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Research article

Spatial mapping and visualization of earthquake data using Quantum Geographic Information System (QGIS) for seismic activity

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ABSTRACT

Earthquakes are highly destructive natural hazards that cause severe risks to human life, infrastructure, and economic stability. The effects of earthquakes are analyzed using a Geographic Information System (GIS). This study explores the spatial distribution and impacts of earthquakes across different geographical regions utilizing QGIS 3.42.0, an open-source GIS software. The integration of historical earthquake data with the global fault data base and socio-economic variables enabled a comprehensive system for interpreting seismic activity and its consequences. Multiple GIS-based information layers were generated, including active faults, and map depicting earthquake magnitude, intensity, estimated damage, fatalities, and high seismic zones. Heat map analysis was employed to generate density surfaces that highlight areas with higher frequencies of seismic activity, aiding in the identification of high-risk zones. Heat map analysis identified seismic hotspots and visualized the spatial concentration of earthquake occurrences across affected regions. The attribute tables linked with the dataset provide detailed information for each earthquake event, facilitating targeted decision-making for disaster management and emergency response. This research highlights the potential of GIS-based methodologies in enhancing seismic risk assessment, thereby aiding in urban planning, risk reduction, and emergency response strategies.

1. Introduction

Earthquakes are natural phenomena resulting from the sudden release of accumulated energy within the Earth's crust, generating seismic waves responsible for the shaking of the Earth's surface (Hardebeck and Okada, 2018). This energy gradually accumulates over time as a result of tectonic stresses acting along faults and fractures within the Earth's crust, particularly at plate boundaries where tectonic plates meet, collide, or slide past one another. Once the accumulated stress exceeds the strength of the surrounding rocks, it is abruptly released in the form of seismic activity (Ziebarth et al., 2020). The severity and impact of these events vary with geological factors, ranging from minor tremors to massive, destructive earthquakes capable of altering landscapes and devastating communities (Rosca and Stancu, 2024). The magnitude and impact of earthquakes are governed by multiple parameters, including epicenter location, depth, subsurface geology, infrastructure type, and the vulnerability of nearby human settlements. Urban regions are generally more susceptible to severe casualties and significant economic disruption owing to dense populations and concentrated infrastructure (Fayaz et al., 2023). In India, major historical earthquakes in the Himalayan region, the Kutch region of Gujarat, Latur, and Bihar have caused extensive devastation, highlighting the necessity for region-specific seismic risk assessment frameworks (Sinha and Sarkar, 2020).

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To address these complexities, GIS have proven to be effective tools for earthquake hazard assessment and disaster management (Atik and Safi, 2024). GIS provides a robust framework for integrating spatial and attribute datasets, enabling multi-dimensional analysis and visualization of earthquake patterns, impact zones, and risk levels (Fayaz et al., 2023). The system integrates historical earthquake records with diverse geospatial and socio-economic data sets to generate multi-layered outputs, including active fault lines, maps depicting earthquake magnitude, intensity, estimated damage, fatalities, and high seismic-risk zones (Atanasova-Zlatareva et al., 2024). Through layered mapping, GIS facilitates the exploration of complex relationships between seismic activity and socio-environmental factors, providing an effective framework for managing, analyzing, and visualizing earthquake data (Gohil et al., 2024). The attribute tables linked with the data further enhance the analytical capability of the system, providing detailed event-based insights that support targeted decision-making.

This research presents GIS-based framework generated using QGIS 3.42.0 software to analyze and visualize the spatial and socio-economic impacts of earthquakes across global and Indian scales. The study contributes a multi-parameter impact layers approach to seismic risk assessment. This approach integrates 50 years of historical global and Indian earthquake datasets with active fault mapping, heat map analysis, seismic magnitude, intensity, population exposure, and housing damage information within an integrated GIS workflow, providing a more comprehensive spatial representation of seismic vulnerability and earthquake impacts.

