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APPLYING SELENA FOR STRATEGIC POST-EARTHQUAKE SHELTER PLACEMENT: A CASE STUDY FROM NEPAL

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ABSTRACT: Shelter planning following an earthquake is a critical component of disaster response and management, directly influencing the affected populations. Strategic shelter allocation must consider factors such as population density, infrastructure vulnerability, and accessibility to optimize emergency response efforts. This research introduces SELENA V7.0 (SEismic Loss EstimatioN using a logic tree Approach), an advanced open-source risk assessment tool designed to estimate potential physical damage and human losses from seismic events. Developed by NORSAR and the University of Alicante, this software has been used to enhance emergency planning through scenario-based risk analysis. The tool examines the anticipated seismic damage in the seven provinces of Nepal resulting from a probabilistic seismic hazard assessment (PSHA)-based design earthquake with a 475-year return period, reference to a 10% probability of exceedance in 50 years. Fragility models are integrated with Geographic Information System GIS-based spatial analysis to assess seismic risk across the provinces. The approach also supports identifying optimal shelter locations based on predicted infrastructure damage and accessibility constraints. The study outcomes are evaluated in terms of structural damage, economic losses varying from 0 to 1 billion Euros, number of homeless populations ranging from 2,330 to 57,463, and other relevant impact parameters as discussed in the results. The findings will equip policymakers and emergency planners to develop more effective shelter strategies, ultimately improving disaster resilience by providing critical evidence demonstrating how integrated technical and policy approaches can significantly enhance disaster resilience and emergency response effectiveness in seismic regions.

Keywords: Seismic Risk Assessment, Disaster Response, Shelter, SELENA Software.

1. INTRODUCTION

Earthquakes are among the most devastating natural hazards, causing serious threats to life, infrastructure, and economic stability. Globally, natural disasters have resulted in over $2.97 trillion in economic losses and affected more than 4 billion individuals over the past two decades [1]. Nepal is one of the countries most affected by earthquakes due to its sensitive location in the Himalayan region. It's located at the collision boundary of the Indian and Eurasian tectonic plates, which is particularly vulnerable to seismic activity. The 2015 Gorkha earthquake, with a magnitude of 7.8, caused over 8,700 deaths and 20,000 injuries, extensive infrastructure damage, and the collapse of more than 500,000 buildings [2, 3].

In such disasters, shelter intervention becomes a critical humanitarian need. However, the effectiveness of shelter responses is often hampered by poor planning, delays in implementation, and inadequate integration with critical infrastructure [4]. Damage to road networks and bridges frequently limits access to shelters and impedes the delivery of emergency assistance [4]. This demonstrates the necessity for proactive shelter planning strategies.

International frameworks such as the Sphere Standards and the Sendai Framework provide valuable guidance for shelter response and disaster risk reduction [5, 6]. Nevertheless, these are often general and lack the integration of technical seismic risk assessment tools required for precise, context-specific planning [7, 8].

To address this gap, this study utilizes the SELENA (SEismic Loss EstimatioN using a logic tree Approach) tool, a globally adaptable, open-source software designed to model seismic risk by simulating building damage, human losses, and economic impacts [9, 10]. Through integration with Geographic Information System, QGIS tools, this tool enables spatial analysis of seismic impact, helping identify priority zones for shelter deployment.

This paper applies SELENA to the Nepalese context to demonstrate a replicable, evidence-based framework for optimizing post-earthquake shelter placement. By bridging engineering-based risk modeling with humanitarian planning standards, the study contributes to more resilient and strategic emergency shelter planning in seismically active regions.

2. RESEARCH SIGNIFICANCE

This study uniquely combines seismic risk modeling with humanitarian shelter planning and response using SELENA (SEismic Loss EstimatioN using a logic tree Approach) software, integrating probabilistic risk analysis, infrastructure accessibility, and international standards such as sphere's standrads. It aids decision-makers in identifying vulnerable zones during, before or after the disaster and optimizing shelter placement, thereby advancing strategic disaster preparedness and fostering more resilient post-earthquake responses in high-risk regions. It is critical to reduce the human losses and increase the quality of emergency response. This study's originality lies in linking quantitative hazard modeling with practical post-earthquake shelter planning and policy implementation.

