Probabilistic Seismic Hazard Assessment of Central Nepal Himalayan Region

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ABSTRACT

The Central Nepal Himalayan region is one of the most seismically hazardous areas on Earth due to the ongoing collision of the Indian and Eurasian tectonic plates. This study presents a comprehensive Probabilistic Seismic Hazard Assessment (PSHA) for this region, utilizing an updated earthquake catalog and modern analytical techniques. We compiled seismic data for the central Himalayas, removed aftershocks through declustering, and estimated earthquake recurrence parameters using the Gutenberg-Richter relation. The frequency–magnitude analysis yields a Gutenberg-Richter b-value of approximately 0.9, indicating a slightly higher proportion of larger earthquakes compared to the global average. Using these parameters and appropriate ground motion models, we computed the likelihood of exceeding various levels of ground shaking across the region. The results are synthesized in a seismic hazard map for peak ground acceleration (PGA) with a 10% probability of exceedance in 50 years (equivalent to a 475-year return period). The hazard map reveals significant potential ground motions, with PGA values ranging from 0.3 to 0.5 g in portions of central Nepal. These levels of seismic hazard are comparable to or exceed previous estimates, underscoring the significant earthquake risk faced by the region's population centers. Our findings highlight the critical need for earthquake-resistant design and risk mitigation measures in central Nepal. This study not only updates the seismic hazard profile of the region, considering recent data (including the 2015 Gorkha earthquake), but also provides a methodological framework for ongoing hazard assessment efforts. The comprehensive PSHA presented here will aid engineers, urban planners, and policymakers in developing effective strategies to improve resilience against future earthquakes.

Key words: PSHA; Seismic Hazard in Himalaya

1 INTRODUCTION

Nepal lies in the active Himalayan collision zone where the Indian Plate thrusts under the Eurasian Plate, resulting in frequent earthquakes and a high seismic hazard. The country's historical record includes devastating large earthquakes, such as the Mw 8.0 1934 Nepal–Bihar earthquake, which severely damaged Kathmandu and caused approximately 10,600 fatalities, and the more recent Mw 7.8 Gorkha earthquake of 2015, which struck central Nepal, resulting in nearly 9,000 deaths (Avouac et al., 2015; Bai et al., 2019; Dixit et al., 2015; Kurashimo et al., 2019; Pandey et al., 1999b). These events starkly highlight Nepal's vulnerability to seismic disasters. Indeed, despite large earthquakes being relatively infrequent on the Main Himalayan Thrust, the region's dense population and infrastructure exposure make even moderate events potentially catastrophic. This context underscores the importance of robust seismic hazard assessment for Nepal.

Probabilistic Seismic Hazard Assessment (PSHA) is a methodology to quantify the likelihood of different levels of earthquake ground shaking occurring in a region over a given time period. Unlike deterministic scenarios, PSHA considers the full range of possible earthquakes and their uncertainties in size, location, and recurrence. The approach, first formalized by Cornell & Toro (1970), combines information on earthquake recurrence with models of ground motion attenuation to estimate the probability of exceeding various ground-motion levels. PSHA results are often expressed as hazard curves or maps for specified probability levels, which are crucial for developing building codes and risk mitigation strategies.

In Nepal, systematic seismic hazard assessments began in the 1990s. A UNDP-supported project in 1993 produced the first seismic hazard map for Nepal as part of the national building code development (NBC 105:1994). That study estimated peak ground accelerations (PGA) for a 500-year return period (10% probability in 50 years) and delineated seismic zones used in the building code. Subsequent studies have refined the hazard model. Notably, Pandey et al. (1999a) carried out a country-wide PSHA using the CRISIS99 software, dividing Nepal into 12 seismic source zones and employing an attenuation relation from Youngs et al. (1997). Their results, shown in Figure 1, provided an updated seismic hazard map for Nepal with PGA values ranging roughly from 0.10g to 0.45g (on rock, 10% in 50 years) across the country. This map informed Nepal's engineering design practices in the early 2000s. More recent analyses have continued to update Nepal's hazard