2. Methodologies

QGIS 3.42.0, open-source desktop GIS software, was used to perform spatial analysis and visualize the impact of earthquake events (QGIS, 2025). QGIS was selected for its strong analytical capabilities, compatibility with various spatial data formats, and ability to handle both raster and vector datasets (Atik and Safi, 2024). The primary goal of this study was to systematically collect, integrate, and analyze geospatial datasets; to visualize earthquake-prone regions through heat maps; and to assess the spatial extent of earthquake impacts using multi-source geospatial data. Fig**.**1 represent GIS-based methodological framework of the study

2.1 Study area:

The study investigated earthquake data spanning a 50-year period (1975-2025) to capture temporal variations and trends at both global and Indian scales. The analysis focused on significant seismic events that caused extensive structural damage, fatalities, and socio-economic disruptions. This dual-scale approach helps interpret both global and regional seismic vulnerabilities through QGIS-based spatial mapping and analysis.

2.2 Geospatial Data Sources

Multiple authoritative geospatial datasets were compiled and integrated to facilitate a comprehensive analysis of seismic activity:

2.2.1 Natural Earth

The Natural Earth dataset served as the base map, providing high-resolution topographic, political, and physical features. It was used for background referencing, delineation of country boundaries, and landform features to ensure accurate overlay of thematic layers.

2.2.2 GEM Global Active Faults Database

This dataset provided detailed vector information on the location and characteristics of active faults worldwide. These fault lines were spatially mapped and analyzed to assess their proximity to major earthquake events and to delineate zones of tectonic vulnerability (Styron and Pagani, 2020).

2.2.3 United States Geological Survey (USGS) Earthquake Data

The USGS earthquake catalog was considered and examined for its comprehensive historical seismic records (USGS, 2025). However, for this study, the National Oceanic and Atmospheric Administration (NOAA, 2025) Earthquake Database was selected as the primary dataset due to its comprehensive inclusion of crucial damage and socio-economic variables necessary for a multi-parameter impact assessment.

2.2.4 NOAA Earthquake Database

According to the **NOAA (2025)**, earthquake database served as the primary dataset for seismic event records, contributing historical data on global earthquake events, including dates and time of occurrence, latitude, longitude, focal depth, magnitude, intensity, casualties, injuries, houses destroyed, houses damaged, and tsunami-linked earthquakes. The dataset was filtered to extract significant seismic events for the analysis of spatial patterns, clustering, and intensity zones. The inclusion of this dataset enhanced the overall analysis, especially for under-reported regions and offshore seismic events (NOAA, 2025).

2.2.5 Google Satellite Imagery (Google Earth/QGIS XYZ Tiles)

This tool provided high-resolution background imagery for visual validation of geographic features, map preparation, land surface analysis, and evaluation of earthquake-impacted areas.

2.2.6 HERE Maps, Bing Maps, Car to base maps

These map services were integrated as supplementary base map layers to enhance visualization quality. Each platform offered distinct cartographic styles and labelling systems, contributing to clearer and more informative thematic maps.

2.3 QGIS Plugins utilized

To strengthen the analytical framework and visualization process, multiple QGIS plugins were enabled. The QMS (Quick Map Services) plug in enabled the use of web mapping services, allowing the addition of base maps from various providers into the QGIS interface. The OSM (Open Street Map) plug in provided detailed vector datasets, including road networks, urban infrastructure, and landmarks, which were essential for assessing settlement vulnerability. The Map Tiler plug in enabled the integration of high-quality custom base maps

For improved cartographic detail and enhanced map visualization. Heat map tools were used to perform spatial density analysis, representing the frequency of earthquake events over space and identifying seismic hotspots (Agustin et al., 2023). Table 1 represent Spatial and non-spatial data on major earthquake events across India (1975-2025). The dataset was imported from the NOAA Earthquake Database and processed in QGIS, and includes records of earthquake events, such as date and time of occurrence, latitude, longitude, focal depth, magnitude, injuries, houses damaged, and total deaths in the affected regions.

