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REVIEW **Open Access**

State-of-the-art review of probabilistic seismic hazard analysis in Nepal: status, challenges, and recommendations

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Abstract

Background This paper presents a state-of-the-art review of probabilistic seismic hazard analysis (PSHA) in Nepal. Over the years, numerous studies have estimated seismic hazards in terms of peak ground acceleration (PGA) and spectral acceleration (SA). However, the results often exhibit significant variation, contributing to uncertainty among engineers, designers, planners, and policy makers. This variation underscores the need for a critical evaluation of existing studies to identify the underlying factors driving these differences in hazard predictions and to provide informed guidance on the most appropriate estimates for practical application.

Results This study systematically analyzes and compares multiple PSHA studies that have estimated seismic hazard either for the entire country or for specific urban regions within Nepal. The observed variation in hazard levels arises from several methodological differences. Key contributing factors include the selection of ground motion prediction equations (GMPEs), differences in seismic source characterization and zonation, assumptions regarding local soil conditions, the choice of computational tools and modeling approaches, methods of declustering earthquake catalogs, and the extent and quality of seismic data employed. More recent studies tend to incorporate updated earthquake catalogs, refined seismic source models, and improved regional data, thereby enhancing their relevance for the design of typical structures and for the preliminary assessment of large infrastructure projects. Notably, many of these newer studies report hazard levels that exceed those specified in the current Nepal National Building Code, suggesting that existing code provisions may underestimate the present-day seismic risk.

Conclusion Improving the accuracy and reliability of future seismic hazard assessments in Nepal necessitates the development of region-specific GMPEs derived from locally recorded strong ground motion data. Incorporating comprehensive information on local geological conditions, active fault characteristics, and seismic source parameters, together with the application of advanced computational methods, can significantly enhance the precision of hazard estimates. Such improvements are critical for supporting safer structural design practices and for strengthening earthquake resilience across Nepal's seismically vulnerable regions.

Keywords Seismic hazard analysis, Probabilistic seismic hazard, PGA_{475}, PGA_{2475}, Ground motion prediction equation, Seismic source zonation, Spectral acceleration

Introduction

In nearly all major past earthquakes, devastation has always been caused by either non-engineered or insufficiently engineered buildings (Arya 2000). For example, the 2010 MW 7 Haiti Earthquake caused catastrophic impacts, with fatalities estimated between 250,000 and 300,000 and affecting one-third of the

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population (Margesson and Taft-Morales 2010). The devastation was attributed primarily to the absence of earthquake-resistant construction; the infrastructure was, in fact, designed for hurricanes rather than seismic events (Audefroy 2011). Similarly, the 2005 MW 7.6 Kashmir Earthquake claimed approximately 100,000 lives, largely due to the collapse of over 400,000 buildings, which were not designed to withstand seismic forces either (Haseeb et al. 2011). On the other hand, the 2010 MW 8.8 Chile Earthquake in fully prepared Chile resulted in significantly fewer casualties, with approximately 525 individuals killed. Since seismotectonics, hypocenter depth, and population density greatly influence the degree of devastation, direct comparisons between different earthquakes may not be entirely valid. Nonetheless, the prevalence of nonengineered structures underscores the negative correlation between preparedness and devastation.

While preventing deadly earthquakes is impossible, their impact can be mitigated through seismic-resilient construction practices (Booth 2018). For better earthquake preparedness, seismic hazard analysis could significantly aid in identifying potential risk levels and improving building codes accordingly (Ellingwood 2001; Malhotra 2007; Chaulagain et al. 2015; Ayele et al. 2021; Kazemiasl et al. 2025). Seismic hazard analysis is the assessment of the severity of ground shaking at a site via two methods: deterministic seismic hazard analysis (DSHA) and probabilistic seismic hazard analysis (PSHA) (Saputra et al. 2017). The DSHA assumes the occurrence of the maximum credible earthquake at the nearest distance to the site, providing an upper bound value for the seismic hazard. However, PSHA accounts for all major uncertainties in the earthquake process, providing different seismic hazard values for various return periods (Kramer 2021; Das et al. 2025).

SHA began in Mexico in the 1960s and has gained significant importance in Nepal over the last two decades. In Nepal, almost all SHA studies are based on the probabilistic approach, with very few studies employing the deterministic approach. Studies estimating ground motion hazards in Nepal have shown significant variations. For example, the PGA_{475} (475-year return period PGA) for Kathmandu is reported as 0.33 g by Rout et al. (2015) and 0.77 g by Chaulagain et al. (2015), 133% more than that of Rout et al. (2015). Similarly, in Dhangadhi, PGA_{475} is 0.25 g according to Maharjan et al. (2023) and 0.49 g per Rahman et al. (2018), a 96% difference. The differing seismic hazard results in Nepal are influenced by several factors, including variations in data quality, methodological approaches (e.g., PSHA vs. deterministic methods), and assumptions about seismic sources and regional tectonics. Variations in data quality, such as the density of seismic stations, the duration of available records, and the completeness of historical data, contribute to differences in hazard predictions (Joyner & Boore 1981; Atkinson & Boore 2006).

Additionally, the choice of different GMPEs developed for different plate tectonic regimes, computational tools, and spatial scales has led to variations in the results. Different GMPEs incorporate distinct datasets and assumptions, resulting in varying predictions of ground shaking (Abrahamson et al. 2016). Different SHA studies in Nepal have considered different local site conditions, such as soil properties, topography, and geological features, which can amplify or reduce hazard predictions, as noted by Borcherdt (1994) and Dev et al. (2017). The consideration of foreshocks and aftershocks or their removal (declustering) also introduces inconsistencies (Sitharam et al. 2018), and some SHA studies of Nepal have performed declustering, whereas others have not. Moreover, the timing of studies, particularly in the context of pre- and post-2015 Gorkha earthquake data, has influenced the results. Finally, the integration of seismological, geotechnical, and geological data plays a key role, with different levels of integration leading to variations in seismic hazard assessments (Bazzurro et al. 2004). To improve the consistency and reliability of seismic hazard models in Nepal, it is crucial to standardize methodologies and regularly update models to reflect new data and advancements in technology.

Regardless of the reasons behind the discrepancies in SHA results, having multiple PGA values for the same location is not ideal from a design perspective. A streamlined design process requires a single, consistent PGA value as input so that designers can select the appropriate data for specific conditions accordingly. Additionally, it is imperative to stay updated with advancements in SHAs to ensure that design codes are adjusted or modified accordingly to make buildings resilient against potential future earthquakes. For example, the PGA value proposed by Nepal's first seismic code, (NBC 105, 1994), is significantly lower (0.33 g) than those suggested by the more recent SHA literature. In this context, a state-of-the-art review of seismic hazard analysis in Nepal is essential for enhancing the development of more effective earthquake preparedness and mitigation strategies, ensuring the protection of lives and infrastructure.

This review systematically analyzes seismic hazard assessments from multiple studies, highlighting both their contributions and discrepancies. The primary objective is to offer a comprehensive understanding of seismic risk despite variations in data quality, methodologies, assumptions, and technological tools. By synthesizing these analyses, this review identifies uncertainties and knowledge gaps, which are essential for refining hazard predictions and improving mitigation strategies. For the engineering community, this review provides valuable insights that can inform updates to design standards and promote innovation in earthquake-resistant solutions, ensuring infrastructure resilience. Furthermore, it serves as an educational resource, enhancing the expertise of engineers in seismic hazard assessment. For policymakers, this review provides a solid foundation for informed decision-making related to land use, building codes, and disaster preparedness. It also supports strategic resource allocation and the development of effective public safety policies, improving community resilience against future earthquakes.

Seismotectonics of Nepal

The 2400 km long Himalayan mountain chain, created by the collision between the Indian and Eurasian plates, is one of the most seismically active regions in the world (Sharma and Deng 2019; KC et al. 2025a; KC et al. 2025b). Nepal is situated at the center of this Himalayan mountain chain and is influenced by significant tectonic zones (Fig. 1), including the Tibetan–Tethys Himalaya Zone, Higher Himalaya Zone, Lesser Himalaya Zone, Siwalik Zone and Terai Zone (Upreti 1999). Each of these zones has a distinct geological history, lithology and topographical features (Pradhan et al. 2006) and are separated from each other by the tectonically active main central thrust (MCT), main boundary thrust (MBT), main frontal thrust (MFT), and southern Tibetan detachment system (STDS) (DeCelles et al. 2001; Thankur et al. 2020). The MCT, MBT and MFT, which are south of the STDS, propagate from north to south and run through the entire length of Nepal. These surface faults merge with the main Himalayan thrust (MHT), which is the principal interface between the Indian Plate and the Eurasian Plate (Pandey et al. 1995, 1999).

The seismicity in the Himalayan region is influenced primarily by the MHT, as most of the crustal deformation in the Himalayas occurs in this region. The MHT is characterized by a mid-crustal ramp linked by southern and northern flats (Chamlagain et al. 2020). The major

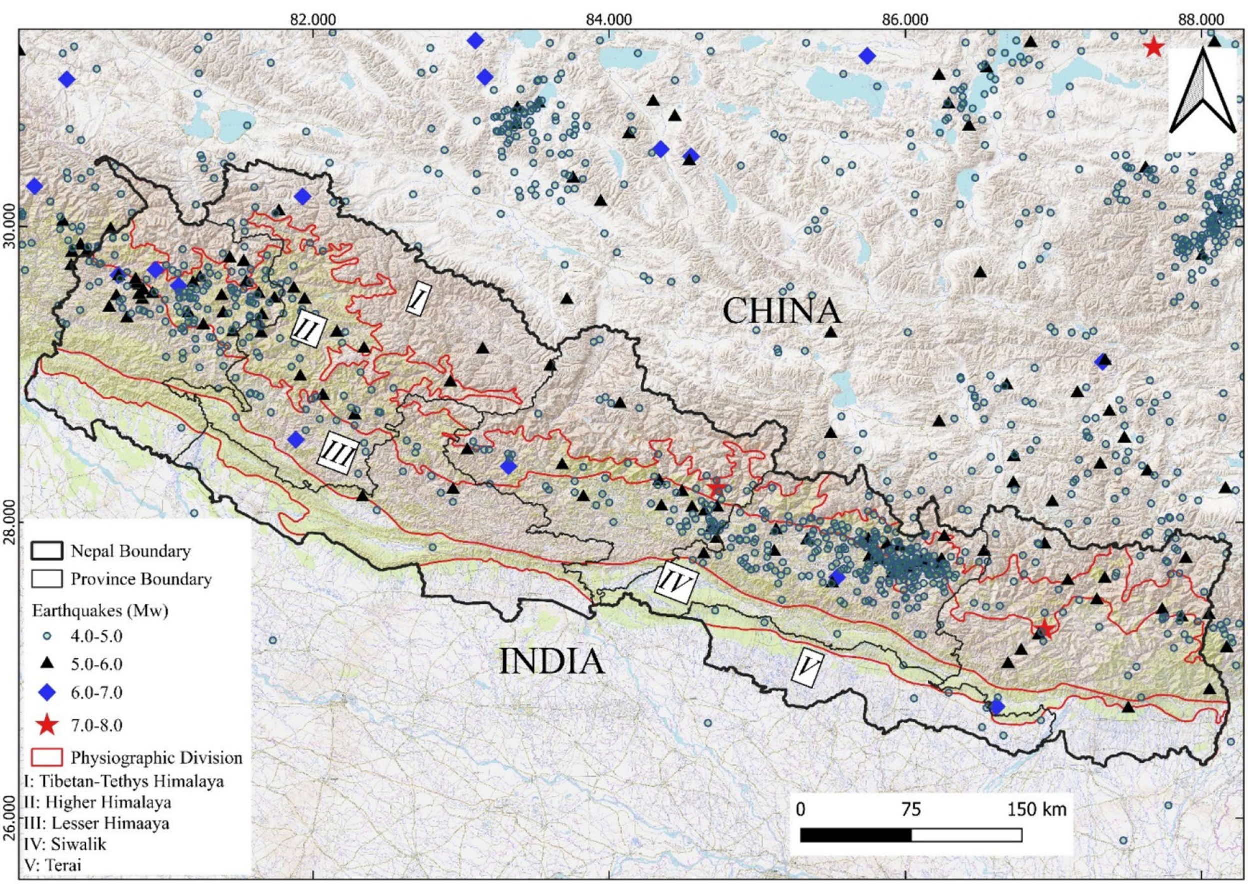

Fig. 1 Earthquake epicenters in Nepal and surroundings (1900–2024 AD) with moment magnitudes $(_{MWs})$ from USGS data, overlaid on physiographic divisions and provincial boundaries

earthquakes occurred mostly along the southern flat hinge of the ramp, which governs the seismicity at the subduction interface beneath the higher Himalayan front. The MCT is a north-dipping thrust fault extending 2400 km along the Himalayan Mountain belt and is situated between the higher Himalayas and the lower Himalayas. It was the first thrust that disrupted the Indian Plate approximately 24 million years ago (Shanker et al. 2011). While the MCT was active during the early stages of Himalayan Mountain formation, it is now less seismically active than other faults in the region are (Chamlagain et al. 2020). The MBT is located approximately 50 km south of the MCT and separates the Lesser Himalayas from the Siwalik Formation. It continues throughout the Himalayan range and has active north–south traverse faults in many places (Nakata 1989). The MFT is the southernmost thrust of the Himalaya, which is located at the foothills of the Himalayas and formed during the Quaternary period. The MBT and MFT are among the most active faults in the region and have the potential to generate large earthquakes (Lavé and Avouac 2000).