3. LITERATURE REVIEW

Effective disaster response requires an integrated approach combining engineering, policy, social, and humanitarian. Various international frameworks guide post-earthquake shelter planning, but challenges persist in aligning them with real-world application, especially in terms of infrastructure limitations and technical risk assessments.

The minimum standards in the humanitarian response 'Sphere handbook' provide widely accepted humanitarian guidelines for shelter design, including a minimum living space of 3.5 m^2 and 4.5-5.5 m^2 in cold areas. fire safety distances of 3 m between shelters, and site planning of 30 m of fire breaks in each 300 m of built-up area of the camp. However, they often lack structural engineering detail, especially regarding seismic resilience [5]. In parallel, the Sendai Framework for Disaster Risk Reduction (2015–2030) highlights infrastructure resilience, risk governance, and stakeholder coordination but is primarily policy-oriented and lacks prescriptive engineering content [6].

From the engineering point of view, Eurocode 8 (EN 1998-1) offers a rigorous standard for designing earthquake-resistant structures across Europe. It includes parameters such as base shear calculations, ductility considerations, and provisions for masonry structures. Nonetheless, its application in low-resource or humanitarian contexts is limited due to complexity and high implementation costs.

Rohwerder has also highlighted numerous operational gaps in post-disaster shelter response, including delays due to land ownership disputes, lack of integration with water/sanitation networks, and poor coordination between civil engineers and humanitarian agencies [7, 8]. The experience in Nepal after the 2015 earthquake revealed that many displaced populations depended on non-engineered shelters, with limited oversight on structural safety [1, 3].

Seismic risk assessment involves various methods and concepts, which are visually summarized in Figure 1. A keyword co-occurrence map was generated from 1,225 Scopus-indexed publications (2016–2020; data collected 30 April 2025), highlighting “risk assessment” as the central and most interconnected term. It is closely linked with key concepts such as “seismic risk,” “fragility curves,” and “structural dynamics,” reflecting the multidisciplinary integration of engineering, hazard

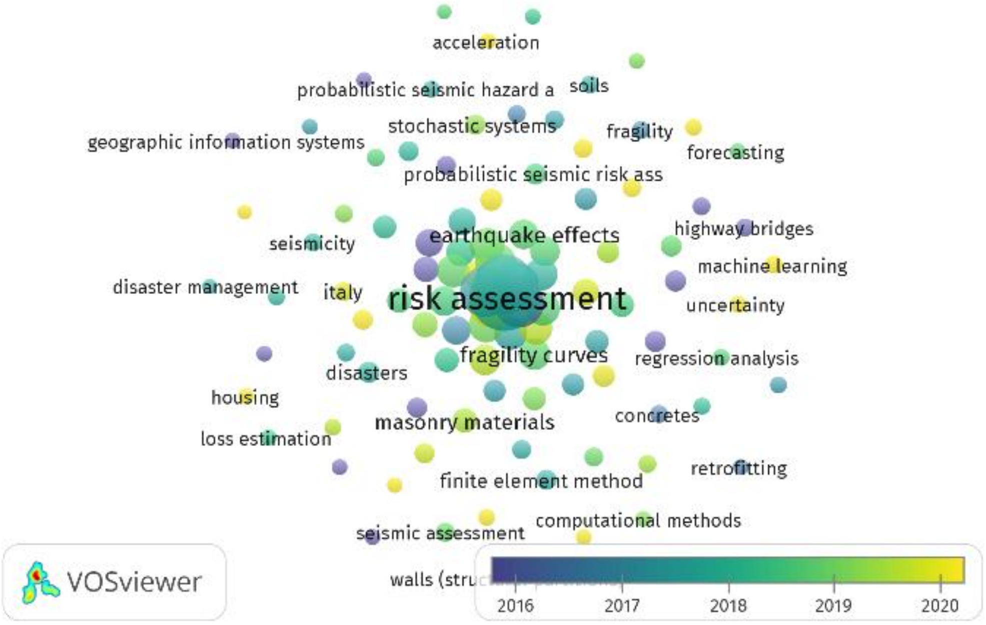

Fig. 1 Keyword mapping of seismic risk from Scopus (Source: authors)

modeling, and decision-making. Emerging terms like "machine learning" and "uncertainty" indicate a growing trend toward data-driven, probabilistic approaches, while keywords such as "building codes," "retrofit," and "masonry buildings" emphasize practical considerations in infrastructure resilience and seismic preparedness.