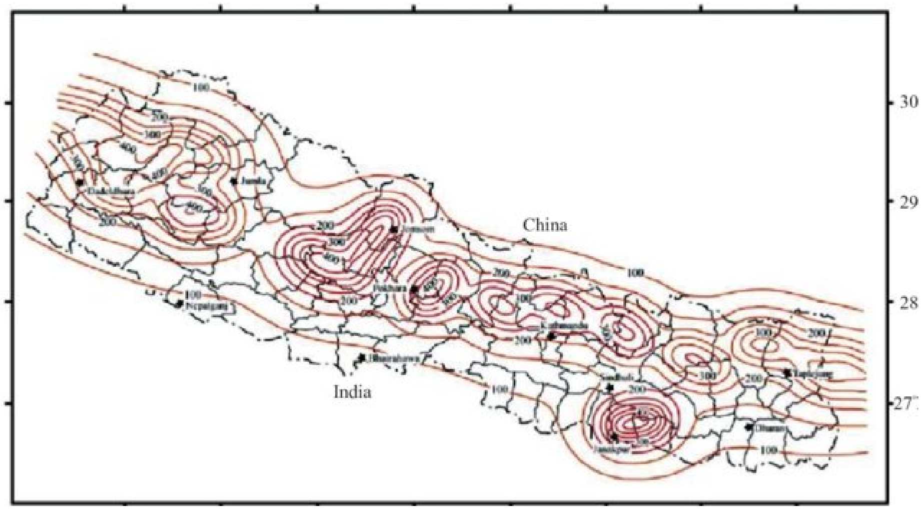

Figure 1: : Seismic hazard map of Nepal from Pandey et al. (2002), showing contours of peak horizontal acceleration (in units of %g) with 10% probability of exceedance in 50 years. This prior study identified significant hazard across the Nepal Himalaya, with values ranging up to 0.45g in parts of the country. It provided the basis for Nepal's building code seismic zonation.

assessment: for example, Parajuli et al. (2010) applied kernel-based earthquake density estimation and multiple ground-motion prediction equations to account for epistemic uncertainties, finding especially high hazard around the Kathmandu Valley. Thapa & Wang (2013) further refined the source zonation (delineating 23 seismic source zones) and produced hazard maps for various probability levels, noting significant hazard in the far-western and eastern Nepal Himalayas. These studies commonly conclude that central and eastern Nepal face very high seismic risk and emphasize the need to update hazard models as new data become available periodically.

Given the advances in data collection and methodology since the early 2000s – including an expanded earthquake catalog and lessons from the 2015 Gorkha event – it is imperative to reassess the seismic hazard in central Nepal with up-to-date information. The central Nepal Himalayan region, encompassing the greater Kathmandu area and surrounding districts, is of particular concern due to its concentrated population and infrastructure in a zone of high tectonic strain. This paper presents a detailed PSHA for the Central Nepal Himalaya, using an updated earthquake catalog and state-of-the-art methods. We aim to quantify the current level of hazard (in terms of PGA for a 10% exceedance in 50 years) for the region and compare it with previous assessments. In the following sections, we describe the data and methodology, present the resulting seismic hazard model and maps, discuss their implications in the context of prior studies, and finally conclude with recommendations for earthquake risk management in Nepal.

2 METHODS

Our probabilistic seismic hazard assessment follows the standard PSHA procedure, which involves: (1) assembling a seismic source model from earthquake occurrence data, (2) selecting ground-motion prediction models to estimate shaking from those earthquakes, and (3) performing a probabilistic calculation to obtain hazard levels for specified exceedance probabilities. Below, we detail each of these steps as applied to the Central Nepal Himalayan region.

2.1 Study Region and Earthquake Catalog

The study region spans approximately 80°E–88°E in longitude and 26°N–30.5°N in latitude, covering central Nepal and adjoining areas of the Himalayan frontal fault system. We compiled an earthquake catalog for this region from multiple sources, including the United States Geological Survey (USGS) and Nepal's National Seismological Centre, incorporating both historical events and modern instrumental records. The catalog extends back to the year 1255 A.D. for major historical earthquakes and is comprehensive for instrumental events roughly since the early 20th century. To ensure consistency, all earthquakes magnitudes were converted to moment magnitude (Mw) using appropriate empirical relationships for different original magnitude scales. The raw compiled catalog contained on the order of a few thousand events down to small magnitudes.

A key aspect of preparing the catalog for PSHA is declustering, which removes dependent events (aftershocks and foreshocks) so that the remaining events represent a Poissonian, independent occurrence process. We applied a standard declustering algorithm (the Gardner and Knopoff window method) to eliminate aftershocks from the catalog. This reduced the total event count significantly, from 2250 events to 1271 events in the final declustered catalog (for the magnitude range considered). The declustered catalog is assumed to represent the activity of the principal seismogenic sources in the region without double-counting clusters of shocks from single earthquake sequences. We then assessed the completeness of the catalog to determine a magnitude threshold above which the data can be considered complete for the time period of interest. By examining the rate of earthquake occurrences over time, we identified a magnitude of completeness around $Mc \simeq 4.4$, meaning that all earthquakes of about 4.4 and greater are reliably recorded in the catalog over the past several decades. We therefore base our recurrence analysis on events with $M \geq 4.4$ in the declustered catalog.

