Review of GIS-based Approaches in Earthquake Disaster Management

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Review of GIS-based Approaches in Earthquake Disaster Management

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Abstract: *The unpredictability of earthquakes causes severe damage and loss to communities due to inadequate disaster preparedness and management strategies. Geographic information systems can employ relational geodatabase models to incorporate massive geospatial layers to assess regional seismic risks and quantify building and population vulnerabilities. This review discusses and compares recent literature on GIS-based earthquake risk models to identify similarities and novelties in methodologies and calculations using geostatistical functions and multi-criteria decision analysis. Generated maps illustrate different approaches to visualizing risk levels and damage and loss estimation. Insights on the visualized data were provided to assess the correlation between overlain data layers and their influence on the resulting risk assessment. Research gaps were identified and outlined to encourage further research on seismic risk using dynamic relational geodatabases in the Philippines. Addressing the identified research gaps and focusing on the suggested improvement areas can enhance seismic risk assessments.*

Keywords: Geographic information systems; earthquake disaster management; seismic risk assessment; relational geodatabase, vulnerability

1. INTRODUCTION

Unforeseen natural disasters such as earthquakes severely damage human settlements, structures, and the natural environment. One-fifth of the estimated annual economic losses from natural disasters are attributed to earthquakes, with a yearly casualty toll of 25,000 [1]. These damage and loss figures can be exacerbated by inadequacies in risk identification, disaster management, exposure assessment, and substandard infrastructure [2]. Exposure levels to seismic risks face a two-fold increase due to rapid population growth in urbanized regions of developing countries [3], which corresponds to a steady yet uncontrolled expansion in asset concentration and land use, leading to a higher potential for structural damage and economic losses. Mitigating these losses requires effective earthquake disaster management strategies through systematic preparation, response, and recovery. Modeling scenarios through risk assessments identify critical areas of concern to aid in establishing and strengthening risk mitigation policies [4]. This requires developing a model constituted of multiple geospatial inventories to account for socioeconomic and structural vulnerabilities. This review aims to examine existing literature on the use of geospatial models to estimate the impacts of seismic hazards to determine appropriate tools which can be implemented in the Philippine context. Although numerous studies have quantified damages and losses, this paper focuses on the utilization of Geographic Information Systems (GIS) in earthquake disaster management.

2. GIS-BASED MODELS

Past seismic risk and vulnerability assessment models in developed countries are listed in Table 1. Despite their comprehensive methodologies, these are considered region-specific frameworks due to the incompatibility of the models with data and conditions in other regions [5,6]. A comparison of these models highlights the necessity of a dynamic database, which can be attained using Geographic Information Systems (GIS). A critical advantage of GIS-based approaches is their ability to geocode and map essential infrastructure and vulnerable areas. By leveraging this spatial data in a relational geodatabase, earthquake losses can be quantified, which is necessary for assessing risk, allocating resources, and planning effective emergency response and recovery strategies.

A relational geodatabase is an amalgamation of geospatial data into a schema to facilitate modeling and visualization [7]. This structured approach enables efficient querying and manipulation of data using Structured Query Language (SQL). SQL queries can filter data based on specific criteria, join data from different tables, and perform calculations to generate new insights relevant to earthquake disaster management [2,8]. The success of GIS applications in earthquake disaster management is fundamentally dependent on data. Table 2 summarizes the data used in the reviewed literature. No standard layers have been established for seismic microzonation [2,5,8], as existing models have been customized for localized use. However, comparing existing models in Table 1 and past research in Table 2 suggests earthquake data, geological data, building inventory, and population as the primary base data for risk models. Other data, such as Gross Domestic Product (GDP) [2,5], essential and lifeline facilities [5,9,10], groundwater levels [8], and road networks [8,10], can be added to provide targeted assessments beyond the usual damage and loss estimates.

3. SEISMIC RISK MAPPING USING GIS

Seismic risk assessment forms the foundation for effective earthquake disaster management. The seismic risk methodologies shared across GIS-based models, as exemplified in Fig. 1, feature selecting a seismic scenario, creating intensity and seismic microzonation maps, and generating a composite ground shaking map [2,8–12]. Calculation of worst-case seismic scenarios using the maximum magnitude potentially generated by nearby fault lines [2,6] can be expedited using geostatistical functions such as “Measure” and “Linear Direction Mean” for fault length and strike angle, respectively [2,8]. Event-based comparisons also consider multiple segments with varying magnitudes, as shown in Fig. 2 [11]. The selection of seismic events dictates the approach used to create the isoseismal map shown in Fig. 3. Areas with active fault lines can employ Deterministic Seismic Hazard Analysis (DSHA) to estimate intensities or peak ground acceleration (PGA) / peak ground velocity (PGV) values from site-specific attenuation relationships. In contrast, fault lines with sparse seismic activity must use the probabilistic approach (PSHA) [8].