In terms of simulation tools used to estimate expected losses, SELENA (SEismic Loss EstimatioN using a logic tree Approach) was not commonly featured, as few studies have adopted this approach. In this study, SELENA V7.0 has been applied as a robust tool for simulating structural damage, human losses, and economic losses under seismic conditions [9, 10]. Unlike tools such as HAZUS, which focus on the U.S. context, SELENA is globally adaptable and uses fragility curves and capacity spectrum methods to estimate damage at varying levels of intensity [9, 10]. Its integration with QGIS further supports spatial analysis for decision-making in emergency response.

3.1 Global Applications of SELENA in Seismic Risk Modeling:

Despite SELENA's potential, its real-world adoption has been concentrated in focused case studies across different countries:

Algeria: Bellalem, Molina, Daniell, Maouche, Talbi, Mobarki, Ymmel, & Djellit applied SELENA to model seismic scenarios in downtown Blida, one of Algeria's most seismically active regions[11]. By simulating four distinct earthquake scenarios, they observed mean damage ratios (MDRs) reaching up to 90% in some cadastral zones. Their study also highlighted the sensitivity of this tool to ground motion prediction equations (GMPEs) and performance point methods helping authorities identify high-risk areas and prioritize retrofitting initiatives.

China: Yang, Xiang, and Bao, estimate building damage and casualties in primary schools across 15 counties impacted by the 2008 Wenchuan earthquake using the software. The study demonstrated SELENA's capability to function effectively in data-limited environments. By combining probabilistic models with CSM, they visualized varying damage distributions and identified vulnerabilities among unreinforced structures. it further validated these outcomes by comparing damage levels across regions, reinforcing the model's consistency [13].

Norway: In Oslo, Molina, Lang, & Lindholm, conducted seismic risk modeling using SELENA, supported by detailed data on subsoil properties and building typologies. The study simulated a hypothetical M6.5 earthquake on the Oslofjord fault and successfully mapped potential economic and structural losses. The comprehensive urban dataset enhanced the precision of the outputs, underscoring its utility for seismic risk planning in well-documented European urban centers [10].

Romania: In Bucharest, I. Armaş, D. Toma-Danila, and D. A. Gheorghe, used SELENA to simulate the impacts of a repeat of the 1977 Vrancea earthquake. They applied the Improved Displacement Coefficient Method (I-DCM) to assess 358 buildings, identifying unreinforced masonry structures with timber floors as highly vulnerable. Spatial maps produced using GIS and SELENA revealed MDRs up to 32%, alongside significant economic loss projections. These outputs informed both emergency preparedness and long-term urban mitigation strategies [14].

Nepal: Two studies demonstrate SELENA's critical role in assessing seismic risk in Nepal. Vineetha and Rajaram modeled a hypothetical Mw 8.4 earthquake across eleven districts, estimating losses up to €0.6 million and predicting 1,000–5,000 casualties. They identified brick masonry structures as most vulnerable and earthquake magnitude as the dominant factor influencing loss. Additionally, this study expands upon that analysis by using SELENA to assess the Koshi Province, revealing more than 57,000 displaced individuals, over 900 fully collapsed buildings, and economic losses exceeding €158 million. Spatial analysis in QGIS further enabled shelter planning based on infrastructure proximity and accessibility challenges [15].

Global Modeling: On a broader scale, Martins and Silva developed a global database that can used as inputs for SELENA of fragility and vulnerability functions for over 500 building classes as part of the GEM Foundation's risk assessment initiatives. Their work demonstrated SELENA's value in standardizing global seismic risk modeling and guiding multi-regional disaster resilience planning [16].

These diverse applications confirm SELENA's strength as a globally adaptable and analytically rigorous tool. Whether in data-rich urban centers or resource-constrained regions, the software has proven effective for estimating structural vulnerability, casualty potential, and economic losses—supporting both local interventions and international disaster risk reduction strategies.