The seismicity of Nepal is controlled by the collision between the Indian and Eurasian tectonic plates, with the Indian plate subducting beneath the Eurasian plate at a rate of 18–21 mm/year (Ader et al. 2012; Bollinger et al. 2014; Lave and Avouac 2000). This ongoing convergence has produced significant earthquakes in Nepal, with major events recorded in 1255, 1810, 1866, 1934, 1980, 1988, and 2015 (Pandey et al. 1995; Maharjan et al. 2023). Most of these earthquakes have clustered in the Farwestern, Central, and Eastern parts of Nepal, mainly around the MCT, as depicted in Fig. 1.

Historically, studies have indicated that each subregion of the Hindu Kush Himalaya (HKH) experiences a mega-earthquake of magnitude Mw 8 or higher approximately once every 100 years (Bollinger et al. 2014; Hossler et al. 2016). Eastern Nepal experienced the devastating M_W 8 Bihar-Nepal Earthquake in 1934, and central Nepal experienced the strong M_W 7.8 Gorkha Earthquake in 2015. However, western Nepal experienced a megascale earthquake as far back as 1505 AD, more than 576 years ago, which was more than five times the average recurrence interval for a mega-earthquake in the HKH subregion. These findings suggest that western Nepal is much more likely to experience strong to megascale earthquakes than other regions of the country are (KC et al. 2025a; KC et al. 2025b). On the basis of the performance of infrastructure in western Nepal, specifically in Jajarkot, Rukum West, and Salyan, during the moderate M_W 5.7 Jajarkot earthquake in November 2023, it is evident that the region is far from being able to adequately protect lives and property. Although the M_W 5.7 earthquake, historically, is not considered highly devastating, it resulted in more than 150 deaths and the collapse of more than 25,000 residential buildings. This shows an up-to-date SHA, emphasizing the need for retrofitting existing structures in western Nepal and other regions. Since the spatial distribution of earthquakes is inherently uncertain, proactive measures are essential throughout the country.

Methodology

Deterministic seismic hazard analysis (DSHA) in Nepal is notably rare. The DSHA does not account for the uncertainties associated with seismic source characteristics and magnitude; instead, it focuses solely on the worst-case scenario, which is too conventional to consider when designing infrastructure. Conversely, PSHA considers the full range of possible earthquake magnitudes that can be induced by all potential sources for various return periods. SHA in Nepal started two decades ago when PSHA was already well established and was widely recognized for its more realistic nature than DSHA. This is why almost all SHA studies of Nepal have favored its adoption, which is systematically reviewed in this study. To comprehensively analyze the state-of-the-art PSHA of Nepal, this review adopted a systematic and structured methodology. The process involved extensive literature collection, critical review, comparative analysis, and synthesis of findings, as illustrated in Fig. 2.

Literature search

The first step involved identifying relevant studies via targeted keywords such as "seismic hazard analysis (SHA)," "probabilistic seismic hazard analysis (PSHA)," "deterministic seismic hazard analysis (DSHA)," and "Nepal." In addition to the most repetitive keywords several other keywords were also employed during the literature search to ensure that no relevant literature was overlooked. These additional keywords include "ground motion prediction equation," "seismic source zonation," "PGA475," "PGA2475," "spectral analysis," "Kathmandu," "Pokhara," and few others. These searches were conducted across several major academic platforms, including Google Scholar, Web of Science, and Scopus, to ensure extensive literature related to the seismic hazard analysis (SHA) of Nepal was covered.

Systematic review

The collected studies were systematically reviewed to extract critical information on key components of SHAs. The review emphasized the ground motion prediction equations (GMPEs) employed, the seismic source zonation they considered, and the earthquake catalogs utilized, including their time ranges. Additionally,

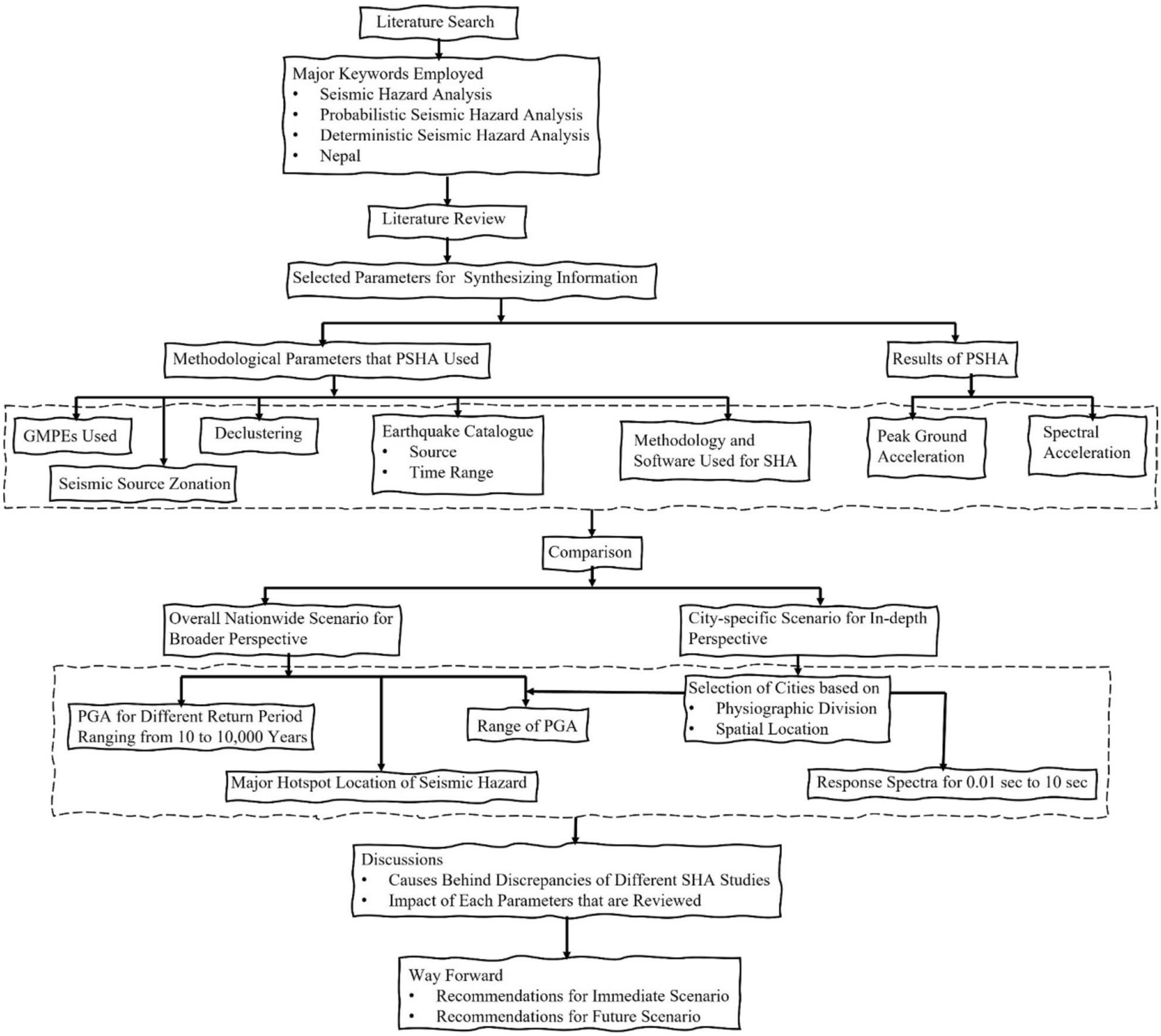

Fig. 2 Methodological flowchart of a state-of-the-art approach for probabilistic seismic hazard analysis in Nepal

attention was given to whether these studies considered foreshocks and aftershocks through declustering methods, and the methodologies and software tools employed for SHAs were examined to identify commonalities and variations.

Comparison and analysis

A detailed comparison of findings across the reviewed studies was conducted to highlight differences and trends. The peak ground acceleration (PGA) values proposed for various return periods, ranging from 10 to 1000 years, were noted, along with the range of values predicted for different regions of Nepal. Major seismic hotspot locations identified in the studies were recorded to provide insights into high-risk areas. For a more in-depth review, several representative cities were selected on the basis of their physiographic regions to encompass all types of topography while also ensuring coverage from eastern Nepal to far-western Nepal. The PGA trends for these cities were analyzed to understand spatial variations. Furthermore, spectral acceleration values for periods ranging from 0.01 to 10 s were compared across studies and evaluated against the Nepal Building Code (NBC 105, 2020).

Synthesis of findings and recommendations

The review culminated in a comprehensive synthesis of the current state of SHAs in Nepal, clearly outlining the strengths and gaps in existing studies. On the basis of these findings, practical recommendations were proposed to increase the precision of the SHA in Nepal.

Results

Some SHA studies focus on Nepal overall, others focus on specific locations (e.g., Kathmandu, Pokhara), and some examine broader regions, including multiple countries with Nepal as one of them. Studies covering Nepal overall include Parajuli et al. (2010), Ram and Wang (2013), Chaulagain et al. (2015), Rahman and Bai (2018), Stevens et al. (2018), Chamlagain et al. (2020), Parajuli et al. (2021), and Maharjan et al. (2023). Those focusing on specific regions within Nepal include Baruwal et al. (2020), Rajaure (2021), and Chhetri et al. (2022). Studies covering broader areas, including Nepal, include Nath and Thingbaijam (2012), Rout et al. (2015), Rahman et al. (2018), and Sreejaya et al. (2022).

Generally, these studies used historical seismic data from earthquakes affecting Nepal and its vicinity, followed by declustering in some cases. The subsequent steps involve ensuring data completeness and seismic source zoning, determining the Gutenberg-Richter coefficients (a and b) through magnitude–frequency analysis, estimating the maximum number of probable earthquakes from identified seismic sources, and selecting suitable ground motion prediction equations (GMPEs). To account for epistemic uncertainty, a logical tree framework is typically employed. Finally, ground motion hazards in terms of the PGA are estimated, which generally incorporates site-specific characteristics or bedrock conditions.

Earthquake catalog

The earthquake catalog is a fundamental requirement for PSHA, as it is essential for delineating the seismic source, determining the mean seismicity of the region, calculating the Gutenberg–Richter coefficients, and identifying the maximum probable earthquake (Rahman and Bai 2018; Stevens et al. 2018; Chamlagain et al. 2020). All the reviewed literature uses both instrumental and historic seismic databases due to limited instrumental data, as seismological stations in Nepal were established only after the 1980s. Nepal still lacks a sufficient number of instrumental stations to accurately collect real-time ground motion parameters during earthquakes (Subedi et al. 2024; KC et al. 2025a). Furthermore, relying solely on a short-term instrumental catalog underestimates the actual seismicity of an area, as the real seismicity is always higher than what is indicated by the instrumental catalog alone (Stevens et al. 2018). The instrumental data range spans from the late twentieth century to the present, while the historical data extend back to approximately 1200 in most of the reviewed literature. In all the reviewed literature, the earthquake data collected from different catalogs include different magnitude units, necessitating homogenization. Most studies have been standardized to the moment magnitude scale (M_W), considering only earthquakes above 4.0 MW, as earthquakes below this threshold are generally not devastating. The National Seismological Centre (NSC), National Earthquake Information Centre (NEIC), International Seismological Centre (ISC), United States Geological Survey (USGS), Global Centroid Moment Tensor (GCMT), and Global Historical Earthquake Archive (GHEA) are some commonly employed earthquake catalogs in these studies (Fig. 3). In addition, some studies have used databases from previous studies.

Declustering

Declustering involves the removal of foreshocks and aftershocks from the earthquake dataset before starting source zonation and hazard estimation calculations. PSHA assumes that seismicity is independent of time and location, following a Poisson process. However, foreshocks and aftershocks are dependent events that do not follow the Poisson process. Consequently, some studies have performed declustering (Rout et al. 2015; Rahman and Bai 2018; Rahman et al. 2018; Chamlagain et al. 2015; Baruwal et al. 2020; Parajuli et al. 2021; Maharjan et al. 2023), although a few have argued that foreshocks and aftershocks of significant magnitude can also be devastating and should be included in the PSHA. Stevens et al. (2018) even argued that nonclustered catalogs align better with historical and paleoseismic datasets. Gardner and Knopoff (1974) is used in all the literature where declustering has been applied, except for Chhetri et al. (2022), who also used Reasenberg (1985).