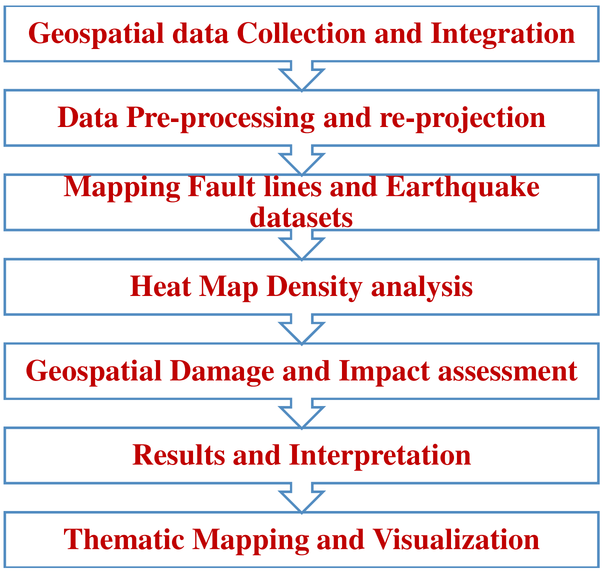

Fig.1 GIS-based methodological framework of the study

3. Results and discussion:

The QGIS-based spatial analysis of earthquake data over the 50-year period (1975-2025) at the global and Indian scales revealed significant spatial patterns and trends in the distribution, magnitude, and intensity of seismic activity.

3.1 Validation of global fault lines with seismic data:

The integration of active fault lines and earthquake datasets reveals a spatial correlation between major earthquake events, active tectonic boundaries, and seismic hotspot zones, highlighting regions of elevated seismic vulnerability.

Fig. 2 (a-b) validates global fault lines using seismic data: Fig. 2(a) Illustrate widespread active fault lines across Asia, showing dense fault networks corresponding to major plate boundaries. Fig. 2(b) shows the spatial validation of earthquake events with fault lines, indicating high concentrations of seismic activity near plate boundaries and active fault zones.

Earthquake events with magnitude ranging from 1.6 to 9.1 are primarily concentrated along major tectonic boundaries, particularly in zones such as the Himalayan belt, where the Indian plate collides with the Eurasian plate, and the Pacific Ring of Fire, encompassing Japan, Indonesia, and the western coasts of the Americas (Mukherjee et al., 2025). The East Anatolian Fault in Turkey and the Alpide Belt, stretching from the Mediterranean to the Himalayas, also exhibit similar clustering patterns. These regions consistently exhibit high earthquake frequency and intensity, confirming that stress accumulation and release along active fault zones are the primary drivers of global seismicity. The spatial clustering near fault lines shown in Fig. 2(b) validates that most high-magnitude seismic events occur along or near active fault zones, highlighting the critical influence of tectonic structures on earthquake distribution.

3.2 Spatial mapping of seismic vulnerability in India

Fig. 3 (a-d) presents seismic vulnerability across India: Fig. 3(a) highlights the spatial distribution of high-magnitude earthquakes, showing concentrations above magnitude 7.0 in the Andaman and Nicobar Islands, Bhuj (Gujarat), and the north-eastern region, while lower-magnitude events (3.5-5.5) dominate central and southern India. Fig. 3(b) presents the temporal distribution of earthquake events across India. Fig. 3(c) demonstrates the extent of housing damage from major earthquakes in India, with maximum destruction recorded in Bhuj and Jammu and Kashmir, reflecting high population exposure near seismically active areas. Fig. 3(d) reveals the spatial distribution of earthquake fatalities in India, showing the high death toll recorded in Bhuj and Latur.