4. RESEARCH METHODOLOGY

This study integrates seismic risk modeling with spatial analysis to support evidence-based post-earthquake shelter planning in Nepal. The methodological framework is built on the application of the SELENA V7.0 simulation software and QGIS for geospatial analysis. The process involves three main stages: risk modeling, spatial mapping, and shelter site evaluation.

4.1 Seismic Risk Simulation Using SELENA

SELENA was employed to simulate the probabilistic analysis effect of earthquake across Nepal’s seven provinces, as shown in Table 1. To ensure the reliability of the SELENA analysis, a reanalysis was performed using a previously validated case study from the Philippines. This verification step confirmed the software’s accuracy in simulating seismic risk scenarios before applying it to the Nepal context. Ground motion parameters were derived from probabilistic seismic hazard analysis, with PGA values ranging between 0.25 and 0.4 g, representative of Nepal's seismicity. Also, before running the simulations, raw input data—including building typologies, population distributions, and cost per square meter —were reviewed, cleaned, and converted to ASCII format to ensure consistency with SELENA’s input structure and data requirements. This analysis estimates building damage, casualties, and economic losses by combining datasets such as: Seismic hazard inputs, derived from regional ground motion prediction models [2], Building typologies, obtained from OpenQuake and categorized by structural characteristics [16], Population distribution, adjusted for occupancy patterns at different times of day [1], Soil classification, using Vs30 values to account for local amplification effects [2,15], Fragility and capacity curves, sourced from global vulnerability databases and GEM standards [17]. SELENA applies the Capacity Spectrum Method (CSM) and a logic tree structure to capture uncertainties in both hazard and vulnerability models [9,10]. Outputs include damage states (none, slight, moderate, extensive, and complete), projected displacement, casualties, and direct economic losses per region.

4.2 Spatial Analysis with QGIS

Simulation results were imported into QGIS 3.36.2, a Geographic Information System (GIS) used to visualize and analyze the spatial distribution of earthquake impacts [18]. QGIS enabled layering of SELENA outputs to identify high-risk areas and infrastructure exposure. Key visualized data included: Damage distribution and collapse densities by administrative region, Estimates of displaced populations and homeless individuals [16], economic losses and number of injuries. This mapping was essential in guiding shelter planning by highlighting accessible and high-need zones.

Table 1 Administrative regions level 1 of Nepal include 7 Geounits and relevant building stock (source: The Open Quake Platform, accessed: 01 April 2025)

Region Name	ID	Number of buildings
Bagmati	NP-P3	1,108,047
Gandaki	NP-P4	1,064,718
Karnali	NP-P6	948,806
Lumbini	NP-P5	634,612
Madhesh	NP-P2	612,709
Province 1 (Koshi)	NP-P1	266,458
Sudur Paschim	NP-P7	630,546

4.3 Shelter Site Identification and Planning

The city of Biratnagar, located in Koshi Province as shown in the Figure 2, was selected for focused shelter planning due to its high vulnerability as shown by SELENA outputs. Satellite imagery and infrastructure data were used to locate and assess potential shelter areas as shown in Figure 7. Each site was evaluated using the Sphere Standards [5], which define A minimum area of 3.5 m² per person for emergency shelters, Spatial layout guidelines for safety, privacy, and Water, Sanitation, and Hygiene WASH, Accessibility standards for emergency response logistics and mobility. Shelter capacity was calculated using available free area based on critical infrastructure evaluation in the area, and WASH needs (water points and latrines) were estimated based on Sphere’s recommended ratios. Road access and redundancy were also considered to ensure rapid deployment and minimize logistical delays [4,6].

Fig. 2 Administrative region level 1 of Nepal with seven provinces (Source: authors)

5. RESULTS

This study used SELENA V7.0 and QGIS 3.36.2 to assess seismic vulnerability and improve guidance of shelter planning and response across Nepal's provinces. The results highlight spatial patterns of seismic hazard, building damage, human casualties, economic losses, and shelter requirements. The findings support evidence-based decisions for disaster preparedness and emergency response.