Seismic source zonation

Seismic source zonation is the process of dividing a region into zones with similar seismic hazard characteristics on the basis of factors such as fault plane, historical seismicity, and geological conditions. In PSHA, seismic source zones are commonly categorized into area sources, fault sources (linear types), and point sources. An active fault is defined as a linear source. In contrast, regions of diffuse seismicity, where earthquakes arise from a complex network of buried faults, are represented as areal source zones. Additionally, events such as volcanoes are treated as point sources (Atkinson and Boore 2003). In the context of Nepal, all these source areas are classified as either subduction zone sources or shallow crustal zone sources. Intercontinental and volcanic zones are less represented in Nepal, although Chaulagain et al. (2020) and Chhetri et al. (2022)

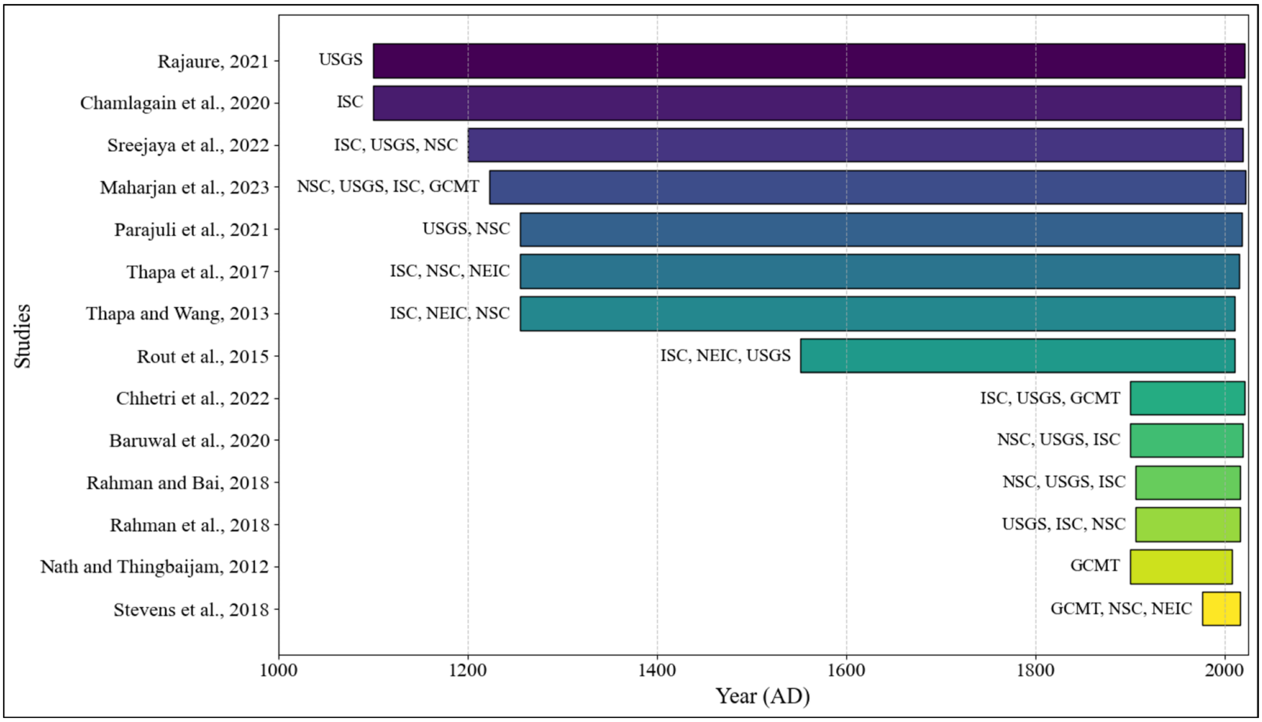

Fig. 3 Sources of earthquake catalogs used by different studies for seismic hazard analysis, showing the corresponding time periods covered by the catalogs

have given them some consideration. In the reviewed literature, despite similarities in the study area and seismic catalogs, variations in seismic source zonation are observed across different studies except for the MHT. The MHT is considered a fault source in all the literature.

Chamlagain et al. (2020), Chhetri et al. (2022), Rajaure (2021), Stevens et al. (2018), and Baruwal et al. (2020) provide detailed specifications on seismic source zone classification, Gutenberg–Richter coefficients, and maximum probable earthquake magnitudes. In contrast, other studies broadly categorize sources into subduction zones and shallow crustal zones, with less emphasis on individual sources. For those studies covering broader regions that include Nepal (Nath and Thingbaijam 2012; Rout et al. 2015; Rahman et al. 2018), this review considers only the seismic source zones that partially or completely overlap with Nepal. Detailed information on the seismic sources and related parameters of some reviewed literature is provided in Table 1.

Selection of ground motion prediction equations

Ground–motion relationships connect earthquake activity to ground shaking at a site, specifying median amplitudes and their variability. They are used to estimate the likelihood of surpassing a certain ground motion amplitude by aggregating contributions across various magnitudes and distances (Atkinson and Boore 2003). Ground motion prediction equations (GMPEs) are major controlling factors that directly influence hazard quantification. The selection of GMPEs depends on criteria such as the seismotectonic region, suitability across various distances and magnitudes, coverage of spectral periods, ability to account for site effects, and conformity with regional wave propagation characteristics (Chaulagain et al. 2015). Ground motion prediction equations are classified into four major types: (1) subduction zones, (2) shallow crustal zones, (3) intercontinental zones, and (4) volcanic zones. A subduction zone is a geological area where one tectonic plate is forced beneath another plate into the Earth's mantle, typically occurring at convergent plate boundaries. However, the characteristics of an active shallow zone include tectonics with comparatively higher strain rates nearer to plate boundaries, earthquakes occurring near the surface at depths typically ranging from approximately 20–30 km, and identifiable faults.

As a consequence of limited instrumentation and the resulting lack of strong-motion data, Nepal does not have local GMPEs available. Therefore, studies often utilize GMPEs designed for subduction zones and active shallow crustal zones elsewhere. Only a few studies have incorporated GMPEs for intercontinental zones

Table 1 Seismic source zonation, Gutenberg–Richter coefficients (a and b), and maximum likelihood earthquake moment magnitude (M_W)

Studies	Seismic source zone							
	Subduction zone				Active shallow crust zone			
	Source name	a	b	M_W	Source name	a	b	Max M_W
Chamlagain et al. (2020)	MHT	4.07	0.77	8.5	Northern grabens 1	3.56	0.77	7.1
					Northern grabens 2	3.86	0.81	7.1
					Northern grabens 3	4.95	1.07	7.1
					Northwest	4.18	0.88	7.1
					South	4.34	1.01	7
Chhetri et al. (2022)	MHT	6.7	1.15	8.1	SZ1	5.4	1	5.6
					SZ4	5.75	0.77	6.9
					SZ5	5.26	0.75	8.2
					SZ6	5.36	0.74	8.2
Rajaure, (2021)	MHT		0.95	8.5	MHT		0.95	8.3
Stevens et al. (2018)	MHT	6	1	9.2	Karakoram	4.67	1	8
					Pum Qu garben	4.87	1	7.3
					Thakkola garben	4.87	1	7.3
					Gyirong garben	4.87	1	7.3
					Kung Co garben	4.87	1	7.3
					Western Nepal Strike Slip and Normal	4.5	1	7.1
					Eastern Nepal Strike Slip	5.21	1	7.2
Baruwal et al. (2020)	East2	3.94	0.89	8.4				
	East1	4.35	1.01	8.4				
	Gorkha	4.61	1.04	8.3				
	Pokhara	3.62	0.89	8.2				
	Mid West	4.29	1	8.3				
	Far West1	5.16	1.14	8.3				
	Far West2	3.07	0.7	8.3				

in seismic regions where historical seismic records are sparse. GMPEs for volcanic zones are not highly applicable in Nepal. The details of these GMPEs used to calculate ground motion hazards are listed in Table 2.

In total, 36 unique GMPEs are used across both zones. Specifically, in the subduction zone (SZ), there are 19 unique GMPEs, whereas in the active shallow crustal zone (ASCZ), there are 17 unique GMPEs (Fig. 4). The four most frequently used GMPEs in the subduction zone are Atkinson and Boore (2003), Abrahamson et al. (2016), Boore et al. (2014), and Youngs et al. (1997). In the Active Shallow Crustal Zone, the four most frequently used GMPEs are Youngs et al. (1997), Zhao et al. (2006), Abrahamson et al. (2016), and Chiou and Youngs (2008).

Summary of the reviewed literature

Most of the literature predicts ground motion hazards in terms of the PGA, either for a 10% probability of exceedance in 50 years, i.e., the 475-year return period (PGA_{475}), or for a 2% probability of exceedance in 50 years, i.e., the 2475-year return period (PGA_{2475}), or both (Fig. 5). This section summarizes the findings of all the literature reviewed. Additionally, a comparison between the minimum and maximum PGAs for the 475-year return period (Fig. 6) and the 2475-year return period (Fig. 7) is presented.

Parajuli et al. (2010) pioneered PSHA and reported that the PGA_{475} under soft soil conditions with 5% damping is greater around Kathmandu than in other parts of Nepal. Specifically, the PGA values were 0.51 g near Kathmandu, 0.41 g in the western part, and approximately 0.31 g in the remaining parts of the country. Another PSHA study was performed by Nath and Thingbaijam (2012), which used logic tree analysis to account for epistemic uncertainty, giving equal weight to each GMPE. The PGA_{475} ranged from 0.1 to 0.4 g, and the $PGA_{2475\ ranged}$ from 0.3 to 0.8 g for Nepal under firm rock site conditions, with the maximum PGA found in western Nepal. Ram and Wang (2013) conducted another PSHA study and divided Nepal into 23 seismic source zones to estimate the PGA at the

Table 2 Ground motion prediction equations used in different SHA studies of Nepal

Papers	Subduction zone	Active shallow crustal zone
Chamlagain et al. (2020)	Zhao et al. (2006), Atkinson and Boore (2003), Abrahamson et al. (2016)	Abrahamson et al. (2014), Chiyou and Youngs (2014), Campbell and Bozorgnia (2008)
Chhetri et al. (2022)	Atkinson and Boore (2003), Kanno et al. (2006), Zhao et al. (2006)	Abrahamson et al. (2014), Chiou and Youngs (2014), Campbell and Bozorgnia (2008)
Chaulagain et al. (2015)	Boore and Atkinson (2008), Chiou and Youngs (2008), Campbell and Bozorgnia (2008), Atkinson and Boore (2003), Youngs et al. (1997)	Boore and Atkinson (2008), Chiou and Youngs (2008), Campbell and Bozorgnia (2008), Atkinson and Boore (2003), Youngs et al. (1997)
Rahman and Bai (2018)	Abrahamson et al. (2014), Chiou and Youngs (2014), Ambraseys et al. (2005), Zhao et al. (2006), Abrahamson et al. (2016), Atkinson and Boore (2003), Youngs et al. (1997)	
Rajaure (2021)	Abrahamson et al. (2014), Chiou and Youngs (2014)	Zhao et al. (2006), Abrahamson et al. (2016)
Rahman et al. (2018)	Abrahamson et al. (2015), Atkinson and Boore (2003), Youngs et al. (1997), Zhao et al. (2006)	Abrahamson et al. (2014), Ambraseys et al. (2005), Chiou and Youngs (2014)
Parajuli et al. (2010)	Crouse (1991), Fukushima and Tanaka (1990), Molas and Yamazaki (1995), Young et al. (1997), Gregor et al. (2002), Atkinson and Boore (2003), Atkinson and Boore (2008), Kanno et al. (2006), Zhao et al. (2006)	
Nath and Thingbaijam (2012)	Atkinson and Boore (2003), Lin and Lee (2008), Youngs et al. (1997)	
Ram and Wang (2013)	CEA (2005)	CEA (2005)
Stevens et al. (2018)	Abrahamson et al. (2016), Zhao et al. (2006), Atkinson and Boore (2003), Boore et al. (2014), Chiou and Youngs (2008), Boore and Atkinson (2008)	
Maharjan et al. (2023)	Atkinson and Boore (2003), Zhao et al. (2016), Abrahamson et al. (2016), Boore et al. (2014), Campbell and Bozorgnia (2014)	Chiou and Youngs (2014)
Parajuli et al. (2021); Bhusal and Parajuli (2019)	Abrahamson et al. (2014), Boore and Atkinson (2008), Chiou and Youngs (2008), Zhao et al. (2016), Campbell and Bozorgnia (2000), Kanno et al. (2006), Lin and Lee (2008), Youngs et al. (1997)	Zhao et al. (2016)
Rout et al. (2015)	Akkar and Bommer (2010), Boore and Atkinson (2008), Campbell and Bozorgnia (2008), Chiou and Youngs (2008), Zhao et al. (2006)	
Baruwal et al. (2020)	Youngs et al. (1997)	
Sreejaya et al. (2022)	Boore et al. (2014), Abrahamson et al. (2014), Campbell and Bozorgnia (2014), Chiou and Youngs (2014)	Gupta and Trifunac (2018), Dhanya and Raghukanth (2020)

bedrock level. The values of PGA_{50}, PGA_{475}, and PGA_{2475} predicted in this study range from 0.07–0.16 g, 0.21–0.62 g, and 0.38–1.1 g, respectively. This result was used for India and its surrounding regions, including Nepal, to prepare the global seismic hazard map by Pagani et al. (2020).