India's seismic profile exhibits distinct spatial and temporal patterns of earthquake activity. High-magnitude earthquakes are concentrated near zones such as Jammu and Kashmir, Uttarakhand and the north-eastern states, corresponding with inter-plate boundaries and major active fault systems, including the Main Central Thrust and Main Boundary Thrust (Verma and Bansal, 2013). However, India's seismic vulnerability is not confined to these primary plate-boundary zones. Significant events such as the 1993 Latur and 2001 Bhuj earth quakes occurred in intra-plate regions, far from the plate edges, where ancient tectonic features such as the Son-Narmada Lineament exert structural control. Although less frequent, these intra-plate events can be highly destructive due to their shallow focal depths and the lack of seismic preparedness in these regions. For example, the Latur earthquake (Magnitude 6.2) resulted in over 11,000 fatalities because of its shallow 7-km focal depth and widespread collapse of non-engineered masonry structures (**NOAA,** 2025).

These observations demonstrate that seismic vulnerability is heavily influenced by local conditions, such as focal depth, geological setting, building quality, and population density, rather than earthquake magnitude alone. While some high-magnitude events result in limited casualties due to sparse populations or better preparedness, severe damage is typically observed in densely populated regions with poor construction practices. The spatial correlation between earthquake occurrences and fault systems further highlights the dominant role of tectonic structures in shaping seismic vulnerability and reinforces the need for resilient infrastructure and improved preparedness measures in high-risk regions.

Table 1 Spatial and non-spatial data on major earthquake events across India (1975-2025)

S. No.	Year	Month	Day	Location Name	Latitude	Longitude	Focal Depth (km)	Magnitude	Deaths	Injuries	Damage ($Mil)	Houses Damaged
1	1975	1	19	India: Kashmir	32.46	78.43	33	6.8	47			
2	1980	8	23	India: Kashmir	32.913	75.633	25	4.9	15	40		
3	1982	1	20	India: Nicobar Island	6.946	94.002	19	6.3				
4	1983	11	30	Indian Ocean	-6.852	72.11	10	7.6				
5	1984	12	30	India: Assam	24.641	92.891	23	5.6	20	100		
6	1986	4	26	India: Kashmir	32.128	76.374	33	5.3	6	30		
7	1991	10	19	India: Chamoli	30.78	78.774	10	7	2000	1800	60	7500
8	1993	11	12	India: Latur	18.12	76.533	10	4.6		25		
9	1993	9	29	India: Latur	18.066	76.451	7	6.2	11000	30000	300	
10	1997	5	21	India: Southern: Jabalpur	23.083	80.041	36	5.8	56	1000	143	8546
11	1997	11	21	India-Bangladesh	22.212	92.702	54	6.1	23	200		
12	1999	3	28	India: Chamoli	30.512	79.403	15	6.6	100	394	70	21100
13	2001	1	26	India: Gujarat: Bhuj	23.388	70.326	17	7.6	20005	166836	2623	339000
14	2002	9	13	India: Andaman Islands	13.036	93.068	21	6.5	2			
15	2003	7	15	Indian Ocean	-2.598	68.382	10	7.6				
16	2005	3	14	India: Maharashtra	17.145	73.73	10	4.9		45		
17	2005	12	14	India: Jausari	30.476	79.255	44	5.3	1	4		1
18	2005	7	24	India: Andaman Islands	7.92	92.19	16	7.2				
19	2008	2	6	India: West Bengal	23.433	87.111	10	4.3	1	50		
20	2008	9	16	India: Maharashtra	17.438	73.915	10	5	1	20		
21	2009	8	10	India: Andaman Islands	14.099	92.888	5	7.5				
22	2010	3	30	India: Andaman Islands	13.667	92.831	34	6.7		10		
23	2010	6	12	India: Nicobar Island	7.881	91.936	35	7.5				
24	2011	10	20	India: Gujarat	21.211	70.533	10	5		34		3000
25	2011	9	18	India: Sikkim	27.73	88.155	50	6.9	127	441	2100	40000
26	2013	5	1	India: Kashmir	33.061	75.863	15	5.7	3	90	19.5	95532
27	2016	1	3	India: Impahl	24.804	93.651	55	6.7	13	100	75	
28	2016	4	13	India: Assam	23.094	94.865	136	6.9	2	170		4
29	2017	1	3	India: Ambasa	24.015	92.018	32	5.7	3			5200
30	2021	4	28	India: Assam	26.782	92.436	34	6	2	12		428
31	2023	1	24	India: Uttar Pradesh	29.597	81.652	25	5.6	4			42