Table 1. Risk and vulnerability methodologies in developed countries [2,5]

Methodology	Description	Layers
Earthquake Disaster Risk Index (EDRI)	Assessment of earthquake risk, including seismic hazards, exposure, and vulnerabilities	Seismic data, soil map, population, number of housing units, time history of population growth, number of hospital beds, housing vacancy rates
Hazards United States (HAZUS)	An interactive GIS-based damage, casualty, and lifeline loss estimation considering physical, economic, and social elements using an SQL server database	Building inventory, critical facilities, transportation utilities, demographic
Risk Assessment Tools for Diagnosis of Urban Areas against Seismic Disasters (RADIUS)	A static aggregated preliminary loss estimation using building and population vulnerabilities in Excel	Building inventory, population, ground condition, lifeline facilities
Methods for the Improvement of Vulnerability Assessment in Europe (MOVE)	Risk and vulnerability based on exposure, susceptibility, and resilience components	Building inventory, soil classification, cadastral information, property value, building occupancy, statistical information about locality, population density
Integrated Earthquake Safety Index (IESI) and Relative Seismic Risk Index (RSRi)	Hazards, vulnerability, and response capacity localized to Tehran, Iran.	Earthquake, building, danger, and shelter data
SEISMOCARE	A static relational geodatabase created for the assessment of regional seismic damage in Greece	Building inventory, population, geology, geomorphology, peak ground acceleration, peak ground velocity
Global Earthquake Model (GEM)	A web-based global public-private relational geodatabase targeted towards developing countries	Population, administrative boundaries, global land cover, building inventory, global GDP grid
Central American Probabilistic Risk Assessment (CAPRA)	An interactive GIS-based quantitative assessment of physical, economic, and human risk	Population, building inventory, peak ground acceleration, infrastructure
Seismic Loss Estimation (SELENA)	Static MATLAB-based calculation using the capacity spectrum method for ground shaking maps and damage & loss estimation	Building inventory, demographic data, seismic scenario, soil classification

Table 2. Comparison of geospatial layers in reviewed literature [2,5,6,8–13]

Literature	Year	Layers in Relational Geodatabase
Nath [12]	2005	Seismic events, earthquake catalog, waveform data, historical earthquakes, geodetic survey, crustal and subcrustal information, lithology, shear wave velocity, fault and lineaments, drainage, slope
Hassanzadeh et al. [2]	2013	Geology, active fault, microtremor, groundwater level, alluvial thickness, geotechnical layers, topography, roads, population, building, land use, cities, and villages
Karimzadeh et al., [8]	2014	Earthquake catalog, geoid height map, microtremor dataset, alluvial thickness, groundwater level, geology, sedimentology, topography, active faults, population census, building census, earthquake distribution, geoid slope
Sauti et al. [5,9]	2021 2022	Fault lines, seismic zones, administrative boundaries, roads, slopes, buildings, residences, public facilities, schools, healthcare services, cities, population
Miura et al. [6]	2008	Geomorphological map, soil profile based on borehole data, building inventory from remote sensing
Tan et al. [13]	2019	Remote sensing imagery, elevation, vector maps, earthquake parameters (magnitude, time, coordinates, attenuation direction, focal depth)
Rusydy et al. [11]	2018	Tectonic maps, fault lines, geology, amplification map based on SPT data, building inventory, population
Hashemi and Alesheikh [10]	2011	Dwelling unit inventory, building inventory, roads, hazardous lifeline facilities, temporary settlements