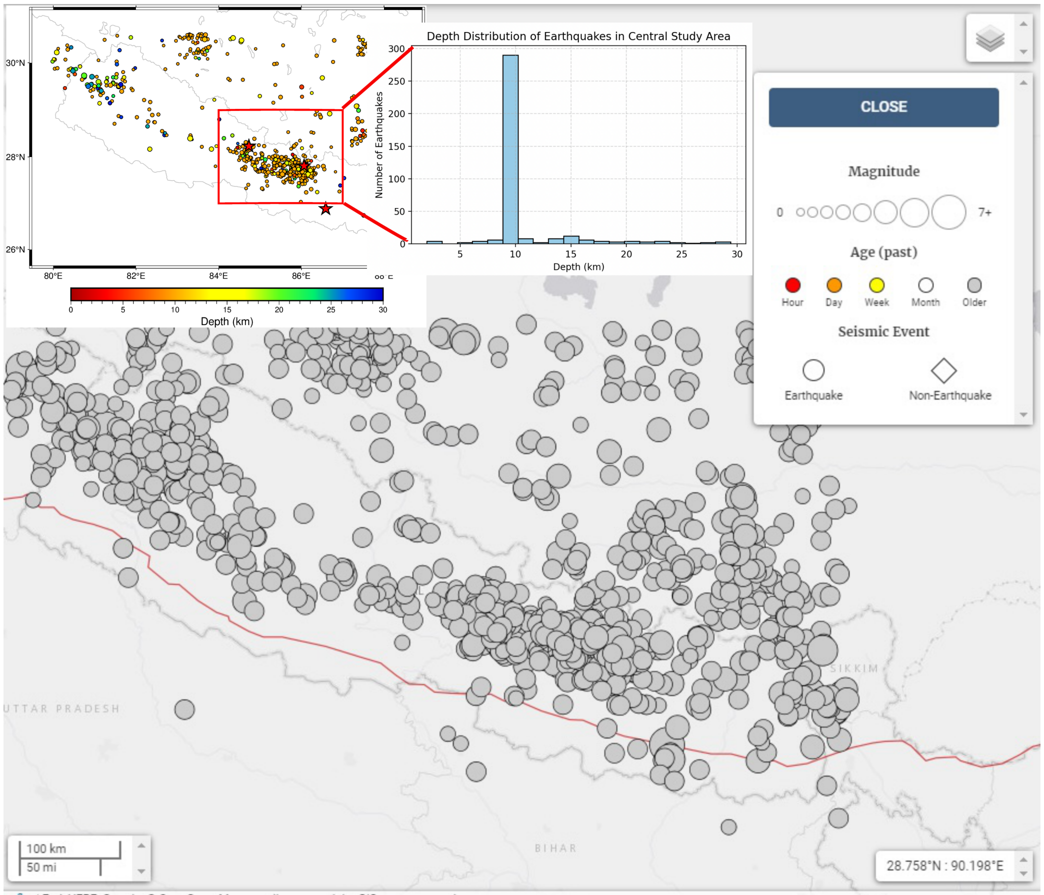

Figure 2: Spatial distribution of earthquakes in the declustered catalog for central Nepal (circles denote earthquake epicenters). This map, generated from the USGS earthquake database, shows 1,271 independent events (after aftershock removal) in the study region. The density of epicenters is highest along the Himalayan belt, delineating the active Main Himalayan Thrust and associated structures. The red line represents the Main Frontal Thrust (southern border of the Himalayas).

2.2 Earthquake Recurrence Model

We characterized the seismic source for PSHA using an area-source model covering the central Nepal Himalaya. Within this source, earthquakes are assumed to follow the Gutenberg-Richter frequency–magnitude relationship, which is commonly expressed as:

$$\log_{10} N(M) = a - bM \tag{1}$$

where $N(M)$ is the cumulative annual frequency of earthquakes with magnitude $\geq$ M, b is the slope (the Gutenberg-Richter b-value), and a is the productivity constant representing overall activity rate. We estimated the parameters a and b from the processed earthquake catalog. The Gutenberg-Richter b-value was calculated using the maximum-likelihood method of Aki (1965), which provides an unbiased estimator even for incomplete data bins. In this method, b is given by (Aki, 1965; Bender, 1983; Utsu, 1965):

$$b = \frac{\log_{10}(e)}{\overline{M} - \left(M_c - \frac{\Delta M}{2}\right)} \tag{2}$$

where $\overline{M}$ is the mean magnitude of events above the completeness threshold Mc, and ΔM is the binning interval (here 0.1, so $\Delta M/2 = 0.05$). For our catalog (with Mc = 4.4), the maximum-likelihood computation yielded b $\approx$ 0.90, with a standard error on the order of 0.03. The statistical uncertainty for maximum likelihood b-value estimates was determined using Shi & Bolt (1982).

$$\sigma_b = \frac{b^2}{\log(e)} \sqrt{\frac{\sum_{i=1}^{n} (M_i - \bar{M})}{n(n-1)}}, \tag{3}$$

This b-value indicates that the relative frequency of large to small earthquakes in central Nepal is slightly below unity, which is in line with typical active tectonic regions (a b-value around 1.0 is often observed globally). The Gutenberg-Richter a-value was determined from the rate of events above Mc; in our case, the catalog data suggest an annual rate of roughly 5.41 earthquakes of $M \geq 4.4$, corresponding to an a-value (intercept) of about 6.6 (in the log10 scale). The resulting regional recurrence relationship can be written as $log_{10} N = 6.6 - 0.90M$, which was used as the seismic source model for the PSHA calculations.