The heat map analysis identifies prominent seismic hotspots globally and across India. High earthquake clusters are observed along the Himalayan arc, Japan, Indonesia, Turkey, and the Andean Belt, coinciding with major tectonic plate boundaries. In India, major earthquake zones are concentrated in Bhuj (Gujarat), the north-eastern states, Latur and the Himalayan belt (Jammu and Kashmir), confirming their elevated seismic vulnerability. The integration of heat maps and fault line data confirms that seismic clustering closely follows tectonic boundaries, further validating tectonically controlled seismic activity. Although Agustin et al. (2023) used QGIS to visualize earthquake time-series in the Cila cap region and focused primarily on temporal variations in magnitude using USGS datasets, their analysis remained limited to a single regional study area. In contrast, the present research adopts a broader multi-scale framework. Beyond examining magnitude trends, this study integrates global and Indian earthquake records with active fault systems, heat-map-based density analysis, intensity and damage attributes, and population-exposure layers within a unified GIS environment.

This expanded spatial coverage and multi-parameter integration provide a more comprehensive and detailed assessment of seismic vulnerability.

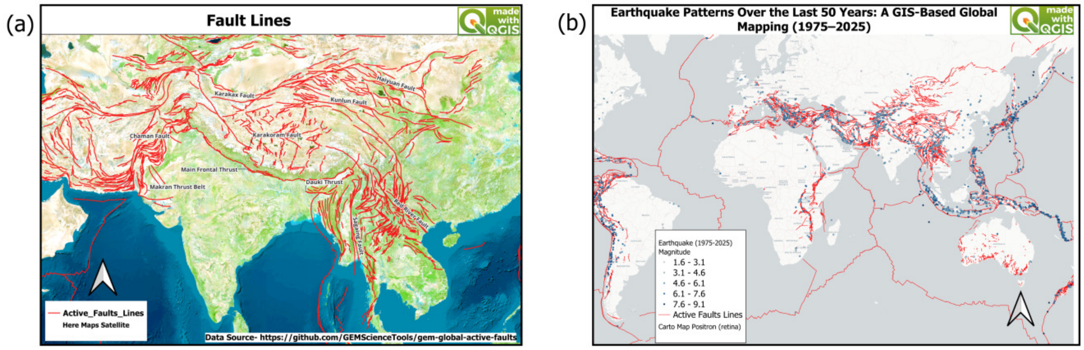

Fig. 2 Validates global fault lines using seismic data: (a) Illustrate widespread active fault lines across Asia, showing dense fault networks corresponding to major plate boundaries and (b) Shows the spatial validation of earthquake events with fault lines, indicating high concentrations of seismic activity near plate boundaries and active fault zones.