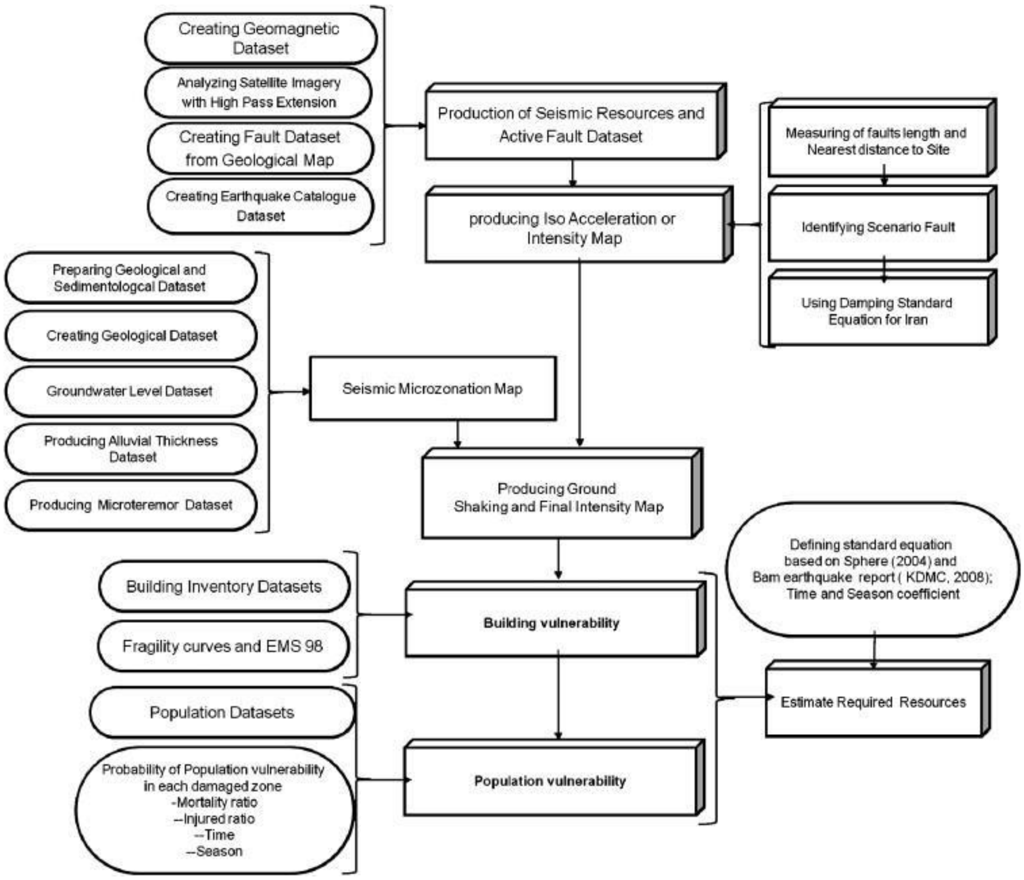


Fig. 1. Karmania hazard model methodology [2]

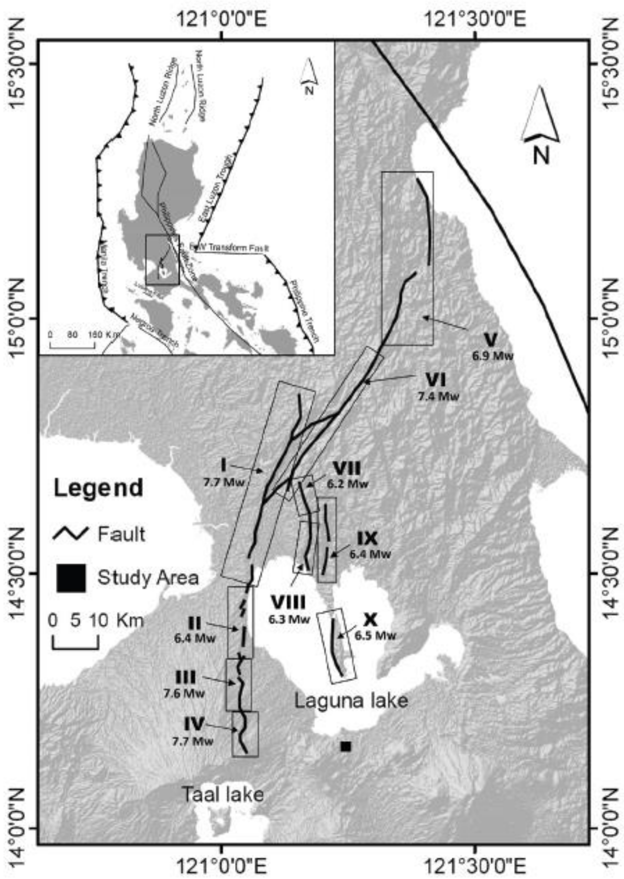


Fig. 2. Valley Fault System segments with the corresponding magnitude estimate [11,14]

Microzonation maps involve the arithmetic overlay of various geological data to estimate seismic amplitudes [2]. Geological layers can be transformed from point data to grid data through simple kriging interpolation [8]. Kriging analyzes the spatial relationships between known data points to predict values across a continuous surface, effectively filling in gaps within the data. The simplest microzonation approach uses Standard Penetration Test (SPT) N-values to identify site amplification coefficients of local soils when lacking site-specific data such as shear wave velocities [10,11]. Comprehensive geodatabases apply multicriteria decision analysis to assign relative weights to each geological layer [8,12], as detailed in Fig. 4. The models applied Eq. 1 and Eq. 2 to produce the microzonation map [2,8].

