

# **SEISMIC HAZARD ANALYSIS OF NEPAL**



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**FOR THE AWARD OF DOCTOR OF PHILOSOPHY  
IN GEOLOGY**

BY

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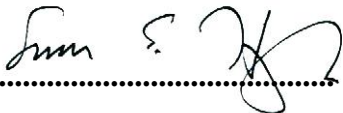
**JUNE 2019**

## RECOMMENDATION

This is to recommend that **Sudhir Rajaure** has carried out research entitled “**Seismic Hazard Analysis of Nepal**” for the award of Doctor of Philosophy (Ph.D.) in **Geology** under my/our supervision. To my/our knowledge, this work has not been submitted for any other degree.

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## LETTER OF APPROVAL

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On the recommendation of Prof. Dr. **Lalu Prasad Paudel**/Senior Seismologist Dr. **Susan Hough**, this Ph.D. thesis submitted by Mr. **Sudhir Rajaure** entitled “**Seismic Hazard Analysis of Nepal**” is forwarded by Central Department Research Committee (CDRC) to the Dean, IOST, T.U..

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## DECLARATION

Thesis entitled “**Seismic Hazard Analysis of Nepal**” submitted to the Central Department of Geology, Institute of Science and Technology (IOST), Tribhuvan University, Nepal for the award of the degree of Doctor of Philosophy (Ph.D.), is a research work carried out by me under the supervision of Prof. Dr. Lalu Prasad Paudel, Central Department of Geology, Tribhuvan University, Nepal and co-supervised by Senior Seismologist. Dr. Susan Hough, United States Geological Survey, USA.

This research is original and has not been submitted earlier in part or full in this or any other form to any university or institute, here or elsewhere, for the award of any degree.

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## ABSTRACT

Nepal is situated in the central part of the Himalaya, which is one of the most seismically active zones in the world. Nepal has witnessed several mega-quakes, with magnitude above 8, and thousands of smaller earthquakes. The 2015 Mw 7.8 Gorkha earthquake is the most recent significant event in the country. Large and moderately large earthquakes can have a tragic impact on people and society as a whole. The preparation of seismic hazard map and evaluation of site specific ground motion due to earthquake are recognized as the fundamental steps towards the earthquake risk reduction.

An attempt is made to develop seismic hazard maps of Nepal using available data of earthquakes, recent knowledge of seismotectonics and refined geological features. A comprehensive and magnitude-homogenized earthquake catalogue is prepared from the processing of earthquake catalogues collected from different sources. Thus prepared catalogue contains earthquake data since 1100 AD to 2017 AD. Nine sets of potential earthquake source models are delineated after the analysis of the seismicity distribution, geological structures, results of different geophysical and geodetic surveys and the experience of 2015 Gorkha Earthquake.

Probabilistic technique of seismic hazard analysis is applied to evaluate seismic hazard in Nepal. The result shows high hazard in an east-west elongated belt that runs parallel to the front of the Higher Himalaya. The maximum PGA reaches about 0.45 g in far-west Nepal and about 0.4 g in Kathmandu Valley for 10 % probability of exceedance in 50 years, at engineering rock site.

The effect of the sediments of the Kathmandu sedimentary basin is investigated using strong motion data of earthquakes recorded in the Kathmandu Valley. During the Mw 7.8 (Gorkha) earthquake, the largest PGA (0.25 g) was recorded at Kirtipur (KTP), which is a rock site. The record shows a single and unusual spike, which is attributed to the permanent displacement of the Main Himalayan Thrust. The second largest PGA (0.23 g) was recorded at the Central Department of Geology (Tribhuvan University (TVU)), which is a soil site. During the Mw 7.8 earthquake, the PGAs were

comparatively smaller at all soil sites, whereas the peak ground velocity (PGV) was small at KTP (rock site) and were larger at all other soil sites.

The strong motion records of the earthquakes depict the predominant period being between 3 and 5 seconds at the soil sites. The high frequencies ( $>2.5$  Hz), were strongly damped and the low frequencies ( $<2.5$  Hz) were amplified at the soil sites, therefore tall buildings suffered more and the low rise buildings suffered less when compared. The amplification factor was small during the stronger earthquakes and was large during smaller earthquakes; thus demonstrating non-linear response of soil. The analysis shows that the azimuthal effect of earthquake sources was not observed in the Kathmandu Valley.

Earlier reports on the 1934 Bihar-Nepal Earthquake ( $M_w$  8.2) and 1833 North Kathmandu Earthquake ( $M_w \sim 7.6$ ) report localized massive destruction in the Kathmandu valley and attribute the massive destruction to local geology of the basin (Pandey and Molnar, 1988). Contrary to these claims, amplification of ground acceleration was not observed in the Kathmandu valley during the 2015 Gorkha Earthquake but the low frequencies were amplified.

The seismic hazard map and ground response results are mandatorily considered in policy making, planning, formulation and revision of building codes, design of new infrastructures and retrofitting of existing infrastructures. It facilitates the seismic risk assessment, insurance policies and many other related matters.



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## LIST OF SYMBOLS

$\lambda$	: Annual exceedance rate of earthquake
$\beta$	: 2.303 * b-value
$\int$	: function of
$\Delta$	: increment
$\sum$	: sum
$g$	: Acceleration due to gravity (9.8 m/sec <sup>2</sup> )



## LIST OF ACRONYMS AND ABBREVIATIONS

DMG	: Department of Mines and Geology
DSHA	: Deterministic Seismic Hazard Analysis
GSHAP	: Global Seismic Hazard Program
IRIS	: Incorporated Research Institutions for Seismology
ISC	: International Seismological Centre
ISC-GEM	: International Seismological Centre-Global Earth Model
Jyb	: Shortest distance between a site and the surface projection of the rupture surface
MBT	: Main Boundary Thrust
MFT	: Main Central Thrust
MCT	: Main Central Thrust
MHT	: Main Himalayan Thrust
NEHRP	: National Earthquake Hazard Reduction Program
PGA	: Peak Ground Acceleration
PSA	: Peak Spectral Acceleration
PSHA	: Probabilistic Seismic Hazard Analysis
Rrup	: Rrup is the closest distance to the rupture surface from a site
SA	: Spectral Acceleration
SHA	: Seismic Hazard Analysis
USGS	: United States Geological Survey

# CHAPTER 1

## INTRODUCTION

### 1.1. Background

The world faces and suffers from a number of disasters such as floods, droughts, landslides, cyclones, earthquakes, tsunamis and fires every year. A disaster is a serious disruption, occurring over a relatively short time of the functioning of a community or a society involving widespread human, material, economic or environmental loss and impacts, which exceed the ability of the affected community or society to cope using its own resources. Some of the disasters are natural and some are human induced. Earthquake, flood, cyclone etc. are natural disasters caused by the natural processes. Developing countries suffer more when a disaster hits. More than 95 percent of all deaths and casualties caused by hazards occur in developing countries, and losses due to natural hazards are greater (as a percentage of GDP) in developing countries than in developed countries (<https://www.usgs.gov/faqs/>).

Earthquake is one of the most frightening and destructive phenomena of nature because of its terrible impacts not only to people but also to the society and the nation or beyond. Scientifically speaking, an earthquake is a sudden movement on geological faults, which causes the abrupt release of strain that has accumulated over a long time. The tectonic forces have acted for millions of years and resulted in shaping the Earth as it is at present. Tectonic plates move at certain rate over, under and past each other. During interseismic periods, the plates are locked together, and are unable to release the accumulating energy. When the accumulated energy grows strong enough, the plates break and displacement occurs on geological faults. In general, earthquakes with magnitude smaller than 5 do not cause considerable damage. If the earthquake magnitude is large (usually larger than 5) and occurs in a populated area, the consequences may be very catastrophic. The effect of an earthquake depends on its magnitude, distance between earthquake source and sites, local site effect, construction types, season (rainy or dry), time of occurrence (day, night, and holiday or office hours) and response of people during earthquake. An adverse event will not rise to the level of a disaster if it occurs in an area without vulnerable population. In a

vulnerable area, however, an earthquake can have disastrous consequences with significant damage, which may require years to recover.

Earthquakes in Nepal and the Himalaya region are caused by the release of energy that accumulates on account of the collision between the Indian and the Eurasian Plates (Dewey & Bird, 1970; Powell & Conaghan, 1973). The collision between the two plates is believed to have started about 50 million years ago (Le Fort, 1975; Coward *et al.*, 1986) and it is still active. Collision between these two plates leads to the straining of the crust. This process causes accumulation of energy in the form of elastic deformation in the medium. Continuous collision of tectonic plates and cyclic accumulation and release of elastic energy has been attributed to the development of the Himalayan range.

Nepal is situated in the central part of the Himalaya and has witnessed a number of large earthquakes since the historical times. Earthquakes have occurred more or less in the same regions from pre-historic times. Large earthquakes are rare events in comparison to others. However, the consequences of occasional large earthquakes have remained very painful to the people, society, economy and the nation.

Prediction of earthquakes, till now, is not possible. However, its effects can be minimized by assessing the probability of occurrence of large earthquakes and their probable effects in advance and working out the reduction of earthquake vulnerability. The preparation of a seismic hazard map of an area and the identification of the site-specific response of a ground motion during earthquake could be the fundamental step in mitigating the earthquake risk.

Seismic hazard maps are updated regularly when new findings, knowledge and data become available. Several attempts have been made to assess seismic hazard of Nepal in the past with limited data, limited source models, and limited attenuation relations. A lot of researches have been carried out and the new seismic phenomena have been observed like new seismotectonics of the sources and effects of earthquakes in Nepal. The seismic hazard in Nepal requires a new approach for its investigation utilizing logic tree so that uncertainties in earthquake source geometry, earthquake source location, attenuation relation and maximum potential magnitude could be minimized. Present research incorporates new findings in the field of seismotectonics, source

zonation, size of maximum potential earthquake and observation of 2015 Gorkha Earthquake.

The present research aims to evaluate seismic hazard in Nepal and prepare a seismic hazard map so that the map can be utilized for estimating probable peak ground acceleration of an area during an earthquake. Such data can be used in designing earthquake resistant infrastructures so as to minimize the effect of an earthquake. In addition to the seismic hazard analysis of Nepal, site-specific ground response of the Kathmandu valley was also analyzed using the strong motion data from the 2015 Gorkha Earthquake. Present study, in this regard, is a latest contribution in the field of seismic hazard study of Nepal by considering multiple source models and multiple attenuation relations. Site-specific ground response analysis of the Kathmandu valley using the 2015 Gorkha Earthquake is also a new study for the Kathmandu valley. It is envisaged that, the results of the present study will be very useful for the earthquake-resistant infrastructure development in Nepal.

This thesis is the result of six years continuous work. One paper has been published in an international journal with impact factor and three papers have been published in indexed journal (Appendix 1). Similarly, the results were presented in national and international conferences (Appendix 2). This thesis provides a detailed elaboration of the research questions, objectives, methodology, results and conclusions of the study.

## **1.2. Geological setting of the Nepal Himalaya**

Geologically, Nepal is divided into five major units (Figure 1 and Figure 2), which are the Indo-Gangetic Plain (Terai), the Sub-Himalaya, the Lesser Himalaya, the Higher Himalayan and the Tethys Himalaya, successively from south to the north (Gansser, 1964). These geological units extend approximately parallel to each other and run all along the Nepal Himalaya. The geological units are characterized by their own lithology, tectonics, structures and geological history. Besides the major geological zones, Nepal comprises a number of intermontane basins and dun valleys. The Kathmandu valley is one of the major intermontane basins in Nepal. A brief description of each tectonic zones and geological setting of the Kathmandu valley is given in the following sections.

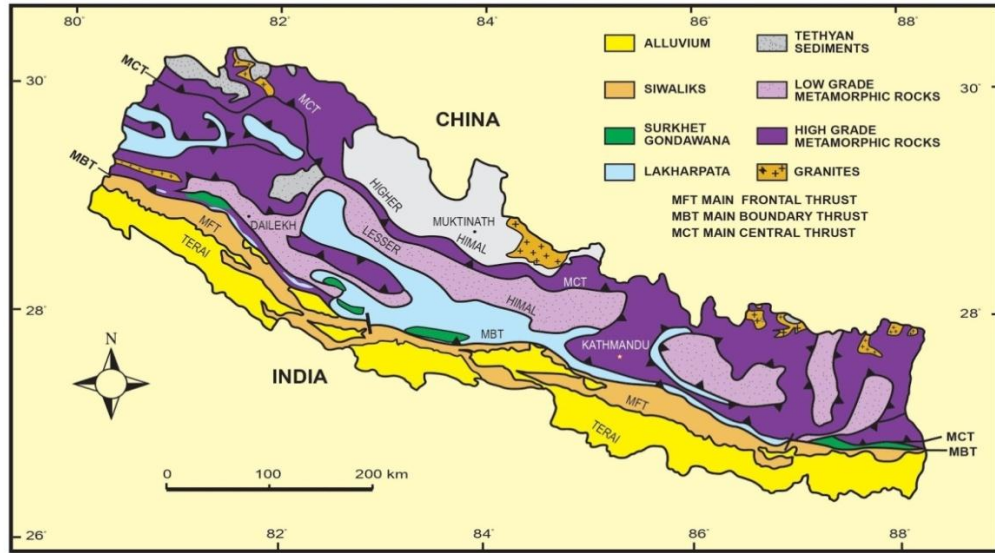
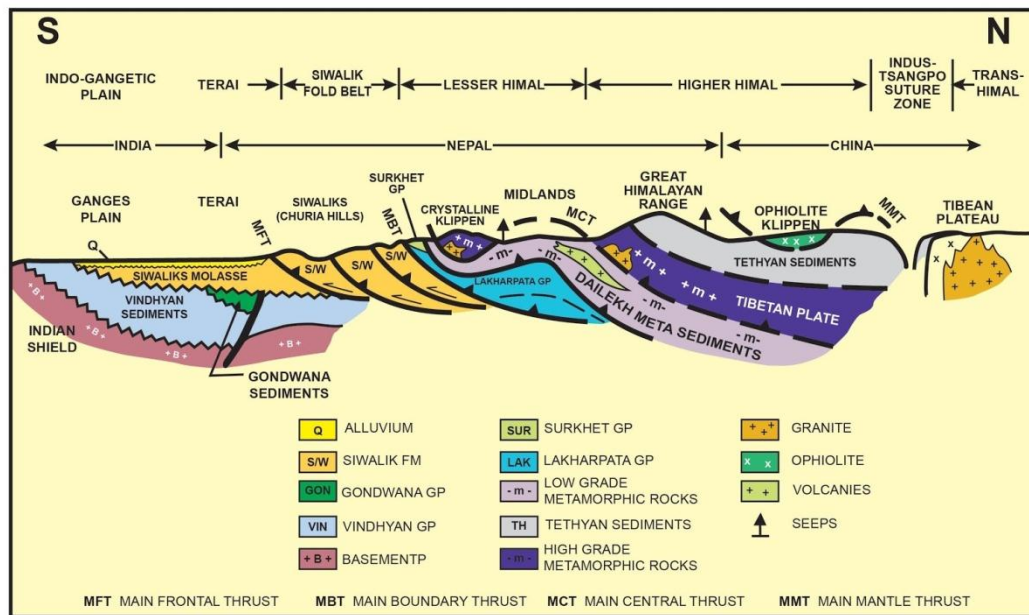


Fig. 1

**Figure 1:** Geological Map of Nepal prepared by Petroleum Exploration Promotion Project, Department of Mines and Geology, Government of Nepal (Source: <https://petroleumnepal.gov.np/>).



**Figure 2:** Geological cross section at the longitude of Kathmandu prepared by Petroleum Exploration Project, Department of Mines and Geology, Government of Nepal (Source: <https://petroleumnepal.gov.np/>).

### 1.2.1. Indo-Gangetic Plain

It is the southernmost geological unit, which is called Terai in Nepal. It is a foreland basin, which developed after the collision of the Indian and Eurasian Plates, which is directly linked with the rise of the Himalaya. The basin is filled in with by Pleistocene to Recent alluvial deposits. In the north, it is bounded by the Main Frontal Thrust

(MFT). The average thickness of deposit is about 1500 m. The Terai Zone shares a significant proportion of current Himalayan stress accumulation which is evidenced by presence of blind thrusts and thrust-propagated folds beneath the sediments.

### **1.2.2 Sub-Himalaya (Siwalik)**

The foothill ranges of the Himalaya are called the Sub-Himalaya or Siwaliks. It is bounded to the south by the MFT while in the north it is separated by the Main Boundary Thrust (MBT). The Sub-Himalayan rocks represent the Late Tertiary (Middle Miocene to Early Pleistocene) continental molassic sediments deposited within the southern foredeep basin of the Himalaya. The Siwalik succession is 4-6 km thick in Nepal Himalaya and in general represents a coarsening upwards sequence with individual fining up cycles which reflects the rising history of the Himalaya (Gansser, 1964).

### **1.2.3 Lesser Himalayan Zone**

The Lesser Himalaya lies between the Sub-Himalaya and Higher Himalaya. Both the southern and northern boundaries are represented by thrust-faults, i.e., the MBT and the Main Central Thrust (MCT), respectively. It comprises mainly sedimentary to low-grade meta-sedimentary rocks of Late Precambrian to Oligocene (Hashimoto *et al.*, 1973; Stöcklin & Bhattarai, 1977; Sakai, 1983). In the eastern part, it consists of many windows consisting of low grade meta-sedimentary rocks around the crystalline rocks of the thrust sheets.

### **1.2.4. Higher Himalaya**

The Higher Himalaya is bound by the MCT in the South and the South Tibetan Detachment System (STDS) in the north. The Higher Himalaya is composed of about 10 km thick pelitic, psammatic and calcareous para-gneisses, granitic ortho-gneisses and migmatites of amphibolite facies containing kyanite and sillimanite (Le Fort, 1975; Arita, 1983; Colchen *et al.*, 1986). The MCT has transported the high-grade Higher Himalayan rocks over the low-grade meta-sedimentary rocks of the Lesser Himalaya. The Higher Himalayan rocks form nappes (e.g. Kathmandu Nappe,

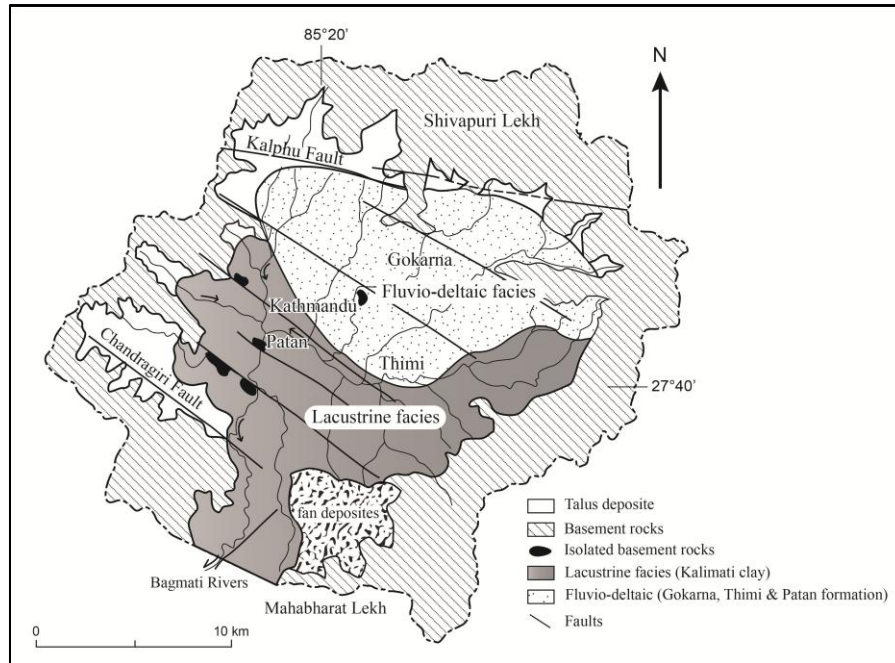
Dadheldhura Nappe) and klippes (e.g., Jajarkot Klippe, Kahun Klippe) at different places in the Lesser Himalaya.

### **1.2.5. Tethys Himalaya**

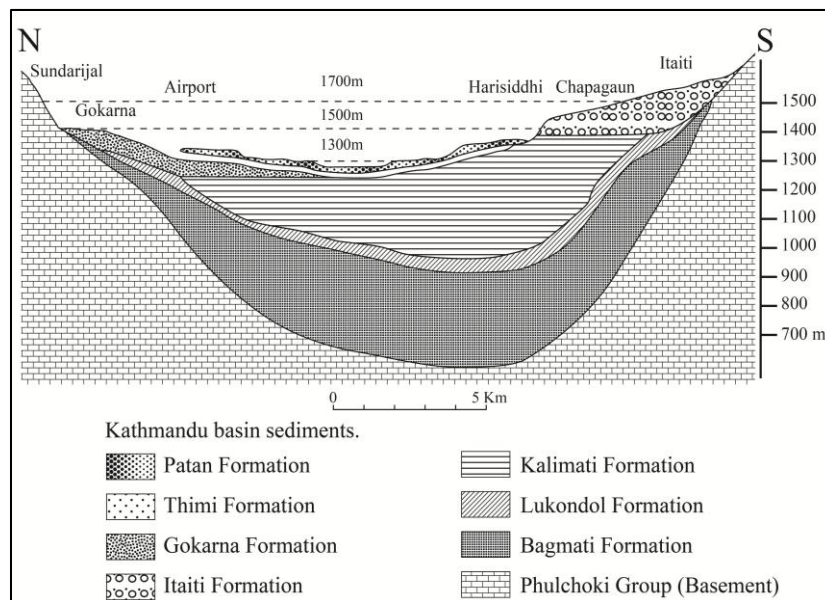
The Tethys Himalaya lies between the STDS in the south and the Indus-Tsangpo Suture (ITS) Zone in the north. This zone comprises sedimentary rocks (e.g. shales, limestones, and sandstones), which range in age from Cambrian to Cretaceous from shelf-sediments deposited on the northern margin of the Indian Continent (Hagen, 1968; Bodenhausen & Egeler, 1971; Bordet *et al.*, 1971; Colchen *et al.*, 1981).

### **1.2.6. Geology of Kathmandu valley**

The Kathmandu valley is located within the Lesser Himalaya (Figure 3). The basin falls in the Midland Zone of the Lesser Himalaya, and is bounded by the Mahabharat Lekh in the south and the Shivapuri Lekh in the north. The basement of the Kathmandu basin is interpreted to be a huge nappe (Kathmandu Nappe) formed by thrusting along Mahabharat Thrust (MT), probably the southward extension of the Main Central Thrust (MCT) (Stöcklin, 1980). It is made up of the Precambrian Bhimphedi Group and Paleozoic Phulchoki Group (Stöcklin, 1980). The Kathmandu valley is filled in with young fluvio-lacustrine sediments (Figure 3) of Pliocene to Quaternary age (Yoshida & Igarashi, 1984). The maximum depth to bedrock is more than 500 m at the middle of the basin. Geologically, the Kathmandu valley falls in the Midland zone of the Lesser Himalaya (Dhital, 2015).



**Figure 3:** Geological map of Kathmandu valley (Modified from Sakai, 2001).



**Figure 4:** Schematic cross section beneath the Kathmandu valley (Modified after Sakai, 2001).

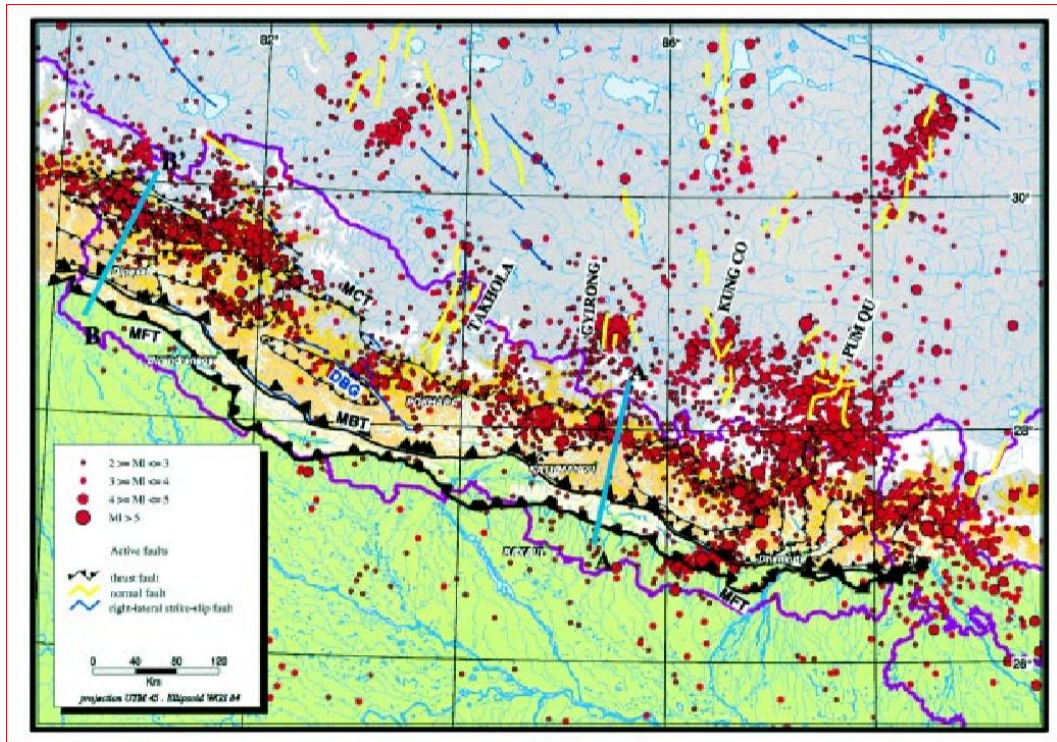
The sediments of the Kathmandu basin unconformably lie on the Kathmandu Complex rocks (Figure 4). The sediments range in age from 2.5 Ma to about 20 kyr with a total thickness of about 600 m at the central part of the basin.



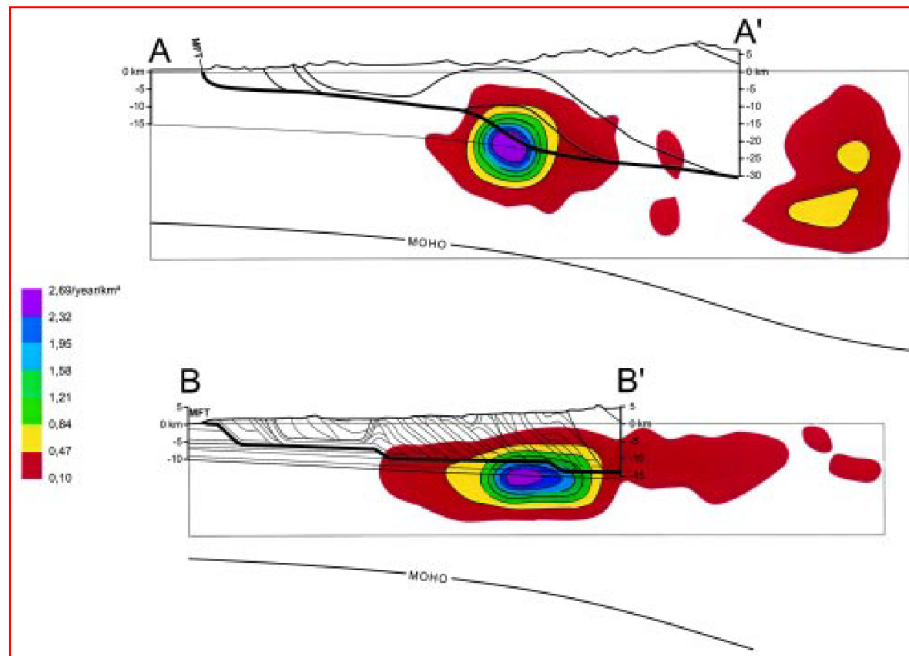
### 1.3. Seismicity and seismotectonics of the Nepal Himalaya

The Himalayan range is one of the seismically active regions in the world, which has produced several destructive earthquakes in the past (e.g. Bilham *et al.*, 2001; Bilham, 2004; Szeliga *et al.*, 2010; Ambraseys & Jackson, 2003; Chitrakar & Pandey, 1986; Pant, M. R., 2002). The Himalayan region has witnessed six destructive earthquakes in less than 150 years, which are the 1987 Shillong Earthquake (Mw 8.3), 1905 Kangra Earthquake (Mw 7.8), 1934 Bihar-Nepal Earthquake (Mw 8.4), and 1950 Assam Earthquake (Mw 8.6), 2005 Muzafarabad (Pakistan) Earthquake (Mw 7.6), and the recent 2015 Gorkha Earthquake (Mw 7.8). Historical documentation shows that the region between the 1905 Kangra Earthquake and the 1934 Bihar Nepal Earthquake (between 78°E and 84°E) has not produced any major earthquake since approximately the last five hundred years and is feared as a seismic gap (e. g. Khattri & Tyagi, 1983; Khattri, 1987; Bilham *et al.*, 1995; Pandey *et al.*, 1999), where destructive earthquakes could be overdue.

A belt of seismic activity can be traced all along the Nepal Himalaya (Figure 5) (Pandey *et al.*, 1999). This belt of seismic activity correlates to a zone of maximum uplift rate revealed in leveling data (Jackson & Bilham, 1994; Pandey *et al.*, 1995; Bilham *et al.*, 1997 and Lave & Avouac, 2001), and a zone of maximum horizontal GPS velocity (Cattin & Avouac, 2000) at the geometrical ramp, which is a transition zone between locked southern part of the Main Himalayan Thrust (MHT) and aseismically creeping part in the north, beneath South Tibet. The seismicity of the Himalayan belt is characterized by shallow focus ( $10 < \text{depth} < 25 \text{ km}$ ) earthquakes (Figure 6). The 1988 Udayapur Earthquake area is an exception, where the earthquakes occur in the upper mantle (Chen *et al.*, 1981; Chen & Molnar, 1983; Pandey, M. R. & Nicolas, M., 1991; Zhao & Helmberger, 1991; Zhu & Helmberger, 1996; Chen & Yang, 2004; Kayal, 2001; Pandey *et al.*, 1999).



**Figure 5:** Seismicity map of Nepal (Pandey *et al.*, 1999).



**Figure 6:** Structural cross sections across the central Himalaya and far-west of Nepal (AA' and BB' in Figure 5) (Pandey *et al.*, 1999). The figure shows the density of earthquake foci concentrated at shallow depth.