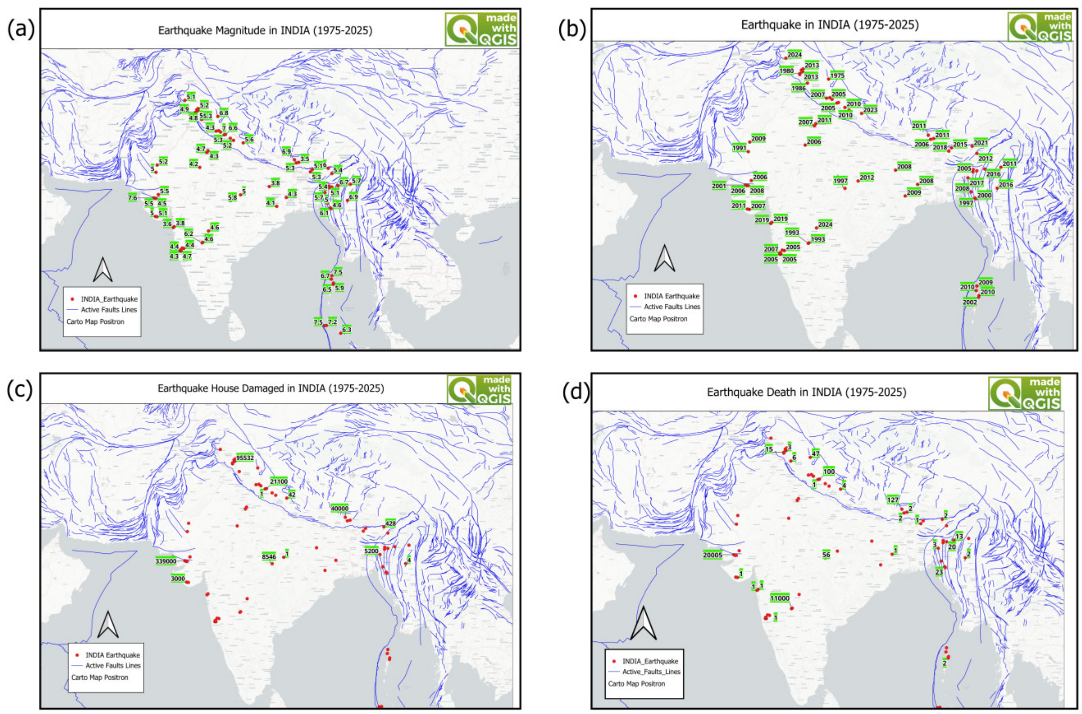

Fig. 3 Seismic vulnerability across India: (a) Highlights the spatial distribution of high-magnitude earthquakes, showing concentrations above magnitude 7.0 in the Andaman and Nicobar Islands, Bhuj (Gujarat), and the north-eastern region, while lower-magnitude events(3.5-5.5) dominate central and southern India, (b) Presents the temporal distribution of earthquake events across India, (c) Demonstrates the extent of housing damage from major earthquakes in India, with maximum destruction recorded in Bhuj and Jammu and Kashmir, reflecting high population exposure near seismically active areas and (d) Reveals the spatial distribution of earthquake fatalities in India, showing the high death toll recorded in Bhuj and Latur.

3.3 Heat map visualization

Fig. 4 (a-d) visualizes seismic hotspot heat maps: Fig. 4a visualizes the global seismic hotspot heat map, where high earthquake frequency and high-intensity zones are shown in dark red to brown shades, indicating severe seismic vulnerability. Fig. 4 (b) and (c) represent the seismic hotspot heat maps of India, highlighting high activity zones shown in dark red to brown shades, with distinct concentration around the Bhuj (Gujarat) earthquake zone. Fig. (4d) overlays the seismic hotspot heat map on global active fault lines, showing that brighter zones correspond to regions of frequent earthquake occurrences and elevated seismic intensity.