$$S = \sum \quad G_iW_iA_iM_i \ \#(1)$$

Where: S_i – seismic microzonation map in area,
G_i – geology and sedimentology in area i,
W_i – groundwater level in area i
A_i – alluvial thickness in area i
M_i – microtremor measurement in area i

$$A = \sum \quad G_iW_iT_iM_iS_i \ \#(2)$$

Where: A_i – amplification map in area i
G_i – geology and sedimentology in area i,
W_i – groundwater level in area i
T_i – alluvial thickness in area i
M_i – microtremor measurement in area i
S_i – geoid slope value in area i

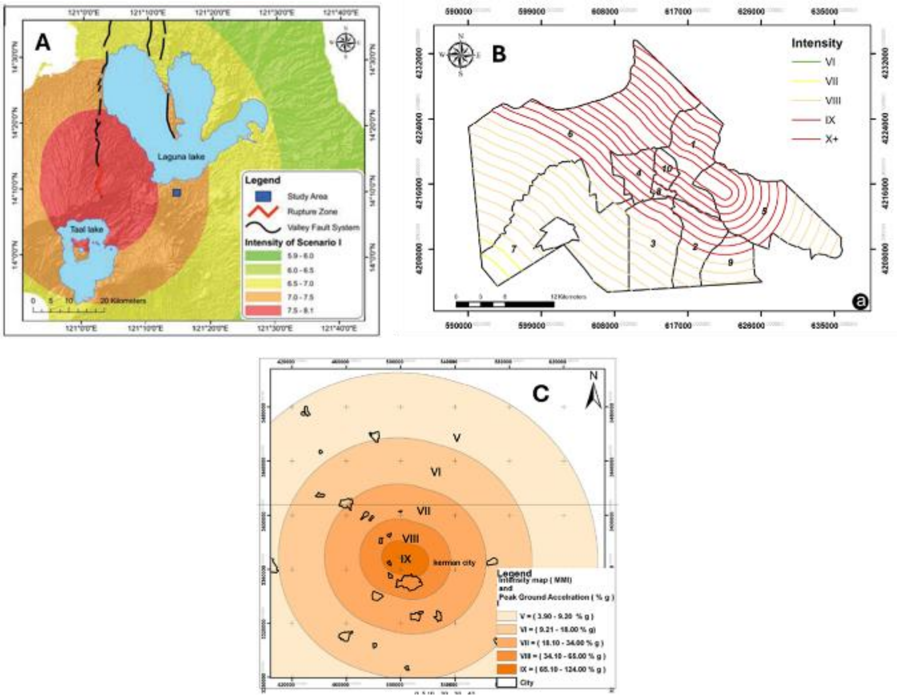


Fig. 3. Intensity maps generated across reviewed literature (a) University of the Philippines – Los Baños [11] (b) Tabriz, Iran [8] (c) Karman, Iran [2]

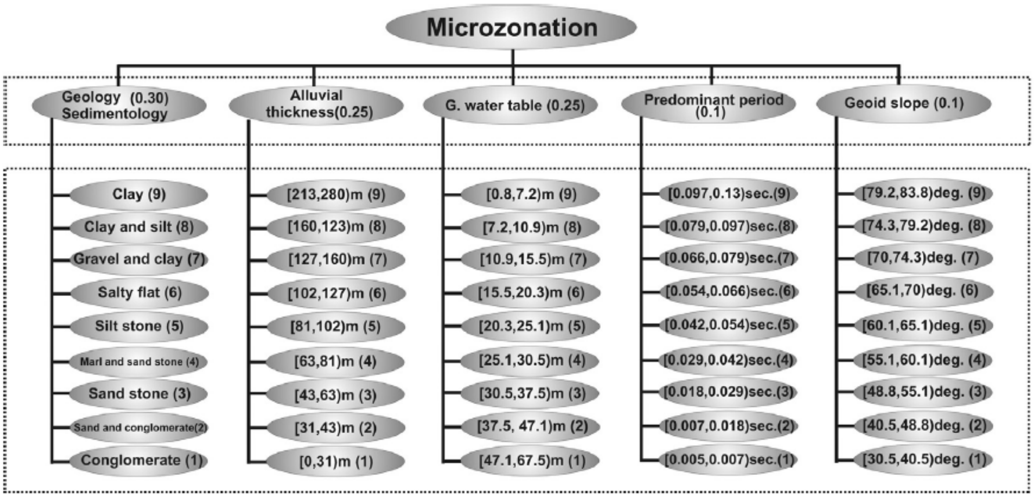


Fig. 4. Relative weights are determined using the analytical hierarchy process to assess the impact of each geological layer on the resulting seismic amplitude [8].