2.3 Ground Motion Prediction Models

To compute ground shaking at sites due to potential earthquakes, we adopted empirically-based ground motion prediction equations (GMPEs) appropriate for

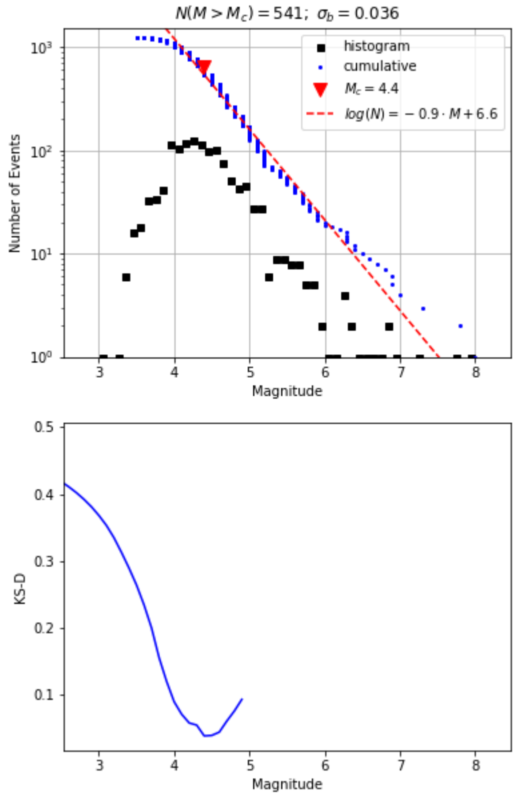

Figure 3: Magnitude-frequency analysis of the central Nepal earthquake catalog. (Top panel): Logarithmic plot of the earthquake magnitude distribution. Black squares represent the histogram of events, while blue dots show the cumulative number of events. The red inverted triangle indicates the magnitude of completeness, $M_c = 4.4$, above which the Gutenberg–Richter law is applied. The red dashed line is the best-fit Gutenberg–Richter relation, $\log_{10} N = -0.9M + 6.6$, derived using the maximum likelihood method. The catalog includes 541 independent events above M_c, with an estimated b-value uncertainty of $\sigma_b = 0.036$. **(Bottom panel)**: Kolmogorov–Smirnov (K–S) statistic as a function of magnitude, showing the goodness-of-fit between the observed and modeled distributions. The minimum K–S distance at $M = 4.4$ supports the choice of completeness magnitude.

the Himalayan region. Previous PSHA studies in Nepal have used attenuation relations developed for similar tectonic environments (for example, Youngs et al. 1997 for subduction-zone interface earthquakes). For this study, we selected a modern GMPE that has been validated against strong-motion data in active continental collision zones comparable to Nepal. In particular, we utilized a ground-motion model that accounts for the magnitude, distance, and site conditions to estimate peak ground acceleration (PGA) on rock sites. The chosen GMPE provides a median PGA value and associated standard deviation (log-normal dispersion) for a given earthquake scenario (magnitude and distance). To capture epistemic uncertainty in ground motion estimates, one could in principle use multiple GMPEs; however, for simplicity, our base case uses a single representative GMPE while we later comment on the potential range of results. All sites in the region were assumed to be rock or firm soil (reference site condition for the GMPE) to produce a regional hazard map on bedrock; this can later be adjusted for local soil conditions if needed.

2.4 PSHA Calculation

Using the defined seismic source model—characterized by a Gutenberg–Richter recurrence relationship within a uniform area source—and the selected ground motion prediction equation (GMPE), we conducted probabilistic seismic hazard calculations over a grid of sites covering the central Nepal Himalayan region. We assumed a *Poissonian model* for earthquake occurrence, which treats earthquakes as statistically independent events in time. This assumption is standard in probabilistic seismic hazard analysis (PSHA), as it simplifies the mathematical treatment and aligns with the use of declustered seismic catalogs.

At the heart of the PSHA is the estimation of the likelihood that ground motion at a site will exceed a certain threshold within a given time frame due to earthquakes of various magnitudes and distances. This is achieved using the *total probability theorem*, originally formulated for seismic applications by Cornell & Toro (1970). According to this framework, the annual rate of exceedance $\lambda(Y > y)$ of a ground motion level y is obtained by integrating over all possible earthquake magnitudes and source-to-site distances, weighted by their respective occurrence probabilities and ground motion exceedance probabilities:

$$\lambda(Y > y) = \int_{m_{\min}}^{m_{\max}} \int_{r_{\min}}^{r_{\max}} \nu(m) \cdot f_R(r|m) \cdot P(Y > y \mid m,r)\, dr\, dm \qquad (4)$$

where:

- $\lambda(Y > y)$ is the annual frequency of exceedance of ground motion level y,
- $\nu(m)$ is the magnitude-dependent annual occurrence rate, derived from the

Gutenberg–Richter recurrence law,

- $f_R(r|m)$ is the probability density function of source-to-site distance r for a given magnitude m,

- $P(Y > y \mid m,r)$ is the conditional probability of exceeding ground motion y given an earthquake of magnitude m at distance r, as modeled by the GMPE.