The MHT is the major geological structure beneath the Himalaya. The MFT, MBT and the MCT are inferred to join this mega thrust at depth (e.g. Avouac, 2003). Most of the crustal deformation in the Himalaya occurs on MHT (Cattin & Avouac, 2000;

Lave & Avouac, 2000). The MHT is a detachment thrust and its surface expression is the MFT (Nakata, 1989), where the long term slip rate has been estimated from the study of uplift of Holocene terraces to be  $21.5 \pm 1.5$  mm/yr in central Nepal (Lave & Avouac, 2000) and  $19 \pm 6$  mm/yr in western Nepal (Mugnier *et al.*, 2003).

Geodetic investigations carried out in Nepal show that the MHT absorbs about 20 mm/year of the India-Eurasia convergence (Bilham *et al.*, 1997), which is about 50 percent of the India-Eurasia convergence rate (Bettinelli *et al.*, 2006). Geodetic studies also show that the MHT is nearly fully locked from the surface trace of MFT to a width of about 100 km in the north, beneath the front of the Higher Himalaya (Bilham *et al.*, 1997; Jouanne *et al.*, 1999; Larson *et al.*, 1999; Bettinelli *et al.*, 2006; Ader *et al.*, 2012). This locking decreases towards north abruptly, within a transition zone of smaller than 30 km width. This transition occurs at a depth of about 15-20 km, where the temperature on the MHT is estimated to reach  $350^\circ\text{C}$  (Ader *et al.*, 2012). In the north of the locking zone the MHT extends into a sub horizontal shear zone, which is interpreted to be associated with aseismic creep, probably, thermally enhanced by ductile flow (Cattin & Avouac, 2000). At present, the MFT is considered to be the most active fault system regarding the surface deformation of Holocene terraces across it (Lave *et al.*, 2000; Lave *et al.*, 2001). At the time of great earthquakes, it is believed that the nucleation of earthquake occurs at the geometrical ramp and propagates towards the south resulting in surface deformation and surface break close to MFT. Possibly MFT does not rupture during magnitude less than 8.0 earthquakes and leaves the frontal area stressed to be ruptured in next great earthquake or with smaller magnitude local earthquake in the south of the ramp. The other thrusts/faults are not considered very active in comparison to the MFT (Pandey *et al.*, 1999). The shallow earthquakes (depth  $<20$  km) in South Tibet show normal faulting whereas the relatively deeper events (depth  $>60$  km) show strike slip mechanism (Rajaure *et al.*, 2013).

#### **1.4. Seismic hazard and seismic hazard map**

Seismic hazard is the hazard associated with potential earthquakes in a particular area, and a seismic hazard map shows the relative hazards in different areas (USGS, 2019). Geology, seismicity and seismotectonic setting of the Himalayan region show that Nepal and its adjoining regions are in seismically high hazard zone. Historical data of

last five centuries show high casualty rate during the earthquakes of more than 6 magnitudes in the Indian subcontinent. More than 1.7 million people have died in the Indian subcontinent in the last two centuries due to earthquake (Bilham, 2004).

Kathmandu valley was destroyed by 9 major earthquakes since 1255 (Chitrakar & Pandey, 1986) and thousands of people were killed, millions of peoples became homeless, many historical monuments including the Dharahara collapsed, and epidemic had spread. Latest in the series of earthquakes is the 25 April 2015 Gorkha Earthquake of Mw 7.8. It occurred at about 80 km in north-west direction from the Kathmandu valley. This earthquake claimed about 9000 lives; injured thousands and hundreds of thousands were made homeless (e.g. <http://drrportal.gov.np/>).

### **1.5. Rationale**

Geological and seismotectonic settings reveal that Nepal falls in one of the most seismically active zone of the world as discussed earlier. The 2015 Gorkha Earthquake (Mw 7.8), followed by a number of strong aftershocks has once again left us message that destructive earthquakes are less frequent, but can cause unimaginable loss of lives and property leaving the economy of the region in a poor condition, which might sometimes result in social unrest.

Earthquakes cannot be predicted reliably so far. Therefore, in order to minimize loss of lives and property, earthquake resistant structures must be designed and constructed. Assessment of seismic hazard is the primary and crucial input in an effort to make safer structures. Results from seismic hazard assessment can provide input to design earthquake resistant structures as well as to strengthen existing structures at sites of interest. It also helps to formulate national level development policies, planning, upgrade of existing building code and making land use planning. In recent years, growing number of urban centers and construction of high-rise buildings, reservoir-type hydropower projects and road tunnels in Nepal have warranted for more specific and reliable peak ground acceleration (PGA) values for safer design and construction. Seismic hazard assessment map provides PGA values for any construction sites.

Present research was undertaken to develop a new probabilistic seismic hazard map of Nepal utilizing also the lessons from 2015 Gorkha Earthquake and the relevant characteristics, such as, new multiple source models, multiple attenuation relations, different datasets and earthquake recurrence parameters estimated using different methods.

The 2015 Gorkha Earthquake also provided a unique opportunity to study the ground response of the Kathmandu valley using locally recorded strong motion data. The 2015 Gorkha Earthquake and its aftershocks were well recorded by accelerometers operating in the Kathmandu Valley.

### **1.6. Research gap**

There are a number of seismic hazard maps of Nepal published by different researchers in the past. However, the researchers have used limited earthquake data available at that time, limited attenuation relations, less known seismotectonics of the region than at present, and less known earthquake sources. Additionally, in some cases only instrumentally recorded data were used by previous researchers, whereas seismic hazard assessment requires records of historical earthquakes in addition to instrumentally recorded data.

The ground response study of the Kathmandu valley sediments carried out by the previous researchers was based on microtremors. Records of strong earthquakes were not available for such studies in the past. The predominant period and amplification of ground motion in the Kathmandu valley is not properly understood. On the other hand, it is still not clear whether the site-effects are linear or non-linear.

### **1.7. Research questions**

There are a number of research questions related to the seismic hazard assessment of Nepal and ground response of the Kathmandu valley during a large earthquake. They are as follows:

- (i) What are the potential earthquake sources for Nepal?
- (ii) How much is the peak ground acceleration for major cities in Nepal?
- (iii) Are the site-effects in the Kathmandu valley linear or non-linear?

- (iv) What is the predominant period of ground motion in the Kathmandu valley?
- (v) Do the Kathmandu valley sediments amplify the seismic waves? If so, how much is the amplification?
- (vi) Should the existing building code of Nepal be revised or not?

## **1.8. Objectives**

### **1.8.1 General objectives**

The general objectives of the present research are as follows:

- (i) To develop probabilistic seismic hazard map of Nepal
- (ii) To estimate the ground response of Kathmandu valley sediments

### **1.8.2. Specific objectives**

The specific objectives of present research are as follows:

- i. To prepare Earthquake catalogue for Nepal and adjoining areas
- ii. To identify potential earthquake sources for Nepal and adjoining region
- iii. To evaluate peak ground acceleration in major cities in Nepal
- iv. To investigate whether the site-effects are linear or non-linear
- v. To identify the predominant period of ground motion in the Kathmandu valley
- vi. To calculate the seismic wave amplification in Kathmandu valley sediments
- vii. To recommend concerned authorities for building code revision according to new results

## **1.9. Outputs**

The following are the outputs of this research

- (i) Comprehensive, magnitude-homogenized earthquake catalogue for seismic hazard analysis.
- (ii) Probabilistic seismic hazard map of Nepal.
- (iii) Ground response of Kathmandu valley sediments using strong motion records of earthquakes recorded in the valley.

## **1.10. Applications**

Seismic hazard maps are basic input in planning, policy making, formulation and revision of building codes and strengthening of existing structures. Seismic hazard results are therefore very important in the development of any country like Nepal, which requires acceleration of its development works in a sustainable way. Results of present research are useful in the revision of the existing National Building Code prepared by the Government of Nepal.

Similarly, there are several projects of national priority, which require appropriate and reasonable assessment of seismic hazard in Nepal. This thesis provides basic requirements in the revision of building code and design of projects of national priority as well as other development projects.

## **1.11. Limitations**

Seismic hazard assessment requires data recorded for a long period of time. Such a period should cover a complete earthquake cycle of great earthquakes. However, earthquake monitoring started in the early of 20<sup>th</sup> century with very few seismic stations globally. Because of sparse distribution of seismic stations and early technology, only strong earthquakes only were recorded ( $M_w > 5$ ) in the past. The world saw a revolution in the monitoring of earthquakes after the expansion of existing networks that improved the detection threshold for earthquakes.

The Department of Mines and Geology (DMG) started to operate its nationwide seismic network in 1995. The network was installed in a technical collaboration between DMG and Department Analyze Surveillance Environment (DASE), France. The network has short-period, vertical component seismometers at 21 locations in Nepal and its detection threshold is local magnitude (M<sub>l</sub>) 2.0 for earthquakes in Nepal.

Proper seismic hazard analysis is based on available data, understanding of the seismotectonics, experience of strong earthquakes and strong motion records. The following are the limitations in this study:

- i. Limited pre-instrumental records of earthquakes and their uncertainties in terms of location and magnitude, which might have partly increased the uncertainties.
- ii. Maximum potential magnitude as well as earthquake recurrence parameters of earthquake source zones are important factor in any seismic hazard assessment. The maximum potential magnitude of earthquake sources were adopted from published literatures in some cases. Similarly, the earthquake recurrence parameters were estimated from available data assuming the b-value does not vary with time.
- iii. Locally derived attenuation relations for Nepal Himalaya do not exist. In the present study attenuation relations derived for other regions with similar tectonic settings are used, which might not represent the real situations of the Nepal Himalaya.
- iv. Ground response analysis was carried out only for the Kathmandu valley because the strong motion data were not available for other major cities of Nepal.
- v. Strong earthquakes occur in many tens to hundreds of years but we have record of earthquakes recorded by instruments that is not longer than one hundred years. Of course, the instrumental record is supplemented from historical record in the form of different types of documents but their uncertainty in terms of location and magnitude is large.

### **1.12. Layout of the Thesis**

There are six chapters in this dissertation thesis.

Chapter I deals with general introduction of subject matters.

Chapter II presents an overview of reviewed literatures in seismology, geology, seismotectonics, seismic hazard and ground response. The major review was carried out in seismic hazard assessment of Asia, India and Nepal along with the site-response in the Kathmandu Valley.

Methods and materials are described in the Chapter III. Probabilistic seismic hazard technique was applied to the comprehensive, magnitude-homogenized earthquake catalogue prepared during this study. In addition to the prepared earthquake catalogue; geological map, geological structures were used in the seismic hazard



assessment. Ground acceleration records of earthquakes, which were recorded in the Kathmandu Valley, were utilized to estimate local site effects.

Probabilistic seismic hazard map of Nepal and response of the Kathmandu valley sediments to earthquake ground motion are the major areas of results of this study, which are presented in Chapter IV,

The major source of seismic hazard in Nepal is the MHT. The soil in the Kathmandu valley responded non-linearly during the Gorkha Earthquake sequence. Such conclusions are described in Chapter V.

The references are presented separately in Chapter VI.

## **CHAPTER 2**

### **LITERATURE REVIEW**

#### **2.1. General**

In order to achieve the objectives as mentioned earlier, relevant literatures were reviewed on various aspects. The review was carried out on:

1. Chronological development of hazard assessment
2. Seismic hazard assessment of Asia and Indian subcontinent
3. Seismic response of Kathmandu valley sediments

#### **2.2. Chronological development of seismic hazard assessment**

Inclusion of seismic provisions in building codes were first practiced after the 1933 Long Beach, California Earthquake. At the beginning, in the 1940s and 1950s, seismic design provisions in building codes were based on qualitative evaluations of hazard.

A quantitative seismic hazard map based on probabilistic analysis was introduced in Canada after the work of Milne and Davenport (1969). The researchers used extreme value statistics to calculate a gridded map of Peak Ground Acceleration (PGA) having an annual exceedance probability of 0.01 (100 year return period). A related amplitude recurrence method was also developed, based on counting the annual number of exceedance of a specified acceleration at a site.

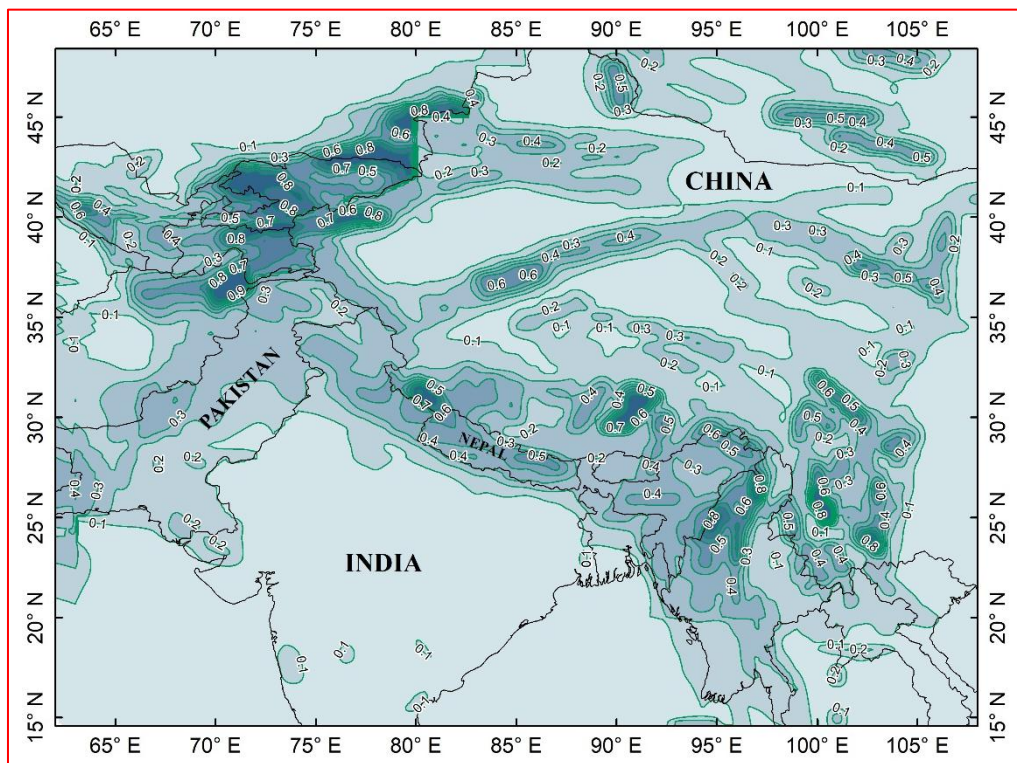
Cornell (1968) developed a different methodology which was later coded into a FORTRAN algorithm by McGuire (1976). It is widely referred to as the Cornell-McGuire method. In the Cornell-McGuire method, the spatial distribution of earthquakes is described by seismic source zones; an active fault was defined as a linear source, and geologic information and historical seismicity were used to represent the sizes of events and their rates of occurrence at the fault. Areas of diffuse seismicity are represented as area source zones. Because of its ability to incorporate both seismicity and geologic information, the Cornell-McGuire method quickly became popular and was widely used throughout the world. Its application to seismic zoning in Canada has been described by Basham *et al.*, (1982; 1985); Adams *et al.*, (1999); Adams & Halchuk (2003, 2004) and Adams & Atkinson (2003).

Over the period of last 30 years, improved data and knowledge have become available, particularly on the origin, occurrence and effects of earthquakes; accordingly the strong ground motion as a result of earthquakes has been better understood in terms of their generation and propagation. It has facilitated in minimizing the uncertainties in the assessment of seismic hazard.

### 2.3. Seismic hazard assessment of Asia and Indian sub-continent

#### 2.3.1. Seismic hazard assessment of Asia

Giardini *et al.* (1999) published probabilistic seismic hazard map of Asia (Figure 7) under the Global Seismic Hazard Assessment Program (Figure 7). The map shows seismic hazard in terms of peak horizontal ground acceleration (PGA) at engineering rock site condition. The PGA was calculated for 10% probability of exceedance in 50 years (~500 year return period). This map provides a broader overview of the seismic hazard in Nepal and surrounding regions. According to this map, the PGA varies between 0.4 g and 0.6 g in Nepal.

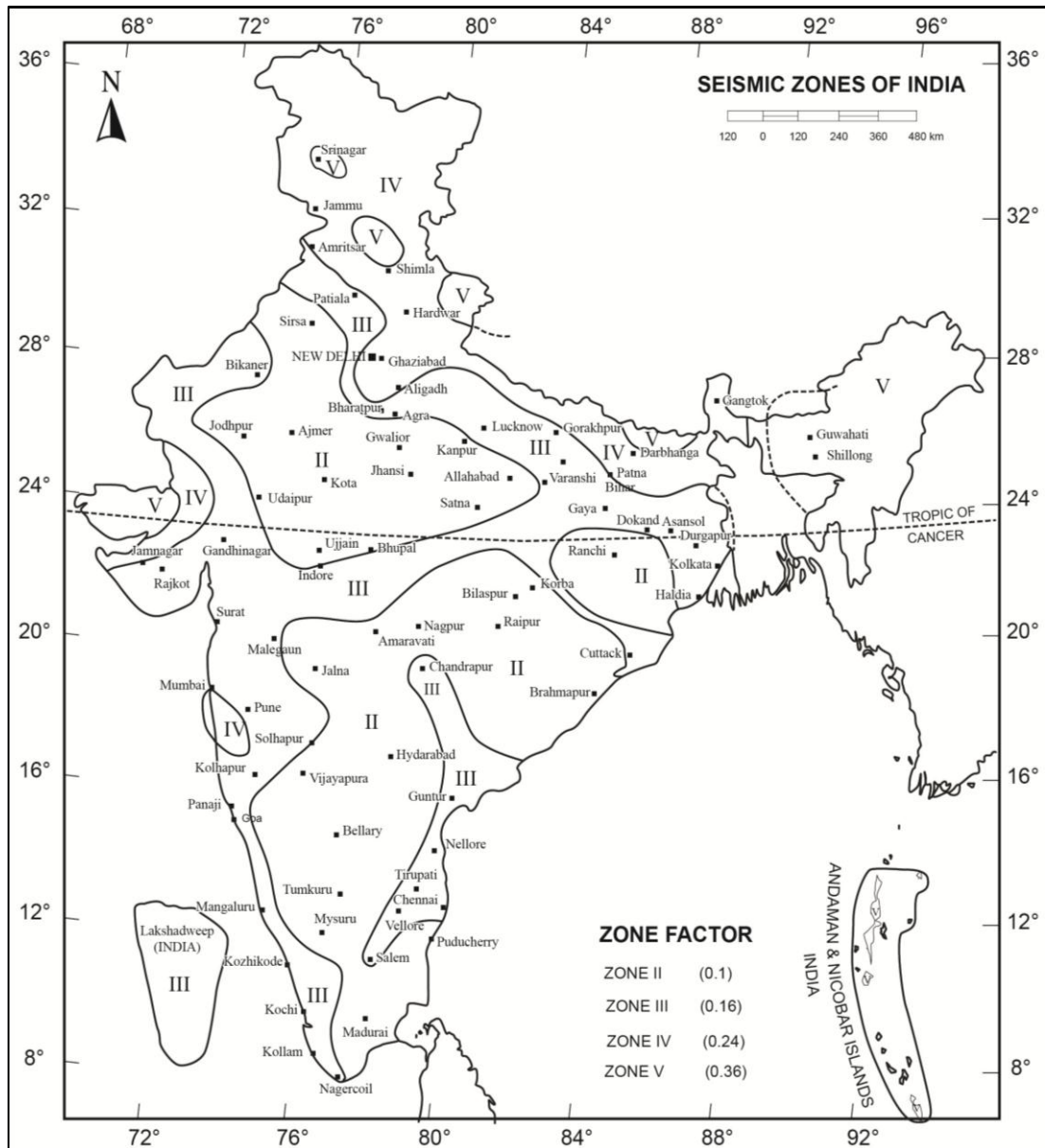


**Figure 7:** Probabilistic seismic hazard map of Asia by GSHAP (Redrawn using data from <http://www.seismo.ethz.ch/static/GSHAP>). The PGA values were calculated for engineering rock site condition.

### **2.3.2. Seismic hazard map of India**

#### **(a) Geological Survey of India**

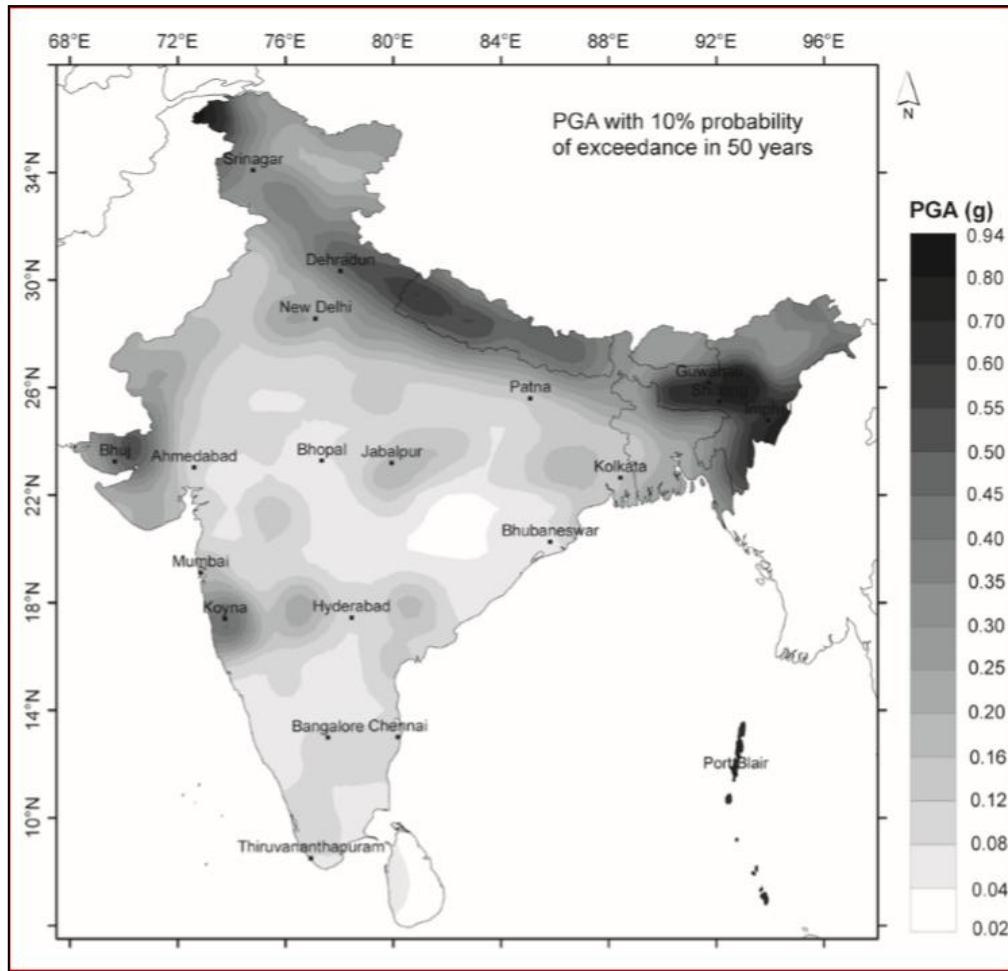
The first attempt was made in 1935 to prepare seismic zoning map of India by the Geological Survey of India (GSI) (Khattri, 2006). The map divides the Indian Territory into three zones (Severe, moderate and minor hazard). A new seismic zoning map of India included in IS1893:2002, was published in 1962 by GSI (Khattri, 2006). The map utilizes intensity distribution of past destructive earthquakes as the basis for zoning and therefore represents damages in past destructive earthquakes as high hazard zone. The map was subsequently revised in 1966, 1970, 1984 and 2002 (Khattri, 2006) to incorporate weights of known tectonic features, which still retains the intensities of destructive earthquakes as in the earlier versions. The presently adopted seismic hazard map of India (Figure 8) (IS-1893:2002): Geological Survey of India, (2002) divides India into four zones: Zone II (Intensity VI), Zone III (Intensity VII), Zone IV (Intensity VIII) and Zone V (Intensity IX or larger), which have anticipated peak ground acceleration of 0.1 g, 0.18 g, 0.24 g and 0.36 g. This map is based on the intensity of past destructive earthquakes of the region and therefore does not consider probability.



**Figure 8:** Seismic zoning map of India (modified from IS: 1893 (Part-1)). Nepal falls in a region, which has PGA larger than 0.24 g.

(b) Nath and Thingbaijam (2012)

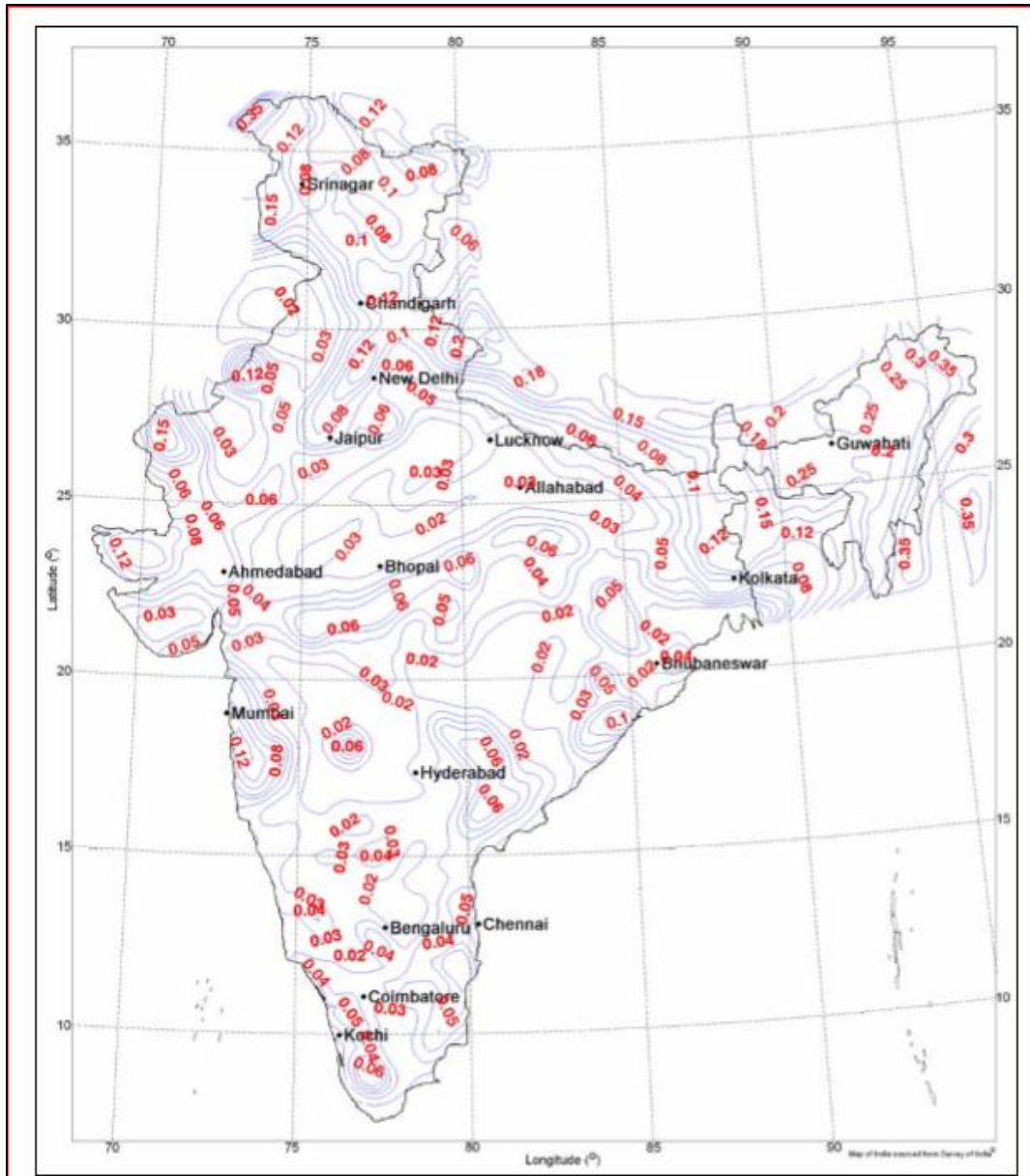
Nath and Thingbaijam (2012) prepared probabilistic seismic hazard map of India and adjoining regions (Figure 9). The seismic hazard map shows the seismic hazard corresponding to 10% probability of exceedance in 50 years. The maximum hazard is noticed near the Nepal-India border in the west and Indo-Myanmar border region and reaches up to 0.6 g in some regions.



**Figure 9:** Probabilistic seismic hazard map of India and adjoining region corresponding to 10% probability of exceedance in 50 years at engineering rock site condition. The PGA over Nepal ranges between 0.3 g and 0.5 g (Nath & Thingbaijam, 2012).

(c) National Disaster Management Authority (NDMA), India

A working committee of expert formed by the National Disaster Management Authority, Government of India (NDMA, India 2010) submitted its final report on “Development of Probabilistic Seismic Hazard Map of India” to the Government of Indian 2010. The seismic hazard map (Figure 10) shows the PGA corresponding to Type ‘A’ site conditions. According to the National Earthquake Hazard Reduction Program (NEHRP), Type ‘A’ site has shear wave velocity ( $V_s$ ) larger than 1500 m/s. Type ‘A’ sites have  $V_s$  larger than that at engineering soil sites ( $760 < V_s < 1500$  m/s). The largest PGA in Nepal is about 0.18 g in the western part of Nepal and the lowest is 0.06 in the southern part. The site classification for seismic site response (NEHRP 1994) is given in Appendix 3.



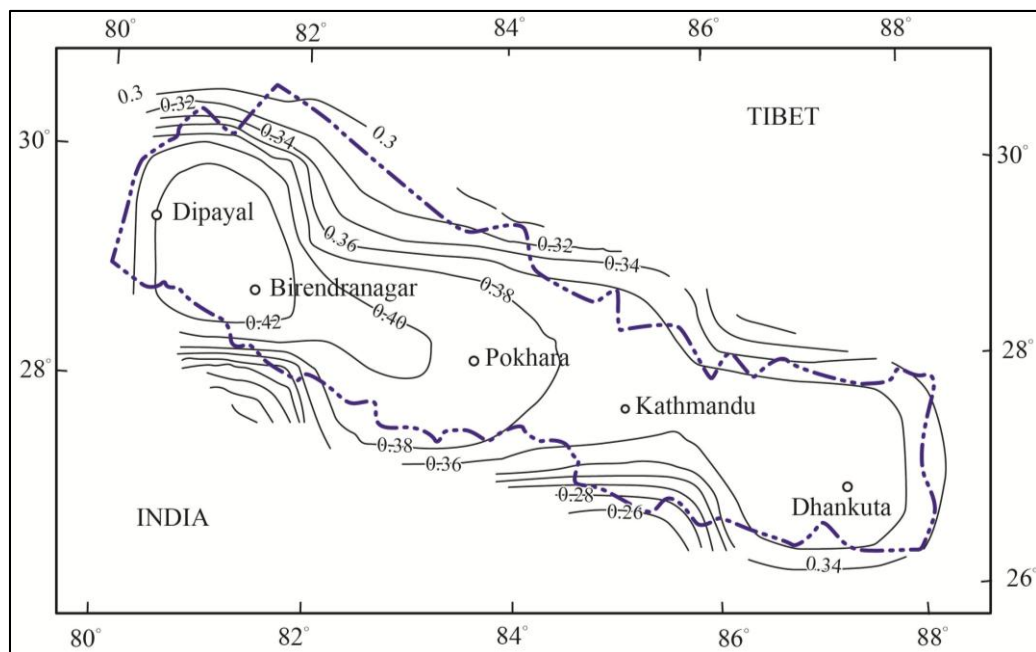
**Figure 10:** Probabilistic seismic hazard map of India and the adjoining region corresponding to 10% probability of exceedance in 50 years. The PGA was calculated for ‘A’ type soil class. According to this map the PGA varies between 0.06 g and 0.18 g in Nepal (NDMA, 2010).