Chaulagain et al. (2015) conducted a PSHA using the same seismic source zonation as Ram and Wang (2013). In their study, Chaulagain et al. (2015) performed equal weightage logic tree analysis to estimate ground motion for 1%, 2%, 5%, and 10% probabilities of exceedance in 50 years. The estimated PGA values ranged from 0.51–1.07 g, 0.42–0.85 g, 0.30–0.64 g, and 0.22–0.50 g, respectively. The study revealed the highest ground motions in the eastern and midwestern regions and the lowest in the southern region of Nepal. Rahman and Bai (2018) conducted another PSHA that incorporates the same 23 aerial seismic sources as Ram and Wang (2013). In addition, their study included 14 linear sources and was the first to incorporate data from the 2015 Gorkha earthquake. It assigns equal weights to each GMPE to account for epistemic uncertainties in hazard estimation. The PGA_{475} and PGA_{2475} values for the bedrock level are greater in the Lesser Himalaya region, which spans from east to west. The PGA_{475} ranges from 0.21 g to 0.64 g, whereas the PGA_{2475} ranges from 0.40 g to 1.02 g.

Rout et al. (2015) conducted a PSHA for the Northwest and Central Himalayas, spanning from Jammu in India to Sikkim, including Nepal, in between. The study area was divided into 22 seismic source zones. The PGA_{475} was estimated to be between 0.06 g and 0.36 g, whereas the PGA_{2475} ranged from 0.11 g to 0.65 g, both of which were estimated via a declustered earthquake catalog. The highest PGA values were observed in the western

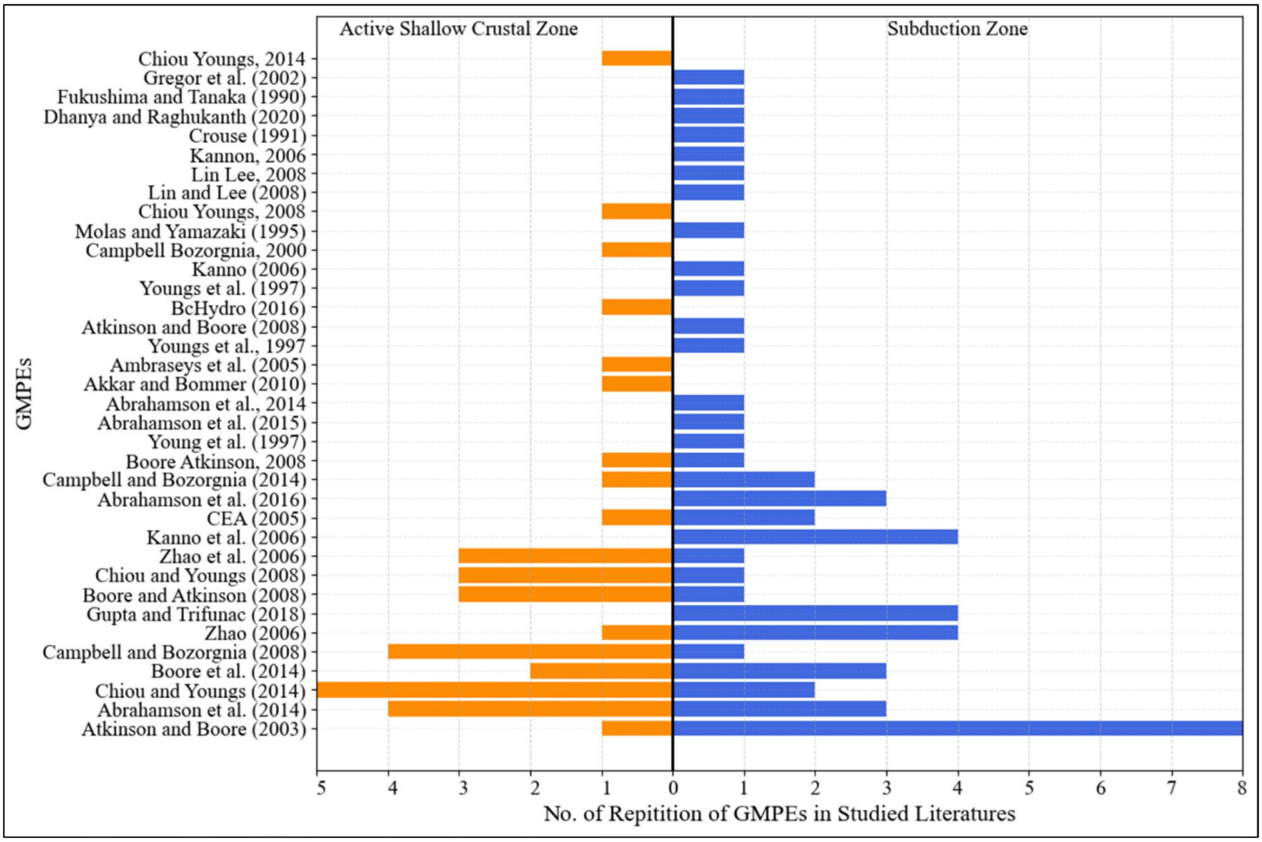

Fig. 4 Comparison of the number of studies using GMPEs in the active shallow crustal zone (left) and subduction zone (right), with bars representing the number of studies for each GMPE. The X-axis shows the study counts, and the Y-axis lists the GMPEs

part of Nepal. Another PSHA for a broader region of the Himalayan–Tibetan region, extending from Tajikistan in the east to Sichuan, China in the west, encompassing Nepal, was carried out by Rahman et al. (2018). This study estimates the PGA by considering a total of 301 seismic source zones across the entire study area. Equal weights were assigned to the estimates generated by each GMPE. The PGA_{2475} was estimated to range from 0.75 g to 1.06 g, and the PGA_{475} was estimated to range from 0.27 g to 0.67 g for Nepal. The highest hazard was observed in western Nepal, followed by eastern Nepal, while the central Terai region was safer.

Stevens et al. (2018) were the first to incorporate updated characteristics of the MFT following the 2015 Gorkha earthquake. This approach has incorporated eight seismic source zones, along with an equal-weight logic tree approach. The findings indicate that a significant portion of Nepal is expected to experience ground shaking between 0.4 g and 0.6 g for a 475-year return period and between 1.0 g and 1.3 g for a 2475-year return period. The highest hazards are in the northwestern and eastern regions, where the influence of the MHT is suggested to be greater. To revise the National Building Code NBC 105 (2020) after the 2015 Gorkha earthquake exceeded the PGA limits of the previous NBC 105 (1994), Chamlagain et al. (2020) conducted a PSHA for Nepal. This is another study that incorporates updated information about MFTs), such as that by Stevens et al. (2018). This study has indeed considered stable continental zones as well, with equal weights assigned to each GMPE. The results revealed that higher PGA values of 0.36 g to 0.46 g were concentrated above the locked segment of the MHT in Nepal for the 475-year return period, with PGA values decreasing to the north and south of the MFT.

Bhusal and Parajuli (2019) reported another PSHA and calculated the PGA for 1%, 2%, 5%, 15%, and 40% exceedance probabilities over 50 years for bedrock conditions (Vs,30 = 760 m/s). The area sources suggested by Pandey et al. (2002), Thapa and Guoxin (2013), and Parajuli et al. (2015), as well as the linear sources suggested by Pandey et al. (2002), Parajuli (2015), Stevens et al. (2018), and Bothara et al. (2002), were used as seismic sources. Western Nepal was found to be the most vulnerable to seismic hazards, followed by central Nepal, with PGAs ranging from 0.19 g to 0.52 g for a

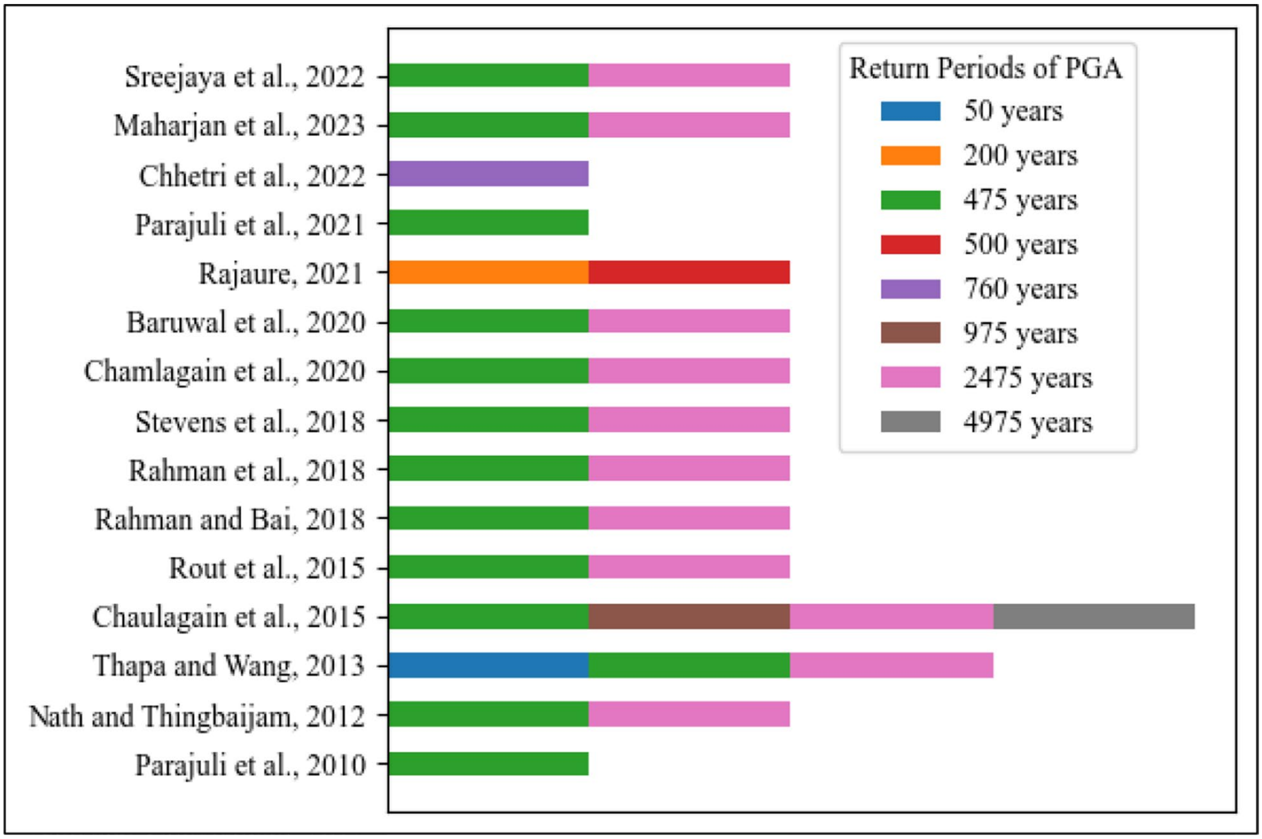

Fig. 5 Seismic hazard studies by return period: This chart displays the return periods (50, 200, 475, 500, 760, 975, 2475, 4975 years) analyzed in various studies, with the legend highlighting the coverage across studies

475-year return period. Parajuli et al. (2021) is another PSHA that uses seismic sources from Thapa and Guoxin (2013), Pandey et al. (2002), and Parajuli et al. (2010), as well as several other linear sources. The estimated PGA_{475} ranges are 0.12–0.52 g for hard soil, 0.22–0.55 g for medium soil, and 0.25–0.59 g for soft soil. The seismic hazard map shows higher PGA concentrations in the seismically active far western, central, and eastern Himalayan regions, whereas lower values are found in the northern and southern parts of Nepal.

Sreejaya et al. (2022) conducted a PSHA of India and adjacent regions, including Nepal, for rock site conditions. The PGA is calculated considering a total of 33 seismic sources in the entire region along with 18 combined regional and global GMPEs with logic tree analysis of unequal weightage, following the ranking given by Kale et al. (2019). From South Nepal to North Nepal, the PGA increases from approximately 0.1 g to 0.25 g for a 475-year return period and from 0.2 g to 0.7 g for a 2475-year return period. The ground motion hazard is highest for the Himalayan region, where Nepal is located. Maharjan et al. (2023) presented one of the latest PSHAs and presented an updated probabilistic seismic hazard model for Nepal, representing an improvement over the previous model. The PGA_{475} values range from ~ 0.1 g in South to 0.5 g in North, with the highest values in Far Northwest (> 0.45 g) and Northeast (0.45–0.50 g). The central region has medium to low seismic hazard values (0.25–0.3 g), whereas southern and far northern Nepal have the lowest values (< 0.25 g). Similarly, PGA_{2475} ranges from 0.3 g to ~ 1 g, with the highest hazard in Northwest (> 0.9 g) and slightly lower values (~ 0.7 g) in Eastern region. A brief overview of the results from the reviewed SHA literature is presented in Table 3.