5.1 Seismic Hazard and Ground Motion

Probabilistic analysis revealed that provinces like Bagmati and Gandaki exhibit the highest PGA values (0.375 – 0.6 g), indicating elevated seismic hazard levels. This distribution aligns with Nepal’s tectonic profile and underscores the need for targeted risk reduction in central regions.

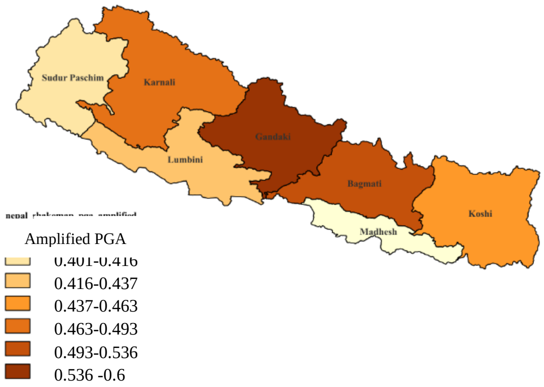

Fig. 3 Spatial distribution of amplified PGA values across Nepal's provinces from probabilistic seismic analysis (Source: authors).

5.2 Structural Damage Assessment

SELENA simulations estimated building damage across 20 taxonomies and four damage states. Koshi, Bagmati, and Madhesh provinces consistently report the highest counts of slightly, moderately, extensively, and completely damaged buildings. For example, complete collapse in Koshi exceeded 900 buildings, pointing to urgent retrofitting needs. In contrast, western provinces like Karnali and Sudur Paschim reported minimal damage, reflecting lower hazard exposure and/or smaller urban footprints.

5.3 Displacement and Homelessness

As shown in Figure 4, the projected number of homeless individuals is highest in Koshi and Madhesh, with up to 57,000 people will be displaced. driven by building collapse and dense urban populations. These figures directly inform emergency shelter planning and resource allocation, especially in provinces with limited resilience capacity.

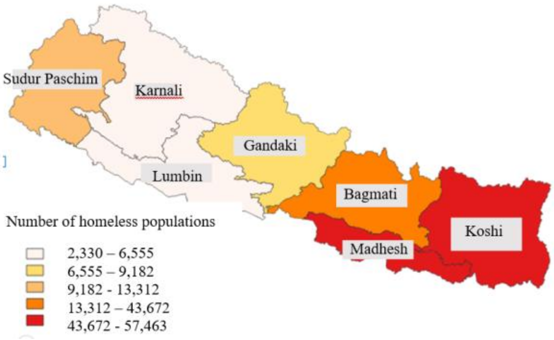

Fig. 4 Spatial distribution of the homeless population across provinces of Nepal (Source: authors).

5.4 Casualty and Injury Estimates

The number of injury projections across three critical time frames, which are 2:00 A.M., 10:00 A.M., and 5:00 P.M. Nighttime injuries are significantly higher due to residential occupancy. At 2:00 A.M., Koshi, Madhesh, and Bagmati show the greatest injury rates. During the daytime, injuries are less due to population dispersion, but the ratio rises again by 5:00 P.M. as people return home. These trends emphasize the importance of time-sensitive emergency medical planning. Figures 5 illustrate the highest peak hour of injuries at midnight.

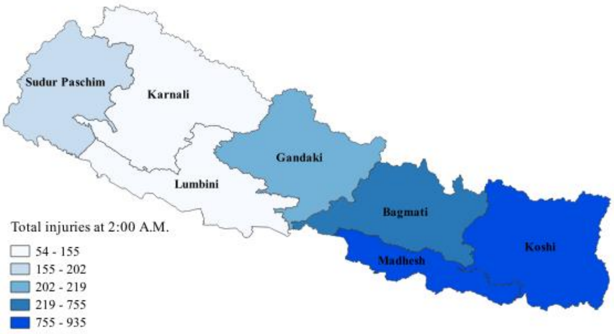

Fig. 5 Total number of injuries at 2:00 A.M (Source: authors)

5.5 Economic Loss Estimates

The direct economic losses were estimated using a probabilistic methodology that incorporates damage probabilities, structural typologies, and spatially distributed exposure. The total economic loss was calculated using this formula from the tool's manual [10]:

$$L_{eco} = C_r \times \Sigma_{i=1}^{N_{OT}} \Sigma_{j=1}^{N_{BT}} \Sigma_{K=1}^{N_{DS}} \times A_{i,j} \times P_{j,k} \times C_{i,j,k} \qquad (1)$$