### 2.3.3. Seismic hazard assessments of Nepal

The research on seismic hazard in Nepal has been carried out by several institutions and researchers. Some of the important works in this regard have been reviewed in the following sections.

#### 2.3.3.1. Seismic hazard mapping and risk assessment for the National Building Code, Nepal (1993)

This work on "Seismic hazard mapping and risk assessment" was carried out by Beca Worley International *et al.* (1993) for the seismic design of buildings in Nepal in 1994 (NBC-105). The map (Figure 11) shows horizontal PGA at rock site for 10% probability of exceedance in 50 years. According to this result, the PGA values vary between 0.26 g and 0.42 g. The maximum PGA (>0.42 g) is estimated in the western part of Nepal.



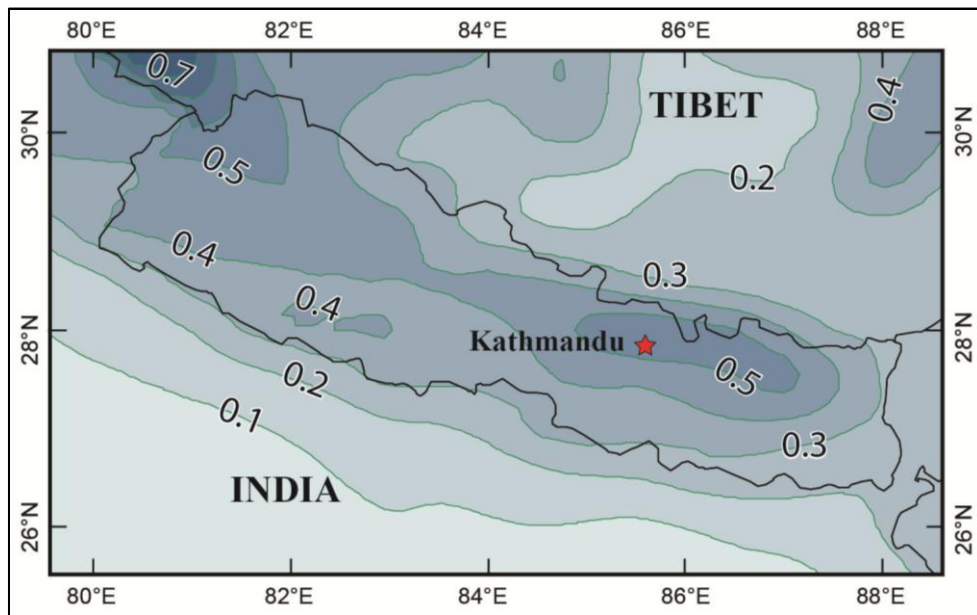
**Figure 11:** Probabilistic Seismic hazard map (NBC-105) of Nepal corresponding to 10% probability of exceedance in 50 years for an engineering rock site condition. The PGA varies between 0.26 g and 0.42 g across Nepal (Modified from Beca Worley *et al.*, 1993).

#### 2.3.3.1.1. Global seismic hazard program map (1999)

The Global Seismic Hazard Assessment Program (GSHAP) was launched in 1992 by the International Lithosphere Program (ILP). The program was supported by the



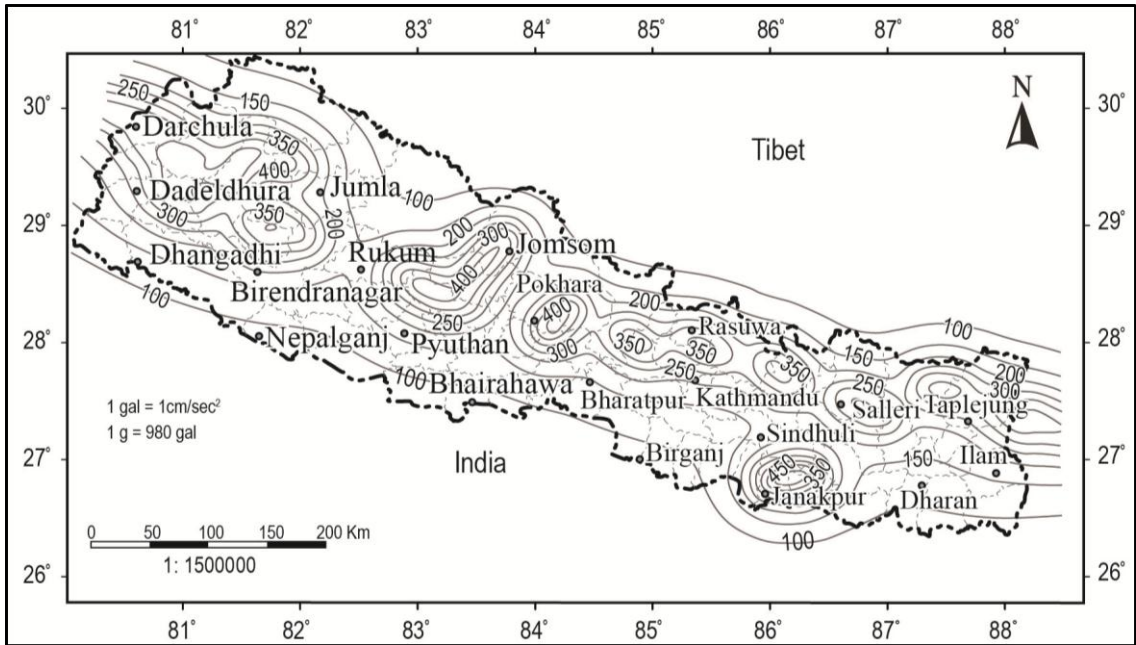
International Council of Scientific Unions (ICSU) and was completed in 1999. The GSHAP prepared probabilistic seismic hazard map for different regions of the world. Figure 12 is the probabilistic seismic hazard map (Figure 12) of Nepal reproduced using GSHAP data. The PGA value varies between 0.3 g and 0.5 g in Nepal.



**Figure 12:** Probabilistic seismic hazard map of Nepal corresponding to 10% probability of exceedance in 50 years at an engineering rock site condition. (Reproduced using data from <http://www.seismo.ethz.ch/static/GSHAP>).

#### 2.3.3.1.2. Pandey *et al.* (2002)

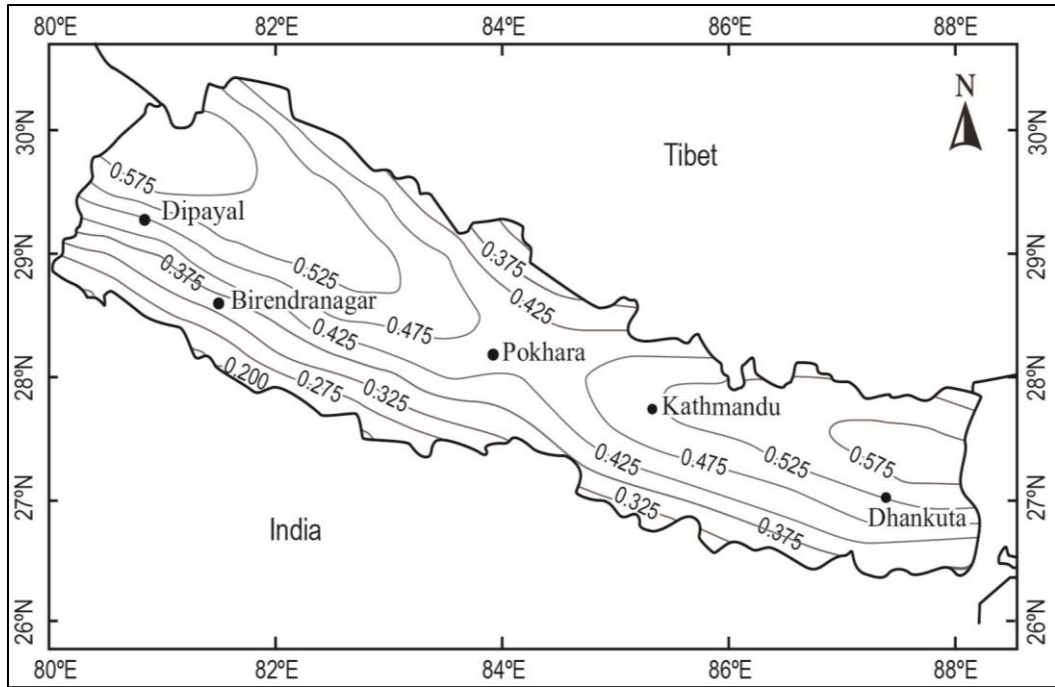
Pandey *et al.* (2002) prepared seismic hazard map of Nepal (Figure 13). The seismic hazard map depicts a belt of high hazard ( $PGA > 200 \text{ gal}$ ;  $1 \text{ gal} = 1 \text{ cm/sec}^2$ ) that runs parallel to the Himalaya. The PGA varies between 50 gal and 450 gal ( $1 \text{ gal} = 1 \text{ cm/sec}^2$ ), which was calculated for an engineering rock site condition.



**Figure 13:** Probabilistic seismic hazard map of Nepal corresponding to 10% probability of exceedance in 50 years for engineering rock site condition (Redrawn from Pandey *et al.*, 2002). The PGA varies between 100 and 400 gal

#### 2.3.3.1.3. Thapa & Wang (2013)

Thapa & Wang (2013) prepared seismic hazard map of Nepal using probabilistic seismic hazard analysis technique developed by China Earthquake Administration (CEA), 2005. They estimated horizontal peak ground acceleration corresponding to 63%, 10% and 2% probability of exceedance in 50 years at engineering bedrock, using attenuation relation developed by CEA (2005) for western China. The result shows that the estimated PGA value varies between 0.2 g and 0.57 g (Figure 14).

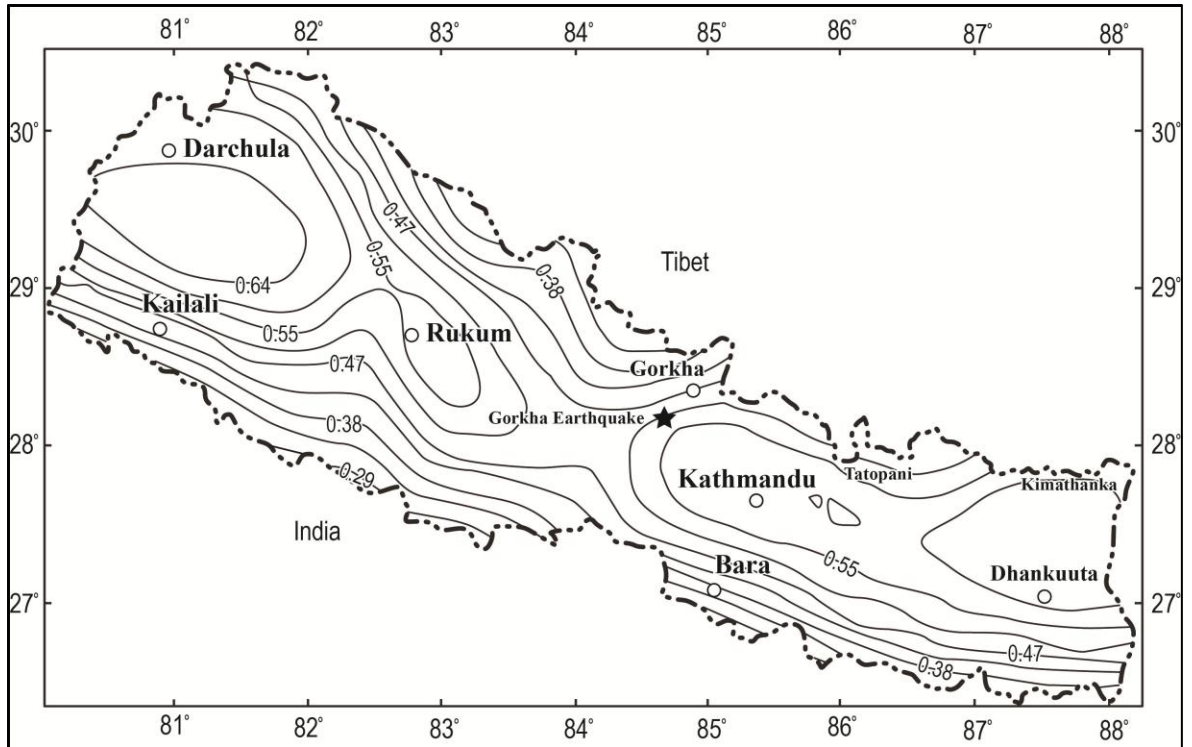


**Figure 14:** Probabilistic seismic hazard map of Nepal corresponding to 10% probability of exceedance in 50 years for an engineering rock site condition. (Modified from Thapa & Wang, 2013). The PGA varies between 0.2 g and 0.57 g across Nepal.

#### 2.3.3.1.4. Rahman & Bai (2018)

Rahman & Bai (2018) prepared probabilistic seismic hazard map of Nepal using multiple source models. They have estimated maximum PGA of about 0.64 g in the far-western Nepal (Figure 15). In this figure also, the largest PGA is estimated in the western and eastern part of Nepal.

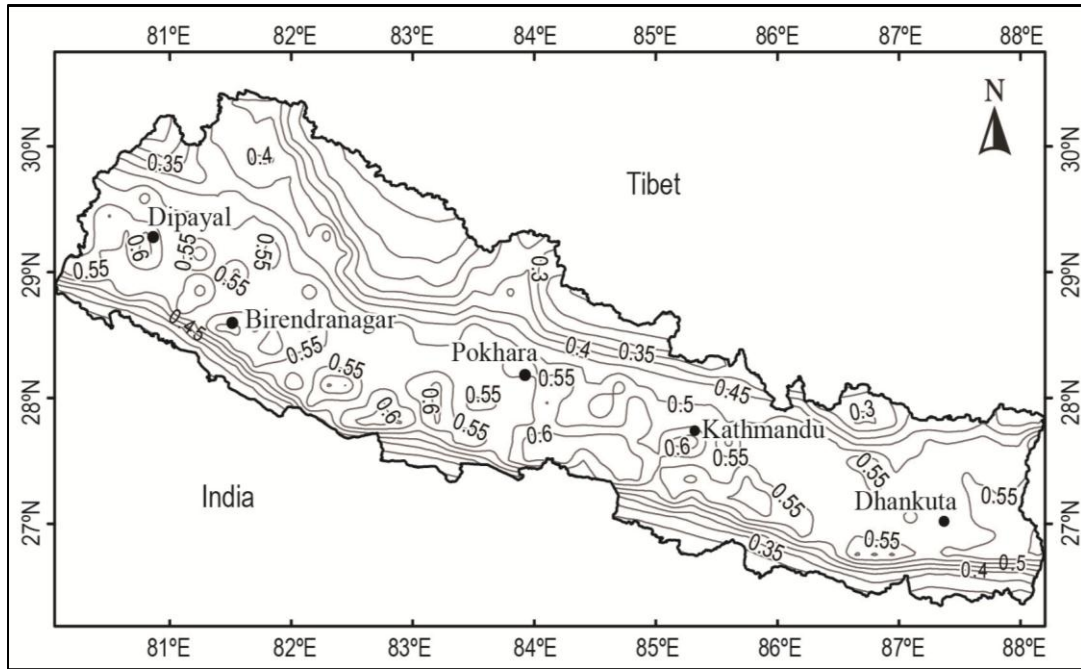
In addition to the earthquake sources used by Thapa & Wang (2013), they used smoothed gridded, linear as well as areal sources.



**Figure 15:** Probabilistic seismic hazard map of Nepal corresponding to 10% probability of exceedance in 50 years (Modified from Rahman & Bai, 2018) for an engineering rock site condition. The PGA varies between 0.29 g and 0.64 g.

#### 2.3.3.1.5. Stevens *et al.* (2018)

Stevens *et al.* (2018) prepared probabilistic seismic hazard map (Figure 16) of Nepal using the detailed geometry of the Main Himalayan Thrust (MHT). The entire MHT, having maximum potential magnitude as large as ( $M_w$ ) 9.2, was used as a single source. In addition to MHT, normal faults in South Tibet also were used as potential earthquake sources. Earthquake catalogue, comprising data between 1995 and 2016, was used to find earthquake recurrence parameters. A fixed  $b$ -value (1.0) was used for the entire region and  $a$ -values were recalculated from the catalogue. The maximum PGA (0.6 g) is estimated in the southern part of Nepal.



**Figure 16:** Probabilistic seismic hazard map of Nepal corresponding to 10% probability of exceedance in 50 years (Redrawn from Stevens *et al.*, 2018) for an engineering rock site condition. The maximum PGA reaches up to 0.6 g at some places.

#### 2.4. Ground response of the Kathmandu valley sediments

The seismic response of a site is affected by many factors, such as source characteristics, propagation path and local site conditions. Among all these factors, the local site conditions may have significant impact on the seismic site response (Borcherdt & Glassmoyer, 1992). These effects caused by local site condition are well known among the geotechnical engineers and seismologists as site effect. Local site conditions may cause significant amplification of ground motion and concentrated damage during an earthquake (Asimaki & Gazetas, 2004).

The Kathmandu valley is a bowl-shaped depression, filled with fluvio-lacustrine sediments, on top of the Precambrian metamorphic rocks. Due to the vertical variation in lithology and lateral variation in sediment characteristics, seismic waves are influenced in the basin. As a result, the Kathmandu valley experiences varying degree of ground shaking/destruction (e.g. Pandey & Molnar, 1988 and Rajaure *et al.*, 2015). The damage pattern of the 1934 (M 8.1) earthquake (Bilham *et al.*, 1995), in particular suggests that ground amplification due to fluvio-lacustrine sediments plays a major role in intensifying the ground motion in the basin (Paudyal *et al.*, 2013).

The ground response of the valley has been studied by some researchers in the past, which are described below.

#### **2.4.1. Pandey (2000)**

Pandey (2000) used relative power spectra of ambient noise recorded at 60 soil sites with reference to that at rock site in the Kathmandu sedimentary basin. He reported that the predominant frequency at 2 Hz was amplified. There are other peaks of amplification in the range between 0.6 and 5 Hz, but the amplification factor varied across the valley. The amplification factor was about 5 to 6 in the lacustrine area, between 2 to 3 in transitional area and between 1 and 2 in fluvial area.

#### **2.4.2. JICA (2002)**

The Japan International Cooperation Agency (JICA) and Ministry of Home Affairs, His Majesty's Government of Nepal, jointly carried out a study entitled "Earthquake disaster mitigation in the Kathmandu Valley, Kingdom of Nepal" in 2002.

Ground condition of the Kathmandu Valley was analyzed and classified to establish ground models. The ground models were used in the investigation of amplification of seismic motion, evaluation of liquefaction and stability of slope. The study team made five boreholes in order to understand essential ground properties such as shear wave velocity, density, N value, groundwater level and mean particle size. One dimensional response analysis was carried out using ground models derived from borehole data. Several layers were identified based on the soil type and shear wave velocity. The amplification factor for the ground models vary between 1.0 and 2.0.

#### **2.4.3. Piya (2004)**

Piya (2004) studied the liquefaction hazard in the Kathmandu valley. He used geological information from boreholes and prepared liquefaction susceptibility map for the valley. He found that Kathmandu valley could be susceptible to liquefaction in case a strong earthquake occurs nearby with strong ground shaking in the Kathmandu Valley. The finding was based on the presence of liquefiable soils (sand and silts), high groundwater level and the possibility of potential strong ground motions in the region.

#### **2.4.4. Khanal (2005)**

Khanal (2005) carried out preliminary seismic microzonation of the Kathmandu valley using one-dimensional seismic response analysis. Borehole logs of deep tube wells from Kathmandu valley and the strong motion record of the 1999 Chamoli (India) earthquake were used in this study. The investigation shows one to two story buildings are safer considering the input ground motion used.

#### **2.4.5. Bhattarai *et al.* (2011)**

Bhattarai *et al.* (2011) reported analysis of acceleration data recorded at DMG and at Kakani (KKN) site (about 20 km in the north of Kathmandu valley on rock). They analyzed two earthquakes one of which occurred at a distance of 25 km (15 July 2010,  $M_L$  3.4 (NSC)), in Nepal, and other occurred over 110 km distance (17 October 2010,  $M_L$  5.7 (NSC)) in South Tibet. The study shows large PGA at a hard rock site located at about 110 km from the accelerometric stations, which they speculate might be caused by topographic amplification at KKN.

#### **2.4.6. Paudyal *et al.* (2012)**

Paudyal *et al.* (2012) applied horizontal-to-vertical ratio of Fourier spectra (H/V ratio technique) of ambient noise recorded at soil sites to estimate fundamental frequency at different parts of the Kathmandu Valley. They reported that the valley has fundamental frequencies in the range between 0.48 to 8.9 Hz in the central and northern part of the sedimentary basin. In addition to the fundamental frequency, they reported other peaks between 4 and 6 Hz in the central and northern part of the basin. Preliminary basement topography of the Kathmandu sedimentary basin was estimated, which correlates with the result from gravity survey carried out by Morayabashi and Maruo (1980) and shows thick sediments in the middle part of the valley.

#### **2.4.7. Takai *et al.* (2016)**

Takai *et al.* (2016) studied the strong ground motion records of the 2015 Gorkha Earthquake. They observed the vertical ground velocities at the sedimentary sites were the same pulse motions that were observed at the rock site. On the other hand,

the horizontal ground velocities as well as accelerations observed at the sedimentary sites showed long duration with obvious long-period oscillations, caused by the valley response. The records reveal that the horizontal valley response was amplified about 10 times (in the long period) and prolonged oscillations. The predominant period and envelope shape of their oscillations was not consistent, across the soil indicating a complicated basin structure. The horizontal long-period oscillations on the sedimentary sites were strong enough to damage the high-rise buildings with natural periods of 3 to 5 s.



## CHAPTER 3

### MATERIALS AND METHODS

#### 3.1. Materials

Different related information have been used for the seismic hazard assessment of Nepal and the ground response analysis of the Kathmandu valley. These are briefly described in the following sections.

##### 3.1.1. Maps and images

Various maps and images were used to gather the secondary data required for the seismic hazard analysis. Epicenter distribution map of Nepal by Pandey *et al.*, (1999) (Figure 5) and local earthquakes relocated by Rajaure *et al.*, (2013) (Appendix 4) were used to understand the seismicity pattern of Nepal and adjoining areas. Geological map of Nepal published by the Department of Mines and Geology (1987) (Appendix 5) and active fault map of Nepal (Nakata, 1989) (Appendix 6) were used to gather information on fault line and active fault sources. Google Earth Images also were used to check features such as lineaments and faults (Appendix 7).

##### 3.1.2. Earthquake catalogue

Earthquake catalogues are fundamental inputs in seismic hazard assessment. Catalogues of earthquakes are used to determining magnitude-frequency relation coefficients ('a' and 'b'-values) in the Gutenberg-Richter recurrence relation and the mean annual rate of occurrence of earthquakes, which are basic requirement in seismic hazard calculation. A complete earthquake catalogue, both in magnitude range and time, is therefore an essential component in such studies. An earthquake catalogue normally has a date and time of origin, location (latitude, longitude, and depth), magnitude and uncertainties in the location. The catalogues can be grouped into two types: instrumentally recorded and pre-instrumental earthquakes. Earthquakes, which occurred after 1900 AD are grouped into "Instrumentally recorded", and which occurred before 1900 AD are grouped into "Pre-instrumental".

### **3.1.2.1. Instrumentally recorded earthquakes**

Instrumentally recorded earthquake data were collected from International Seismological Centre, UK (ISC: [www.isc.ac.uk](http://www.isc.ac.uk)), United States Geological Survey (USGS), USA ([www.earthquake.usgs.gov](http://www.earthquake.usgs.gov)), Incorporated Research Institutions in Seismology, USA ([www.iris.edu](http://www.iris.edu)) and Department of Mines and Geology, Nepal ([www.seismonepal.gov.np](http://www.seismonepal.gov.np)), in a rectangular region between 24° N and 34° N latitude and 75° E and 95° E longitudes. The International Seismological Centre (ISC) has been collecting, reviewing and publishing earthquake catalogue, which contains earthquake data since 1905, however, in the early days; such data was available for strong earthquakes only. The detection threshold of seismic observatories improved afterwards on account of addition of new networks, expansion of existing networks and ever changing technology. Similarly, the USGS has been compiling and publishing earthquake catalogue since 1900. Likewise, the IRIS earthquake catalogue has earthquake data since 1970.

The Department of Mines and Geology, Nepal has been operating a network of short period, vertical component seismic stations since 1995 in collaboration with Departement Analyse Surveillance Environnement (DASE). This network has produced a very important dataset of small earthquakes, particularly in Nepal Himalaya because of the spacing between seismic stations and coverage in the Nepal Himalaya. This catalogue has been used to delineate seismogenic sources and for a comparison of earthquake recurrence parameters with other data sets.

### **3.1.2.2. Pre-instrumental (historical) earthquakes**

Data of large earthquakes is available in historical records in the form of reports of destruction in inscriptions and chronicles. The large destructive earthquakes, which occurred before the arrival of instruments, were collected from literatures. Locations as well as magnitudes of such pre-instrumental earthquakes were estimated from the area of maximum destruction and the intensity of maximum destruction respectively. Therefore, the locations and magnitudes of pre-instrumental earthquakes might have large uncertainties in comparison to instrumentally recorded earthquakes.

The pre-instrumental earthquakes, which occurred before the development of instruments, were collected from Rana (1935), Chitrakar & Pandey (1986), Bilham *et*

*al.* (1995), Pant (2002), Bilham (2004), Ambrasseys & Douglas (2004) and Szeliga *et al.* (2010).

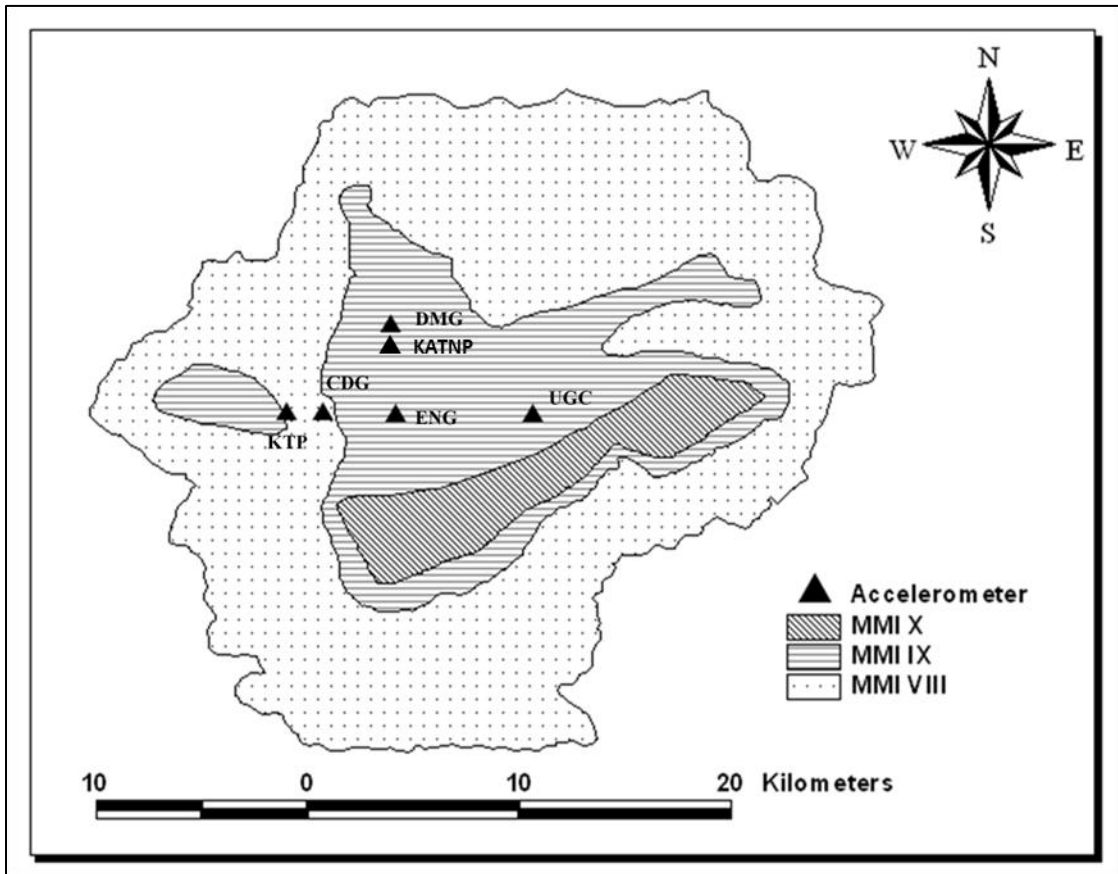
### 3.1.3. Strong ground motion data

The Hokkaido University (Japan), in collaboration with the Central Department of Geology, Tribhuvan University, installed four accelerometers (KTP, TVU, PTN, THM) in 2011 on an east-west profile that runs from Kirtipur to Sanothimi in Bhaktapur (Table 1, Figure 17). One of the accelerometer is at a rock site (KTP) and the rest four are on soil (TVU, PTN, and THM). The accelerometers (Mitsuyo JEP-6A3-2 accelerometers) operate on continuous mode, at 100 Hz sampling rate. In addition to these accelerometers two more accelerometers were operating during the earthquake; one at the premises of the Department of Mines and Geology (DMG), Lainchaur and the other at the US recreation center at Kantipath (KATNP). The DMG and USGS accelerometers were manufactured by GEOSIG. Their dynamic range is 2 g and sampling frequency is 200 Hz.

Strong motion (acceleration) data of earthquakes, which occurred on 30 August 2013, South Tibet Earthquake (M 4.9), the 25 April 2015 Gorkha Earthquake (Mw 7.8) and its three strong aftershocks (25 April, 26 April and 12 May 2012) were used in this study. The earthquakes were recorded by five accelerometers operating in the Kathmandu Valley.