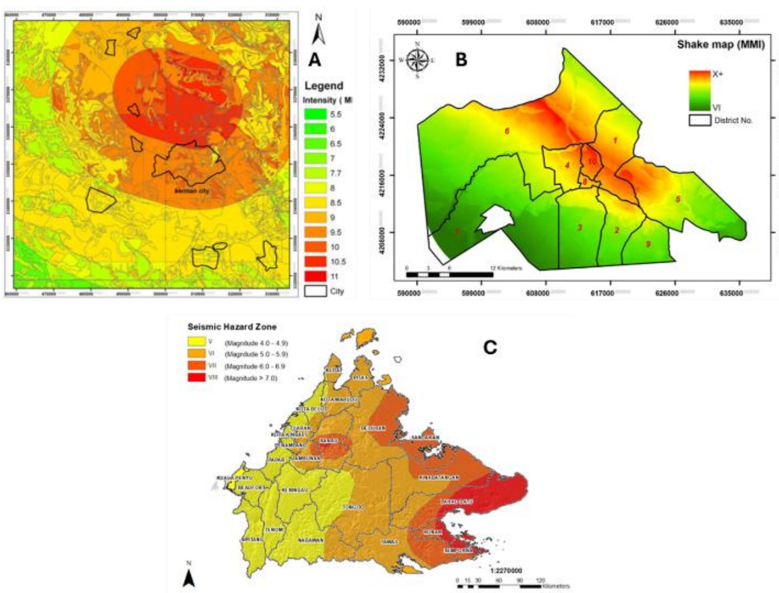


Fig. 5. Ground shaking maps generated after overlaying intensity and microzonation maps (a) Karman, Iran [2] (b) Tabriz, Iran [8] (c) Sabah, Malaysia [9]

Unifying the intensity and microzonation maps yields a composite ground-shaking map with contoured Modified Mercalli estimates for the study area, as displayed in Fig. 5. Areas with soft soil concentrations incur higher intensities due to amplification [2,6,8], which may indicate a higher estimate for predicted damage and loss predictions in the said areas.

4. DAMAGE AND LOSS ESTIMATION

Risk assessments often conclude after generating seismic risk maps, but GIS-based hazard models can be extended into damage and loss estimation phases by quantifying building and population vulnerability.

4.1 Building Vulnerability

Structural damage estimation includes predicted vulnerability, observed vulnerability, and capacity spectrum methods [2], with the latter as the usual approach. The capacity spectrum method uses fragility curves to estimate the probability of exceedance of a damaged state corresponding to a range of spectral displacements [11]. Damage ratios were classified under building capacity categories in Table 5 using queries to generate building destruction maps exhibited in Fig. 6 and 7. The models highlighted the significant probability of collapse for unreinforced masonry structures whose primary weakness lies in their lateral resistance [2,8].

Table 5. Building damage levels and descriptions based on post-earthquake damage reports [2,8,15]

Destruction Level	Damage Percent	Description
No destruction (D6)	0-2	Minimal damages
Light destruction (D5)	3-10	Very tiny cracks
Moderate destruction (D4)	11-30	50-20mm cracks observed
High destruction (D3)	31-60	>20mm cracks observed + some components are destroyed
Very high destruction (D2)	61-80	Part of the roof and a wall is destroyed
Totally destroyed (D1)	81-100	The entire roof and more than one wall are destroyed

Fig.6. A building vulnerability map generated using queries to classify damage ratios to corresponding descriptions [8].