Where:

N_{OT} - Number of occupancy types,

N_{BT} - Number of building typologies,

N_{DS} - Number of damage states ds,

Cr - Regional cost multiplier (currently set to 1.0, but it can have different values for each geographical unit in order to take into account the geographic cost variations),

$A_{i,j}$ - Built area of the model building type j in the occupancy type i (in m^2)

$P_{j,k}$ - Damage probability of a structural damage k (slight, moderate, extensive, or complete) or model building type j,

$C_{i,j,k}$ - Cost of repair or replacement (per m^2) in the provided input currency of structural damage k for occupancy type i and model building type j (provided by input files elossi.txt).

Figure 6 presents estimated direct economic losses per province. Koshi Province shows the highest losses, between €140 million and €158 million, followed by Madhesh and Bagmati. In contrast, Karnali and Sudur Paschim reflect lower financial impacts (under €21 million), corresponding to smaller urban exposure. These disparities stress the need for region-specific investment in mitigation and response capacity.

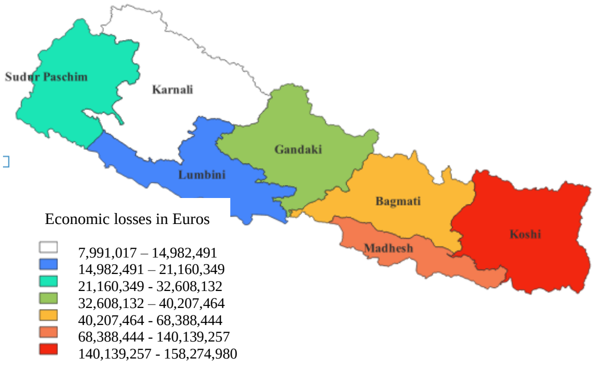

Figure 6 Estimated economic losses by province from seismic events (in Euros) (Source: authors).

5.6 Operationalizing Shelter Planning in Seismic Emergency Scenarios

Effective shelter planning and response in seismic regions requires deep knowledge of the international frameworks, such as the Sendai Framework, Eurocode 8, and Sphere Standards. In the practical field, locally adapted strategies. While these frameworks promote resilience, risk reduction, and community engagement, their implementation often faces barriers in resource-constrained settings. This research demonstrates that integrating advanced seismic risk tools like SELENA with context-specific data enables a multi-dimensional understanding of infrastructure vulnerability and access, essential for emergency shelter planning.

This study applied its findings to a real-world example in Biratnagar, the urban center most affected in Koshi Province. The evaluation of post-earthquake emergency response capacity was conducted by generating a 200-meter resolution map using satellite imagery from Google Earth as shown in Figure 8. This map served as the foundation for evaluating the spatial distribution of critical infrastructure and available open spaces, thereby identifying suitable locations for the deployment of emergency shelters. The analysis yielded three potential shelter areas, designated A1, A2, and A3, with respective areas of 80,404 m², 42,800 m², and 37,140 m², respectively. Furthermore, the analysis identified six critical infrastructure buildings, including hotels, the Morang campus, Sagarmatha Secondary School, the Ganesh Temple, and other schools. In the event of a seismic occurrence, critical infrastructures may be mobilized if they have been designed to resist such events and to provide seismic resilience for the surrounding population. The following map illustrates the locations in question.

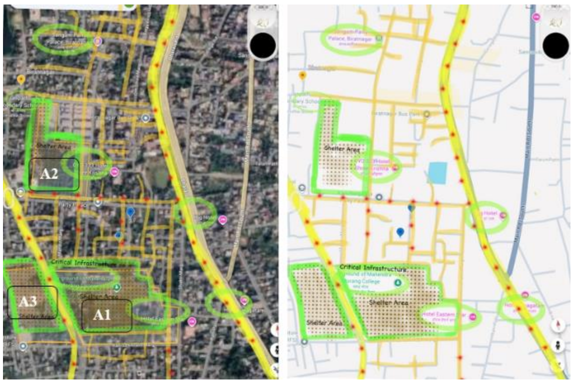

Fig. 7 plan of proposed shelter area based on critical infrastructure in Biratnagar, Koshi Province (Source: authors).