**Table 1:** Location of accelerometers in the Kathmandu Valley.

Site code	Latitude (°N)	Longitude (°E)	Location
KTP (rock)	27.68	85.27	Kirtipur Municipality office, Kirtipur
TVU (soil)	27.68	85.28	Central Department of Geology/Tribhuvan University
PTN (soil)	27.68	85.31	Engineering College, Pulchowk
THM (soil)	27.68	85.37	University Grant Commission office, Sanothimi, Bhaktapur
KATNP (soil)	27.71	85.31	Kantipath, Kathmandu
DMG (soil)	27.73	85.31	Department of Mines and Geology, Lainchaur, Kathmandu



**Figure 17:** Location of strong motion instruments (accelerometers) operating in the Kathmandu Valley. The shaded polygons represent the intensities observed during the 1934 Bihar-Nepal earthquake (Modified from Roy *et al.*, 1939).

### 3.1.4. Software

R-CRISIS (Aguilar & Armandeo, 2017) software was used to compute seismic hazard in terms of peak ground acceleration, peak spectral acceleration and uniform hazard seismic response spectra. The R-CRISIS is a new version of CRISIS2015, which is a versatile tool that has been widely used to perform probabilistic seismic hazard assessment (Armando *et al.*, 2017). It is a Windows based software with the capability to perform PSHA using fully probabilistic approach that allows the calculation of results with different characteristics (i.e. exceedance probability plots, set of stochastic events). It is a free software available at <http://www.r-crisis.com> and has been tested and validated (Armandeo *et al.*, 2017). The software computes seismic hazard by considering earthquake occurrence probabilities, attenuation characteristics and the geographical distribution of earthquakes (Ordaz *et al.*, 2017) using different

source geometry models of earthquakes in order to describe the characteristics of the seismic sources. The available geometry models in R-CRISIS are:

- a) Area sources (where area planes and volumes correspond to particular cases) that are modeled as planes by means of a set of vertexes that account for a three-dimensional representation.
- b) Line sources that are modeled as polylines with constant or variable depths.
- c) Point sources (where grid sources are a particular case).

In addition to this software, some codes were written by myself on FORTRAN77 in order to process data to bring into required formats. ArcGIS, Adobe Illustrator and the Generic Mapping Tools (GMT) were used for drawing maps and figures.

## **3.2. Methods**

### **3.2.1. Probabilistic seismic hazard analysis**

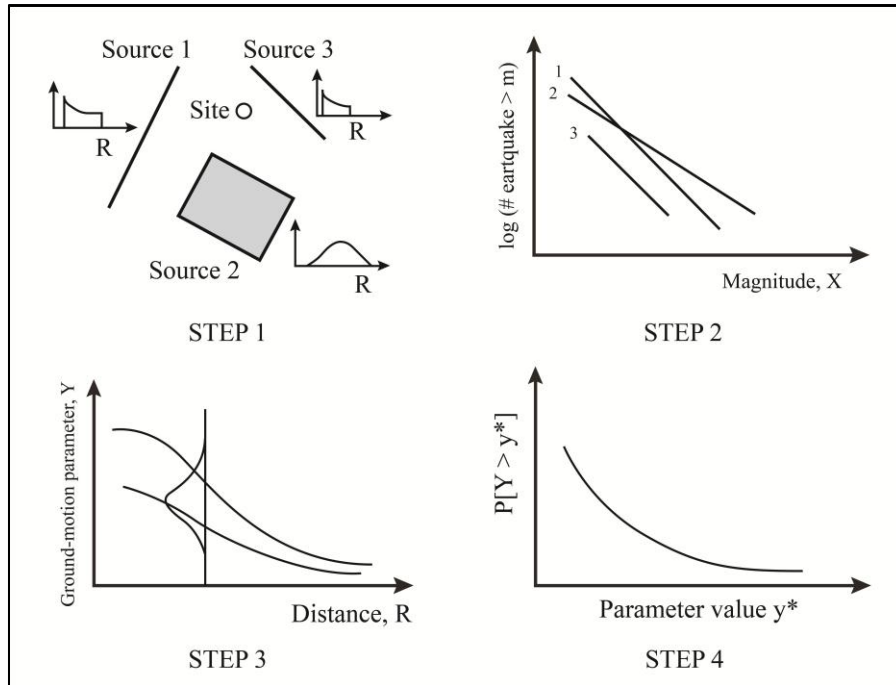
Probabilistic seismic hazard analysis (PSHA) is a methodology based largely on the work by Cornell (1968). Codes for seismic hazard evaluation based on the methods of Cornell (1968) were published by McGuire (1976) and Bender and Perkins (1987). This method estimates the rate of exceedance of some ground motion levels, generally expressed in terms of peak ground acceleration or peak spectral acceleration (McGuire, 2004). It provides a framework in which the uncertainties can be identified, quantified and incorporated to provide a better image of the seismic hazard. The method has four basic steps (Figure 18), which are described below:

Step 1: Identify all earthquake sources capable of producing damaging ground motions.

Step 2: Characterize the distribution of earthquake magnitudes (the rates at which earthquakes of various magnitudes are expected to occur) and the distribution of source-to-site distances associated with potential earthquakes.

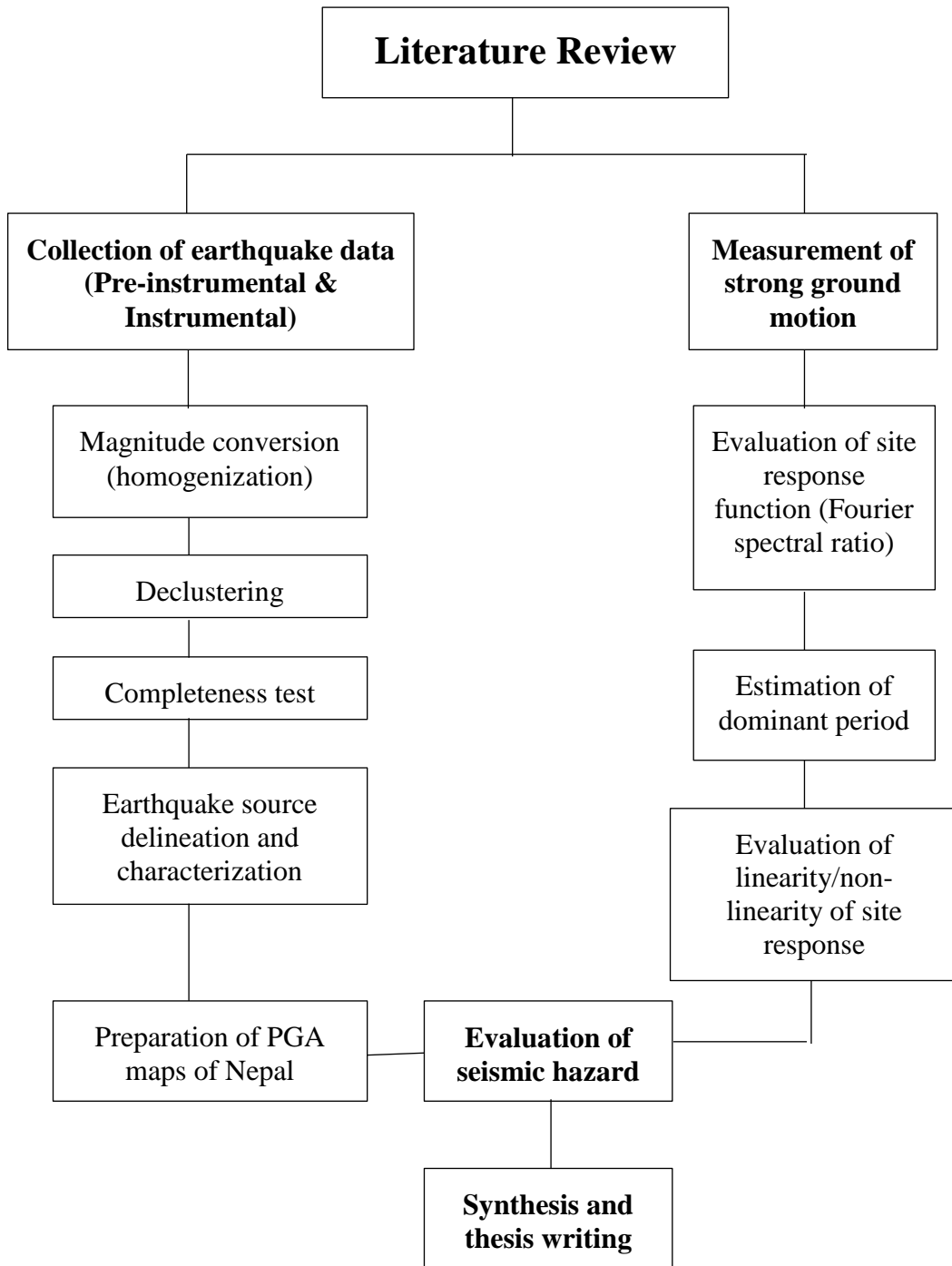
Step 3: Predict the resulting distribution of ground motion as a function of earthquake magnitude, distance, etc.

Step 4: Combine uncertainties in earthquake size, location and ground motion intensity, using a calculation known as the total probability.



**Figure 18:** Four steps of probabilistic seismic hazard analysis (Redrawn from Kramer, 2007)

The methodology adopted in the present research is given in the following flow chart (Figure 19).



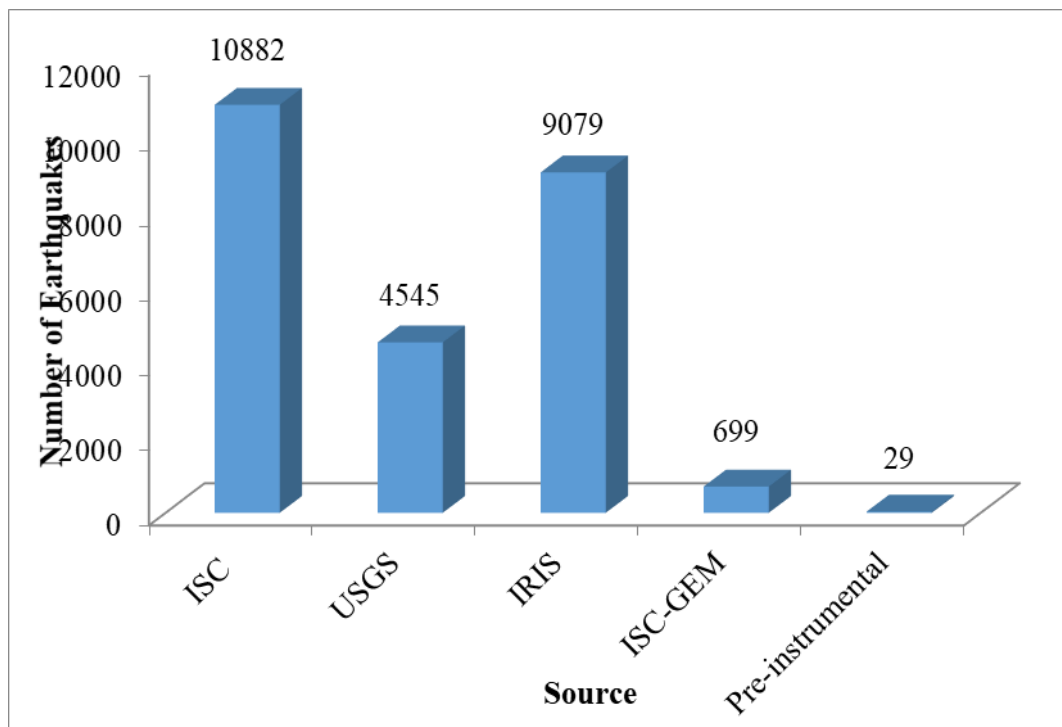
**Figure 19:** Flow chart of the research work.

### 3.2.1.1. Data collection and compilation

Data collected from different sources (ISC, USGS, IRIS and literatures) were merged into a single catalogue (Table 2, Figure 20). This catalogue was processed to develop a comprehensive and magnitude-homogenized standard catalogue to be used in the probabilistic seismic hazard analysis.

**Table 2:** Earthquake catalogues from different sources.

Source	Magnitude		Availability		Number
	Min	Max	From	Up to	
ISC	3	8.2	1901	2017	10882
USGS	3	8	1905	2017	4545
IRIS	3	7.8	1970	2017	9079
ISC-GEM	5	8	1905	2015	699
Pre-instrumental	5.1	8.5	1100		29



**Figure 20:** Different earthquake catalogues used to develop standard catalogue for PSHA.

Required data of earthquakes (origin date, time, latitude, longitude, and depth, magnitude, and magnitude type) were collected from different sources, which have published primary earthquake catalogues. Instrumentally recorded Earthquake catalogues are published by several agencies such as ISC ([www.isc.ac.uk](http://www.isc.ac.uk)), USGS (<https://earthquake.usgs.gov/>), IRIS (<https://ds.iris.edu/ds/nodes/dmc/data/types/events/catalogs/>), and DMG ([www.seismonepal.gov.np](http://www.seismonepal.gov.np)). Historical earthquakes, which occurred before the development of instrument were collected from published literatures (e.g. Szeliga *et al.*, 2010; Chitrakar & Pandey, 1986; Bilham, 2004, Ambrasseys & Douglas, 2004).



After collection of earthquake catalogues from before mentioned sources, the catalogues were merged into a single catalogue for further processing.

### 3.2.1.2. Magnitude homogenization

Earthquake magnitude is a number, which is used to characterizes the relative size of an earthquake. Magnitude is based on the measurement of the maximum amplitude recorded by instrument (seismograph). There are several defined scales in common use, but the most commonly used are (1) local magnitude (ML), commonly referred to as "Richter scale", (2) surface-wave magnitude (Ms), (3) body-wave magnitude (Mb), and (4) moment magnitude (Mw). Scales ML, Ms and Mb have limited range and applicability and do not satisfactorily measure the size of the largest earthquakes. The moment magnitude (Mw) scale, which is based on the concept of seismic moment, is popular and commonly used to all sizes of earthquakes but is more difficult to compute than the other types of magnitudes. Mw is considered the most scientific and the best compared to other magnitudes because it does not saturate even at large earthquakes (Kanamori, 1977; Kanamori & Hanks, 1979). Therefore, the other types of magnitudes (Mb, Ms and ML) reported in the catalogue are required to be converted into moment magnitude (Mw). Empirical relations (Equation 1 to 4) derived by Scrodilis (2006) are commonly used to convert other magnitudes into Mw. The relations were established by regression analysis of global data.

$$M_w = 0.67(\pm 0.005) * M_s + 2.07(\pm 0.03), \quad \text{Equation 1}$$

(For shallow earthquakes (depth <70 Km) and Ms between 3.0 and 6.1),

$$M_w = 0.99(\pm 0.02) * M_s + 0.08(\pm 0.13), \quad \text{Equation 2}$$

(For Ms between 6.2 and 8.2)

$$M_w = 0.813(\pm 0.04) * M_b + 0.367(\pm 0.23), \quad \text{Equation 3}$$

(For Mb between 3.5 and 5)

$$M_w = 1.745 * M_b - 4.191 \quad \text{Equation 4}$$

Similarly, the local magnitude (ML) reported by the National Seismological Center (NSC) of the Department of Mines and Geology (DMG), Government of Nepal was converted into Mw using Equation 5 (Ader et al., 2012).

(For  $ML_{DMG}$  and Mw)

$$M_w = 0.84 * ML_{DMG} + 0.21 \quad \text{Equation 5}$$

### 3.2.1.3. Declustering

An earthquake catalogue may contain foreshocks and aftershocks. Both foreshocks and aftershocks are dependent earthquakes, which precede and follow strong earthquakes and appear in clusters. The number of foreshocks is, in general, small in comparison to aftershocks.

In probabilistic seismic hazard assessment, independent earthquakes are required, which follow Poisson distribution (Gardner & Knopoff, 1974; Shearar & Stark, 2011; Abrahamson, 2006). Therefore, the identification and removal of dependent earthquakes (foreshocks and aftershocks) is carried out to develop a catalogue of only independent events, which will be consistent with a spatially inhomogeneous, temporally homogeneous Poisson process. The dependent earthquakes can be identified on the basis of their spatio-temporal proximity to other, previous earthquakes. The dependent earthquakes occur at rates higher than the average seismicity rate averaged over long durations.

There are two methods commonly used to decluster an earthquake catalogue, which are ‘window’ method and ‘cluster’ method (Van et al., 2012). Gardner and Knopoff (1974) introduced a declustering algorithm (a windowing method) that uses the proximity of earthquakes in space and time as an indicator of clustering. Table 3 shows the time and distance criteria, which is used to identify aftershocks in an earthquake catalogue.

**Table 3:** Aftershock identification windows (Gardner and Knopoff 1974)

Mw	Distance(km)	Time(days)
2.5	19.5	6
3	22.5	11.5
3.5	26	22
4	30	42
4.5	35	83
5	40	155
5.5	47	290
6	54	510
6.5	61	790
7	70	915
7.5	81	960
8	94	985

The ‘cluster’ technique (Reasenber, 1985) identifies aftershocks by associating earthquakes to clusters according to spatial and temporal interaction zones. The algorithm of Reasenber (1985) assumes an interaction zone that is centered on each earthquake. Earthquakes occurring within the interaction zone of a prior earthquake are considered aftershocks. The zone is dynamically modeled with spatial ( $R_{\text{fact}}$ ) and temporal ( $\tau_{\text{max}}$ ) parameters. The length scale  $R_{\text{fact}}$  is proportional to the source dimension, and the temporal scale  $\tau_{\text{max}}$  is determined using a heterogeneous Poisson process for aftershocks with rate  $\lambda(t)$ . Given  $t > 0$ , the probability of observing  $n$  earthquakes in the time interval  $[t, t + \tau]$  is given by:

$$P(\chi([t, t + \tau]) = n) = \frac{e^{-\lambda(t)\tau} [\lambda(t)\tau]^n}{n!} \quad \text{Equation 6}$$

With  $\lambda(t)$  following the Omori law

$$\lambda(t) = k(t + c)^{-p} \quad \text{Equation 7}$$

Where  $\aleph$  is the process, which counts the number of aftershocks occurring in the time interval  $[t, t + \tau]$ , whereas  $k$ ,  $c$ , and  $p$  are positive constants representing the Omori law parameters. The waiting time interval,  $\tau_w$ , required to observe the next event with probability,  $P$ , in a given sequence of aftershocks is

$$\tau_w = \frac{-t \log(1-P)}{10^{2(M_{\text{max}} - m_c - 1)/3}} \quad \text{Equation 8}$$

$M_{\text{max}}$  and  $m_c$  in this equation are the largest magnitude in the sequence and completeness magnitude, respectively. The waiting time is constrained as falling between the minimum and the maximum look-ahead times (i.e.,  $\tau_{\text{min}} \leq \tau_w \leq \tau_{\text{max}}$ ).

### 3.2.1.4. Completeness test

The earthquake catalogue is a combination of instrumental, historic and pre-historic earthquake data. Large events appear in the catalogue since comparatively long time in comparison to smaller events because of either absence of instrument or sparse distribution in the past. The completeness of different magnitudes, in terms of years, is required in order to precisely estimate recurrence parameters of them. The completeness is evaluated visually, using technique proposed by Stepp (1972), which examines the stationary nature of the activity rate. For completeness test, the earthquake data is grouped into different magnitude classes, for example,  $4 \leq M_w < 5$ ,

$5 \leq M_w < 6$ ,  $6 \leq M_w < 7$ ,  $7 \leq M_w < 8$  and  $8 \leq M_w < 9$ . The average number of events per year in each magnitude range is calculated separately. If  $\chi_1, \chi_2, \dots, \chi_n$  are the annual rates of events in a magnitude range, then the mean rate of earthquakes is calculated using Equation (9)

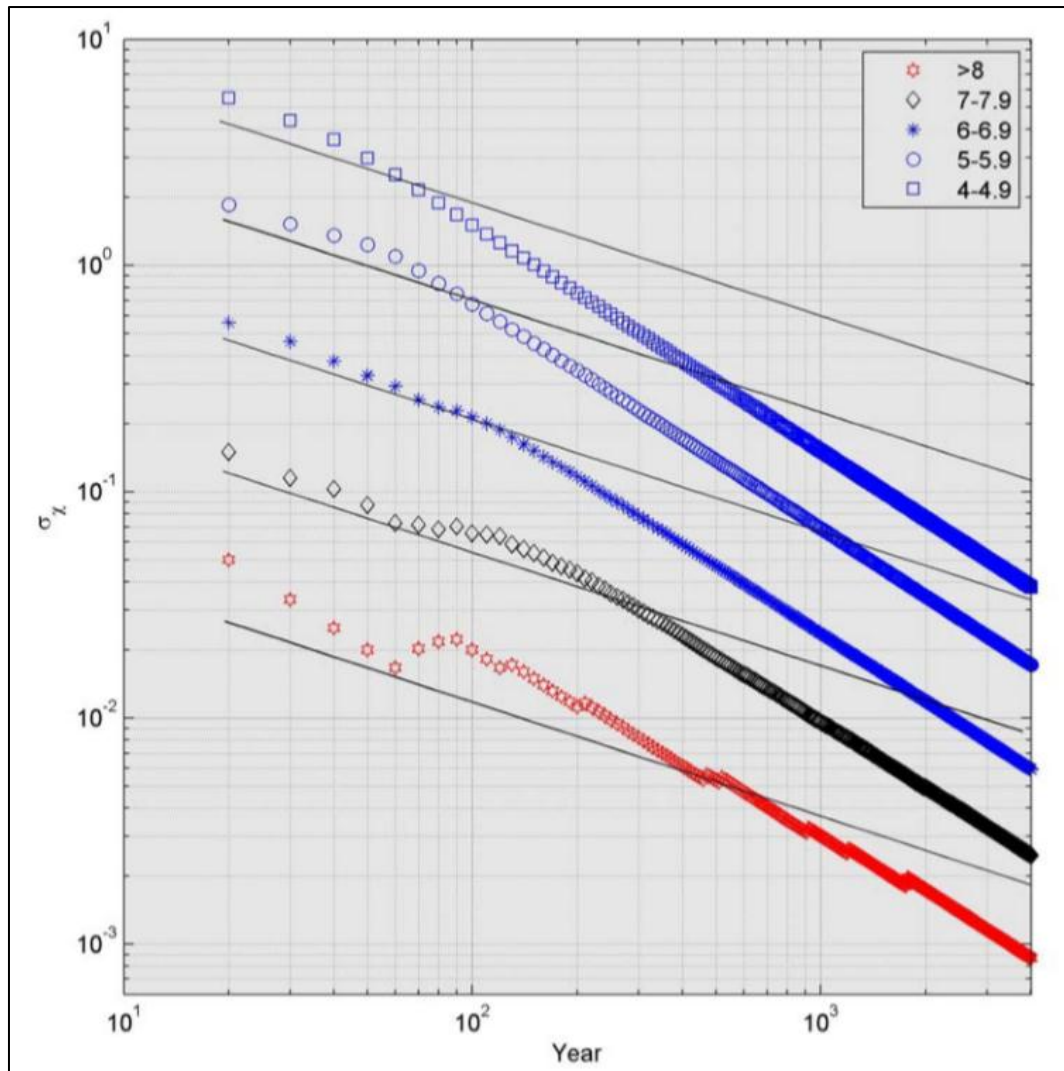
$$\chi = \frac{1}{n} \sum_{i=1}^n \chi_i \quad \text{Equation 9}$$

Where n is the number of unit time intervals. The variance is given by Equation (10)

$$\sigma_\chi^2 = \frac{\chi}{T} \quad \text{Equation 10}$$

Where T is the duration of the sample in years.

This test relies on the statistical property of the Poisson distribution that highlights time intervals during which the recorded earthquake occurrence rate does not change. The test (Figure 21) evaluates the stability of the mean rate of occurrences ( $\chi$ ) of events which fall in a predefined magnitude range in a series of time windows (T). If the rate of occurrence  $\chi$  is constant, then the standard deviation of the rate ( $\sigma_\chi$ ) varies as  $1/\sqrt{T}$  and  $\chi$  is not stable if  $\sigma_\chi$  deviates from the straight line of the  $1/\sqrt{T}$  slope. The length of the time interval for which the standard deviation does not vary from the straight line is the completeness time interval for that particular magnitude class. In general, the standard deviation shows the smaller earthquakes are stable for shorter windows and the large magnitude earthquakes are stable for longer time windows. However, it is true only if the time window is significantly larger than the return period of events. In the figure it breaks for  $M_w > 8$ .



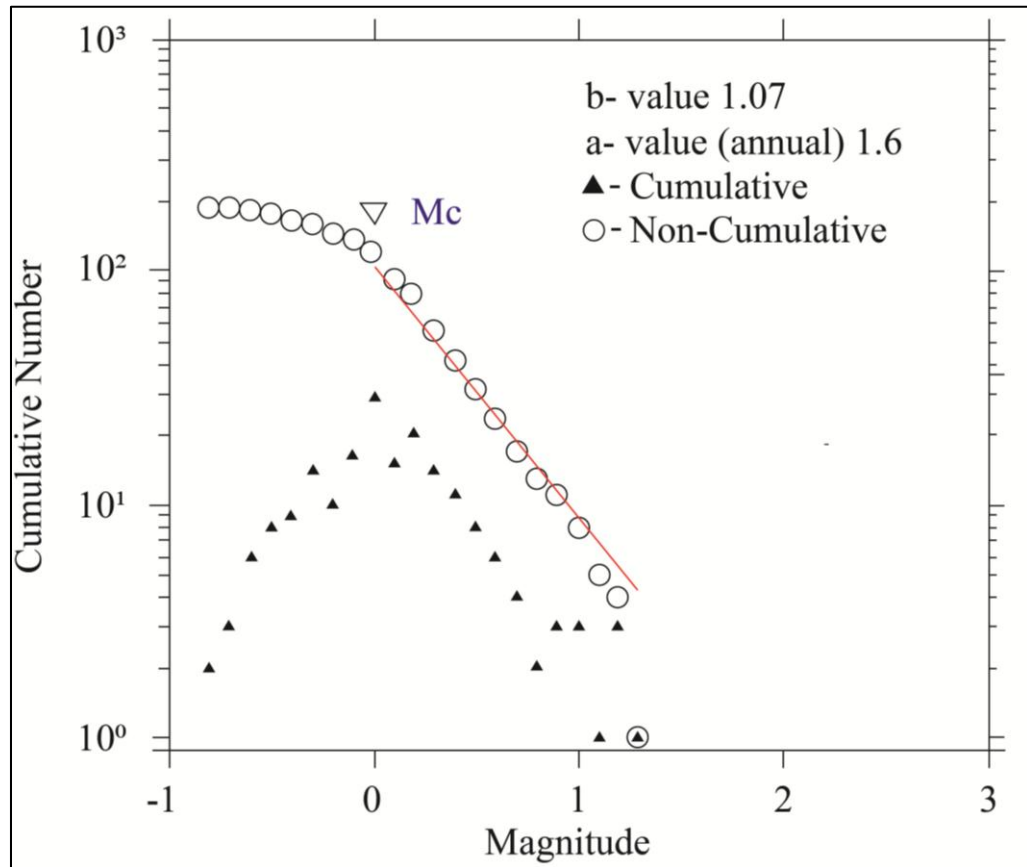
**Figure 21:** An example of completeness test. The blue dots represent data ( $\lambda$ ) and the straight lines represent  $1/\sqrt{T}$  (NDMA, 2010).

### 3.2.1.5. Magnitude of completeness

An earthquake catalogue contains earthquakes, which have magnitudes of all possible ranges. The small earthquakes are not reported completely in comparison to the large ones because the distribution of seismic stations was limited in the early days. In probabilistic seismic hazard analysis, a minimum magnitude, called magnitude of completeness ( $M_c$ ) is important and, therefore, should be estimated. The catalogue is considered complete for earthquakes having magnitude equal to or larger than  $M_c$  and can be used in probabilistic seismic hazard assessment.

The  $M_c$  of the catalogue is estimated using assumption of self-similarity (Wiemer & Wyss, 2000). This method provides a fast and reliable estimate of the  $M_c$  defining the

point of maximum curvature in non-cumulative frequency-magnitude distribution graph. A plot of cumulative and non-cumulative number of earthquakes is plot (e. g. Figure 22) against respective magnitude class to identify the magnitude of completeness ( $M_c$ ). The magnitude corresponding to peak on the non-cumulative curve in the plot is the magnitude of completeness ( $M_c$ ).



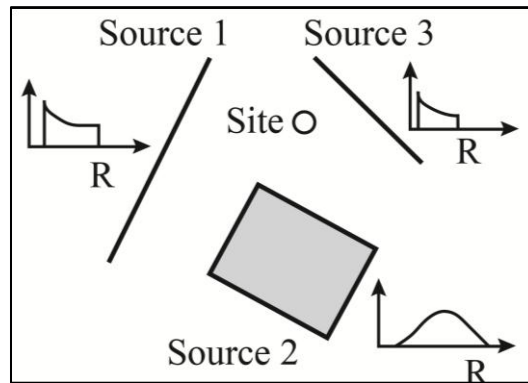
**Figure 22:** An example of determination of  $M_c$ . The curve with triangle corresponds to non-cumulative number of earthquakes and the circle represent the cumulative number. The peak value of the non-cumulative curve is considered to be  $M_c$ . (Modified from Romano *et al.*, 2015)

### 3.2.1.6. Identification and characterization of seismogenic sources

#### (a) Identification of potential sources:

Probabilistic seismic hazard analysis requires identification and delineation of all potential earthquake sources, which are close to the site of interest. Ground motion is calculated using various characteristics (magnitude, distance and recurrence parameters) of the sources and appropriate ground motion prediction model (attenuation relation). Therefore, identification of potential earthquakes sources is very important in any types of seismic hazard assessment. Earthquake sources are

identified and delineated using local seismicity pattern, location of historical earthquakes, seismotectonics, geodetic information and geological structures. The potentially strong earthquake sources are geological faults (e. g. Figure 23: source 1 and source 3), which are planar surfaces. If faults are not easily identifiable (as in the less seismically active regions of the eastern United States), then earthquake sources are simply described by areal regions (e. g. Figure 23, source2), where earthquakes may occur at any place (Baker, 2013).