Several other PSHA studies have been conducted for specific cities in Nepal, primarily for Kathmandu and Pokhara. Baruwal et al. (2020) performed PSHA for the Pokhara valley by dividing it into seven different seismic source zones and employing a GMPE given by Youngs et al. (1997). The maximum PGAs estimated at the bedrock site are 0.387 g and 0.694 g for 475 years and 2475 years, respectively. At the soil site, the maximum PGA is 0.525 g and 0.916 g for the same return period. Rajaure (2021) reported another localized PSHA that estimated ground motion hazards for the Kathmandu

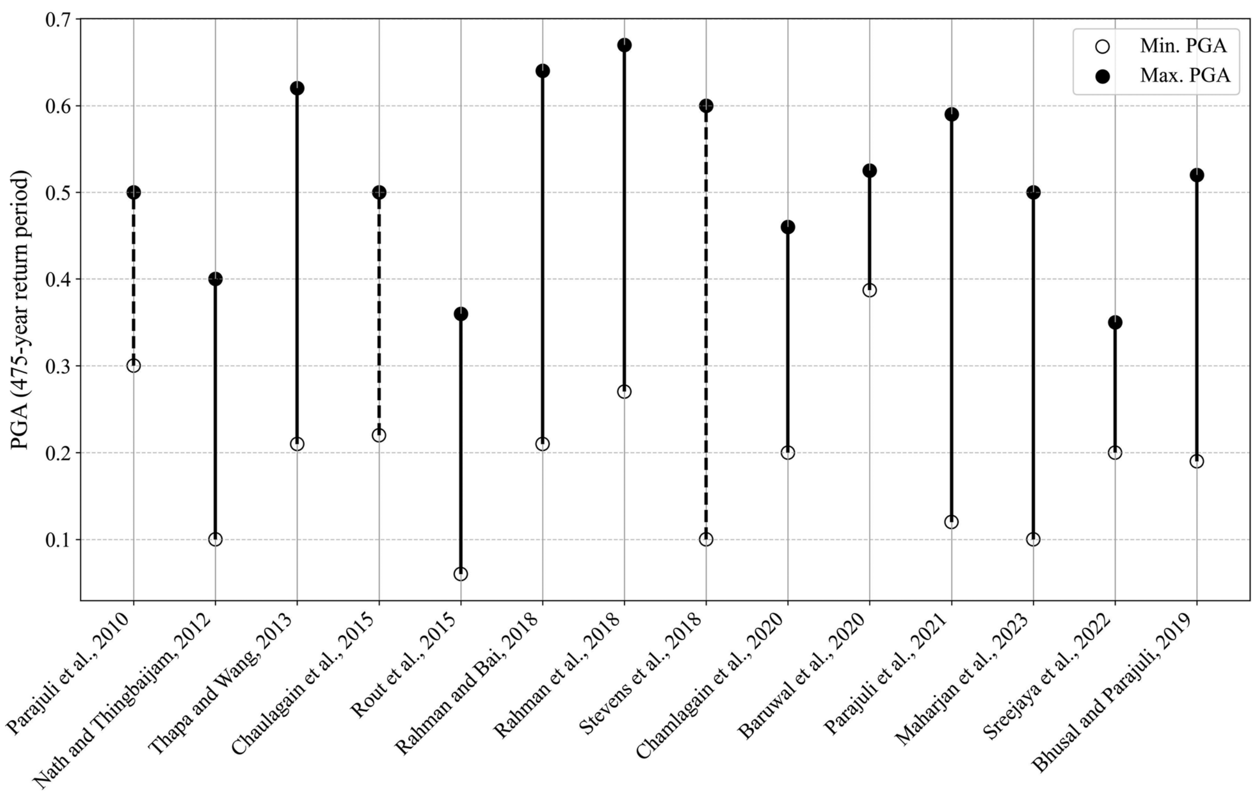

Fig. 6 The maximum and minimum PGAs for Nepal overall, as predicted by different SHA studies, for a 475-year return period (Parajuli et al. (2010), Chaulagain et al. (2015), and Stevens et al. (2018) have considered local soil conditions, while others have considered bedrock for seismic hazard prediction)

Valley and its surrounding region, considering the main Himalayan thrust (MHT) as the seismic source that caused the 2015 Gorkha earthquake. Two rupture models were applied to estimate seismic hazards, each with different weights. The first model replicates the north–south rupture of the 1934 Bihar-Nepal earthquake (M_W 8.2). The second model represents the northern-half rupture, similar to the 2015 Gorkha Earthquake (M_W 7.8) and potentially the 1833 Nepal Earthquake (M_W 7.6). The results indicate that the estimated PGA for Kathmandu is 0.23 g for a 200-year return period and 0.4 g for a 500-year return period. In 2022, Chhetri et al. conducted PSHA for the Kathmandu Valley and estimated the PGA under three scenarios: without declustering, with the Gardner and Knopoff (1974) method, and with the Reasenberg (1985) method. The results were compared with the recorded PGA from the 2015 Gorkha earthquake. For a 760-year return period at the bedrock level, the PGA values ranged from 0.336 g to 0.327 g (unclustered), 0.265 g to 0.257 g (Gardner and Knopoff), and 0.219 g to 0.214 g (Reasenberg). The study concluded that the PGA from the Gardner and Knopoff methods was closest to the recorded PGA.

Seismic hazard analysis in Nepal has been extensively conducted only over the last two decades with the widespread adoption of PSHA, and DSHA has rarely been performed. One of them is Thapa et al. (2017), who computed the PGA at the bedrock level across the entire country. Each seismic event in the updated catalog was treated as a point source, with calculations based on the shortest distances between the source and site and using a ground motion prediction relationship developed by China (CEA 2005). The resulting map from the DSHA shows distinct patterns in the spatial distribution of the PGA across Nepal, highlighting high hazard levels (0.88 g) in Northeast and low hazard levels (0.07 g) in South.

Comparison of PGAs

PGA_{475} is usually used for the design of residential buildings to prevent significant structural damage that could threaten lives and property. However, PGA_{2475} is normally considered during the design of residential buildings to ensure that, even if significant structural damage occurs, the buildings do not collapse catastrophically, thereby providing occupants with a chance to escape. PGA values differ across various

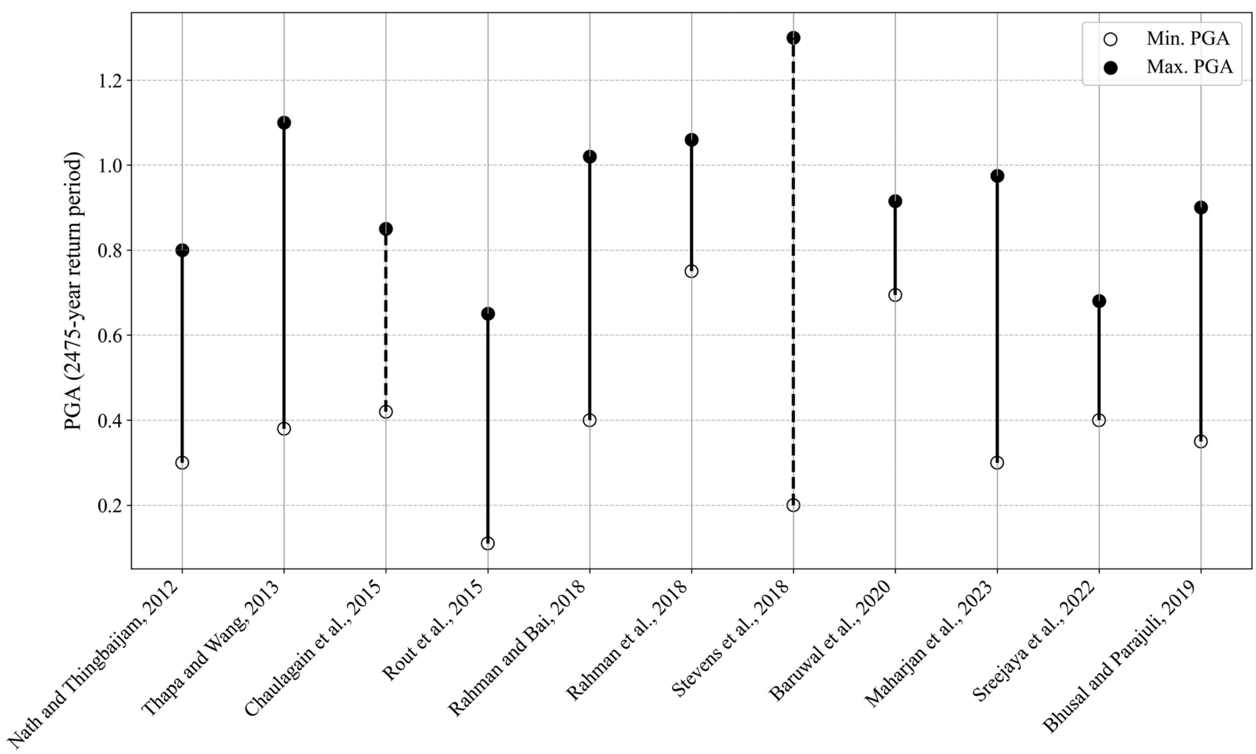

Fig. 7 The maximum and minimum PGAs for Nepal overall, as predicted by different SHA studies, for a 2475-year return period (Chaulagain et al. (2015) and Stevens et al. (2018) have considered local soil conditions, while others have considered bedrock for seismic hazard prediction)

literature sources even for the same location and return period. This discrepancy is due primarily to differences in GMPEs, seismic source zonation, methodologies used, earthquake catalogs, and declustering methods. To analyze this, we consider the PGA variation in two different cities within the same physiographic region (Fig. 1). The selected cities are Dhangadhi and Biratnagar from the Terai Zone, Tulsipur and Bharatpur from the Siwalik Zone, Kathmandu and Pokhara from the Lesser Himalaya Zone, and Gamgadhi and Chautara from the Higher Himalaya Zone. These cities represent both the eastern and western parts of the same physiographic zone and include major populous areas.

The PGA variations in Dhangadhi and Biratnagar are relatively low compared with those in other cities, as shown in Fig. 8. According to NBC 105 (2020), the PGA_{475} is 0.4 g for Dhangadhi and 0.35 g for Biratnagar. For Dhangadhi, Rahman et al. (2018) and Chaulagain et al. (2015) reported higher PGAs than those estimated by NBC 105 (2020), considering local site effects. For Biratnagar, the PGA estimates in most of the literature range from 0.3 g to 0.35 g, except for those of Chaulagain et al. (2015). Overall, the PGA variation in these cities is relatively uniform.

For both cities (Bharatpur and Tulshipur) in the Siwalik zone, the proposed PGA_{475} by NBC 105 (2020) is 0.4 g. In Bharatpur, the PGA ranges from 0.25 g to 0.6 g. Chaulagain et al. (2015), Stevens et al. (2018), and Rahman and Bai (2018) reported higher PGAs than the codes proposed. In Tulsipur, the estimated PGA ranges from 0.15 g to 0.65 g, with most studies reporting lower values than the codes did, except Chaulagain et al. (2015), who considered local site effects. For a 2475-year return period, the PGA ranges from 0.4 g to 1.5 g in Bharatpur and up to 1 g in Tulsipur, indicating a high seismic risk for Bharatpur, which requires careful consideration in large, long-term projects such as hydropower and dams.