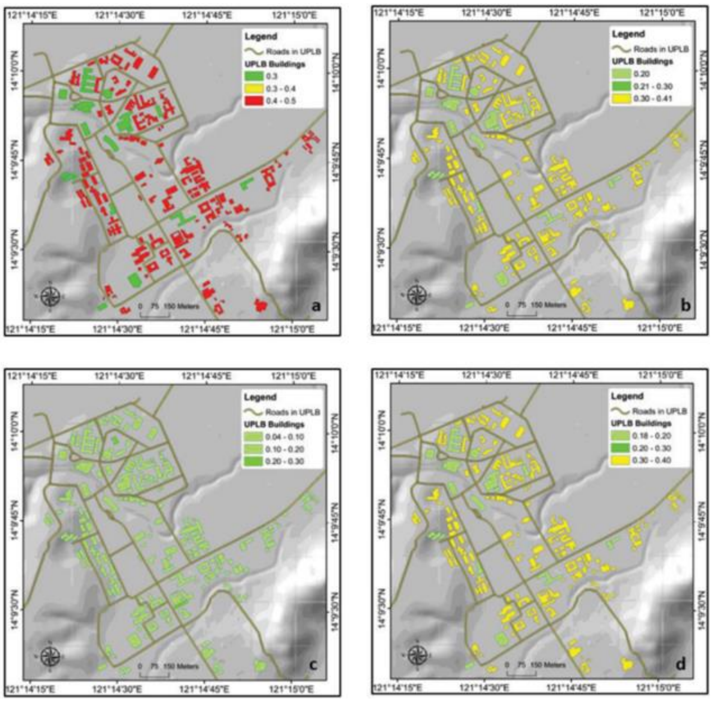


Fig.7. Scenario-based damage ratio maps from fragility curves created for UPLB campus buildings [11]

Despite their ductility against earthquakes, low-rise timber frame structures were also projected to incur significant damages [11] due to the proximity of the fault lines to the study area.

4.2 Population Vulnerability

Population vulnerability assessments were dependent on the focus of the risk assessment study. Exposure models involve identifying and quantifying factors that place the population at risk from seismic hazards, such as age, gender, health status, and socio-economic condition, among the key parameters considered [5,13]. An exposure vulnerability index map in Fig. 8 was generated by overlaying an exposure map produced using an analytic hierarchy model with intensity maps [9,13]. Malaysian studies [5,9,16,17] indicate mainly low vulnerability levels in Sabah, given the moderate seismic activity in the region. However, higher levels were observed in urbanized areas with denser populations and asset concentrations exposed to seismic hazards.