**Figure 23:** Possible earthquake source models (Modified from Baker, 2013).

**(b) Maximum Potential Magnitude:**

After identification and delineation of sources, the maximum potential magnitudes of the identified sources are estimated. The maximum potential magnitudes of identified sources are estimated using empirical relations, which are functions of area of sources, length of faults and displacement on faults, or are adopted from the magnitudes of known, historical destructive earthquakes. Empirical relations (Equation 11 through Equation 15) established by Wells & Coppersmith (1994) were used to estimate the maximum potential magnitudes...

$$M_w = 4.33 + 0.90 \log A, (\sigma_{M_w} = 0.25) \text{ reverse fault} \quad \text{Equation 11}$$

$$M_w = 3.93 + 1.02 \log A, (\sigma_{M_w} = 0.25) \text{ normal fault} \quad \text{Equation 12}$$

$$M_w = 5.0 + 1.22 \log L (\sigma_{M_w} = 0.28) \text{ reverse fault} \quad \text{Equation 13}$$

$$M_w = 5.16 + 1.12 \log L (\sigma_{M_w} = 0.28) \text{ strike slip fault} \quad \text{Equation 14}$$

$$M_w = 4.86 + 1.32 \log L (\sigma_{M_w} = 0.34) \text{ normal fault} \quad \text{Equation 15}$$

In the above relations,  $M_w$  is the maximum possible moment magnitude ( $M_w$ ),  $A$  is the area (in  $\text{km}^2$ ) of the source region,  $L$  is the length of the fault in km;  $\sigma M_w$  is the standard deviation of moment magnitude from the median.

### (c) Gutenberg-Richter Relation

Gutenberg & Richter (1944) were the first to study the distribution of earthquake magnitudes, who noted that the number of earthquakes in a region, greater than a given size, generally follows a particular distribution called Gutenberg-Richter relation (Equation 16).

$$\log \lambda_m = a - b * m \quad \text{Equation 16}$$

Where ' $\lambda_m$ ' is the rate of earthquakes with magnitudes greater than ' $m$ ', and ' $a$ ' and ' $b$ ' are constants called 'a-value' and 'b-value' respectively.

Gutenberg–Richter relation is well known empirical relation in seismology which describes the frequency of occurrence of earthquakes as a function of magnitude. In the relation (Equation 16), the factor 'a' (a-value) is the logarithm of the total number of earthquakes with magnitude greater than or equal to ' $m$ '. It is a constant, which depends on many parameters like size of the area, time interval, total number of earthquakes and magnitudes of each earthquake and the value of "b" (Bora *et al.*, 2018). Mathematically speaking, a-value is the log number of earthquakes with magnitude equal to 0 (Allen, 1986) and describes total activity of earthquakes in the region. The a-value depends on the rate of seismicity and the length of observation time.

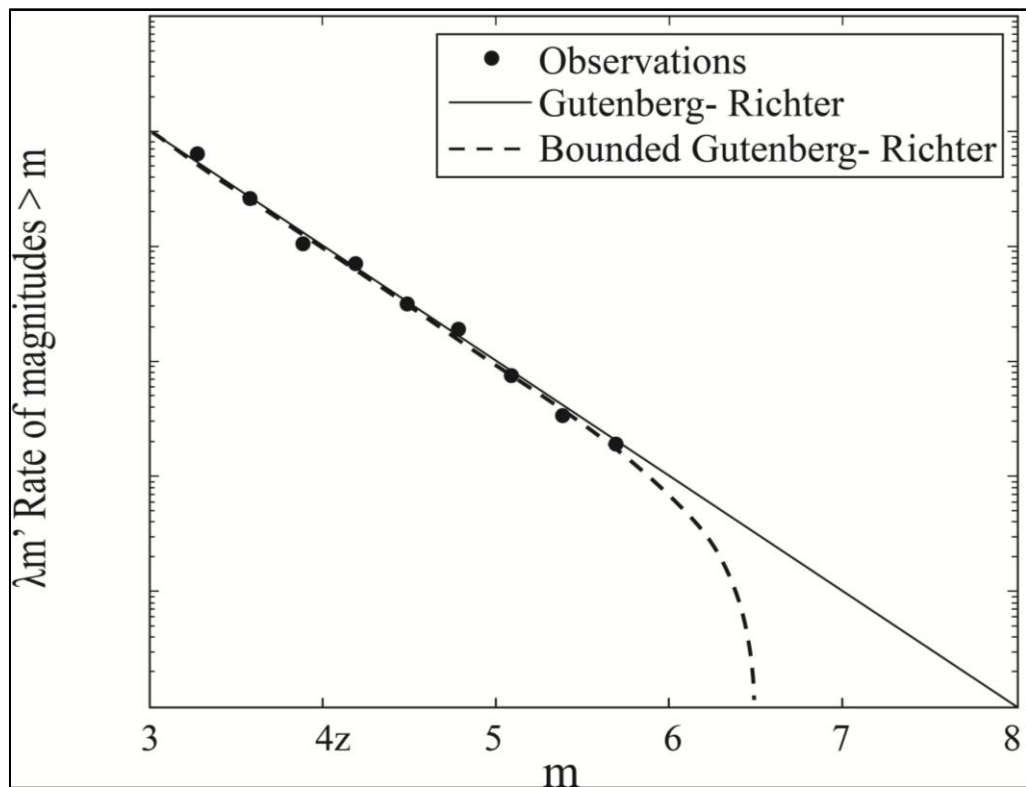
The factor ' $b$ ' (b-value) describes the relative number of large and small earthquakes. It is important because it is used to quantify seismic activity and seismic hazard. The b-value is the slope of the curve (Figure 24) of cumulative number of earthquakes versus magnitude. For active tectonic region its value is about 1 and for volcanic region it is 2.5 (e. g. Throne & Terry, 1995) or higher. A small b-value means strong earthquakes are frequent and vice versa. The b-value depends on tectonics, structural heterogeneity and stress distribution in space (Schorlemmer *et al.*, 2005; Khan & Chakraborty, 2007; Mousavi, 2017a, 2017b). This relationship between earthquake magnitude and frequency of occurrence is found remarkably consistent in worldwide



data, although the values of a-value and b-value may vary from region to region or over time. When b-value is 1.0, for a given frequency of magnitude 4.0 or larger events there will be 10 times as many magnitude 3.0 or larger quakes and 100 times as many magnitude 2.0.

Earthquakes with magnitude larger than or equal to the magnitude of completeness ( $M_c$ ) are used to derive the Gutenberg-Richter relation, because below  $M_c$ ,  $\log \lambda_m$  cannot behave linearly due to insufficient coverage (e.g. Wiemer & Wyss, 2000).

An example of the law is shown in Figure 24 below.



**Figure 24:** An example of Gutenberg-Richter relation plot. The slope of the curve is the 'b' value in the G-R relation.

The common technique of estimating 'b' value is the least squares fit to the logarithm of the data. This technique leads to an answer that is biased for small data sets and apparent errors that are much smaller than the real ones. The maximum likelihood method (Equation 17) of Aki (1965) is preferred over the least square method to calculate 'b' value, but it requires large data sets. Aki (1965) indicate that a minimum of 2000 earthquakes are required to calculate 'b' to within 0.05 at 98% confidence. Significant problems for 'b' value calculation can be caused by choosing a smaller magnitude of completeness ( $M_c$ ).

$$b = \log_{10} e / (M_{mean} - M_{min}) \quad \text{Equation 17}$$

Where 'b' is b-value,  $M_{mean}$  is the average magnitude in the catalogue and  $M_{min}$  is the minimum magnitude.  $\log_{10} e$  equals 0.434 and, therefore, the equation can be rewritten as:

$$b = 0.434 / (M_{mean} - M_{min}) \quad \text{Equation 18}$$

The equation 16 can be rearranged as

$$\lambda_m = 10^{(a-bm)} = \exp(\alpha - \beta * m_0). \quad \text{Equation 19}$$

Where  $\alpha = 2.303 * a$  and  $\beta = 2.303 * b$ .

Equation (19) shows that earthquake magnitudes are distributed exponentially. This relation covers earthquakes of infinite ranges i. e. from infinitely small to infinitely large. Very small earthquakes have importance in science but the effect is of little interest in engineering field, therefore, small earthquakes are commonly ignored because they cannot cause damage to structures. The lower threshold magnitude is set to 4.0 or 5.0 in most PSHAs because earthquakes smaller than these seldom cause damage (Kramer, 2007). If earthquakes with magnitude smaller than a lower threshold are ignored, the mean annual rate of exceedance can be written (McGuire & Arabasz, 1990) as:

$$\lambda_m = v e^{-\beta(m-m_0)} \quad m > m_l \quad \text{Equation 20}$$

Where  $v = e^{(\alpha-\beta m)}$

The standard Gutenberg-Richter relation can predict non-zero mean rates of exceedance for earthquakes of infinitely large size. But earthquakes of size larger than  $M_w$  10 have not been known so far. An earthquake source has its maximum potential

magnitude and if we know the maximum potential magnitude of the earthquakes source, the mean annual exceedance rate can be estimated using Equation (21) (McGuire & Arabasz, 1990).

$$\lambda_m = \nu \frac{e^{[-\beta(m-m_l)]} - e^{[-\beta(m_{max}-m_l)]}}{1 - e^{[-\beta(m_{max}-m_l)]}} m_l \leq m \leq m_{max} \quad \text{Equation 21}$$

Equation (21) is the bounded or tapered recurrence law, which is graphically shown in Figure 24 for constant mean annual exceedance rate of  $m_l$  for different maximum magnitudes. The annual exceedance rate decreases with the increase of maximum magnitude.

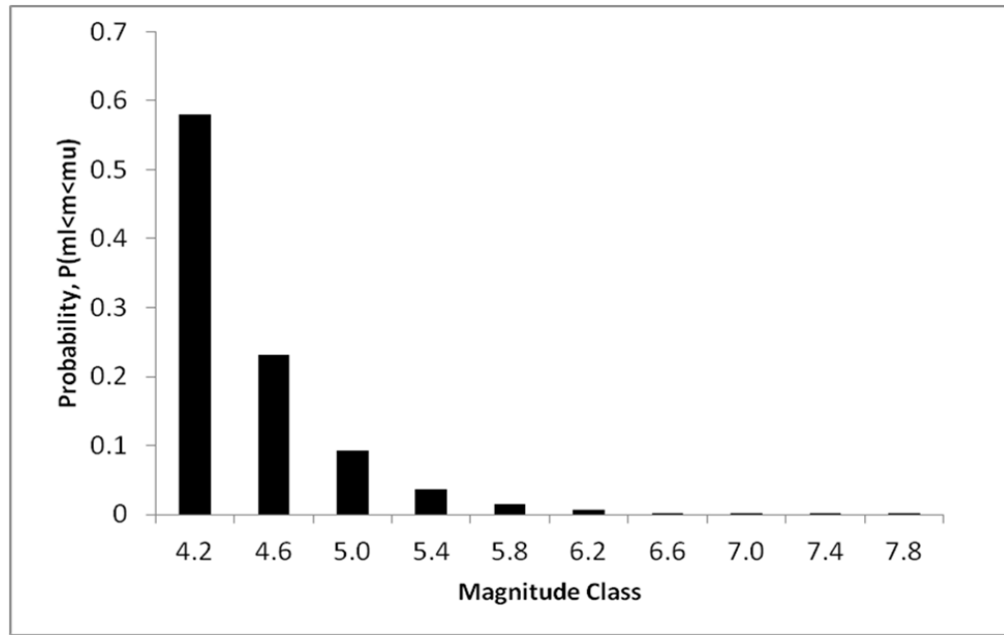
### (c) Magnitude Characterization:

All the earthquake sources have their own maximum potential magnitude. Earthquakes smaller than magnitude 5 are not considered as strong ones to cause damage, therefore, the probability of intermediate magnitudes above Mw 5 and below the maximum magnitude are calculated (e. g. Figure 25). The cumulative density function (CDF) and probability density function (PDF) for the Gutenberg - Richter relation with upper and lower bounds can be expressed as:

$$F_M(m) = P[M < m \mid m_0 \leq m \leq m_{max}] = \frac{1 - \exp[-\beta(m-m_0)]}{1 - \exp[-\beta(m_{max}-m_0)]} \quad \text{Equation 22}$$

$$f_M(m) = \frac{\beta \exp[-\beta(m-m_0)]}{1 - \exp[-\beta(m_{max}-m_0)]} \quad \text{Equation 23}$$

Where,  $F_M(m)$  and  $f_M(m)$  are cumulative density function and probability density function.  $\beta$  is earthquake recurrence parameter and equals to  $2.303 \cdot b$ ,  $m$  is magnitude considered,  $m_0$  is minimum magnitude and  $m_{max}$  is maximum potential magnitude for the given source.



**Figure 25:** An example of probability density function of intermediate magnitude earthquakes.

**(a) Spatial characterization:**

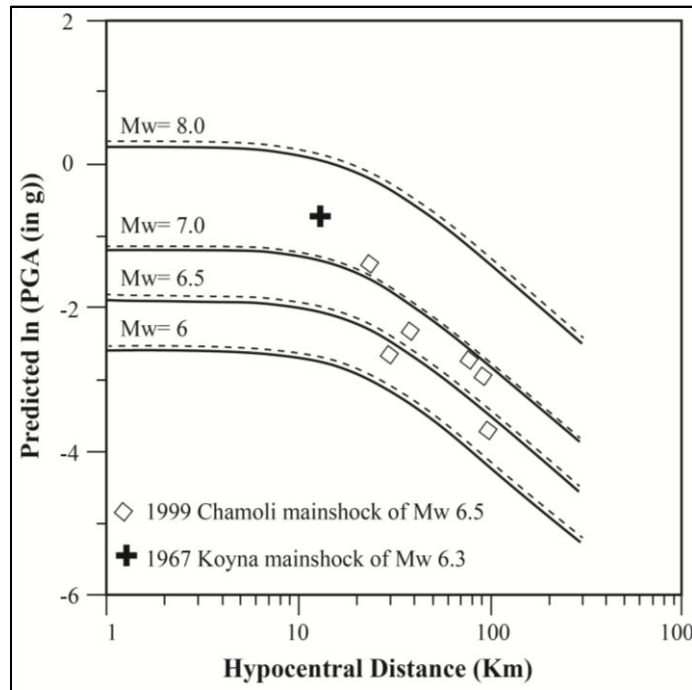
Earthquakes are considered equally likely to occur at any location in any earthquake source. The uncertainty in the location of earthquakes is required to be described by appropriate distance parameter. The spatial uncertainty, generally, is described by a probability density function (e. g. Kramer, 2007). To account for this uncertainty, the source is divided into a number of blocks and distance is calculated from the centre of each block to a particular place where seismic hazard is to be carried out. If the source is divided into  $n \times n$  blocks; there will be  $n^2$  blocks. The calculated distances are divided into equal distance intervals and source-to-site distances falling in each interval is counted and probabilities  $P(R)$  is calculated. An example of the probability of 30 distance classes is presented in Figure 26.



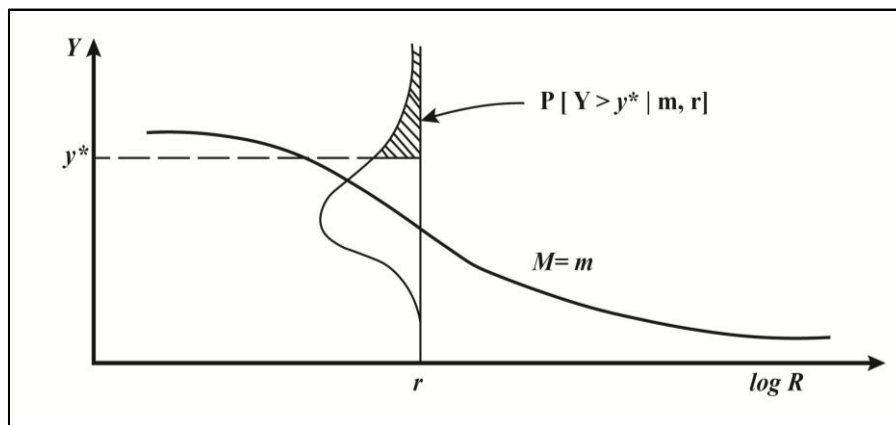
$$P[Y > y^* / m, r] = 1 - F_Y(y^*)$$

Equation 24

Where,  $F_Y(y)$  is the value of the cumulative distribution function of  $Y$  at  $m$  and  $r$ . The value of  $F_Y(y)$  depends on the probability distribution used to represent  $Y$ . In general, ground motion parameters are usually assumed to be log normally distributed (the logarithm of the parameter is normally distributed); however, the unbounded characteristics of that distribution can attribute to a nonzero probability to unrealistic values of the ground motion parameters.



**Figure 27:** An example of Attenuation curves (modified from Mandal *et al.*, 2009).



**Figure 28:** An example of conditional probability of exceeding a particular value of a ground motion parameter for a given magnitude and distance.

### **3.2.1.8. Uncertainties in PSHA**

Probabilistic Seismic Hazard Analysis (PSHA) is a method that deals with uncertainty. While there is considerable information on earthquake ground motions and potential future locations of earthquakes, there is also considerable uncertainty in the inputs to the analysis. Therefore, it is important to identify and address these uncertainties in PSHA. Probabilistic Seismic Hazard Analysis (PSHA) aims to quantify these uncertainties, and combine them to produce an explicit description of the distribution of future shaking that may occur at a site (Baker, 2008). The uncertainties can be grouped into epistemic and aleatory uncertainties.

#### **(a) Aleatory uncertainty**

Aleatory uncertainty arises from the randomness of the phenomenon and cannot be reduced even we have large additional data or information. Aleatory uncertainties are objective, which can be quantified but cannot be modified with the addition of additional data (Ordaz & Arroyo, 2016):

The followings are the examples of aleatory uncertainties:

- Recurrence relations: The Poisson model assumes that even though we know accurately the recurrence relation we cannot predict where or when the next earthquake will occur or what size it will be.
- Standard deviation of the attenuation relation: No matter how accurately we know the magnitude and distance of a postulated earthquake source, there still will be some uncertainty in predicting the ground motion, which is reflected in the standard deviation.

#### **(b) Epistemic uncertainty**

Epistemic uncertainty arises from the lack of knowledge about model and parameter. This type of uncertainty can be reduced using additional data or improved information. In the past it was called statistical or professional uncertainty (McGuire, 2004). Epistemic uncertainty depends on the available information and can be reduced by additional data and therefore varies with time. It is generally subjective, which involves a degree-of-belief in interpretation and probability theory may not apply in this case.

The following are some examples of epistemic uncertainty (Ordaz & Arroyo, 2016):

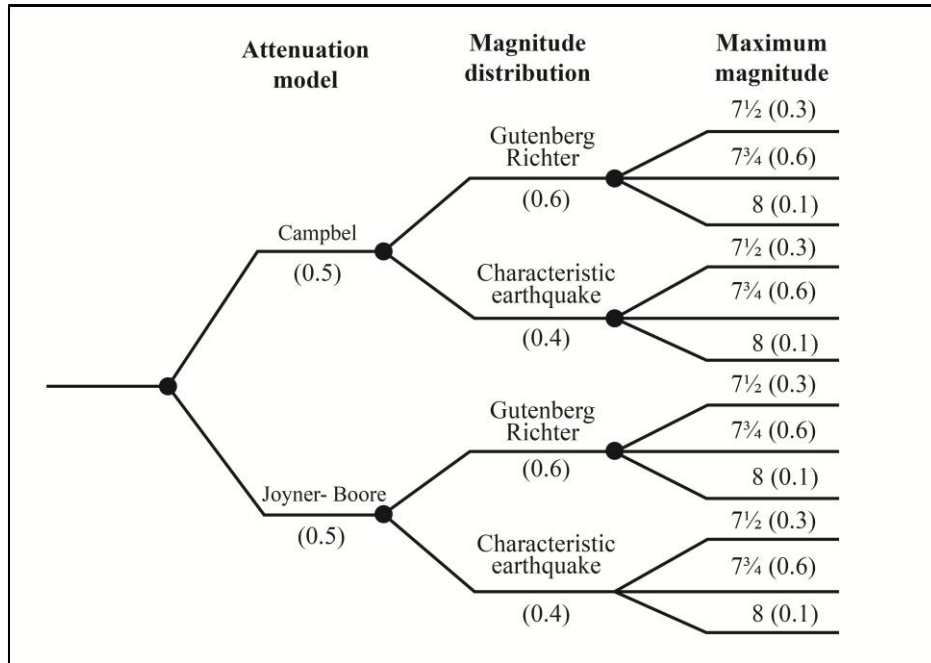
- What and where are the seismogenic sources?
- Are the sources seismically active at present?
- What are the potential magnitudes of the potential earthquake sources?
- Which attenuation relation best applies to the region of interest?

### **3.2.1.9. Logic Tree**

The probability computation allows us systematic consideration of uncertainties in the values of the parameters in any seismic hazard model (Kramer, 2007). Logic trees are important (Power *et al.*, 1981; Kulkarni *et al.*, 1984; and Coppersmith & Youngs, 1986) in PSHA, which are used to incorporate uncertainties providing a convenient framework for the explicit treatment of model uncertainty (Kramer, 2007).

A reliable and trustworthy probabilistic seismic hazard analysis (PSHA) accounts for the intrinsic variability of the system (aleatory variability) and the limited knowledge of the system itself (epistemic uncertainty). This approach uses alternative models, each of which is assigned a weighting factor, which is interpreted as the relative likelihood of that model being correct. A logic tree consists of a number of nodes, which represent points at which models are specified and the branches represent different models specified at each node. The sum of the probabilities of all branches, which are connected to a given node equals 1. The logic tree (Figure 29) allows incorporation of uncertainty in selection of models for attenuation, magnitude distribution and maximum potential magnitude to be considered in the calculations (Kramer, 2007).





**Figure 29:** An example of logic tree (Redrawn from Kramer, 2007). It provides a framework in which the uncertainty is treated assigning certain weight.

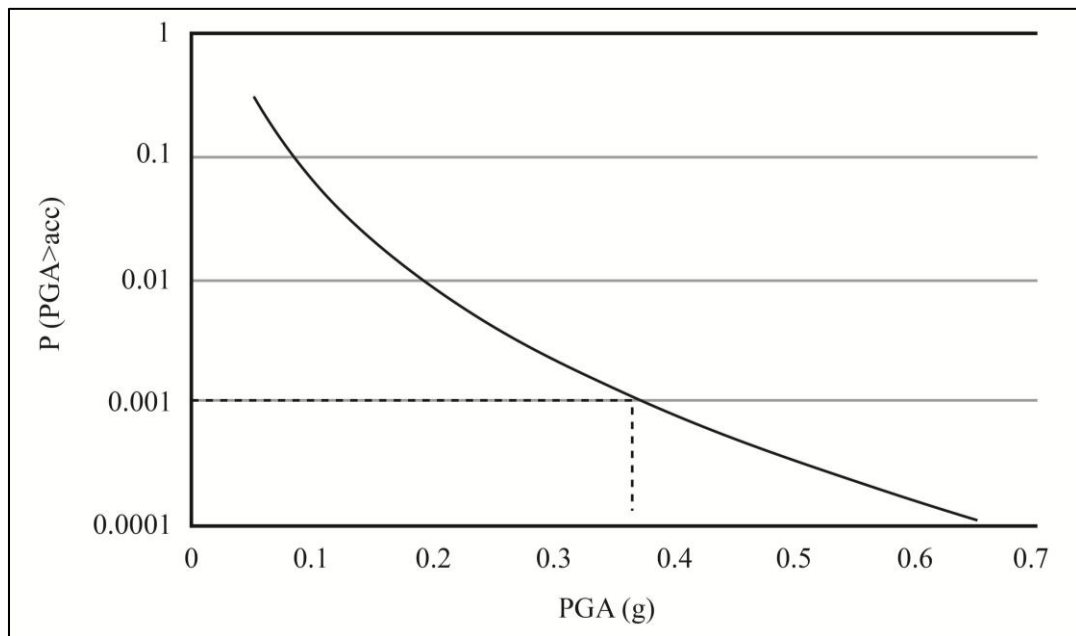
### 3.2.1.10. Probability computation

It is the final step in probabilistic seismic hazard analysis. It calculates the total probability of exceedance of specified level of peak ground acceleration. The uncertainties in earthquake size, location and ground motion prediction are combined to obtain the total probability. In general, the magnitude is divided into ‘j’ number of intervals for ‘i’ number of sources and source to site distance is divided into ‘k’ number of intervals. An attenuation relationship is used to calculate peak ground acceleration in each interval of magnitude and distance. The combined probability of particular ground motion parameter is expressed as mean annual rate of exceedance to that value of ground motion parameter, which is expressed as:

$$\lambda_{y^*} = \sum_{i=1}^{N_s} \sum_{j=1}^{N_m} \sum_{k=1}^{N_r} v_i \rho[(Y > y^*)/m_j, f_k] f_{M_i}(m_j) f_{R_i}(r_k) \Delta m \Delta r \quad \text{Equation 25}$$

where,  $\lambda_{y^*}$  is the annual rate of exceedance of peak ground acceleration  $y^*$  occurring at source from 1 to number  $N_s$  in between magnitudes of total  $N_M$  number at source to site distances of ranges from 1 to  $N_r$  number.  $v_i$  is the annual rate of exceedance of minimum threshold earthquake ( $M=4$ ) at source  $i$  derived using G-R recurrence relationship as represented by Equation (16) in which  $\lambda(m=4) = v$ , and  $P[Y > y^*/m_j, r_k]$  is the probability of exceedance of specified peak ground acceleration  $Y$  to the value

$y^*$  obtained using attenuation relationship for given magnitude  $m$  and distance  $r$  at each of interval of one to  $j$  number and  $k$  number respectively. Probability of exceedance of acceleration is calculated using normal distribution function as given by Equation 25.  $f_M(m)$  is the function of magnitude probability as given by truncated G-R relationship with upper and lower bound as expressed in Equations (22 and 23). An example of seismic hazard curve (annual probability of exceedance versus PGA) is given in Figure 30.



**Figure 30:** An example of seismic hazard curve. It provides mean annual exceedance rate of PGA for a particular site (Source: Kramer, 2007).

### 3.2.1.11. Seismic hazard map

To prepare seismic hazard maps, the area of interest is divided into a number of blocks. PGA is calculated for different exceedance rates at each node of the study area. Finally, the values at the nodes are contoured to produce seismic hazard maps.

### 3.2.2. Seismic ground response investigation

#### 3.2.2.1. Strong ground motion data recording

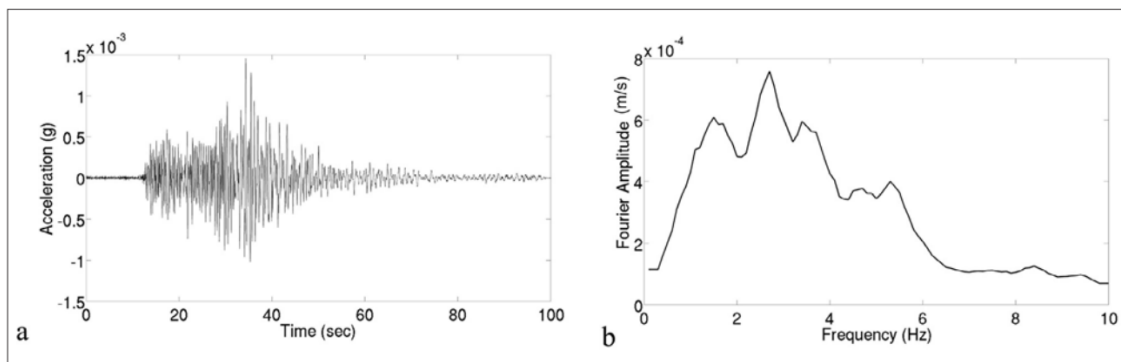
Strong motion (acceleration) data recorded on ground is required in this investigation. The records should be free from effects of structures, therefore, should not be from any instrument installed in structures.

### 3.2.2.2. Determination of PGA in the records

The time series data of strong motion (acceleration) records is baseline corrected and filtered to remove undesirable frequencies. After filtering, the PGA is estimated from the plot of time series data (Figure 31(a)).

### 3.2.2.3. Fourier transformation

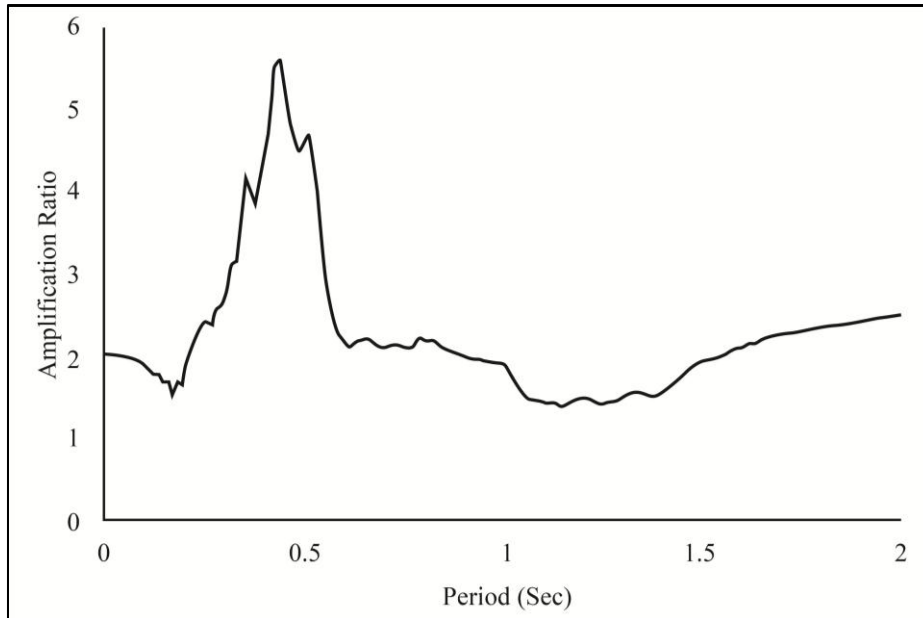
The time series data (Figure 31(a)) which come in time-domain are transformed into frequency-domain using Fourier Transformation. The Fourier spectrum (Figure 31(b)) of Fourier amplitude vs. frequency (or period) shows the fundamental period at the site.



**Figure 31:**(a) An example of time series (acceleration) data of an earthquake recorded at a site. The PGA is the largest absolute acceleration value on the y-axis. (b) Fourier amplitude spectra of the time series data (a) (source Bohhano *et al.*, 2017).

### 3.2.2.4. Amplification factor (ratio) calculation

Amplification of ground motion is estimated using strong motion records in frequency domain. Amplification factor is expressed as a ratio of Fourier spectrum (Figure 32) at soil site to that at reference (rock) site.



**Figure 32:** An example of amplification ratio determination. The curve represents ratio of Fourier spectra at soil site to a reference (rock) site.