5.6.1 Emergency plan for Biratnagar:

An emergency WASH and shelter plan for the three designated areas in Biratnagar was developed based on Sphere Standards, which recommend a minimum of 3.5 m² per person and include 3 m spacing requirements between shelters to ensure safety and privacy. In an emergency camp, each shelter with a 3-meter buffer on all sides requires approximately 54 m². By using this living area for shelter, Area A1 with 80,404 m² can host 1,488 shelters for 7,440 people as the shelter can host one household of 5 family members. Area A2 with 42,800 m² can support 829 shelters for 4,145 people, and Area A3 of 37,140 m² can accommodate 719 shelters for 3,595 people. Corresponding water point and latrine needs were also calculated using Sphere ratios—1 water point per 250 people and 1 latrine per 20 people. Water points must be accessible within 500 meters of all shelters, and latrines should include gender-sensitive and accessible options. The table below summarizes the shelter capacity and WASH requirements for each area. Table 2 summarizes the emergency plan can done in the three identified sites.

Table 2 The summary of emergency WASH and Shelters needed based on the area.

Area	Total Area (m²)	Shelters	People Capacity	Water Points	latrines
A1	80,404	1,488	7,790	30	372
A2	42,800	829	4,145	17	207
A3	37,140	719	3,595	15	180

5.6.2 Prototype shelter design:

Drawing on the author's field experience in emergency shelter programs, particularly with the International Organization for Migration - IOM Shelter and Non-Food Items sector, a practical and scalable prototype shelter is proposed for post-earthquake housing in the selected area. In line with Sphere Association [5], guidelines and humanitarian shelter standards, the design features a 3 × 6 meter structure intended to accommodate a family of five members. The material proposed for the shelter is wood as a primary material due to its environmental sustainability, recyclability, and proven seismic resilience. Wood's flexibility allows the structure to absorb shock during seismic events, making it especially suitable for disaster-prone regions, while its lightweight and simple structure supports rapid assembly, relocation, and long-term usability, aligning with sustainable construction principles that emphasize locally sourced, low-impact materials [17]. This design balances immediate emergency needs with principles of environmental responsibility and structural safety, supporting both short-term humanitarian assistance and long-term recovery efforts as it can be easily upgraded. Figures 8 and 9 illustrate the prototype's plan and longitudinal section.

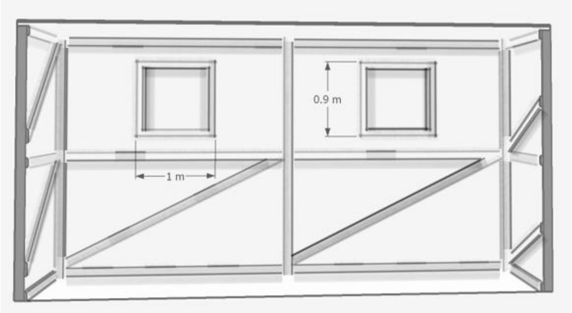

Fig. 8 Shelter prototype longitudinal section (Source: authors)

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6. DISCUSSION

This study aimed to evaluate post-disaster shelter response sustainability and infrastructure resilience interventions in earthquake zones, with a particular emphasis on the civil engineering, technology, and policy-making functions. with simulation tools and case studies, a complex interaction of technical, organizational, and contextual factors shapes disaster preparedness, response, and recovery. The findings confirm that while global disaster risk reduction frameworks—such as the Sendai Framework, Eurocode 8, and the Sphere Standards—provide valuable guidance, gaps remain in operationalizing these standards within resource-constrained, high-risk settings. Eurocode 8 emphasizes structural safety but lacks social context; the Sphere Standards focus on dignity and access but fall short on seismic resilience; and the Federal Emergency Management Agency FEMA's models offer technical depth yet are difficult to apply outside well-resourced environments. These limitations highlight the need for a multidisciplinary approach that blends structural engineering principles, humanitarian needs, and geospatial risk analysis.