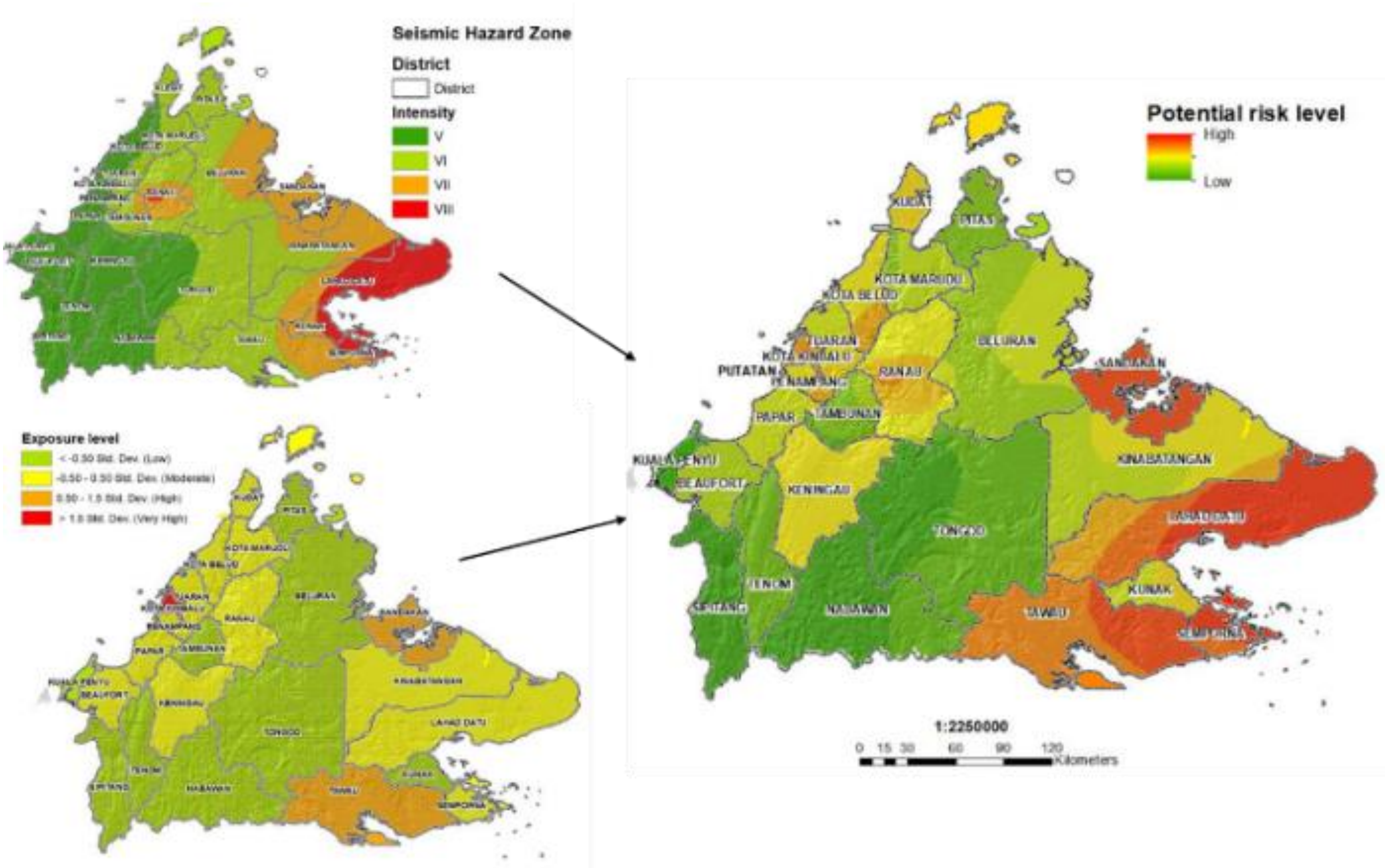


Fig. 8. Composite exposure vulnerability map for Sabah, Malaysia [9,13]

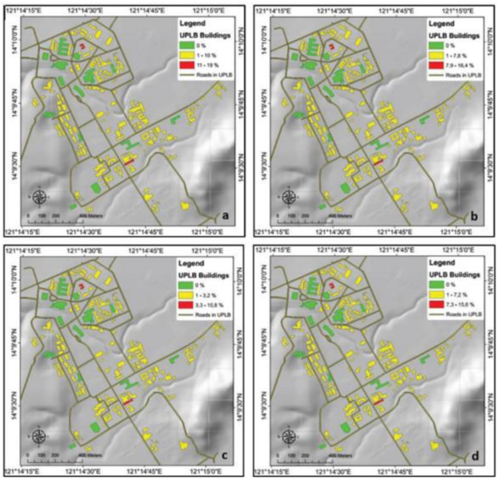
Table 6. Daytime and nighttime scenario estimates for casualties and injuries in Iranian models [2,8]

Destruction Level	Exposed Population	Vulnerable Population	Loss Level
Totally destroyed	58,167	23,848(n) 5962(d)	Dead
		9307(n) 4374(d)	Hospitalized injured
		12,215(n) 8184(d)	Non-hospitalized
		12,797(n) 39,6478(d)	Not injured
Very high destruction	15,233	2,437 (n) 609(d)	Dead
		3351(n) 1575(d)	Hospitalized injured
		4265(n) 2858(d)	Non-hospitalized
		5180(n) 10,191(d)	Not injured
High destruction	10,178	1323(n) 331(d)	Dead
		1730(n) 813(d)	Hospitalized injured
		2341(n) 1568(d)	Non-hospitalized
		4784(n) 7470(d)	Not injured
Moderate destruction	7	0(n) 0(d)	Dead
		1(n) 0(d)	Hospitalized injured.
		1(n) 0(d)	Non-hospitalized
		5(n) 7(d)	Not injured

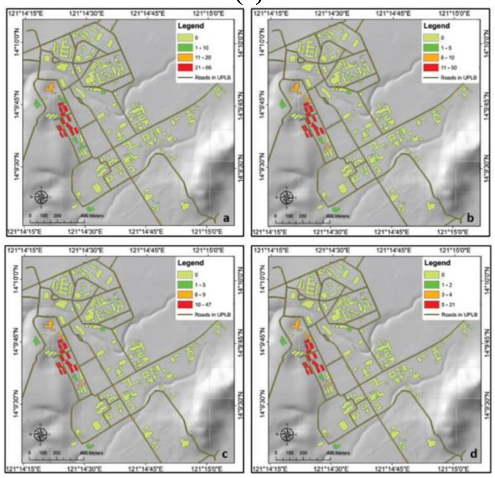
Meanwhile, loss estimation studies consider structural and non-structural damages from collapse, fires, hazardous spills, landslides, and tsunamis, or solely from building damage [8]. Recent models determined population vulnerability as a function of building damage using Eq. 3, as 75% of casualties originate from structural collapse [2,8,10]. Simulation of daytime and nighttime scenarios was also incorporated, given the variation in population distribution [2,11]. Results were tabulated under destruction and loss level categories in Table 6. Models generally suggest that earthquakes occurring at night inflict higher losses as the population remains in their residences [2,8], but daytime earthquakes record higher losses only when considering student [18] or employee populations [11].