## CHAPTER 4

### RESULTS AND DISCUSSIONS

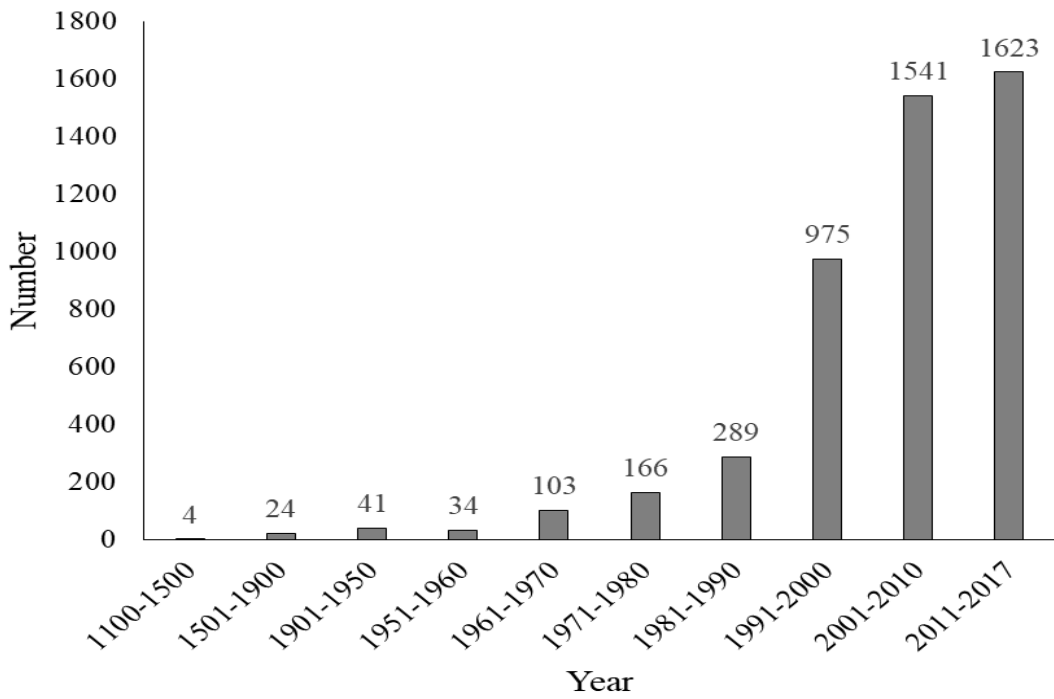
#### 4.1 Data Processing

After collection and compilation of earthquake catalogues collected from different sources (ISC, USGS, IRIS, DMG and published literatures) the catalogue was checked for duplicate events. Duplicate events were removed from the catalogue in order to make catalogue of standard events, which do not have repetition of data in it.

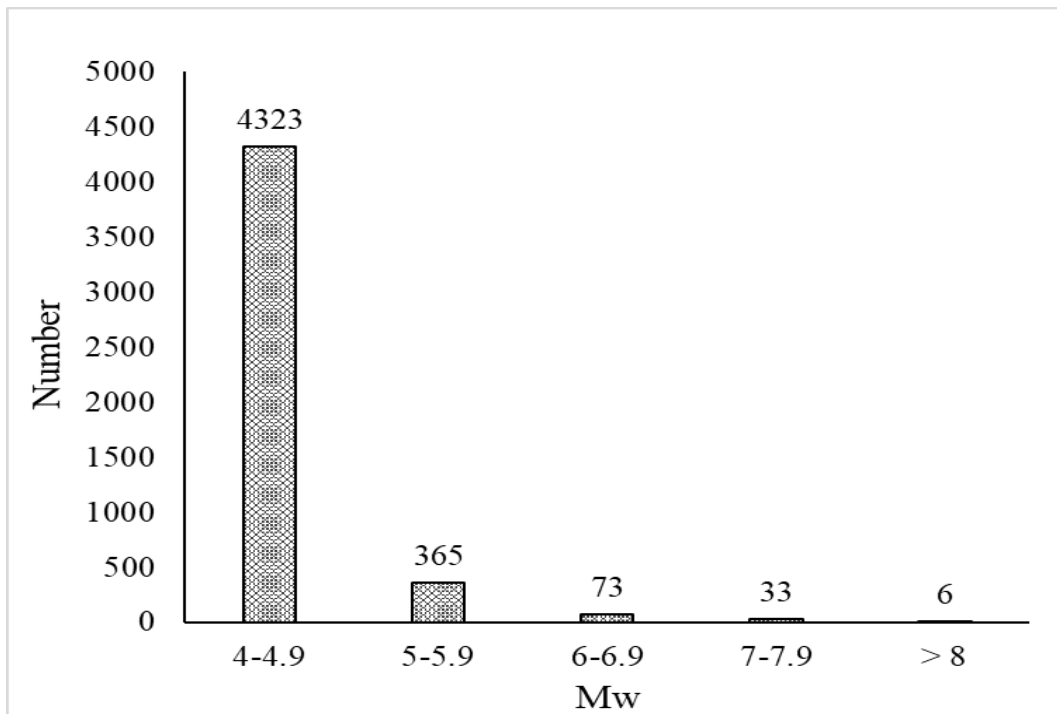
#### 4.2 Magnitude conversion

The merged catalogue had magnitudes presented in terms of moment magnitude ( $M_w$ ), body wave magnitude ( $M_b$ ), surface wave magnitude ( $M_s$ ) and local magnitude ( $M_L$ ). Moment magnitude ( $M_w$ ) is generally considered the best compared to other magnitudes because it does not saturate even at large earthquakes (Kanamori, 1977; Kanamori & Hanks, 1979). The other types of magnitudes ( $M_b$ ,  $M_s$  and  $M_L$ ) reported in the catalogue were converted into  $M_w$  using empirical relations derived by Scrodilis (2006) and a catalogue of magnitude-homogenized earthquakes was prepared. Figure 33 presents the number of earthquakes, after magnitude conversion, in different time intervals. Equations 1, 2, 3, 4 and 5, in Section (§3), were used to convert magnitudes into moment magnitude ( $M_w$ ). The number of earthquakes increased from 289 to 1000 in 2000 and reached to 1623 in 2017 because of the addition of new networks as well as expansion of existing seismic networks that resulted in the reduction of threshold magnitude of the networks.

The number of earthquakes in different magnitude classes is presented in Figure 34. The number of small earthquakes is naturally larger than that of the strong earthquakes. Earthquake of  $M_w$  4-4.9 are 4323,  $M_w$  5-5.9 are 365,  $M_w$  6-6.9 are 73,  $M_w$  7-7.9 are 33 and  $M_w > 8$  are only 6.



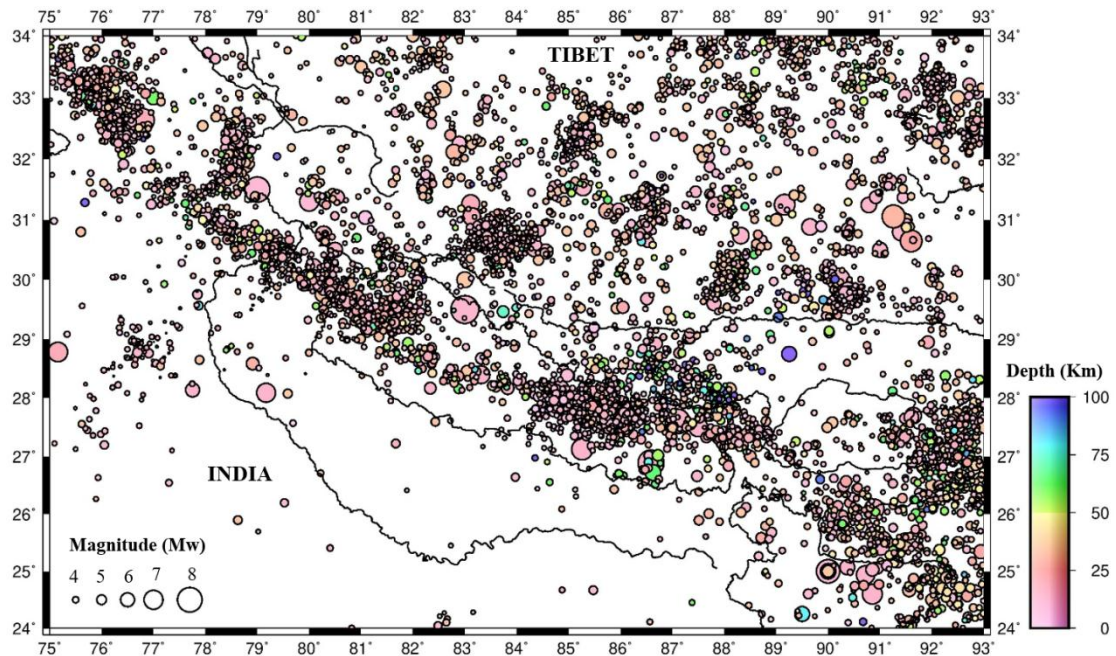
**Figure 33:** Distribution of earthquakes with magnitude ( $M_w > 4$ ) in different time intervals after magnitude conversion.



**Figure 34:** Number of earthquakes in different magnitude classes after magnitude conversion.

### 4.3 Declustering

The earthquakes contained in the magnitude-homogenized catalogue are graphically presented in Figure 35. The clusters of earthquakes in the figure are mostly aftershocks, which are dependent events. The cluster in the central region of Nepal represents the aftershocks of the 2015 Gorkha Earthquake.

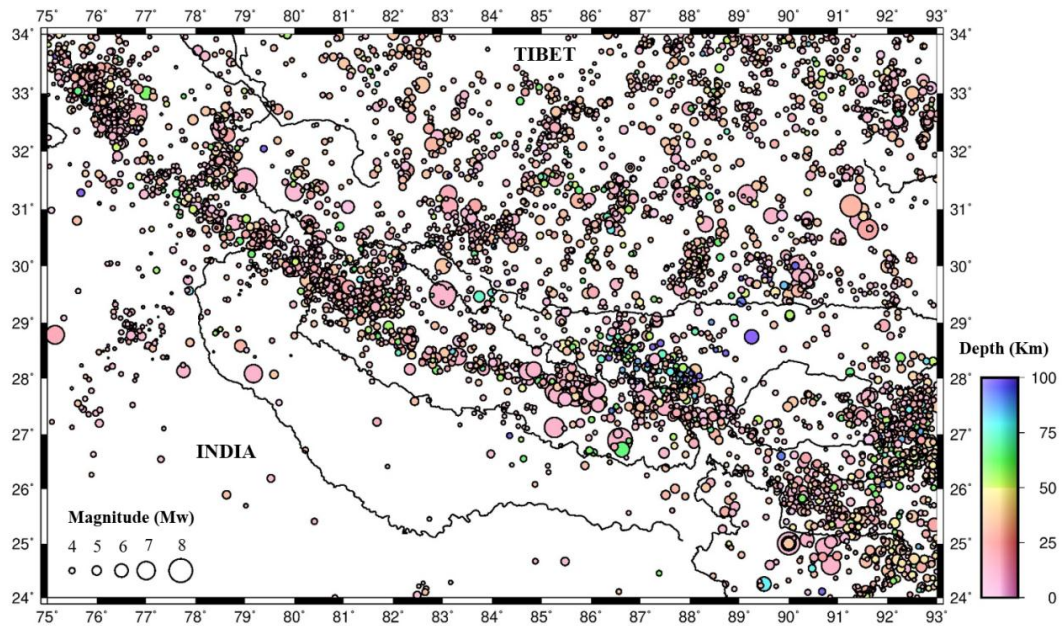


**Figure 35:** Epicenter distribution of earthquakes in the prepared catalogue. The clusters noticed in the figure are dependent earthquakes. The dense clustering in central Nepal compared to other parts is due to the aftershocks of the 2015 Gorkha Earthquake.

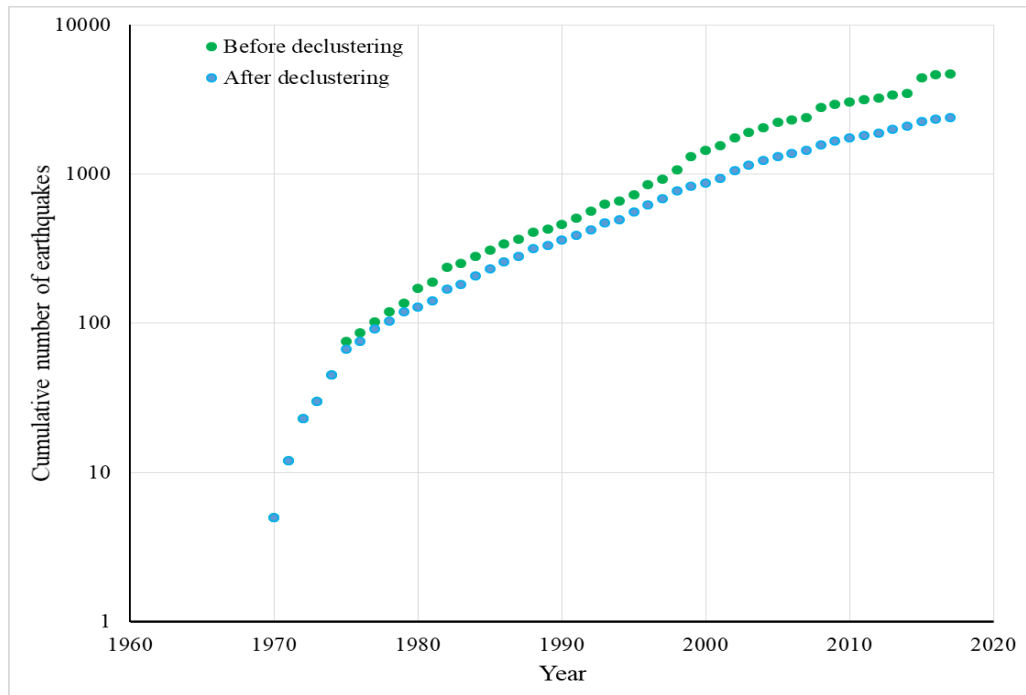
The magnitude-homogenized earthquake catalogue was declustered to identify and remove dependent earthquakes. A FORTRAN program “Cluster 2000” (Equation 6, 7 and 8, §3.2.1.2), was used to decluster the catalogue, which uses ‘cluster’ technique of Reasenberg, 1985. The program is freely available on <https://www.usgs.gov/software/cluster2000>.

The distribution of earthquakes, contained in the declustered catalogue, is graphically presented in Figure 36. The dense clusters of earthquakes, which contain dependent earthquakes, present in the earthquake catalogue (Figure 35) disappeared after declustering. An evidence of declustering is shown in Figure 37. The figure shows the cumulative number of earthquakes since 1970 before declustering (green dotted line) and after declustering (blue dotted line). The green line shows sudden rise in the

number of earthquakes at 1999, 2008 and 2015. The increase in number in 2015 belongs to the aftershocks of the 2015 Gorkha Earthquake (Mw 7.8).



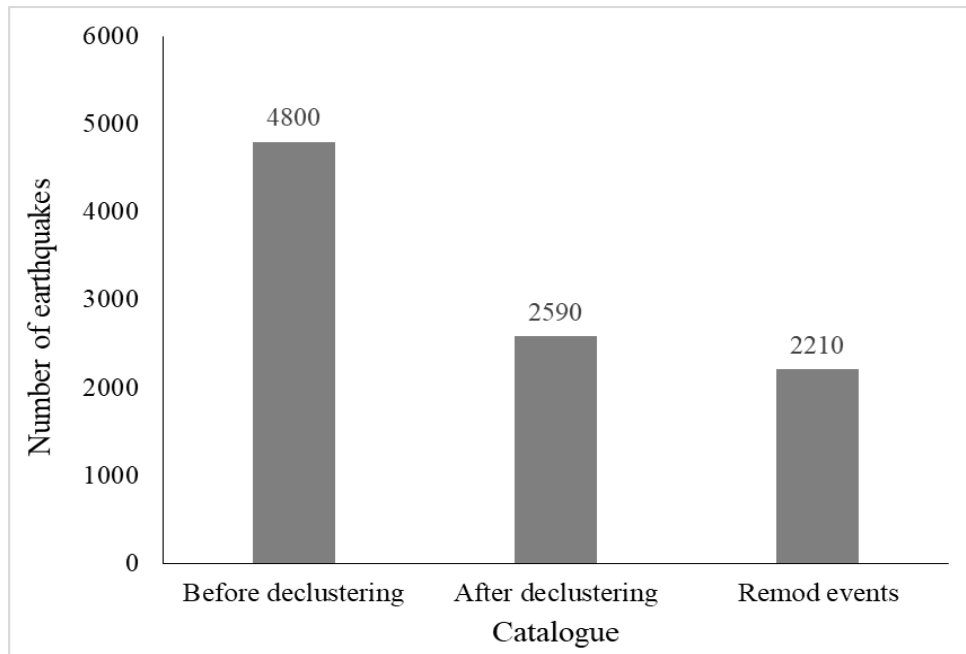
**Figure 36:** Epicenter distribution of independent events after declustering (free of dependent events) of the catalogue. Note that the clusters (aftershocks) of earthquakes, which appear in Figure 35 disappear, after declustering.



**Figure 37:** Cumulative number of earthquakes before and after declustering. The curves show the removal of dependent events in 1999, 2008 and 2015, which belong to the aftershocks of 1999 Chamoli Earthquake, 2008 Earthquake and 2015 Gorkha Earthquake in their order.



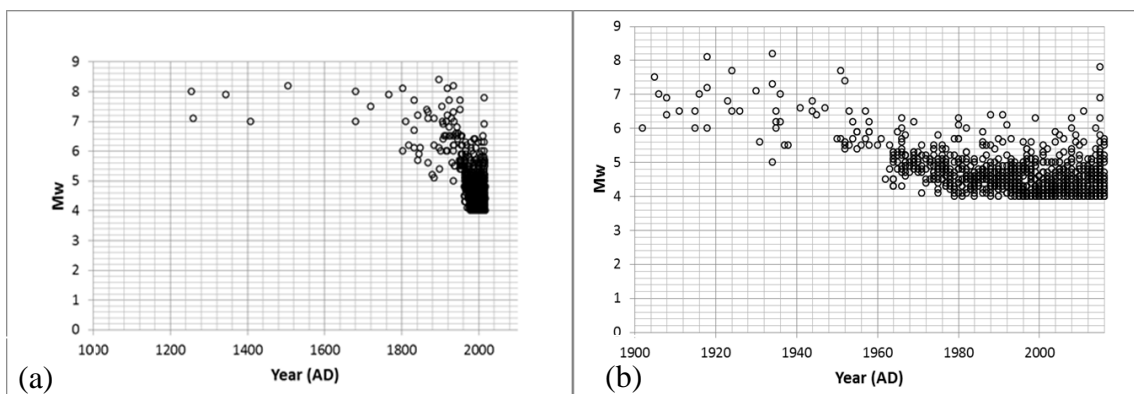
The magnitude-homogenized earthquake catalogue had 4800 earthquakes ( $M_w \geq 4$ ) before the declustering process was applied. After declustering, the number of earthquakes in the catalogue dropped to 2590, whereas 2210 earthquakes were identified as dependent earthquakes (foreshock and aftershock) and removed from the catalogue (Figure 38).



**Figure 38:** Number of earthquakes before and after applying declustering technique.

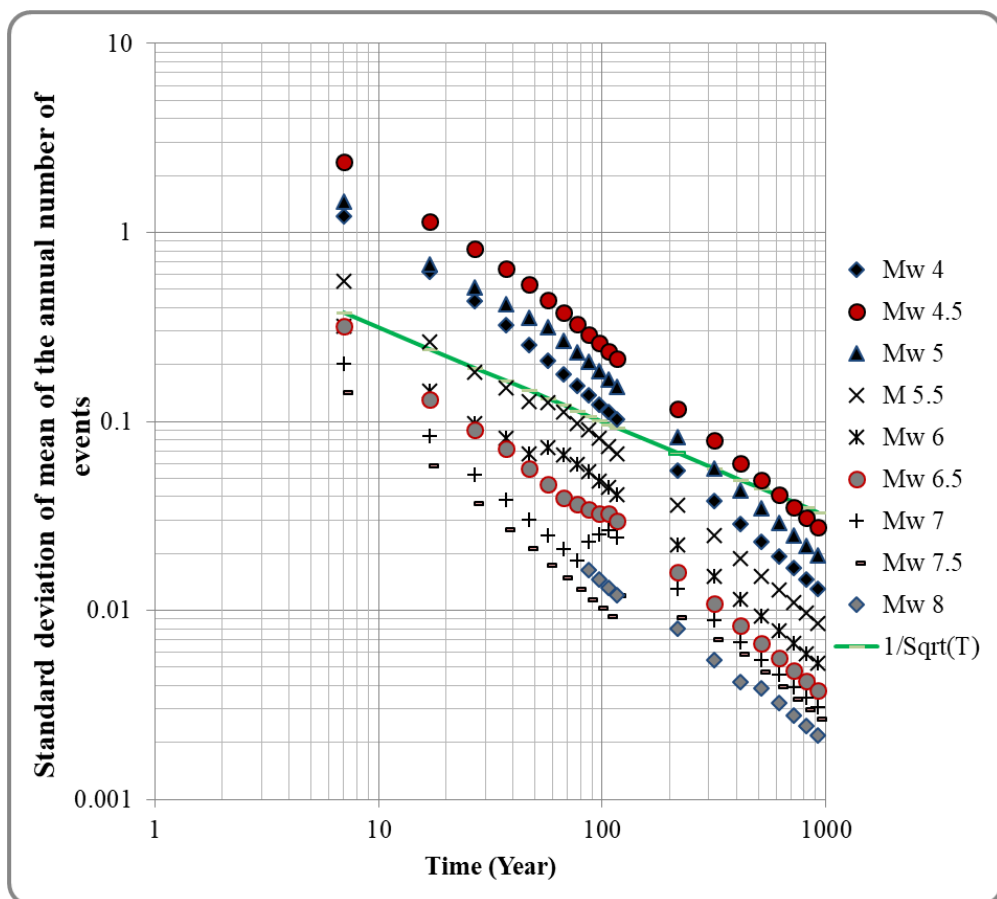
#### 4.4. Completeness test

The magnitude-homogenized and declustered catalogue consists of earthquakes of a range of magnitudes, available for different length of time (Figures 39(a) and 39(b)). Both the figures show that small earthquakes ( $M_w \sim 4.0$ ) appear in the catalogue very lately (around 1960 AD) in comparison to the large earthquakes (around 1255 AD).



**Figure 39:** Earthquake magnitude in the catalogue and their reported time. (a) Earthquake data since 1100AD. (b) Earthquake data since 1900 AD.

The complete time interval of each magnitude class was visually determined from the T (time) versus  $\sigma$  (standard deviation of mean of the annual number of earthquakes) plot as shown in Figure 40. In order to estimate the completeness levels of different magnitude classes, the catalog was split into 8 time windows of 100-year length between 1100 (first data entry in the catalogue) and 1900 AD and 11 time windows of 10-year length after 1900 AD. The results of completeness of different magnitude classes for South Tibet and the Himalaya are given in Table 4. The Table 4 shows that Mw 4.0 earthquakes are completely reported since last 15 years, Mw 4.5 are reported since last 35 years, Mw 5.0 since last 55 years and so on for both Himalaya and South Tibet.



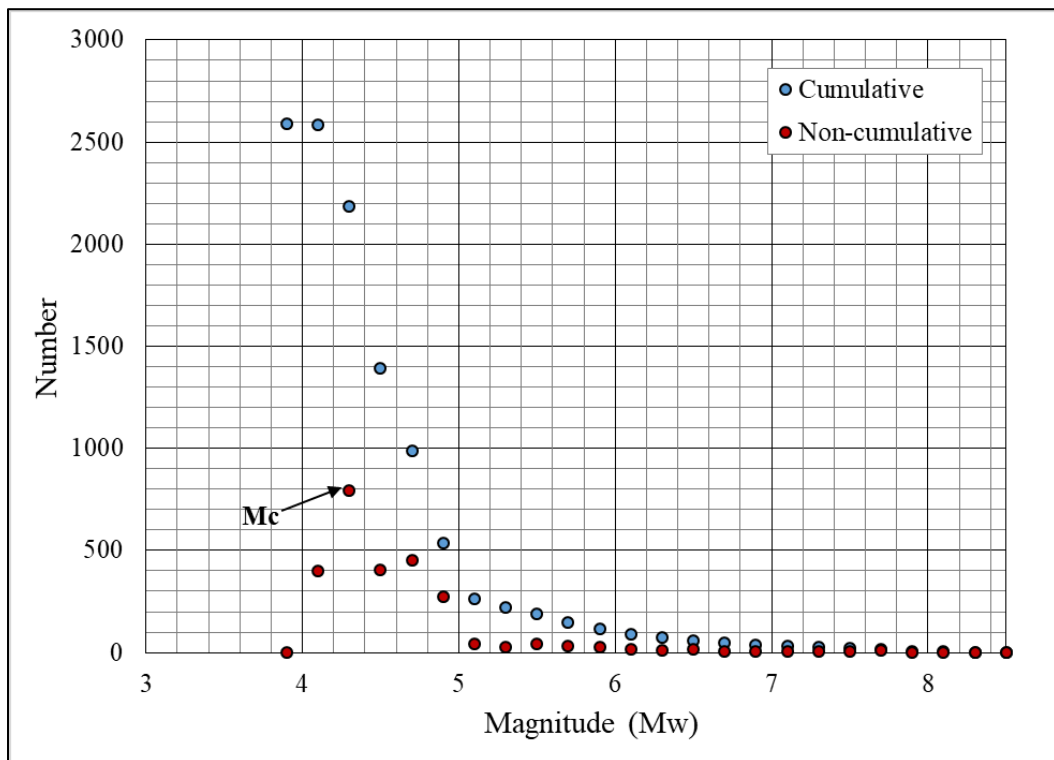
**Figure 40:** Completeness test of homogenized composite catalogue following Stepp (1972) technique. The small earthquakes are complete for short time whereas the large ones are complete gradually for large time-lengths. The green dots represent  $1/\sqrt{T}$  slope.

**Table 4:** Completeness of different magnitude classes for South Tibet and the Himalaya.

Mw	Complete Year	
	Himalaya	South Tibet
4	15	15
4.5	35	35
5	55	45
5.5	75	75
6	100	100
6.5	200	200
7	300	300
7.5	400	
>8	900	

#### 4.4. Magnitude of completeness

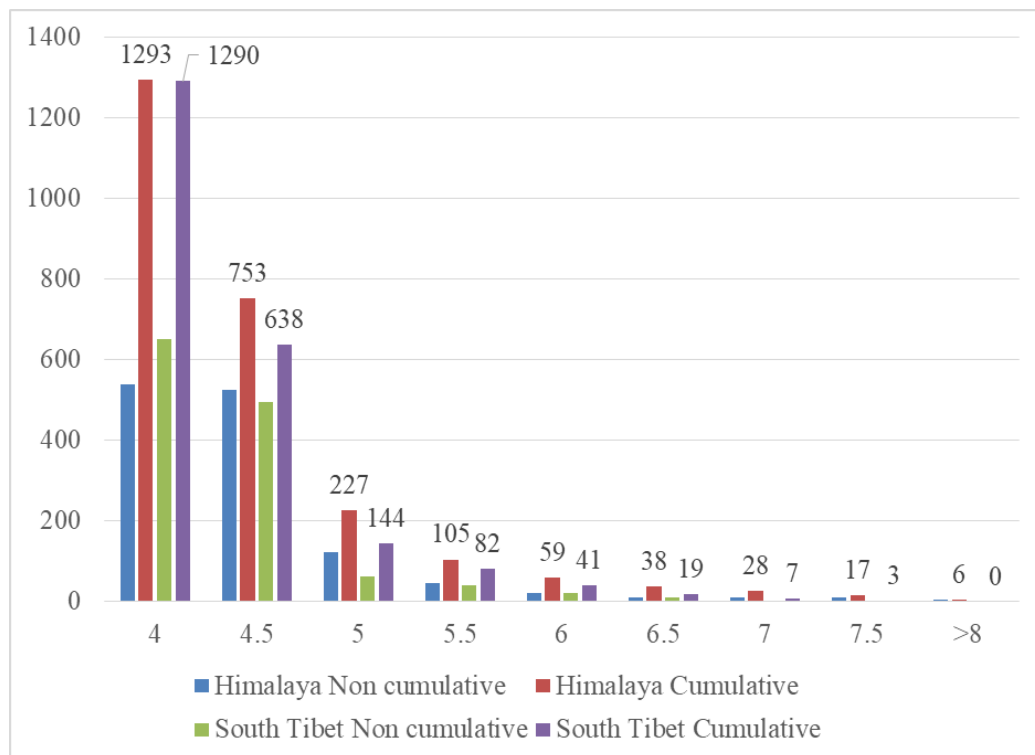
Magnitude of completeness ( $M_c$ ) was estimated, visually, using assumption of self-similarity (Wiemer & Wyss, 2000) from the plot (Figure 41) of cumulative and non-cumulative number of earthquakes of different magnitude classes. In the figure, the non-cumulative curve has a peak at Mw 4.3, which is the  $M_c$  of the catalogue.



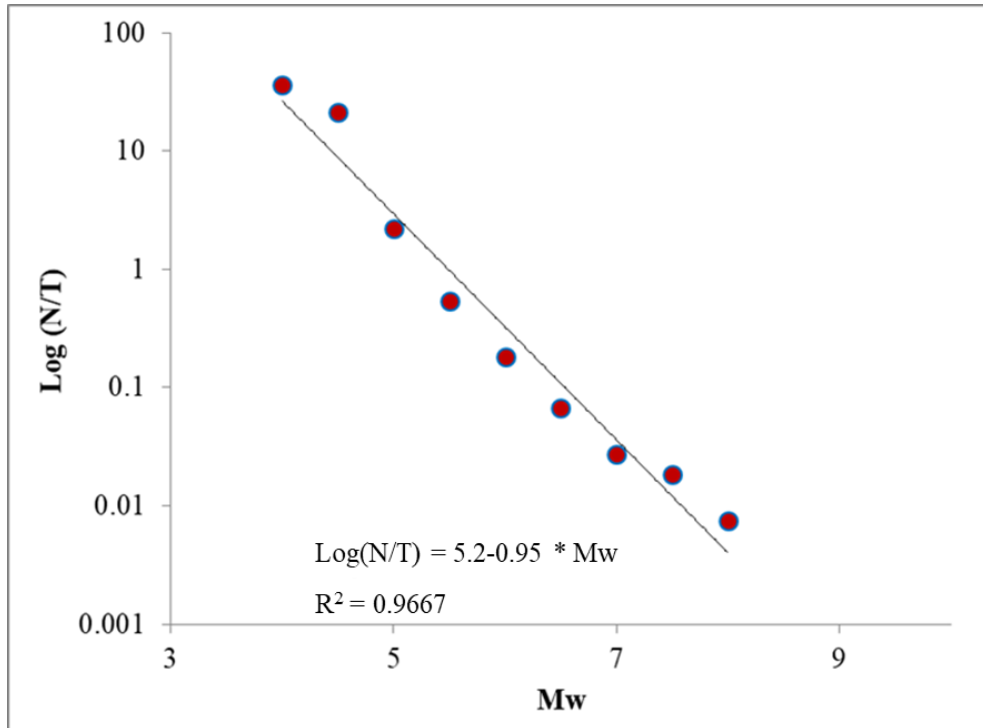
**Figure 41:** Cumulative and non-cumulative frequency of earthquakes in the declustered catalogue. Mw 4.3 has the highest frequency in the catalogue, which is the magnitude of completeness ( $M_c$ ).