This integral quantifies the contribution of all possible earthquake scenarios to the seismic hazard at a specific site. In practice, the integral is evaluated numerically by discretizing both magnitude and distance bins. The magnitude range considered spans from the completeness threshold ($M_c = 4.4$) up to a maximum credible magnitude $M_{\max} = 8.5$, which reflects the upper bound for Himalayan seismicity based on both historical records (e.g., the 1934 M8.1–8.4 Nepal–Bihar earthquake) and geological fault constraints.

The ground motion metric used in this study is Peak Ground Acceleration (PGA), a commonly adopted intensity measure in earthquake-resistant design and building code formulations. The GMPE provides median PGA values along with variability (standard deviation) for each earthquake scenario, taking into account magnitude, distance, and standard site conditions (assumed here as rock or firm soil).

For each site on the computation grid, we calculated a hazard curve—a function describing the annual probability of exceeding various levels of PGA. From this hazard curve, we extracted the PGA value corresponding to a 10% probability of exceedance in 50 years, which is equivalent to a 475-year return period. This level of exceedance is a conventional benchmark in engineering seismology and is widely used in the development of seismic building codes and design spectra.

The resulting hazard values across the study region were spatially interpolated to generate a probabilistic seismic hazard map for central Nepal. This map reflects the spatial distribution of expected shaking intensities under a common design scenario and provides a basis for comparing with prior national assessments, such as those conducted by Pandey et al. (2002), as well as for updating zoning parameters in Nepal's building codes.

In summary, our methodology adheres to established PSHA standards, integrating a rigorously processed earthquake catalog, statistically robust recurrence modeling, and regionally appropriate ground motion predictions. This approach provides a scientifically grounded estimate of seismic hazard and supports efforts in earthquake risk mitigation and resilient infrastructure planning across central Nepal.

3 RESULTS

3.1 Seismicity and Recurrence Characteristics

The processed earthquake catalog for central Nepal provides insight into the region's seismicity and forms the basis for hazard quantification. The spatial distribution of past earthquakes (Figure 2) shows that seismicity is concentrated along the Himalayan arc, especially beneath the higher Himalaya north of the foothills. This pattern aligns with the Main Himalayan Thrust (MHT) fault system, which is the source of large megathrust earthquakes. The declustering process retained mainly mainshock events, including several significant historical earthquakes in the catalog. The magnitude–frequency analysis of these events confirms that the Gutenberg-Richter law is a reasonable representation for central Nepal's seismicity. Figure 3 illustrates the frequency–magnitude distribution and the fitted recurrence law. The plot appears linear above the completeness threshold (M4.4), supporting the use of a power-law recurrence model.

From the Gutenberg-Richter fit, we obtained a b-value around 0.90 for the central Nepal catalog. This b-value is slightly below 1.0, which suggests a somewhat greater relative frequency of large earthquakes compared to an average tectonic region (where b is often near unity). In physical terms, a lower b-value can imply a region of higher tectonic stress or one dominated by large fault structures capable of generating major earthquakes. The $b \approx 0.9$ found here is consistent with other studies of Himalayan seismicity - for example, previous estimates for Nepal have found b-values in the range $\sim$0.8 - 1.0. The total seismic activity rate given by the a-value ($\sim$6.6 in the equation 1) indicates that, on average, the region experiences an earthquake of about M5.0 or greater roughly every 2 - 3 months, and an earthquake of M6.0 or greater roughly every few years (according to the recurrence model). These recurrence characteristics reflect an active plate boundary with frequent moderate earthquakes and occasional great earthquakes. They also set the stage for calculating hazard: the relatively high rate of $M \geq 5$ events and the possibility of $M \geq 8$ events in this region means that there is a significant probability of strong ground shaking within any given 50-year period.

3.2 Probabilistic Hazard Analysis and Hazard Map

Using the recurrence parameters and ground-motion models described, we computed the probabilistic seismic hazard for central Nepal. The primary result is the estimated peak ground acceleration (PGA) values for a 10% probability of exceedance in 50 years. Figure 4 presents the resulting seismic hazard map for the region. Each contour or color band on the map represents the level of PGA (as a fraction of gravity, g) that has a 10% chance of being exceeded at least once in a 50-year interval at that location.