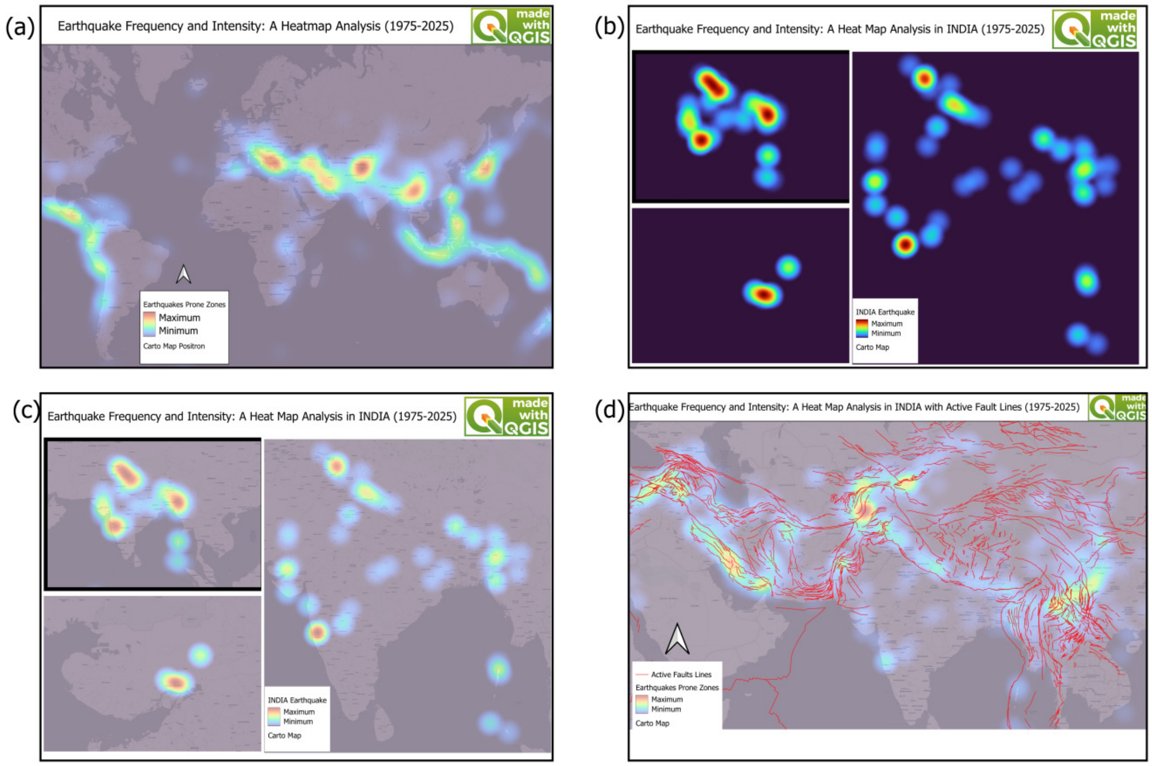

Fig. 4 Visualizes seismic hotspot heat maps: (a) Visualizes the global seismic hotspot heat map, where high earthquake frequency and high-intensity zones are shown in dark red to brown shades, indicating severe seismic vulnerability, (b) and (c) Represent the seismic hotspot heat maps of India, highlighting high activity zones shown in dark red to brown shades, with distinct concentration around the Bhuj (Gujarat) earthquake zone, and (d) Overlays the seismic hotspot heat map on global active fault lines, showing that brighter zones correspond to regions of frequent earthquake occurrences and elevated seismic intensity.

4. Conclusion

The spatial mapping and analysis of historical earthquake data using QGIS reveals a clear correlation between geological structures and seismic activity. Earthquakes are primarily concentrated along major fault lines and plate boundaries; longer faults are associated with a higher maximum potential magnitude, though actual event size depends on rupture extent, slip and local stress conditions. However, the impact of an earthquake extends beyond its magnitude; factors such as depth, epicentral distance, geological conditions, infrastructure quality, and population density significantly influence intensity and damage levels. Consequently, a high-magnitude earthquake in a remote area may cause limited destruction, whereas a moderate event in a densely populated and poorly constructed urban region can result in catastrophic losses. The integration of geospatial layers with seismic data enables precise identification of seismic hotspots and is instrumental for enhancing seismic risk assessment, implementing effective risk reduction strategies, and improving emergency response strategies for urban and regional planners. The utilization of open-source geospatial tools allows for developing scalable and reproducible earthquake-assessment frameworks applicable to other regions and future hazard studies. This GIS-based framework can be further strengthened by integrating real-time seismic monitoring, machine learning, and artificial intelligence to improve disaster resilience and early warning systems, thereby providing critical support to disaster management authorities in urban planning, developing effective mitigation and preparedness strategies.

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Author contributions

Anurag Kumar: Conceptualization, data compilation, GIS-based analysis, and original draft writing. Dr. Anil Kumar: Supervision, review, and editing.

Conflict of interest

The authors declare that they have no conflict of interest.

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