For Kathmandu and Pokhara, which are located in the Lesser Himalaya Sequence, two of the most populous cities in Nepal, NBC 105 (2020) proposed PGAs of 0.35 g and 0.3 g, respectively, for a 475-year return period. Most of the literature exceeds these values, as shown in Fig. 9. In Kathmandu, Chaulagain et al. (2015), Rahman et al. (2018), and Stevens et al. (2018) reported PGAs higher than 0.6 g, suggesting that the codes may underestimate ground motion hazards. For Pokhara, all the literature reports higher PGAs than those proposed by NBC 105 (2020). For a 2475-year return period, most studies estimate PGAs above 0.8 g, with the highest value of 1.15 g reported by Rahman et al. (2018). Both cities have similar highest PGAs according to Rahman et al. (2018). Recent studies incorporating findings from the 2015

Table 3 Overview of peak ground acceleration (PGA) estimates for Nepal from various studies

Study	Published year	Overview
Parajuli et al. (2010)	2010	Highest PGA_{475} (0.51 g) near Kathmandu, 0.41 g in the western part, 0.31 g in other parts of Nepal
Nath and Thingbaijam (2012)	2012	Maximum PGA observed in Western Nepal. PGA ranges from 0.1 to 0.4 g for PGA_{475}, 0.3 to 0.8 g for PGA_{2475}
Ram and Wang (2013)	2013	PGA ranges from 0.07–0.16 g (PGA_{50}), 0.21–0.62 g (PGA_{475}), and 0.38–1.1 g (PGA_{2475})
Chaulagain et al. (2015)	2015	Highest PGA in the eastern and mid-western regions, lowest in the southern region of Nepal
Rahman and Bai (2018)	2018	Higher PGA in the Lesser Himalaya region, from east to west of Nepal (PGA_{475}: 0.21 g–0.64 g, PGA_{2475}: 0.40 g–1.02 g)
Rout et al. (2015)	2015	Highest PGA observed in the western part of Nepal, estimated for the Northwest and Central Himalayas
Rahman et al. (2018)	2018	Highest PGA observed in western Nepal, followed by eastern Nepal, lowest in central Terai region (PGA_{2475}: 0.75 g–1.06 g, PGA_{475}: 0.27 g–0.67 g)
Stevens et al. (2018)	2018	Highest PGA values in the northwest and eastern regions of Nepal (PGA_{475}: 0.4 g–0.6 g, PGA_{2475}: 1.0 g–1.3 g)
Chamlagain et al. (2020)	2020	Higher PGA values concentrated above the locked segment of the MHT in Nepal for the 475-year return period
Bhusal and Parajuli (2019)	2019	Western Nepal is the most vulnerable, followed by central Nepal (PGA_{475}: 0.19 g–0.52 g)
Parajuli et al. (2021)	2021	Higher PGA in far western, central, and eastern Himalayan regions; lower in northern and southern Nepal
Sreejaya et al. (2022)	2022	Highest PGA observed for the Himalayan region (PGA_{475}: 0.1 g to 0.25 g, PGA_{2475}: 0.2 g to 0.7 g)
Maharjan et al. (2023)	2023	Highest PGA in the far Northwest (> 0.45 g) and Northeast (0.45 g–0.50 g), medium to low hazard in the central region
Baruwal et al. (2020)	2020	Maximum PGA (g) for Pokhara valley: 0.387 g (bedrock) and 0.525 g (soil) for 475 years; 0.694 g (bedrock) and 0.916 g (soil) for 2475 years
Rajaure (2021)	2021	Maximum PGA (g) for Kathmandu Valley: 0.23 g for 200-year return period; 0.4 g for 500-year return period
Chhetri et al. (2022)	2022	Maximum PGA (g) for Kathmandu Valley (760-year return period, bedrock): 0.336 g–0.327 g (no declustering), 0.265 g–0.257 g (Gardner & Knopoff declustering), 0.219 g–0.214 g (Reasenberg declustering)

Gorkha earthquake in seismic source zonation suggest higher PGAs.

In Chautara and Gamgadhi, which are located in the higher Himalaya sequence, NBC 105 (2020) forecasts PGAs of 0.3 g and 0.25 g, respectively, for a 475-year return period. However, these estimates are significantly lower than those reported in the literature. Chaulagain et al. (2015) and Rahman et al. (2018) estimated the PGA for Chautara to be as high as 0.60 g. For Gamgadhi, estimates in the literature range from 0.5 g to 0.65 g, with some estimates of approximately 0.3 g, as shown in Fig. 9. For a 2475-year return period, both Chautara and Gamgadhi estimated PGAs of up to 1.15 g by Rahman et al. (2018).

Table 4 presents the PGA_{475} statistics for selected cities in Nepal, reflecting seismic hazard estimates across different SHA studies. The parameters include the mean PGA, standard deviation, minimum PGA, and maximum PGA values, which are expressed in terms of gravitational acceleration (g). Kathmandu presented the highest mean PGA value (0.47 g), followed closely by Chautara (0.42 g) and Gamgadhi (0.41 g), indicating heightened seismic hazard in these regions. The standard deviation is also highest for Gamgadhi (0.11 g), suggesting greater variability in seismic hazard estimates. On the lower end, Biratnagar, a city in the Terai region, has the smallest mean PGA (0.30 g) and minimum PGA (0.20 g), indicative of comparatively lower seismic risk. Overall, this table further strengthens the observed trend of higher seismic hazards in central and western Nepal due to earthquakes.

Similarly, the mean PGA_{2475} (Table 5) values indicate that Kathmandu has the highest mean PGA (0.82 g), followed closely by Chautara (0.77 g) and Bharatpur (0.77 g), highlighting the high seismic hazard in the central region. The standard deviations range from 0.11 g (Biratnagar) to 0.34 g (Bharatpur), reflecting variability in seismic ground motions across different locations. The minimum PGA values range from 0.35 g (Bharatpur and Pokhara) to 0.50 g (Dhangadhi), whereas the maximum PGA values vary significantly, with Bharatpur exhibiting the highest value at 1.55 g.

Comparison of response spectra

Figure 10 compares the response spectra from various literature sources and NBC 105 (2020) for return

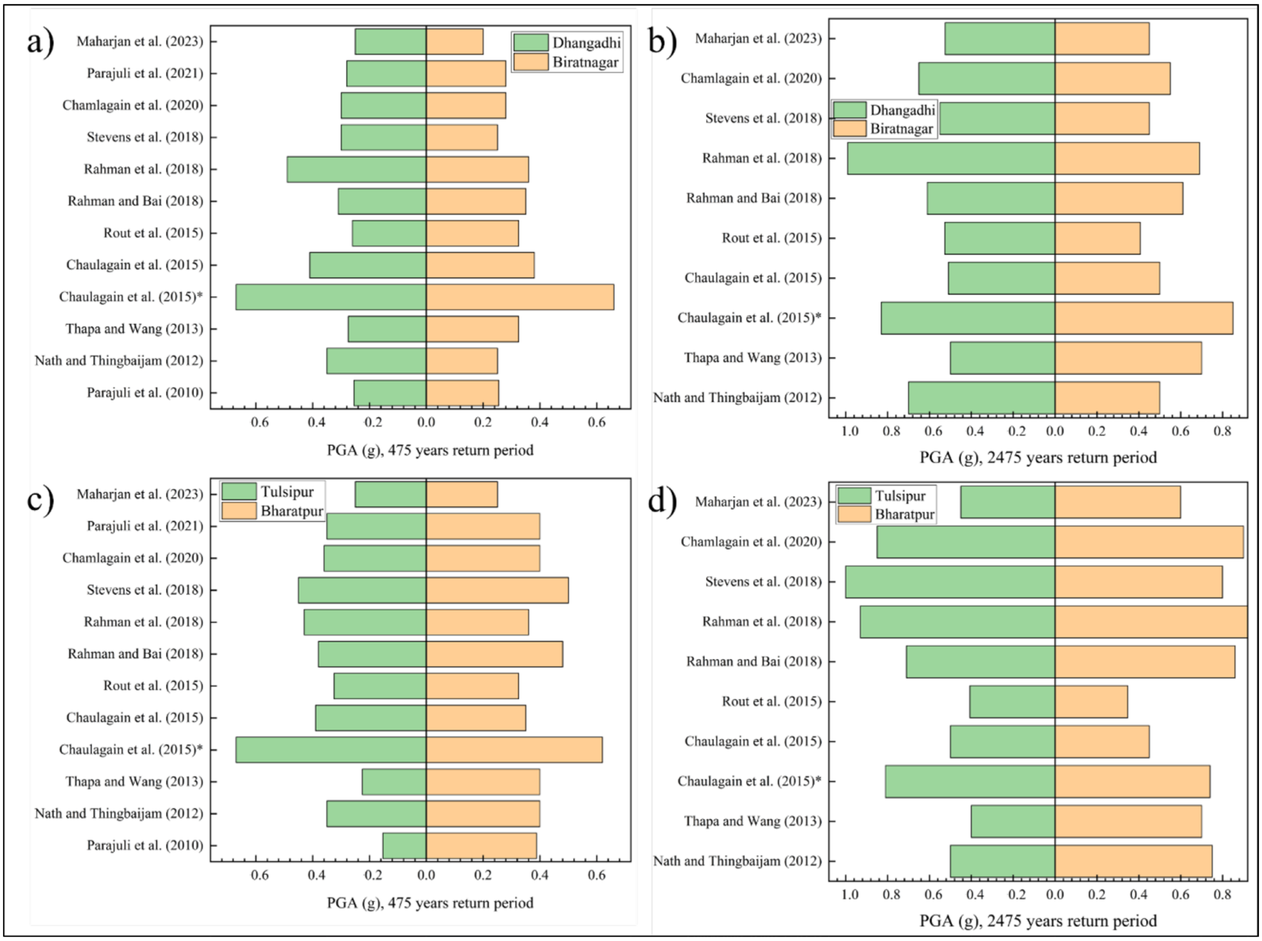

Fig. 8 Comparison of 0.1 s PGAs given by different studies (Parajuli et al. (2010), Chaulagain et al. (2015), and Stevens et al. (2018) have considered local soil conditions, while others have considered bedrock for seismic hazard prediction): (**a**), (**b**) for Dhangadhi and Biratnagr (475- and 2475-year return periods), (**c**) and (**d**) for Tulsipur and Bharatpur (475- and 2475-year return periods)

periods of 475 years. The comparison includes major cities in Nepal, such as Kathmandu, Pokhara, and Biratnagar. NBC 105 (2020) provides response spectra for 475 years for Soil Type A. Soil Type A consists of stiff or hard soils with bedrock, including weathered rock with an unconfined compressive strength greater than 500 kPa and less than 20 m of either very stiff cohesive soil (unconfined compressive strength > 100 kPa) or very dense cohesionless soil (SPT value N > 30). These sites typically have a low-amplitude natural period of less than 0.2 s. Since most of the reviewed literature provides response spectra at the bedrock level with Vs,30 of 760 m/s, the soil type A response spectra from NBC 105 are used for comparison. Response spectra are critical for building design because they provide essential information about the expected seismic demand on structures, enabling engineers to design buildings that can withstand anticipated ground motions (Chopra 2007). Seismic regions such as Nepal are particularly valuable for understanding how structures with varying natural frequencies respond to earthquake ground motions, helping to minimize the risk of structural failure (Boore et al. 1997).

For Kathmandu, the 475-year return period spectral acceleration between 0.1 s and 1 s exceeds the values proposed by NBC 105 (2020) for design purposes. This discrepancy highlights potential inadequacies in current building codes, underscoring the need to update NBC 105 (2020) to reflect more accurate hazard assessments. Studies by Parajuli et al. (2010, 2021), Rahman and Bai (2018), Maharjan et al. (2023), and Chhetri et al. (2022) report higher spectral acceleration than NBC 105 (2020), which is 0.75 g for periods between 0.1 s and 0.5 s. This could be attributed to local geological factors in Kathmandu, such as the presence of deep alluvial deposits and soft soils that amplify seismic waves, leading to higher spectral acceleration values (Sharma and Deng 2019). Additionally,

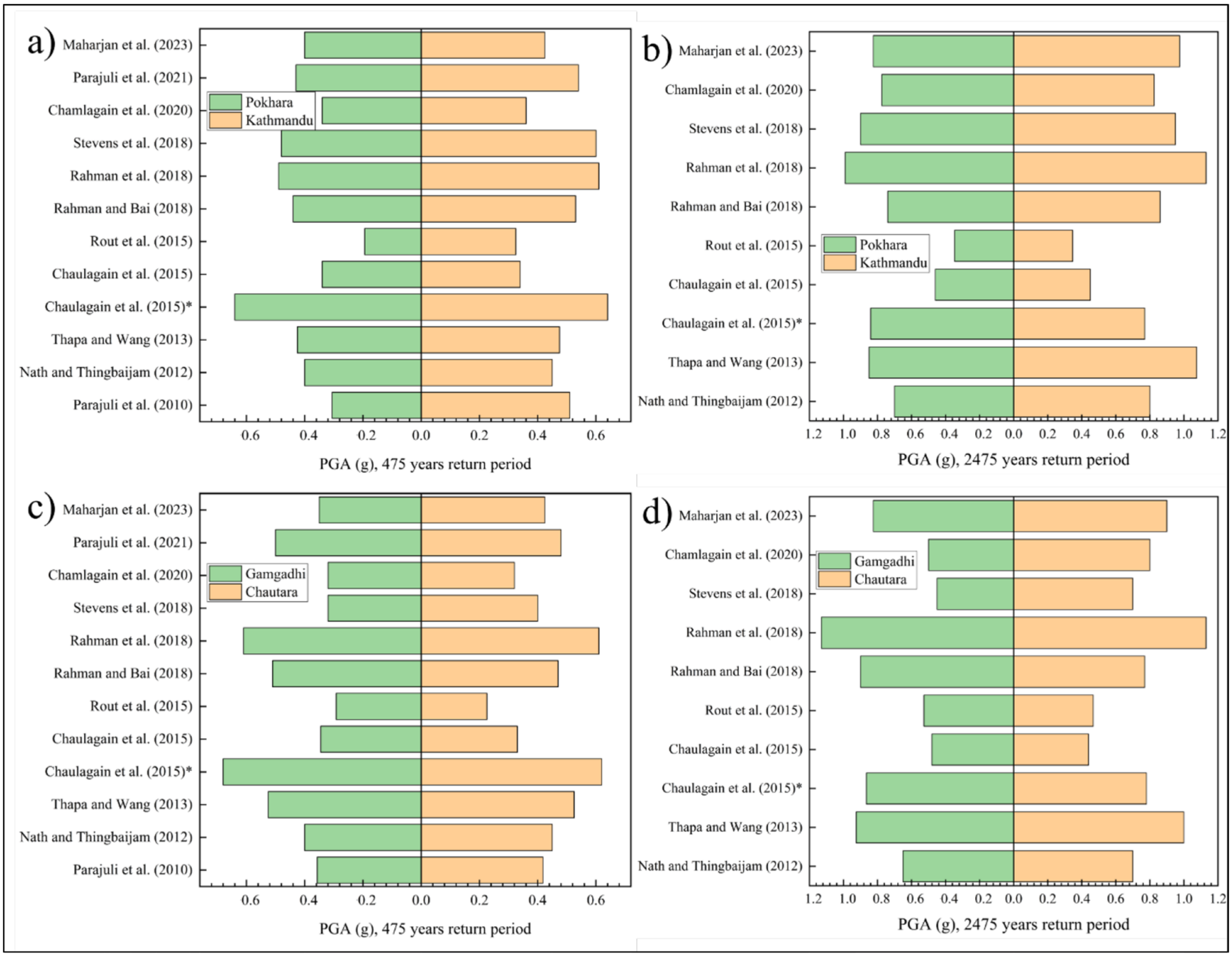

Fig. 9 Comparison of 0.1 s PGA_{475} and PGA_{2475} given by different methods (Parajuli et al. (2010), Chaulagain et al. (2015), and Stevens et al. (2018) have considered local soil conditions, while others have considered bedrock for seismic hazard prediction): (**a**), (**b**) for Pokhara and Kathmandu, (**c**) and (**d**) for Gamgadhi and Chautara