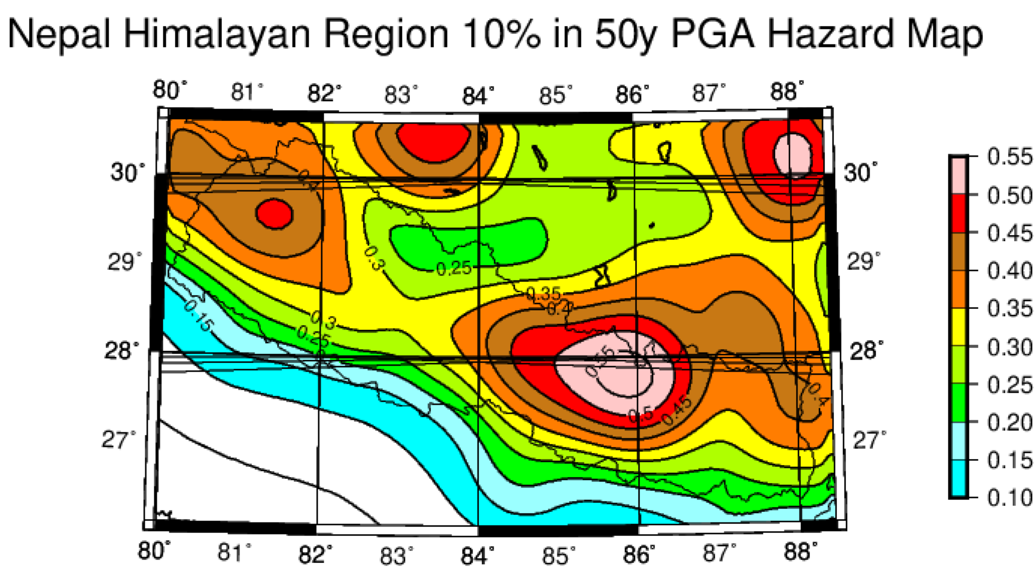

Figure 4: Probabilistic seismic hazard map for the central Nepal Himalayan region, showing the peak ground acceleration (PGA) with 10% chance of exceedance in 50 years (approximately a 475-year return period). The map is in units of gravity (g). Higher hazard levels (warm colors) are predicted along the Himalayan range, indicating where strong shaking is most likely. Notably, parts of central and eastern Nepal exhibit PGA values on the order of 0.4–0.5g (red shades), while areas further south into the Ganges plain have significantly lower values (blue-green shades).

As shown in Figure 4, the hazard is not uniform across the region. PGA values range from about 0.10–0.15g in the southernmost Terai plains (at the foothills of the Himalayas) to over 0.50g in some northern areas closer to the high Himalaya.

Broadly, the highest hazard is concentrated in an belt running west-east along central Nepal, roughly paralleling the main seismic sources. There are two notable high hazard concentrations: one in central-western Nepal and another in east-central Nepal. In these zones, the 10%-in-50yr PGA reaches around 0.45g to 0.55g, which is extremely high and comparable to design level shaking in the world's most earthquake-prone regions. Kathmandu valley, located in central Nepal, falls within a high hazard area – our results indicate a design-level PGA on the order of 0.35–0.40g for stiff soil or rock sites in Kathmandu. This is consistent with the expectation that the capital region, having experienced major shaking in events like 1934 and 2015, remains one of the zones of highest seismic hazard. By contrast, the far-western Nepal Himalaya (e.g., around 80°–81°E longitude) shows somewhat lower hazard in our model (PGA generally under 0.3g). The lesser hazard in the far west from our analysis may reflect the lower frequency of large earthquakes in that segment over the catalog period; however, we note that some other studies have found high hazards in the far-west if considering the potential for an overdue great earthquake there. The southernmost parts of central Nepal (toward the Gangetic plain) have the lowest hazard in the region, with PGA generally below 0.2g, due to their greater distance from the Himalayan seismogenic sources and the attenuative thick sediments of the Ganga basin.

Overall, the 10%/50yr PGA values we obtained for central Nepal are on the order of 0.3–0.5g in the high hazard areas. These values are in line with or slightly higher than the previous national-scale assessment by Pandey et al. (2002), which gave 0.10–0.45g across Nepal. In particular, our estimate of 0.4–0.5g in parts of central/eastern Nepal slightly exceeds Pandey et al.'s maximum of 0.45g, which could be due to the inclusion of the 2015 Gorkha earthquake data and updated ground motion models that predict somewhat higher motions. It is also noteworthy that our hazard map highlights the central Nepal region (including Gorkha, Lamjung, and Kathmandu areas) as having very high hazard, whereas Pandey's map had indicated the highest contours more towards eastern Nepal. Our results show a broad high-hazard region that extends from central to eastern Nepal, reflecting that both the central (e.g., 2015 rupture area) and eastern (e.g., 1934 rupture area) segments of the Himalayan fault system are capable of producing severe shaking in the future. To interpret these results: a PGA of 0.5g at 10%/50yr means that there is a 10% chance that earthquake shaking will exceed 50% of gravity at that location at least once in the next 50 years. Such shaking would be extremely damaging, likely causing collapse of poorly constructed buildings. Even 0.3g shaking (found over wide areas in Figure 4) can cause serious damage without adequate engineering. Therefore, the hazard map quantitatively confirms that central Nepal faces a very high seismic risk. The map also provides a basis for more detailed risk analysis – for example, combining these hazard levels with exposure (buildings, population) would allow estimation of expected losses under the 475-year return period event. It should be noted that the hazard values carry uncertainties. The map represents the mean estimates given our model assumptions. If alternative reasonable GMPEs or slightly different b-values were used, the PGA levels might shift by a few tenths of g. Nonetheless, the overall pattern of highest hazard along the Himalayan front is robust. The results are thus a best-estimate of the current state of seismic hazard in central Nepal, suitable for informing building code updates and disaster preparedness planning.