#### 4.5. Earthquake recurrence (Gutenberg-Richter) relation for the region

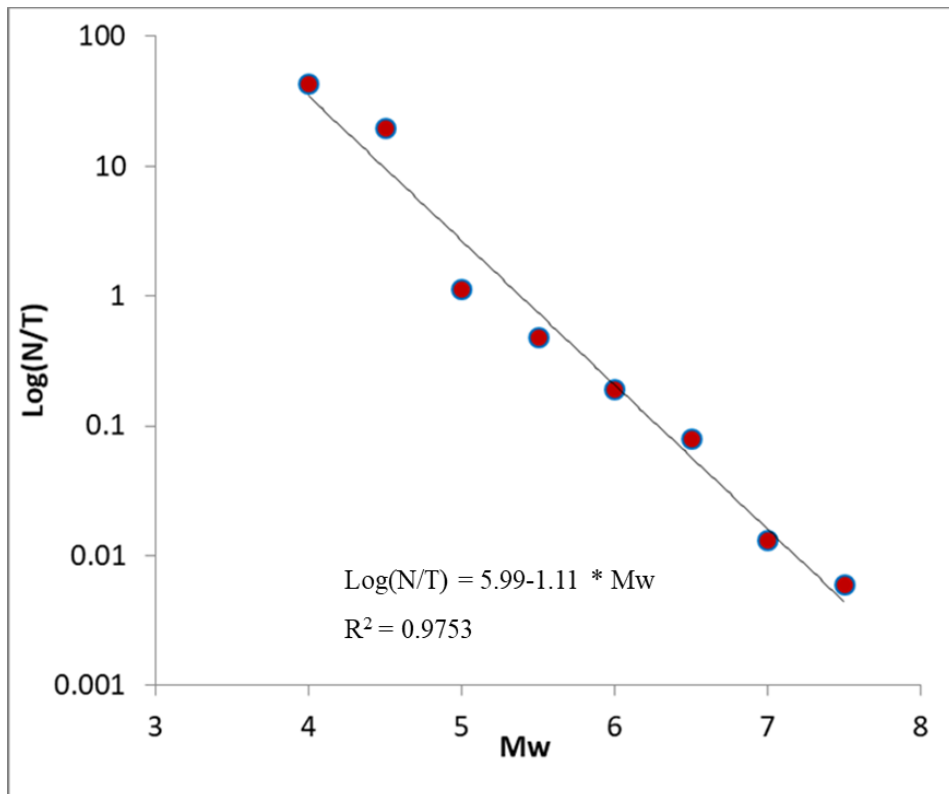
In the Nepal Himalaya, the earthquakes in the south of 3500 m elevation contour line, in majority, are found to occur on account of thrusting, whereas those in the north and above 3500 m contour line occur because mostly of normal faulting (Rajaure *et al.*, 2013). To estimate the recurrence parameters of earthquakes, the prepared composite catalogue was split into two sub-regions (Figure 42) following the mechanism of deformation in the region. The recurrence parameters (seismic parameters: a- and b-values were estimated using Least Square (LS) (Equation 16) and Maximum Likelihood (ML) method (Aki, 1965) (Equation 18) independently. The b-value estimated using LS and ML methods agree well. The Gutenberg-Richter equations using LS method are presented graphically in Figure 43 and Figure 44 for Himalaya and South Tibet, respectively. These figures implicate that large earthquakes are more frequent in the Himalaya than in South Tibet. The b-value for the Himalayan region is  $\sim 0.95$  and South Tibet region is  $\sim 1.1$ , which are very much close to the b-value ( $\sim 1$ ) observed worldwide for converging zones (e.g. Kramer, 2007).



**Figure 42:** Cumulative and non-cumulative number of earthquakes in South Tibet and the Himalayan region.



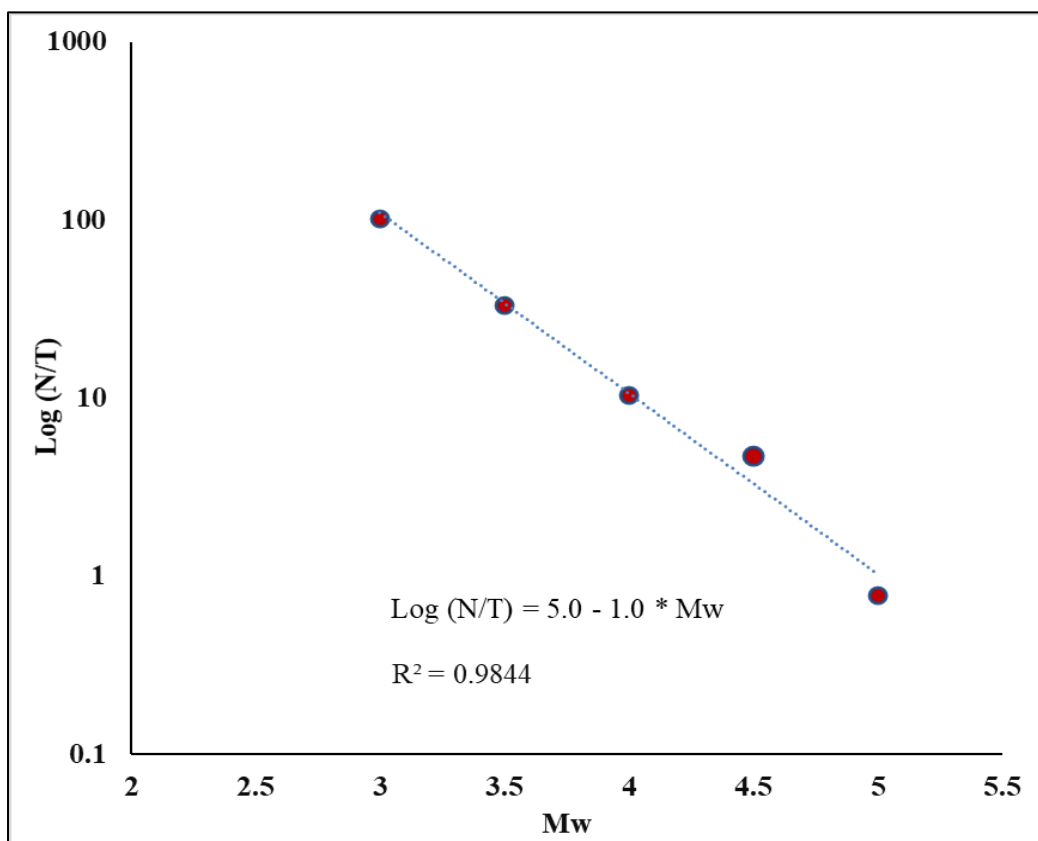
**Figure 43:** Gutenberg-Richter relation for earthquakes in the Himalaya. The dashed straight line represents the best-fit to data. The b-value for the Himalayan region is about 0.95.



**Figure 44:** Gutenberg-Richter relation for earthquakes in South Tibet. The dashed straight line represents the best-fit to data. The b-value for the South-Tibet region is about 1.1.

The DMG earthquake data is available since 1995, which contain earthquake data as low as 2.0  $M_L$  in Nepal. The DMG catalogue reports earthquake size in Local Magnitude ( $M_L$ ). The magnitude was converted into  $M_w$  using Equation (5) (Ader *et al.*, 2012). The earthquake recurrence parameters are estimated for earthquakes in the Nepali territory only because the detection threshold decreases outward from Nepal.

The earthquake recurrence parameters estimated applying LS method to the DMG catalogue is presented in Figure 45. The figure depicts that the b-value ( $\sim 1.0$ ) agrees well with the worldwide observed b-value for such regions (e. g. Kramer, 2007).



**Figure 45:** Gutenberg-Richter relation curve for Nepal using DMG catalogue. The b-value is about 1.0 for the Nepal Himalaya.

## 4.6. Seismic hazard analysis

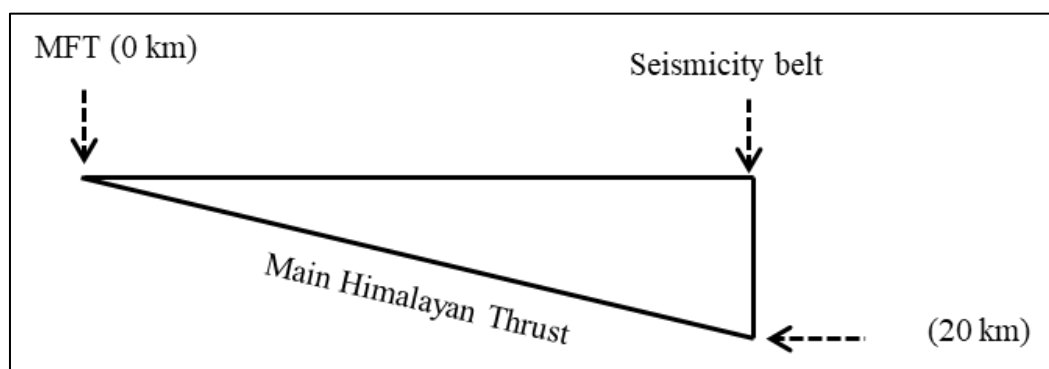
### 4.6.1. Seismic source zones

The Main Himalayan Thrust (MHT) is the major source of seismic hazard in Nepal. There are two schools of thoughts regarding the size of rupture of the MHT. One considers earthquakes of maximum magnitude up to 9.0 may occur, similar to the

2004 Indonesia Earthquake (e. g. Bilham & Wallace, 2005; Kumar *et al.*, 2010; Ader *et al.*, 2012; Stevens and Avouac, 2016; Stevens & Avouac, 2017) and the other considers the maximum potential magnitude, possibly, do not exceed Mw 8.5 and the results of paleoseismic investigations are exaggerated (e. g. Valdiya, 1976; Gahalaut and Arora (2014), Gahalaut & Kundu, 2011; Dasgupta *et al.*, 2012; Srivastava *et al.*, 2013; Mugneier *et al.*, 2016; Hubbard *et al.*, 2016). In this study, the second school of thought was considered in seismic source delineation.

Potential earthquake sources were identified and delineated after the analysis of the prepared comprehensive earthquake catalogue, impact of 2015 Gorkha Earthquake, lateral variation in seismicity pattern (Appendix 4) and geological structures (Appendix 8). Similarly, presence of subsurface ridges in north India, tectonics of the region (Appendix 9), and segments proposed by Bilham (2019) (Appendix 10) also were considered in the identification and delineation earthquake sources.

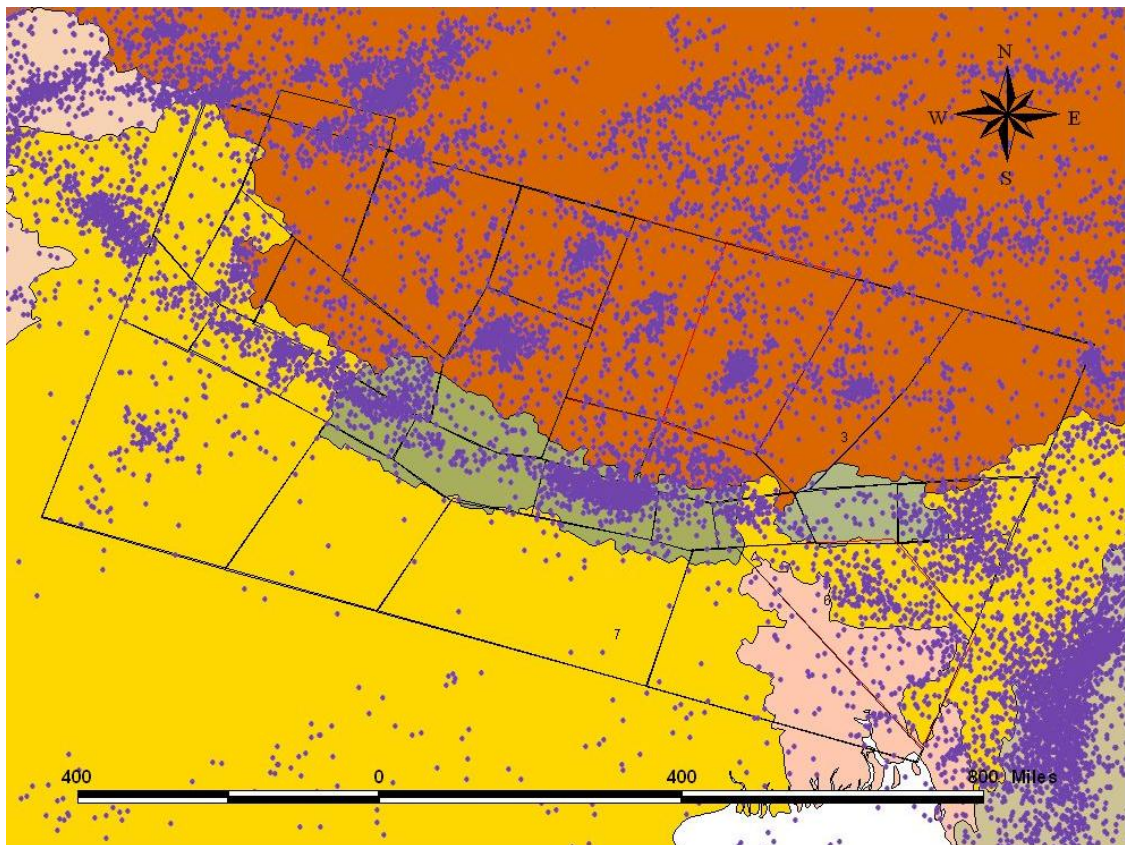
There are several linear sources (faults) in the Nepal Himalaya. However, many of them have not been found to be associated with current seismicity (e.g. Pandey *et al.*, 1999; Rajaure *et al.*, 2013) and, therefore, have not been considered in this study. Altogether nine sets of source models (Appendix 11) were identified and delineated. The sources, which are segments of the MHT, are three-dimensional faults. These sources emerge to the surface along the MHT (Depth = 0 km) and deep to a depth of about 20 km in the north (Figure 46). The depth in the north was adopted from the average depth of earthquakes occurring on the seismicity belt (Pandey *et al.*, 1999, Torre *et al.* 2007, Sheehan A. F. 2008 and Rajaure *et al.* 2013).



**Figure 46:** Geometry of earthquake sources along the Himalaya. The sources are three dimensional area planar sources, which are segments of the MHT.

The depth of sources in South Tibet, which have normal faulting mechanism, have a fixed depth of 10 km. This depth has been adopted from the depth of fault plane solutions of earthquakes in the region (e. g. Torre *et al.*, 2007; Sheehan A. F. 2008 and Rajaure *et al.* 2013). Similarly, the depth of earthquakes in the north-east of Nepal, in South Tibet, have been given a fixed depth of 50 km because the depth of foci of earthquakes in this region are greater than 50 km (e. g. Torre *et al.*, 2007; Sheehan *et al.*, 2008; Rajaure *et al.*, 2013). Similarly, the depth of sources in Northern India (in the south of Nepal) is not known well; therefore, the depth was fixed to 35 km that corresponds to the depth of Mohorovicic Discontinuity in continental regions (e. g. Rai *et al.*, 2006, Sheehan *et al.*, 2008; Nabelek *et al.*, 2009).

An example of source delineation (Model 9) based on seismicity is presented in Figure 47. The polygons in Figure 47 are the identified potential earthquake sources in Model 9.



**Figure 47:** An example of identification and delineation of seismogenic sources (polygons) in and around Nepal based on seismicity pattern (Appendix 11-9).

A test was carried out to check the influence of depth in seismic hazard, keeping source model, attenuation relation and earthquake recurrence parameter same. The



variation in seismic hazard with the variation of depth of the sources along the Himalaya (segments of MHT) are presented in Appendix 12. The geometry of the MHT has been found to have small influence on the seismic hazard.

#### 4.6.2. Maximum potential magnitude

The maximum potential magnitudes of earthquake sources along the Himalaya (i.e. MHT) were calculated using empirical relations derived by Wells and Coppersmith (1994). The relations were derived using rupture area, rupture length and displacement and their respective observed magnitudes. The maximum potential magnitude of earthquake sources in South Tibet and north India were fixed because we don't have the history of very large earthquakes in those areas. The summary of the magnitude characterization for different source models is given in Table 5. Details of the magnitude characterization are given in Appendix 13.

**Table 5:** Summary of magnitude characterization in the study area.

Source model	No. of sources	Min. magnitude	Max. magnitude
1	7	8.0	8.2
2	7	7.5	7.9
3	7	7.5	7.8
4	22	7.5	8.4
5	23	7.5	8.5
6	25	7.5	8.3
7	17	7.5	8.4
8	19	7.5	8.4
9	26	7.5	8.4

Maximum potential magnitude is an important factor in seismic hazard assessment, because overestimation or underestimation might lead to overestimation or underestimation of the results. A test was carried out to check how the seismic hazard varies with different maximum potential magnitudes of sources (Keeping source model (Appendix 11-1), attenuation relation and earthquake recurrence parameters same), the results are presented in Appendix 14 and Table 6.

**Table 6:** Variation in PGA with variation in maximum potential magnitude ( $M_{w_{max}}$ )

$M_{w_{max}}$	PGA (g)
6.5	0.35
7	0.4
7.5	0.45
8	0.5
8.5	0.55

### 4.6.3. Earthquake recurrence parameters of identified sources

Earthquake recurrence parameters of the identified sources were estimated from the prepared catalogue. The b-values were adopted from Figure 43 and Figure 44, which were estimated for the Himalaya and South Tibet respectively, because some of the sources have insufficient data to derive recurrence parameters independently. The a-values of the identified earthquake sources were recalculated from the data of each source zone using Equation 26 using the ‘b-value’ from Figure 43 and Figure 44. The earthquake recurrence parameters of the source models are presented in Appendix 15.

$$a = \log\left(\frac{N}{T}\right) + b * Mc \quad \text{Equation 26}$$

Where 'a' is the a-value, 'N' is the number of earthquake, 'T' is the time of record in years, 'b' is b-value, and Mc is the magnitude of completeness.

Precise earthquake recurrence parameters are very important in seismic hazard calculation because a small error may result in seismic hazard by manifold. A test was carried out to check the influence of b-value on seismic hazard keeping other parameters same. Different b-values ranging from 0.7 to 1.2 were applied to a common source model and common attenuation relation. The variation in seismic hazard with the variation in b-value is presented in Appendix 16. The largest PGA varies from 0.75 g to 0.25 g respectively for the b-values from 0.7 to 1.2 (Table7).

**Table 7:** A comparison of largest PGA (10% probability of exceedance in 50 years) in Nepal and Kathmandu valley estimated from different b-values ranging from 0.7 to 1.2. The a-values were recalculated using fixed b-values and the earthquake catalogue. .

b-value	Largest PGA (g)	
	Nepal	KTM Valley
0.7	0.75	0.6
0.8	0.6	0.5
0.9	0.5	0.45
1	0.4	0.35
1.1	0.35	0.3
1.2	0.3	0.25

### 4.7. Assessment of seismic hazard

Seismic hazard was analyzed comparatively using different datasets, different attenuation relations and different source models. Three datasets, two types of attenuation relations each comprising four attenuation relation for tectonically

different regions and nine source models were used in this assessment, which are described in the following sections.

#### 4.7.1. Different datasets

Different datasets were used to investigate their influence on PGA. Three datasets, which contain earthquakes (i) since 1900 AD (2) since 1100 AD and (3) since 1964AD were, separately, utilized to estimate earthquake recurrence parameters. The first set, contains instrumentally recorded earthquakes only; the second one contains instrumentally recorded as well as historically reported earthquakes; whereas the third set contains earthquakes since 1964. The third set was used because the detection threshold of earthquakes decreased to magnitude 4 on account of expansion of existing networks and establishment of numerous networks globally. The variation in PGA was studied using a common source model (Appendix 11-1), a common attenuation relation (Atkinson, Silva & Kamai, 2014) and common earthquake recurrence parameters (a- and b-values) derived from above mentioned three sets of data. The variation in PGA are graphically presented in Appendix (17) and summarized in Table 8. The result (Table 8) depicts the influence of the datasets on the result. The dataset containing earthquakes since 1900 results in smaller PGA in comparison to the other two.

**Table 8:** Maximum PGA (10% probability of exceedance in 50 years) in Nepal and Kathmandu Valley calculated using different catalogues. A common attenuation relation (Atkinson, Silva & Kamai, 2014), a common source model (Model-1, Appendix 11-1) and different a- and b-values were used for this comparative study.

Largest PGA (g)					
Region	Earthquake catalogue				
	Since 1900		Since 1100		Since 1964 fixed b-value (0.95) and recalculated a-value
	calculated a- and b-value	fixed b-value (0.95) and recalculated a- value	Calculated a- and b-value	fixed b-value (0.95) and recalculated a- value	
Nepal	0.35	0.5	0.45	0.45	0.55
KTM	0.3	0.3	0.45	0.4	0.4

#### 4.7.2. Different attenuation relations

For calculation of ground motion (PGA), two types of attenuation relations, one for subduction zone (Appendix 18-1) and the other for active-shallow-crustal (reverse) earthquakes (Appendix 18-2) were used. The seismic hazard maps prepared using different attenuation relations are presented in Appendix 19 and Table 9 for a comparison. Atkinson & Boore (2003) relation produces unrealistically very small PGA in comparison to others, therefore, it is not considered in further calculations. On the other hand, the Youngs *et al.* (1997) attenuation model produces the largest PGA (0.75 g).

**Table 9:** Maximum PGA (10% probability of exceedance in 50 years) in Nepal and Kathmandu Valley calculated using different attenuation relations. The Atkinson & Boore (2003) relation produces extremely low PGA, whereas the Youngs *et al.* (1997) relation produces the largest PGA. In comparison to the relations for subduction zones, the relations for active-shallow-crustal earthquakes give consistent PGAs.

Attenuation Relation	PGA (g)		Tectonic region
	Maximum	KTM Valley	
Zhao <i>et al.</i> (2006)	0.55	0.35	Subduction Zone
Youngs <i>et al.</i> (1997)	0.85	0.6	
BcHydro (2016)	0.45	0.25	
Atkinson and Boore (2003)	0.18	0.14	
Arroyo and Singh (2017)	0.28	0.2	
Abrahamson, Silva and Kamai (2014)	0.55	0.4	Active Shallow Crustal
Boore <i>et al.</i> (2014)	0.55	0.4	
Chiou and Youngs (2014)	0.55	0.35	
Campbell and Bozorgnia (2014)	0.55	0.35	

#### 4.7.3. Different source models

Nine source models (Appendix 11-1 to Appendix 11-9) were used to calculate seismic hazard keeping earthquake recurrence parameters and attenuation relation same as in previous tests. The source models consider three types of ruptures scenario of the MHT. The first type considers entire north-south rupture of MHT, from the boundary between locked part in south (up to the surface exposure of MFT) and the boundary between currently locked part of MHT and aseismically creeping part in the north. This type of rupture (e. g. Appendix 11-1) was considered following the reports of entire N-S rupture (e.g. 1100 (Yule *et al.*, 2005), 1255 (Sapkota *et al.*, 2013), 1505 (Yule *et al.*, 2006) and 1934 (Sapkota *et al.*, 2013)). In the second type of s, the

northern half (rupture) of the MHT was considered. Such rupture is represented, for example, by Model 2 (Appendix 11-2), which was considered following the rupture of the 2015 Gorkha Earthquake (Mw 7.8) and possibly the 1833 earthquake (Mw 7.6) also ruptured the northern part of MHT. The third type of rupture considers the southern part of the MHT that did not rupture during the 2015 Gorkha Earthquake (Appendix 11-3). Results from these three source models are graphically presented in Appendix 20-1, Appendix 20-2 and Appendix 20-3 respectively and in Table 10. Model 1, 2 and 3 (Appendix 11-1, 11-2 and 11-3) were used for a comparative study only, which were not considered in the final calculations as they do not consider other earthquake sources in the adjoining region.

The seismic hazard maps prepared from above mentioned nine source models are presented in Appendix 20 for a comparison.

**Table 10:** A comparison of PGA (10% probability of exceedance in 50 years) in Nepal and the Kathmandu Valley, calculated using different source models.. The comparison shows approximately comparable result except for Model 3, which is the southern half rupture scenario of the MHT.

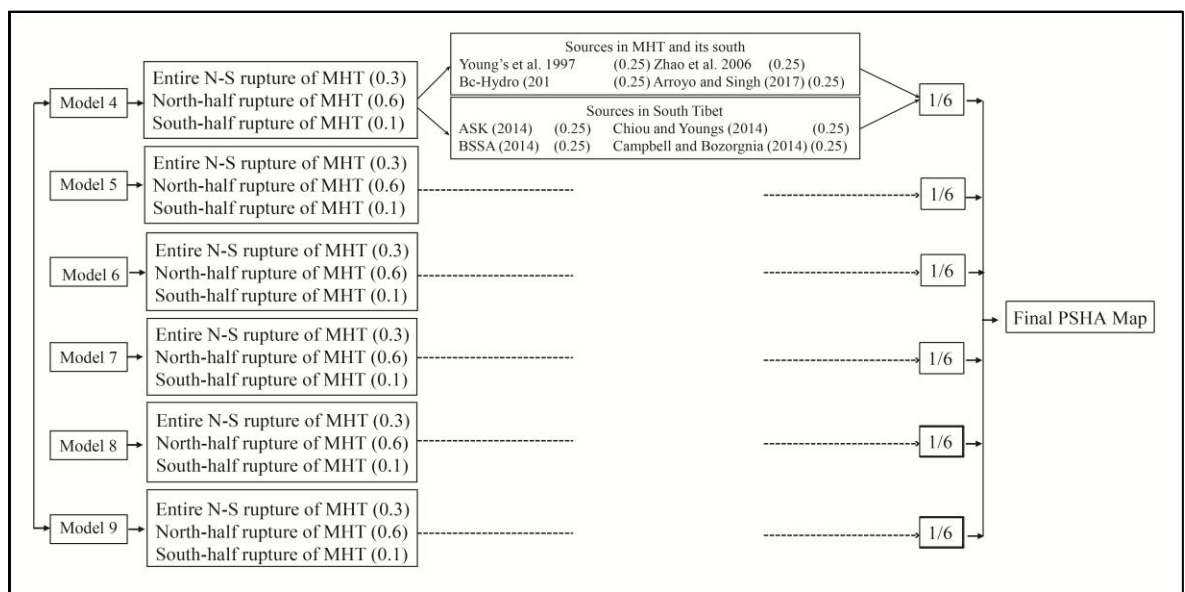
Source Model	PGA (g)		Source region
	Nepal	KTM Valley	
Model-1	0.55	0.4	Himalaya only
Model-2	0.5	0.4	
Model-3	0.7	0.25	
Model-4	0.55	0.4	Himalaya as well as Surrounding
Model-5	0.4	0.4	
Model-6	0.55	0.4	
Model-7	0.45	0.35	
Model-8	0.5	0.3	
Model-9	0.55	0.45	

#### 4.8. Seismic hazard map

Seismic hazard maps have been prepared for five different return periods (approximately 500 year, 1000 year, 2500 year, 5000 year and 10000 year). The seismic hazard maps have been prepared using a logic tree (Figure 48). The logic tree was applied to incorporate uncertainties in earthquake source model, maximum potential magnitude, attenuation relations and ruptures of MHT. Six source models (Appendix 11-4 to Appendix 11-9), two types of attenuation relations (Appendix 18-1 and Appendix 18-2) and three types of rupture scenarios of the MHT (Appendix 11-1,

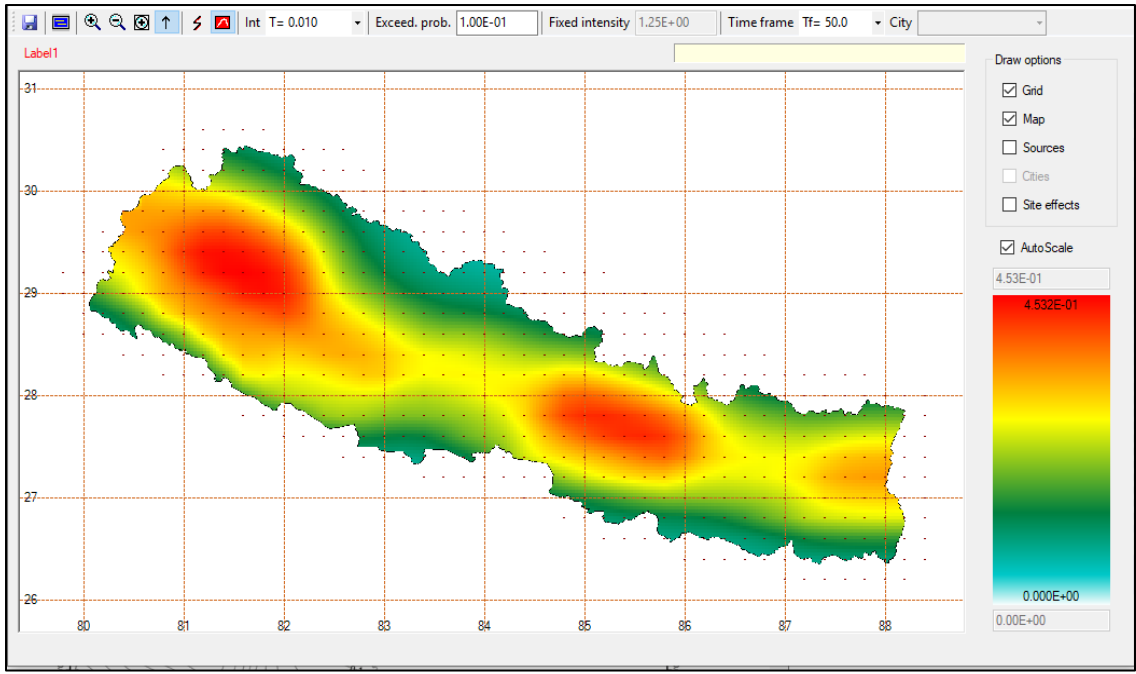
Appendix 11-2 and Appendix 11-3) were utilized to produce seismic hazard maps. The subduction type attenuation relations (Appendix 18-1) were applied to earthquake sources which fall in the MHT and its adjoining region in the south. The second type of attenuation relations (Appendix 18-2) were applied to sources in South Tibet.

