, particularly the Chittagong-Feni coast, were identified as highly vulnerable to cyclones. The Haor region in north-eastern Bangladesh was found to be the most vulnerable to flash floods than the other regions, while the northern and north-eastern regions were at high risk from cold waves and other regions comparatively lower risk. The western districts were highlighted as the most vulnerable to heat waves due to high temperatures and low humidity. This study provides crucial information for disaster risk reduction and adaptation strategies in Bangladesh. The vulnerability maps generated in this study can guide policymakers, disaster management authorities, and local communities in identifying and prioritizing areas at higher risk, enabling them to develop targeted mitigation and preparedness measures. As a way forward, continuous monitoring and updating of vulnerability assessments are recommended to account for changing climate patterns and evolving risk factors. Moreover, efforts should focus on strengthening early warning systems, infrastructure resilience, and community capacity building to enhance disaster preparedness and response.

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