4 DISCUSSION

The PSHA results for central Nepal presented above have important implications and are generally consistent with our understanding of regional seismic risk, though there are some notable points to discuss in comparison to previous studies and in the context of uncertainties.

4.1 Comparison with Previous Hazard Assessments

Our hazard map broadly agrees with earlier assessments in identifying the Himalaya of central and eastern Nepal as a zone of very high hazard. The national seismic zoning in the 1994 Nepal building code (based on the 1993 study) had peak accelerations of about 0.08–0.12g in central Nepal, which is considerably lower than what we find – this is expected, as the 1993 study used a shorter catalog and perhaps more conservative assumptions, and building code values often incorporate safety margins and older attenuation models. The subsequent 2002 study by Pandey et al. raised the estimated hazard levels to as high as 0.45g in eastern Nepal. Our study, incorporating data from the last two decades (including the Gorkha earthquake), suggests hazard levels that are equal or slightly higher in some locales (up to $\sim$0.5g). This could indicate that the central-eastern Nepal segment is at least as hazardous as previously thought, if not more so. On the other hand, our model yielded somewhat lower hazard in far-western Nepal than Thapa and Wang (2013) reported. Thapa and Wang identified the far-west as another high hazard zone (they used a different methodology involving morphostructural zoning and a Chinese GMPE). The difference underscores how sensitive hazard results can be to assumptions about seismic source characterization – if one assumes the 500 km western Nepal segment is capable of rupturing in a single great earthquake (Mw $\sim$8.5+, as some geological studies suggest a large earthquake deficit there), the hazard in the far-west would rise. Our study implicitly assumes the past catalog (which lacks an event of that size in the far-west) is indicative of the future; if that is wrong, hazard there could be underestimated. This points to the need for careful consideration of Mmax and fault segmentation in PSHA. Future work integrating paleoseismic findings (e.g., evidence of great earthquakes prior to 20th century) could refine the source model and possibly raise the hazard in segments that have been quiet in recent centuries.

4.2 Gutenberg-Richter Parameters and Seismotectonic Interpretation

The estimated b-value of $\sim$0.9 for central Nepal is in line with other estimates in active tectonic regions, but slightly on the lower side. A b-value less than 1 suggests relatively more frequent large earthquakes, which could reflect the presence of very large faults (the Himalayan megathrust) that dominate the seismic energy release. It is known that b-values can vary spatially; for instance, some studies have found higher b ($\sim$1.0–1.1) in aftershock sequences and lower b ($\sim$0.7–0.8) in locked, highly stressed fault regions. Our regional b is an average; the 2015 aftershock zone itself had a somewhat higher b, whereas the locked segments might have lower b. This nuance is somewhat averaged out in our area-source approach. The relatively small uncertainty of our b estimate (±0.03) is likely too optimistic, as it's based on assuming completeness above M4.4; if the catalog completeness or magnitude homogeneity had issues, the true uncertainty could be higher. Nonetheless, a b in the 0.8–1.0 range is reasonable for Himalayan seismicity, and our chosen value contributes to hazard mainly by controlling the frequency of moderate vs. large events. We did consider Mmax $\sim$8.5; if a larger maximum (say 8.7 or 9.0) were considered, the hazard might increase slightly at long return periods, but such an event might be beyond what the Himalaya can generate in a single rupture, according to current geological understanding.

4.3 Uncertainties in Ground Motion Modeling

One of the largest uncertainties in any PSHA is the choice of GMPE. We used a single representative GMPE for the Himalayan region; however, different ground-motion models can predict significantly different PGA values at a given distance-magnitude. Parajuli et al. (2010) addressed this by using five attenuation relationships and averaging. They found that Kathmandu's hazard could be quite high (they reported 0.5g PGA for 475-year period on soft rock). Our result for Kathmandu (∼0.35–0.4g on rock) might have been higher if we had included models that predict higher shaking or if site amplification in the valley's soil was considered. We focused on rock site PGA; actual shaking in the basin could be amplified by a factor of 1.5 to 2 at certain frequencies due to deep sediments, which is an aspect beyond the scope of this study but critical for urban seismic risk. The use of different GMPEs also influences the geographic distribution of hazard; some models might predict slower attenuation (thus higher hazard further south into the plains). In future assessments, a logic-tree approach with multiple GMPEs would provide a range (and median) of hazard estimates, increasing the robustness of conclusions.