Table 4 Mean PGA, minimum PGA (Min PGA), maximum PGA (Max PGA), and standard deviation of the PGA, all associated with a 475-year return period, for selected cities in Nepal

City	Mean PGA (g)	Std deviation (g)	Min PGA (g)	Max PGA (g)
Biratnagar	0.30	0.06	0.20	0.38
Dhangadhi	0.32	0.07	0.25	0.49
Bharatpur	0.39	0.07	0.25	0.50
Tulshipur	0.33	0.09	0.15	0.45
Kathmandu	0.47	0.10	0.33	0.61
Pokhara	0.39	0.09	0.19	0.49
Chautara	0.42	0.10	0.23	0.61
Gamgadhi	0.41	0.11	0.29	0.61

Table 5 Mean PGA, minimum PGA (Min PGA), maximum PGA (Max PGA), and standard deviation of the PGA, all associated with a 2475-year return period, for selected cities in Nepal

City	Mean PGA (g)	Std deviation (g)	Min PGA (g)	Max PGA (g)
Biratnagar	0.54	0.11	0.41	0.70
Dhangadhi	0.62	0.16	0.50	0.99
Bharatpur	0.77	0.34	0.35	1.55
Tulshipur	0.64	0.24	0.40	1.00
Kathmandu	0.82	0.27	0.35	1.13
Pokhara	0.73	0.21	0.35	0.99
Chautara	0.77	0.23	0.44	1.13
Gamgadhi	0.71	0.24	0.45	1.13

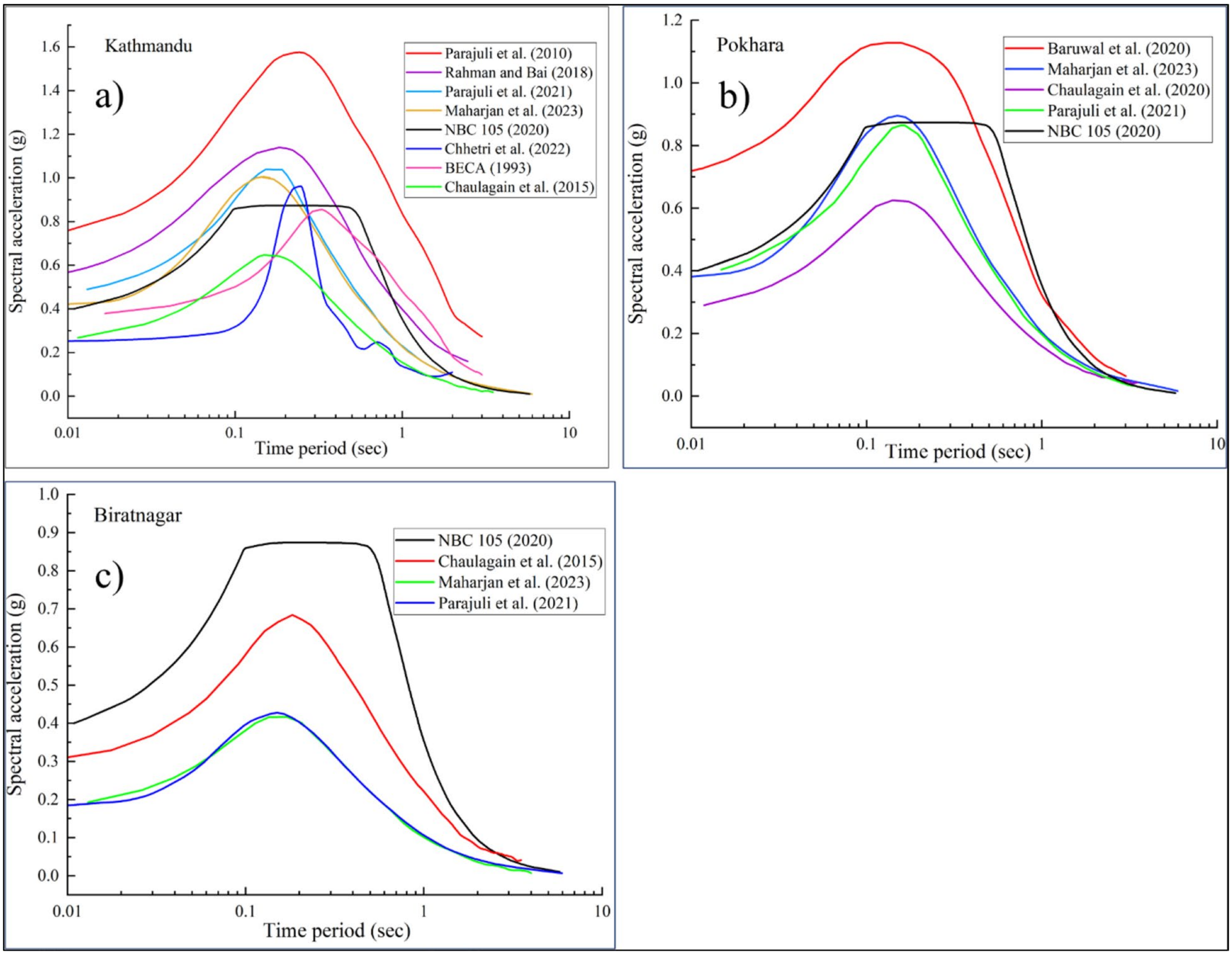

Fig. 10 Comparison of spectral acceleration given by different studies (Parajuli et al. (2010) and Chaulagain et al. (2015) have considered local soil conditions, while others have considered bedrock for seismic hazard prediction) for (**a**) Kathmandu, (**b**) Pokhara, and (**c**) Biratnagar (475-year return period)

Kathmandu's bowl-shaped basin geometry may cause trapped seismic waves to reverberate, further intensifying ground motion (Chaulagain et al. 2015).

For Pokhara, most of the literature reports spectral accelerations within the NBC 105 (2020) values, except for those reported by Baruwal et al. (2020). The lower spectral acceleration compared with that in Kathmandu may reflect differences in geological conditions, such as the prevalence of hard rock formations with minimal soil amplification effects (Rahman & Bai 2018). In Biratnagar, the spectral acceleration values given by all reviewed studies, Chaulagain et al. (2015), Maharjan et al. (2023), and Parajuli et al. (2021), are within the limits proposed by NBC 105 (2020). The geological stability of Biratnagar, characterized by shallow deposits overlying dense soil or bedrock, likely mitigates significant ground motion amplification (Chaulagain et al. 2015).

The observed regional variations could also stem from differences in study methodologies. For example, some studies have used site-specific hazard analysis with detailed soil and subsurface data, whereas others have employed generalized probabilistic seismic hazard analysis (PSHA) models based on broader regional parameters (Maharjan et al. 2023; Parajuli et al. 2021). These methodological differences may account for discrepancies in spectral acceleration estimates across cities, emphasizing the need for consistent and comprehensive hazard assessment frameworks.

Comparison of return period vs *PGA*

Figure 11 compares the return period (ranging from 10 years to 10,000 years) versus the PGA given by various literature sources for major populous cities of Nepal, including Kathmandu, Bharatpur, Pokhara, and Dhangadhi. The variation in the PGA given by

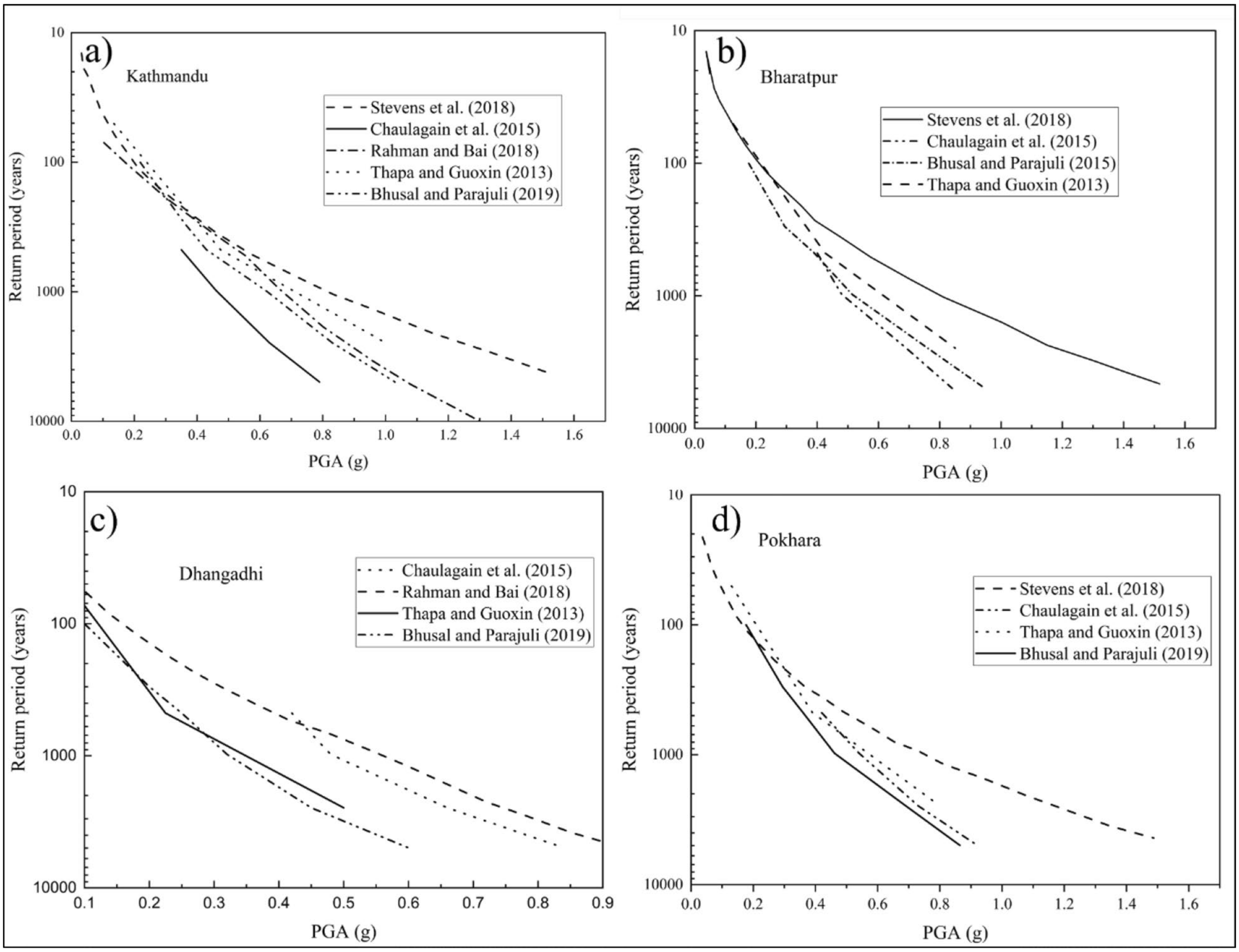

Fig. 11 Comparison of return periods vs. PGA_{475} given by different studies (Chaulagain et al. (2015) and Stevens et al. (2018) have considered local soil conditions, while others have considered bedrock for seismic hazard prediction) for (**a**) Kathmandu, (**b**) Bharatpur, (**c**) Dhangadhi, and (**d**) Pokhara

different studies in these cities varied more as the return period exceeded 1000 years, largely due to epistemic uncertainties such as differences in seismic source models, ground motion prediction equations (GMPEs), and variability in data availability and quality. These uncertainties are inherent in probabilistic seismic hazard analyses (PSHA) and reflect the limitations in our understanding of seismic processes, particularly for rare, high-magnitude events (McGuire 2004).