5. POST-DISASTER RECOVERY

Recent geospatial risk models, such as Fig. 1, extended the usual seismic risk assessment to quantify resources required for immediate post-disaster recovery measures. This creates a more inclusive approach that places greater emphasis on community resilience. The Karmania hazard model [2] used equations to estimate resources listed in Table 7, accounting for the time of earthquake occurrence and the prevailing weather of the next 72 hours. The estimates highlighted the shortages of essential facilities such as food, shelter, human resources, and vehicles. For instance, a M6.3 earthquake in Karmen, Iran, will require 270,000 tents, 1,600,000 cans of food, and 800,000 loaves of bread.



DAYTIME
(a)



NIGHTTIME
(b)

Fig. 9. Injury distribution across UPLB buildings during (a) daytime and (b) nighttime populations considering different seismic scenarios [11]

Table 7. Formulation of required resources for post-disaster recovery [2,8]

Material	Formulation
Total Damaged Population (TDP)	Total Population – Dead People
Rescuer	(Hospitalized injuries + Injured non-hospitalized)/10
Shovel	Rescuer + Not injured people
Emergency toilet	TDP/20
Emergency bath	TDP/20
Stick and splint	(Hospitalized injuries + Injured non-hospitalized) × 10
Bandage	(Hospitalized injuries + Injured non-hospitalized) × 10
Field infirmary	Hospitalized injuries/100
Drinking water bottle per day	TDP × 3
Canned food per day	TDP × 4
Bread pieces per day	TDP × 2
Blanket	TDP × 1

6. RESEARCH GAPS

Integrating GIS with various models has significantly enhanced the capacity to assess seismic risks, prepare for potential impacts, and manage response efforts efficiently. Although comprehensive approaches have been illustrated, several gaps still need to be addressed, especially in the Philippines. The models in Table 1 highlight the necessity of a dynamic database, as most relational geodatabases are static. An interactive GIS-SQL database may be implemented as a public-private partnership to ensure sustained institutional support. Given the limitations in data inventory, GIS-based local seismic risk models have yet to be widely explored. The Metro Manila risk reduction report by the Japan International Cooperation Agency (JICA) [19] implied the use of GIS, yet a transparent assessment methodology needs to be detailed. A GIS-based system can enhance geological data to reduce reliance on empirical correlations for site characterization [20] and to employ multicriteria decision analyses to properly assess the impact of each geological layer on seismic amplitudes. Building inventories can be expanded to detail multiple typologies, age, height, construction quality, and correlation of structural and non-structural components with mortality and injury data. An expanded geotechnical inventory may be considered to introduce landslide and liquefaction susceptibility. Most risk assessment studies have also yet to explore the impact of post-disaster debris distribution [10]. Impeded access to road networks in densely populated areas may exacerbate initial losses, thus reducing community disaster resilience. Post-earthquake resilience data can be used to establish strategically located evacuation facilities for the surviving populace and to dictate land use policies to reduce the exposure of essential infrastructure to seismic hazards. Greater integration of socioeconomic and demographic aspects of exposure and vulnerability also provides a more inclusive approach to assessing risks and allocating post-disaster recovery resources.

7. CONCLUSION

Seismic risk assessments fulfill a vital role in disaster mitigation and preparedness. Risk quantification enables stakeholders to identify vulnerabilities and implement measures that enhance structural resilience, minimize economic loss, and regulate urban planning policies. Geospatial tools facilitate comprehensive risk modeling to accommodate seismic, geological, structural, and socio-economic datasets in relational geodatabases to illustrate potential dangers effectively. Iranian geodatabase models have incorporated layered seismic microzonation models weighted using multi-criteria decision analysis to consider site amplification effects in probabilistic and deterministic seismic risk analysis models and extended the typical damage, loss, and casualty assessments into post-disaster recovery resource estimation. A series of Malaysian studies focused on sociodemographic vulnerabilities to highlight the potential risk of earthquakes despite their low to moderate seismicity. Philippine studies have only implemented a few elements of these GIS tools given the limitations in data inventory. Improving seismic risk assessments across the Philippines requires a concerted collective effort to expand the scope of its geospatial database and to adopt new technologies to reflect the dynamic nature of exposure and vulnerability in an ever-changing world; thus, ensuring effective pre- and post-disaster management from the national down to the local levels. Addressing the identified research gaps and focusing on the suggested areas for improvement can further enhance the effectiveness and reliability of local seismic risk assessments and reduce dependence on international models which may be incompatible with the Philippine setting.

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