4.4 Implications for Building Codes and Risk Mitigation

Our updated hazard assessment for central Nepal carries significant implications for engineering design and public policy. The current Nepal National Building Code (NBC 105:1994) zone factors were based on older studies that gave PGA values of 0.08–0.12g in much of central Nepal. Our findings suggest that design levels should be higher – in the range of 0.3g or more for important structures in Kathmandu and surrounding high-hazard areas – to achieve a comparable level of safety (10% probability of exceedance in 50 years). This corroborates calls by previous researchers to revise the existing hazard estimates and code provisions in Nepal. Incorporating new hazard maps into the building code will ensure that structures are designed with appropriate lateral force levels for the actual seismic threat. Moreover, microzonation within the Kathmandu Valley (accounting for local site effects) should be undertaken using our hazard results as a base, to better guide construction practices on soft sediments. Aside from engineering, the hazard map is valuable for land-use planning: areas with extremely high hazard might avoid critical infrastructure or require special reinforcement. Disaster preparedness and response planning can also be informed by understanding which areas are likely to experience the strongest shaking in future scenario earthquakes.

4.5 Limitations and Future Work

While comprehensive, this study has limitations that should be acknowledged. We treated the entire central Nepal Himalaya as a single area source with averaged properties. In reality, the seismic source characterization could be made more physically-based by incorporating individual fault segments (e.g., differentiating the locked MHT segment that ruptured in 2015 vs. the adjacent segment that ruptured in 1934, etc.) and assigning activity rates to each. Due to limited time and data, we did not explicitly model fault-specific recurrence (e.g., characteristic earthquakes on known faults), which could refine the hazard locally. We also assumed a time-invariant (Poisson) model; however, after a large event like 2015, there could be a temporary reduction in hazard on that fault segment and an increased stress (and hazard) on the unruptured segments immediately to the west and east. Time-dependent PSHA models (which were beyond our scope) could explore how hazard might transiently decrease or increase after big earthquakes. Additionally, our hazard assessment did not explicitly account for induced seismicity or earthquakes in the Indo-Gangetic plains (which are low, but possibly not zero). Despite these simplifications, the broad results are robust for regional planning purposes. Future work should aim to incorporate the latest research on Himalayan earthquake recurrence intervals (for example, geological rupture evidence) and to use a logic-tree PSHA approach that encompasses multiple models of seismic source and ground motion. Regular updates to the hazard model are recommended as more earthquake data are recorded and as seismic science advances. This will ensure that Nepal's seismic hazard assessments remain accurate and useful for mitigating earthquake risk.

5 CONCLUSION

This study provided a detailed probabilistic seismic hazard analysis for the Central Nepal Himalayan region, leveraging an updated earthquake catalog and contemporary methodologies. The analysis yields an estimated b-value of 0.9 for the regional Gutenberg-Richter relation, indicating a slightly higher propensity for larger-magnitude earthquakes relative to smaller ones in the seismicity of central

Nepal. Using these recurrence parameters along with appropriate ground motion models, we calculated the expected levels of ground shaking for a 10% probability of exceedance in 50 years. The resulting hazard map demonstrates that much of central and eastern Nepal faces very high seismic hazard, with peak ground accelerations on the order of 0.4–0.5g possible in the Kathmandu area and surrounding highlands over a 475-year return period. Even the more "moderate" hazard areas in the region have design-level PGAs of 0.2–0.3g, which are significant enough to warrant serious engineering consideration.

Comparing our results with earlier studies, we find overall agreement that the Himalayan frontal region is exceptionally hazardous, though our updated model suggests slightly higher hazard in central Nepal, likely due to the inclusion of recent seismic data and improved ground-motion predictions. These findings reinforce the necessity for updating building codes in Nepal to reflect current hazard levels and for enforcing those codes to ensure structures can withstand the predicted shaking. Implementing our hazard findings in urban planning (for example, avoiding critical facilities in the highest hazard zones, or retrofitting vulnerable structures) could greatly reduce future earthquake losses. The 2015 Gorkha earthquake was a wake-up call that, despite being slightly less severe than the worst-case scenarios, caused tremendous damage and loss of life; our hazard assessment indicates that similar or stronger shaking is plausible and should be anticipated in resilience planning.

In conclusion, the PSHA of central Nepal highlights a continued high risk from earthquakes in the region. By synthesizing geological, seismological, and statistical data, we have provided a comprehensive picture of the threat. This study contributes to the scientific understanding of Himalayan seismic hazard and offers practical inputs for risk reduction efforts. As new data emerge and methods evolve, such hazard assessments should be periodically revised. Ongoing research – including paleoseismic studies, dense seismic instrumentation, and advanced modeling – will further refine these estimates. Nonetheless, the evidence is clear that central Nepal requires rigorous earthquake preparedness. The combination of dense populations and high hazard makes this region one where proactive measures (education, emergency planning, resilient construction) are urgently needed. By adopting policies informed by studies like this, Nepal can improve its resilience and reduce the potential impact of the inevitable future earthquakes in the Himalaya.

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