Such variations in the PGA significantly influence risk perception and infrastructure planning, as higher PGAs for longer return periods may lead to more conservative design strategies for critical infrastructure. For example, infrastructures such as dams and nuclear power plants, which are designed for return periods of 10,000 years, require detailed hazard assessments to account for these uncertainties (McGuire 2004). In Nepal, PGA_{475}, as specified in NBC 105 (2020), is typically used for regular building design to resist significant structural damage, whereas PGA_{2475} is recommended to prevent catastrophic failure in critical structures. Comparatively, international standards, such as those in the United States, adopt similar return periods but often incorporate more detailed regional hazard models (ASCE 7–22, 2022). Updating Nepal's seismic codes with region-specific studies and international best practices can enhance resilience and ensure more robust infrastructure planning in seismic-prone areas.

Discussion

Despite hazard predictions targeting the same study area, the results have exhibited substantial variability. However, all these studies identify similar areas with higher hazard exposure, although the quantified risk varies significantly. All the reviewed literature indicates the highest hazard potential in the Central-Farwestern region, followed by the Central-Eastern and Central parts of Nepal (Table 3). The entire Terai region is relatively less risky from a seismic hazard perspective, with PGA_{475} values typically less than 0.25 g. Another relatively less risky zone is the higher Himalayan range of western Nepal, between Pokhara and Dipayal.

The study by Chaulagain et al. (2015) presents a unique trend, identifying the western region, from the central to the higher Himalayan range, as having the highest seismic hazard potential ($PGA_{475} \sim 0.5$ g), followed by the eastern region. In contrast, Farwestern Nepal is deemed relatively safer ($PGA_{475} \sim 0.30$ g), in contrast to other studies that classify it as highly hazardous. It also highlights significant PGA values in Terai districts such as Jhapa, Morang, Dang, Kailali, and Kanchanpur. These differences likely stem from methodological variations, as Chaulagain et al. (2015) incorporated local soil conditions proposed by the USGS, unlike most SHA studies that focus on bedrock conditions. The deep sediment deposits in the Terai amplified seismic waves, leading to higher PGA values. This underscores the critical role of local soil mapping in SHAs to account for soft soil effects. Integrating these findings into regional seismic planning and updating codes to reflect soil–structure interactions would enhance resilience, especially in regions with deep sedimentary deposits such as the Terai.

All these studies have shown that the area around the MCT has a relatively high seismic risk, as most past earthquakes have occurred in this vicinity (Fig. 1). However, Chamlagain et al. (2020) present a different perspective, suggesting that while the MCT was most active in the past, the MFT/MHT is currently the most active. As a result, the highest PGA values occur along the MHT/MFT, particularly around the boundary between the Terai and Siwalik zones, with a PGA_{475} of approximately 0.4 g. NBC 105 (2020) also uses this study, estimating the PGA_{475} around the MCT to be approximately 0.3 g. This PGA estimation decreases both south of the MFT and north of the MFT. This shift is crucial for updating seismic hazard assessments, as the MFT/MHT zones are now the primary contributors to seismic activity in Nepal (Bollinger et al. 2014).

A comparison between the results of Chamlagain et al. (2020) and Chhetri et al. (2022) highlights the critical role of GMPE selection in seismic hazard assessments for Nepal. Both studies employed three GMPEs each for subduction zones and active shallow crustal zones, with four GMPEs being common between them. However, Chamlagain et al. (2020) used Kanno et al. (2006), whereas Chhetri et al. (2022) adopted Abrahamson et al. (2016), resulting in a modest variation in their PGA_{475} estimates for Kathmandu: 0.36 g and 0.34 g, respectively, a difference of 5.71%. These findings underscore the need for a region-specific GMPE for Nepal to minimize variability in hazard estimates to improve consistency across studies. Currently, Nepal does not have its own GMPEs because of the lack of extensive past ground motion records. Atkinson and Boore (2003) is one of the most repetitively used GMPE in reviewed SHA literatures of Nepal and is developed using data from the Central and Eastern United States (CEUS), focusing on crustal earthquakes. This model is primarily calibrated for the CEUS region. Similarly, Abrahamson et al. (2016) developed region-specific ground-motion models (GMMs) for subduction zone earthquakes using data from the PEER NGA-SUB project. These models cover regions such as Alaska, Cascadia, Japan, and Taiwan, considering factors like site amplification, basin depth, and magnitude scaling. Boore et al. (2014) is another GMPE that is widely incorporated and is based on shallow crustal earthquakes in active tectonic regions, using a global dataset. The equations address magnitude and distance dependencies, site effects based on VS30 values, and aleatory variability. For non-crustal or deeper regions, caution is needed as the model is designed for shallow crustal earthquakes. Zhao et al. (2006) developed a GMPE for subduction slab earthquakes using data from Japan. The model includes geometric attenuation functions, site classes, and nonlinear site amplification ratios. A bilinear scaling function is applied to larger earthquakes, and volcanic zones are considered. This GMPE is mainly applicable to Japan, and should be used with care in regions with different tectonic settings or volcanic activity. Overall, these GMPEs are not calibrated for the complex Himalayan tectonic regime and thus when applying these models outside their region of development, it may not predict the seismic hazard precisely.

Similarly, whether or not geological and geodetic fault parameters are integrated into seismic hazard models can significantly impact the accuracy of seismic hazard assessment (SHA). In most of the reviewed studies, their integration remains limited, which may affect the reliability of hazard predictions, particularly in regions with complex fault systems. Incorporating geological and geodetic data can enhance model precision by improving fault characterization, rupture dynamics, and slip rate estimations. Another factor influencing the estimation of the PGA is the consideration of local site effects. For example, the PGA under bedrock conditions for Pokhara is estimated to be 0.34 g according to Chamlagain et al. (2020). However, when accounting for local soil effects, Chaulagai et al. (2015) estimated it to be 0.84 g (147% greater). Notably, Chaulagain et al. (2015) used only one different GMPE (Youngs et al. 1997) out of five. The results demonstrate that seismic hazard assessments over soft deposits can be substantially greater than those based on bedrock conditions. The soft soil effect is a critical phenomenon that must be considered for precise seismic hazard assessment (SHA); neglecting it can sometimes lead to catastrophic consequences. During the 2015 Gorkha Earthquake, Sharma and Deng (2019) reported that areas in the Kathmandu Valley with soft soil deposits, such as Gongabu, Balaju, Machha Pokhari, Ramkot, and Naikap, experienced extensive damage to reinforced concrete (RCC) buildings. In contrast, similar types of buildings in areas with firmer soil conditions sustained relatively less damage. Similarly, KC et al. (2025) noted comparable effects during the moderate M_W 5.7 Jajarkot earthquake in 2023, albeit on a smaller scale. Interestingly, most of Nepal's populous cities are located along riverbanks, which are potentially underlain by soft deposits, increasing the degree of local soil conditions in SHAs.

Epistemic uncertainty is another factor that can significantly affect the accuracy of SHA. Several seismic hazard assessment (SHA) studies in Nepal that are reviewed have considered epistemic uncertainties using logic-tree frameworks as they often includes different source models and combined various ground motion prediction equations. Among these studies, Nath and Thingbaijam (2012), Rahman et al. (2018), Stevens et al. (2018), Chamlagain et al. (2020), Parajuli et al. (2021), Chhetri et al. (2022), and Rahman and Bai (2018) consider equal weightage to all GMPEs used in their analysis. On the other hand, studies like Maharjan et al. (2023) and Sreejaya et al. (2022) assign different weightage to the GMPEs based on their characteristics, such as their reliability or relevance to the region. To manage epistemic uncertainty more effectively in future seismic hazard assessments in Nepal, adopting a structured expert elicitation process, such as the Senior Seismic Hazard Analysis Committee (SSHAC) methodology used in the United States (Marzocchi et al. 2015), is recommended. SSHAC integrates diverse expert judgments and data interpretations, providing a more reliable and transparent approach to hazard assessment. Furthermore, improving data quality through enhanced seismic monitoring and geological investigations will help reduce epistemic uncertainty over time.

Another factor influencing seismic hazard estimation is declustering. In their study of the Kathmandu Valley with a 760-year return period, Chhetri et al. (2022) first calculated the PGA without applying declustering, yielding a value of 0.34 g. They then calculated the PGA with declustering via the method proposed by Gardner and Knopoff (1974), which resulted in a value of 0.27 g—20.59% lower. Chhetri et al. (2022) reported that the results obtained by declustering were closer to the actual ground shaking observed during the 2015 Gorkha earthquake. All the reviewed studies that used declustering methods other than those of Chhetri et al. (2022) used the Gardner and Knopoff (1974) method. The Gardner and Knopoff (1974) window-based method, a common approach, removes dependent events within predefined temporal and spatial windows around mainshocks. While it is simple to apply, it may oversimplify complex seismic activity by using uniform criteria across regions and times. In contrast, the Reasenberg (1985) algorithm dynamically identifies clusters on the basis of event proximity in space and time, considering interaction probabilities, making it more adaptable but computationally demanding. Moreover, almost all the studies reviewed that performed declustering have done so using a Poisson process. Moving forward, utilizing a time-dependent model, such as the Brownian Passage Time model (Ellsworth et al., 1999), could enhance the accuracy of seismic hazard assessment (SHA) predictions. This model accounts for the fact that another megathrust event along the same segment of a thrust where a mega-earthquake has already occurred is unlikely in the near future, effectively incorporating fault memory.

Additionally, in some cases, the date range of an earthquake catalog can influence seismic hazard assessment (SHA) predictions. The recurrence interval of megascale earthquakes may exceed the time span considered in certain studies. Bollinger et al. (2014) stated, "Paleoseismological studies indicate that the recurrence interval of megathrust earthquakes in the Himalayan region varies across different segments. For instance, in eastern Nepal, great earthquakes ($M \geq 8$) have an estimated return period of 750 ± 140 to 870 ± 350 years." Thus, relying on a short time range may overlook the true seismicity of a region, posing a limitation in some studies.

Conclusions and recommendations

This review examines most seismic hazard analysis (SHA) studies of Nepal that are readily available online. In Nepal, significant attention to SHAs emerged only after the 2000s, when probabilistic seismic hazard analysis (PSHA) was already widely adopted. Therefore, almost all SHA studies for Nepal since then have adopted a probabilistic approach. Owing to the lack of sufficient real-time ground shaking records and instrumental seismic stations in the past, Nepal still does not have its own local ground motion prediction equations (GMPEs), which are literally the most influential variables that can make a significant difference in SHA results. Most PSHA studies in Nepal have relied on GMPEs from other parts of the world (those developed for the Cascadia region, Japan, Chile and others), often in different combinations. Some studies have considered local soil conditions based on USGS data, while most have assumed bedrock conditions due to the lack of precise national-level soil mapping. Seismic source zonation is inconsistent, as thrust conditions have not been extensively explored. Some studies have considered areal sources based on past earthquake clustering, while others, particularly those conducted after the 2015 Gorkha earthquake, have focused on major thrusts based on subsurface fault characteristics. There are discrepancies in the earthquake catalog quality, declustering methods, and software used, which could have some degree of impact on the results. The primary limitation of this review is its reliance on available literature, which may not comprehensively capture all recent advancements in seismic hazard analysis for Nepal. Additionally, while widely used GMPEs are discussed, a detailed evaluation of each GMPE applied in the reviewed studies is not included, as this review primarily focuses on the key parameters influencing seismic hazard analysis results. Additionally, this review compares the results of different studies based on whether they have incorporated site amplification factors, which could be further refined in future reviews. Furthermore, comparing the results of different studies may not always be straightforward due to variations in methodologies. Future reviews of this kind for Nepal should focus on individual factors and their in-depth effects on results, incorporating state-of-the-art advancements adopted elsewhere.

On the basis of this review, several key recommendations are proposed to enhance seismic hazard analysis (SHA) for Nepal, advance the design of resilient infrastructure, and ultimately save lives and protect property. Until then, it is recommended to rely on the most recent studies, as they incorporate updated geological data and more comprehensive earthquake catalogs, including data from the 2015 Gorkha earthquake, has been recommended.

- Development of Region-Specific GMPEs: Nepal urgently needs ground motion prediction equations (GMPEs) tailored to its unique seismotectonic settings. This entails installing a denser network of strategically distributed seismic stations to gather sufficient real-time ground motion data.
- Comprehensive Local Soil Condition Mapping: Precise nationwide mapping of local soil conditions is essential for understanding site-specific amplification effects. This approach enhances the reliability of seismic hazard analysis (SHA) results, particularly in densely populated areas such as the Kathmandu Valley, where soft soil deposits significantly amplify seismic waves.
- Standardization of seismic source zonation: A uniform seismic source zonation framework should be developed, incorporating past earthquake trends along with detailed studies of major thrusts (MHTs/MFTs, MCTs, and MBTs) as well as local faults. Additionally, the integration of geological and geodetic fault parameters in seismic hazard models is crucial for improving the accuracy of SHA in future.
- Improved Earthquake Catalogs and Advanced Techniques: Efforts should focus on developing high-quality earthquake catalogs with unified data on historical and instrumental earthquakes, using declustering methodologies suited to Nepal's seismotectonic environment. Modern computational tools, such as machine learning and geophysical modeling, should be adopted to refine probabilistic seismic hazard assessments (PSHA) and systematically address uncertainties.

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