Using the SELENA simulation platform and QGIS visualization tools, the study presented a probabilistic assessment of seismic risk across Nepal.

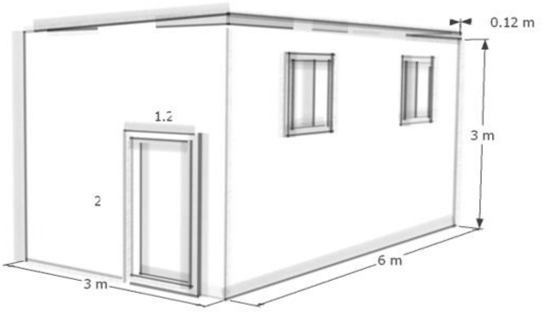

Fig. 9 Shelter prototype design (Source: authors).

The results showed clear regional disparities in hazard exposure, structural vulnerability, and expected damage. Provinces such as Koshi, Bagmati, and Madhesh consistently demonstrated the highest levels of damage, displacement, and economic loss, particularly under nighttime scenarios when residential occupancy peaks. These findings underscore the value of temporal and spatial vulnerability analysis in guiding time-sensitive emergency planning and targeted retrofitting.

The simulation also revealed an east-to-west gradient in seismic intensity and building collapse, closely aligned with tectonic fault zones and population densities. Economic loss estimates further emphasized this regional variation, with Koshi alone expected to incur up to €158 million in direct damages. These high-risk areas demand not only technical upgrades and engineering interventions but also robust planning strategies that account for infrastructure access, road network redundancy, and service delivery.

A real-world application of the study's findings in Biratnagar demonstrated how simulation outputs can directly inform emergency shelter planning. By identifying open spaces, calculating capacity under

Sphere Standards, and evaluating access to critical infrastructure, the study proposed a shelter strategy that is both context-sensitive and scalable. The shelter prototype—based on sustainable materials and seismic resilience—offers an adaptable solution that balances emergency needs with long-term recovery goals.

Ultimately, the study affirms that technical capacity exists to model and address seismic risk comprehensively.However, effective implementation requires greater institutional coordination, investment in local capacity, and mainstreaming of disaster-resilient design into planning systems. Integrating data-driven tools like SELENA into local policy and engineering practice can bridge the gap between analysis and action—ensuring safer, more sustainable shelter responses in future seismic emergencies.

7. CONCLUSIONS

The research assesses seismic risk and shelter planning by utilizing tools like SELENA V7.0 and QGIS-based spatial analysis. It focuses on simulating the impacts of earthquakes on 7 provinces of Nepal, specifically zones like Koshi, Bagmati, and Madhesh, which are estimated to experience the highest number of damages. For instance, Koshi is single-handedly anticipated to experience economic loss of up to €158 million and leave over 57,000 individuals homeless due to the building collapse. The total number of slightly damaged buildings in the 7 provinces is 530,863, 43,196 buildings in moderate damage state, while for extensive and complete damage are 6,315 and 1,851 buildings respectively. Three potential shelter sites in Biratnagar that would accommodate approximately 7,440 people were also identified in the research, based on Sphere Standards for shelter and WASH planning. These findings can support policymakers in making evidence-based decisions for prioritizing shelter allocation, refining urban emergency plans, and investing in region-specific seismic risk mitigation strategies.

8. FUTURE DIRECTIONS

Building Future research should expand on these findings by applying advanced seismic assessment methods, such as deterministic analysis and SELENA–MATLAB integration, to improve accuracy and validate the research findings. Incorporating site-specific ground response analysis, as emphasized by Labar, Bektaş, and Kegyes-Brassai [19], will enhance shelter prototype reliability in varied soil conditions. Strengthening transportation networks and leveraging GIS, drones, and real-time monitoring can improve emergency access and coordination, particularly in low-resource areas. Culturally informed shelter designs and aftershock performance testing will further ensure relevance and resilience. Finally, multi-disciplinary collaboration and institutionalized planning are essential for building communities that can withstand and recover from seismic events. Future studies could integrate seismic site characterization and liquefaction assessment with geophysical analysis for landslide-prone areas to enhance hazard mitigation strategies and improve the resilience of civil infrastructure[20,21].

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