Figure 49 is an example of seismic hazard map prepared by R-CRISIS software. The map corresponds to 10% probability of exceedance in 50 years (approximately 500 year return period). The data calculated by R-CRISIS (latitude, longitude and PGA in three columns), at every 20 km, spacing was used to produce Figure 50 utilizing ArcGIS.

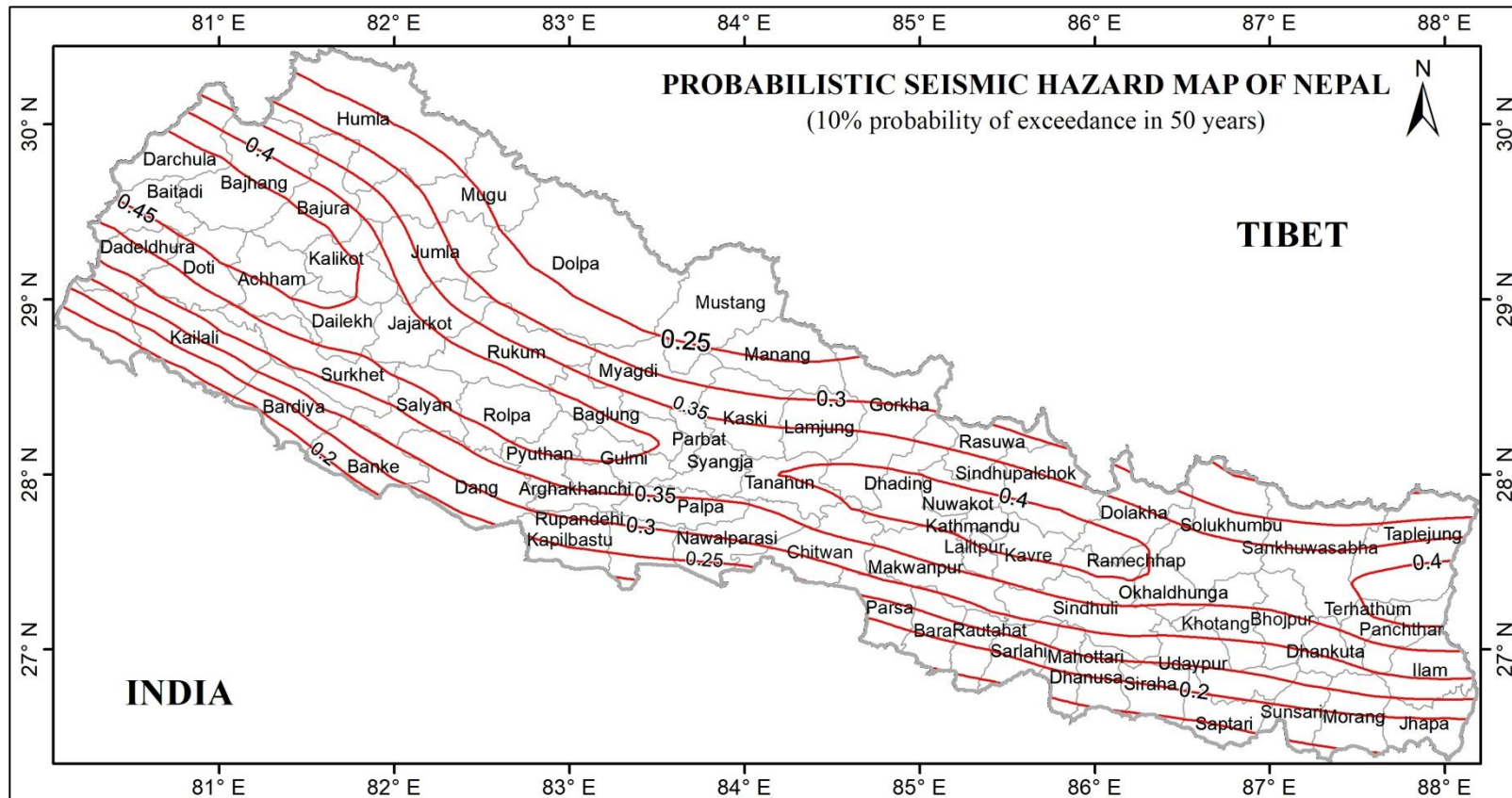


**Figure 48:** Logic Tree used to prepare final seismic hazard maps.

The peak ground acceleration (PGA) in major towns of different parts of Nepal are presented in Table 11.



**Figure 49:** Seismic hazard map (10% probability of exceedance in 50 years) prepared utilizing R-Crisis. The maximum PGA is about 0.45 g in Far-west Nepal.



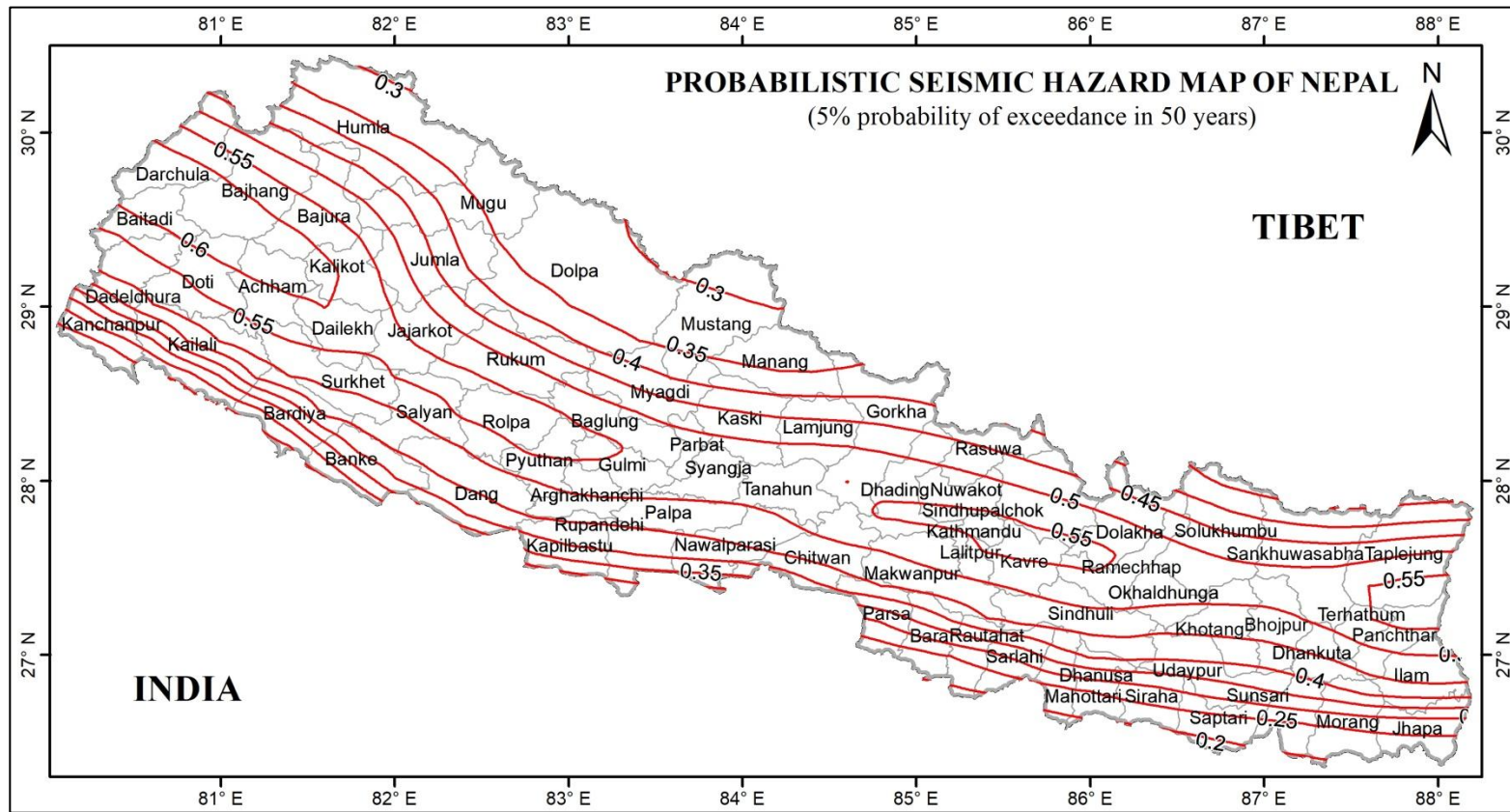
**Figure 50:** Seismic hazard map of Nepal for 500 year return period (10% probability of exceedance in 50 years) for an engineering rock site condition. The largest PGA (0.45 g) is estimated in the far-west Nepal.



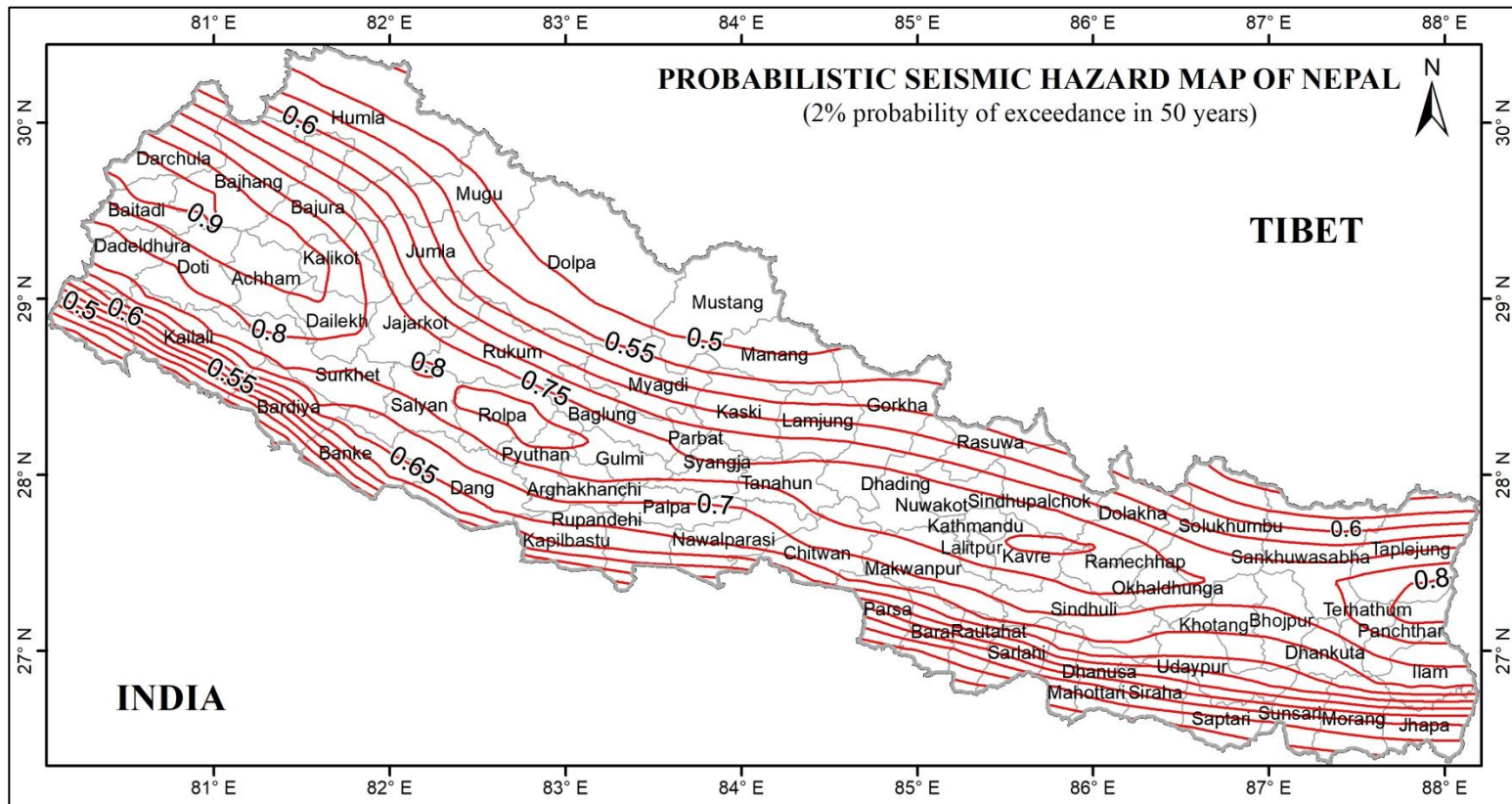
**Table 11:** PGA estimated for major cities of Nepal. The PGA values correspond to 10% probability of exceedance in 50 years for engineering rock site condition.

Place	Latitude (°E)	Latitude (°N)	PGA (g)
Baglung	83.600	28.266	0.370
Bajhang	81.199	29.550	0.470
Bhairahawa	83.450	27.500	0.230
Biratnagar	87.283	26.467	0.150
Birgunj	84.867	27.017	0.160
Chaurjhari	82.193	28.626	0.420
Dadheldhura	80.567	29.300	0.400
Darchula	80.764	29.872	0.466
Dhankuta	87.340	26.970	0.300
Dipayal	80.930	29.243	0.448
Dunai	82.900	28.933	0.280
Gorkha	84.629	28.000	0.410
Hilsa	81.334	30.151	0.290
Ilam	87.910	26.910	0.330
Janakpur	85.917	26.733	0.160
Jiri	86.229	27.628	0.400
Jomsom	83.730	28.783	0.240
Jumla	82.193	29.274	0.320
Kathmandu	85.317	27.700	0.410
Mahendranagar	80.300	28.967	0.240
Mugu	82.085	29.502	0.330
Nepalgunj	81.617	28.067	0.200
Palpa	83.550	27.866	0.350
Pokhara	83.983	28.217	0.370
Pyuthan	82.853	28.101	0.400
Salyan	82.161	28.375	0.380
Simikot	81.819	29.968	0.270
Surkhet	81.600	28.600	0.360
Taplejung	87.650	27.370	0.410
Tumlingtar	87.193	27.314	0.370

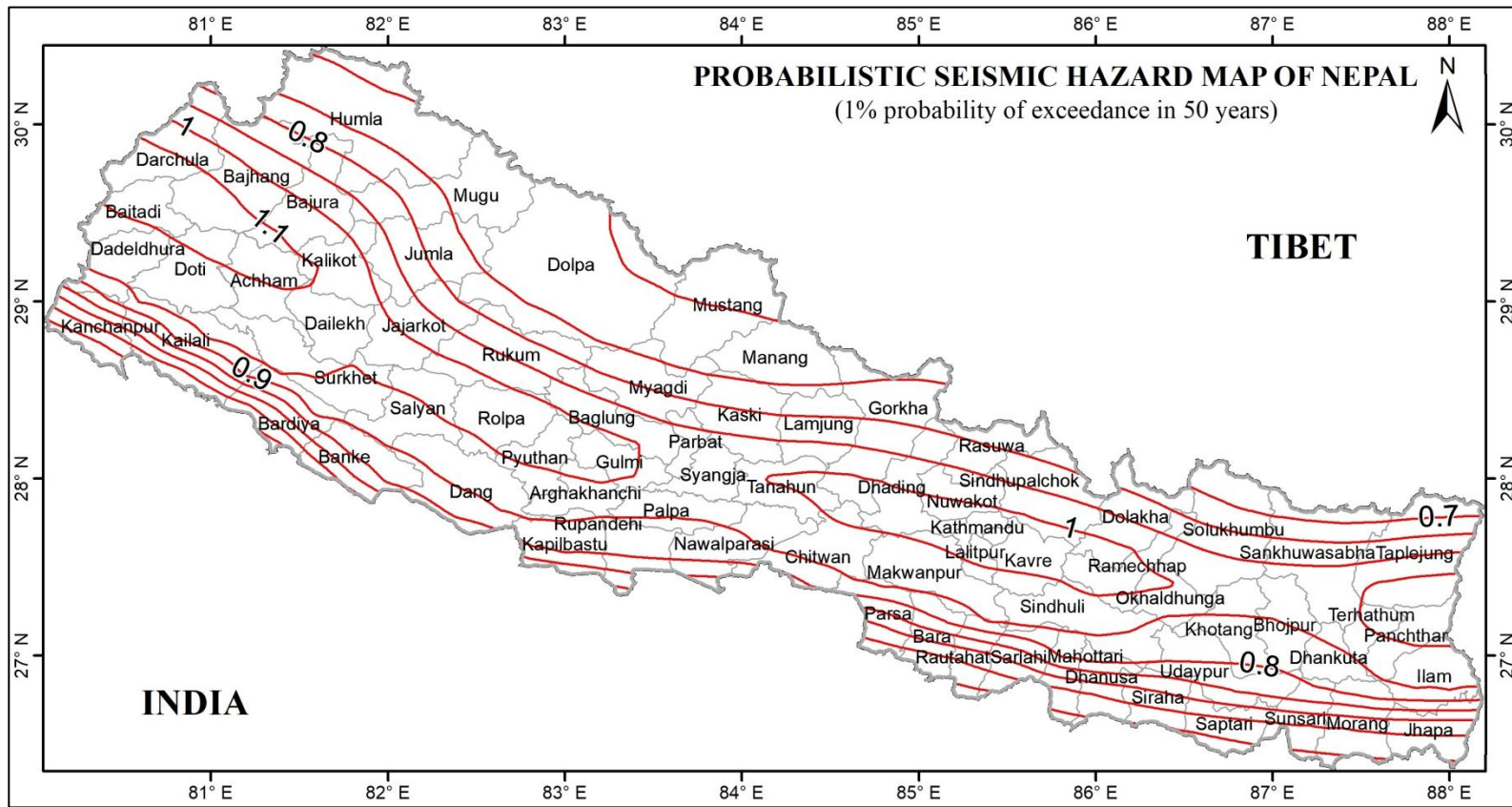
Seismic hazard map corresponding to 10% probability of exceedance in 50 years (500 year return period) is commonly used in building codes. In addition to the seismic hazard map for a 500 year return period, four additional seismic hazard maps are prepared for 1000 year (Figure 51), 2500 year (Figure 52), 5000 year (Figure 53) and 10000 year (Figure 54) return period.



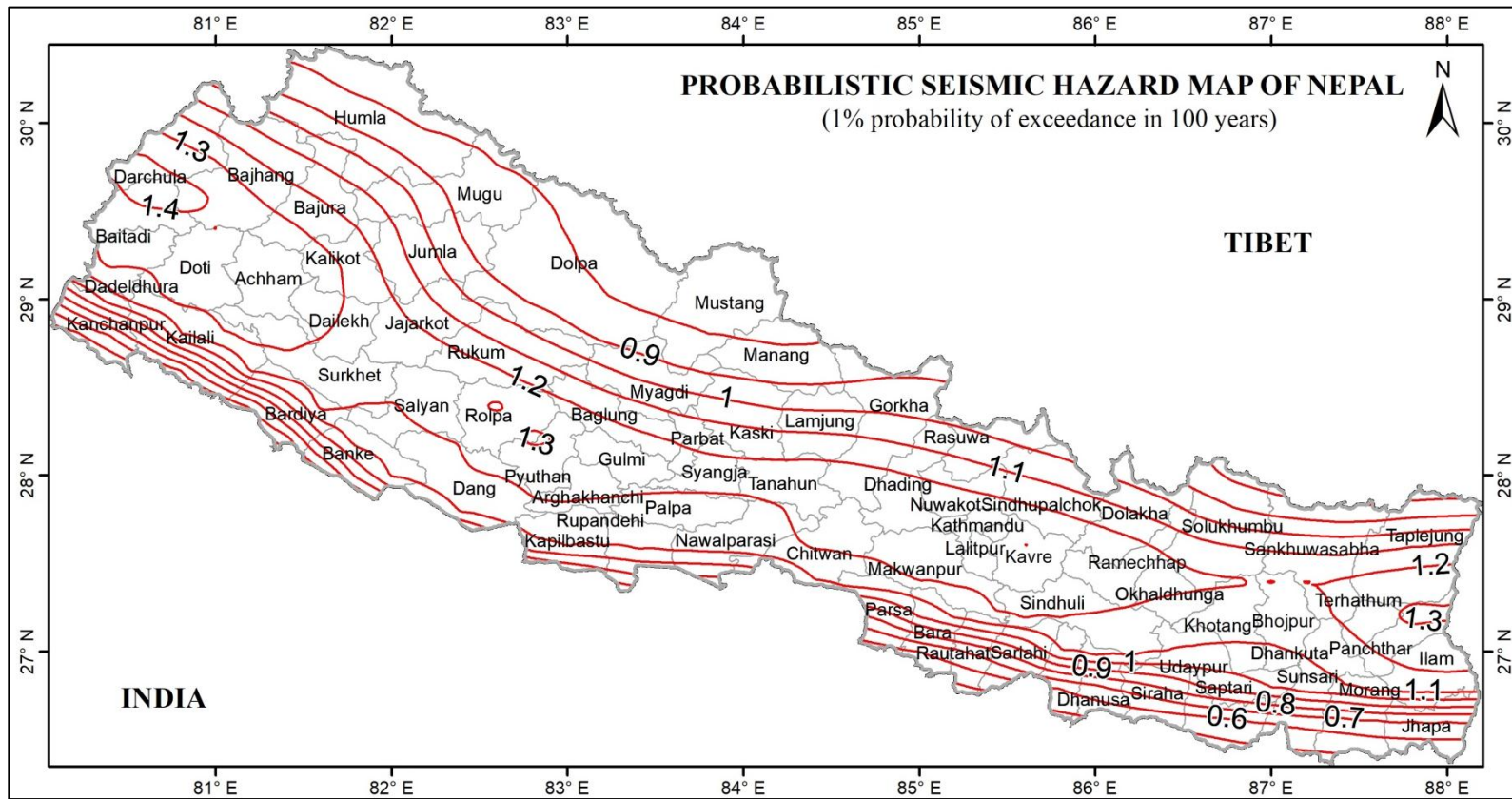
**Figure 51:** Seismic hazard map of Nepal for 1000 year return period (5% probability of exceedance in 50 years) for an engineering rock site condition. The largest PGA (0.6 g) is estimated in the far-west Nepal.



**Figure 52:** Seismic hazard map of Nepal for 2500 year return period (2% probability of exceedance in 50 years) for an engineering rock site condition. The largest PGA (0.9 g) is estimated in the far-west Nepal.



**Figure 53:** Seismic hazard map of Nepal for 5000 year return period (1% probability of exceedance in 50 years) for an engineering rock site condition. The largest PGA (1.1 g) is estimated in the far-west Nepal.



**Figure 54:** Seismic hazard map of Nepal for 10000 year return period (1 % probability of exceedance in 100 years) for an engineering rock site condition. The largest PGA (1.4 g) is estimated in the far-west Nepal.

#### 4.9. Ground response of the Kathmandu valley sediments

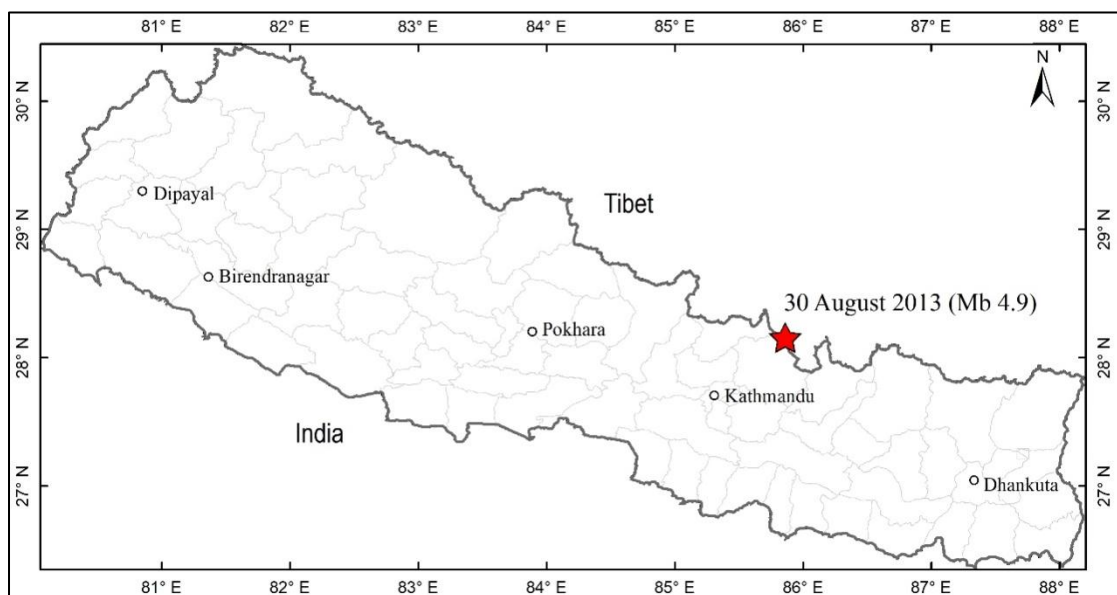
The seismic hazard map presented in Figure 50 is for an engineering rock site, where the shear wave velocity is about 760 m/s or larger. Earthquake ground motions are influenced by local geology and topography. Topographic effect is beyond the scope of this research and an attempt has been made to investigate the response of local geology to seismic ground motion. The required data for ground response analysis is available in Kathmandu valley only.

The response of the Kathmandu Valley sediments to recently recorded earthquakes in the valley is described in the following sections.

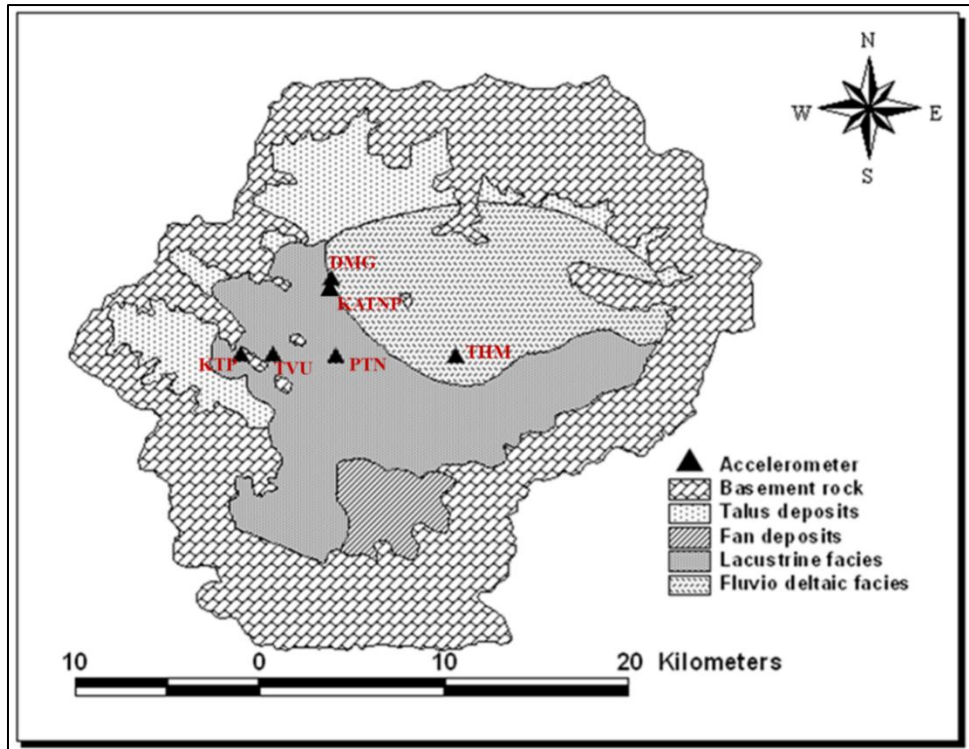
##### 4.9.1. 2013 August 30, south Tibet Earthquake

An Mb 4.9 earthquake occurred in South Tibet (Figure 55), which was felt in Kathmandu and its adjoining region. The ground acceleration of the earthquake was recorded by accelerometers at five sites KTP, TVU, PTN, THM and DMG (Figure 56), which was used in this study. Among the five sites, KTP is a rock site, installed in Kirtipur, and the others are soil sites.

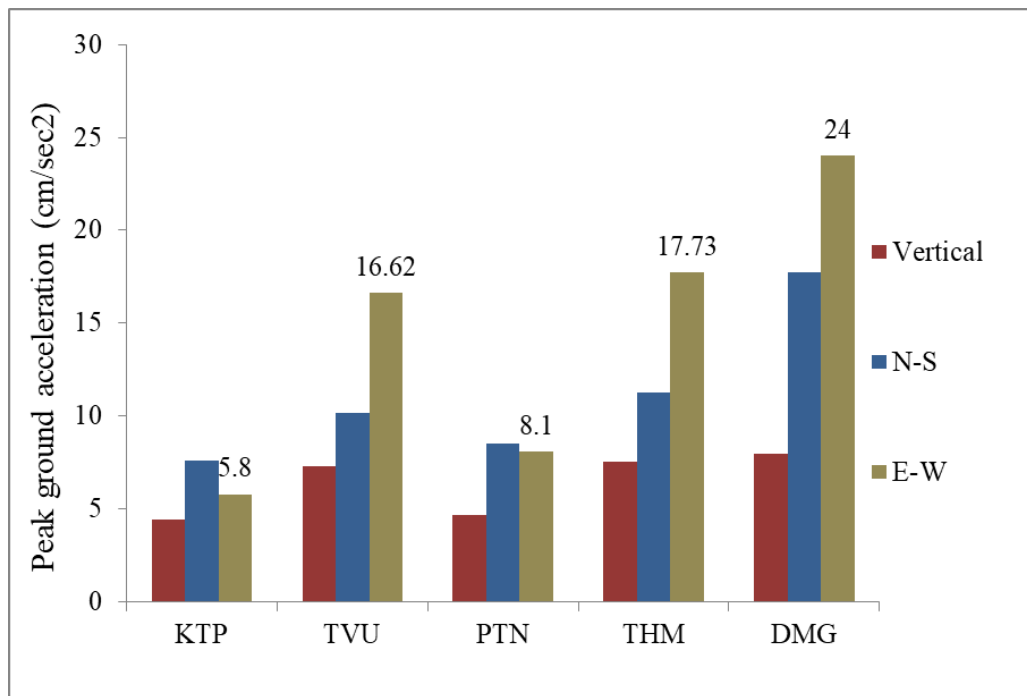
Analysis of the ground acceleration record reveals that that the EW component was dominant across the valley except for at PTN. The other stations on sediments recorded PGA much higher than at the rock site (Figure 57).



**Figure 55:** Location of the 2013 August 30 South Tibet Earthquake (Mb 4.9).

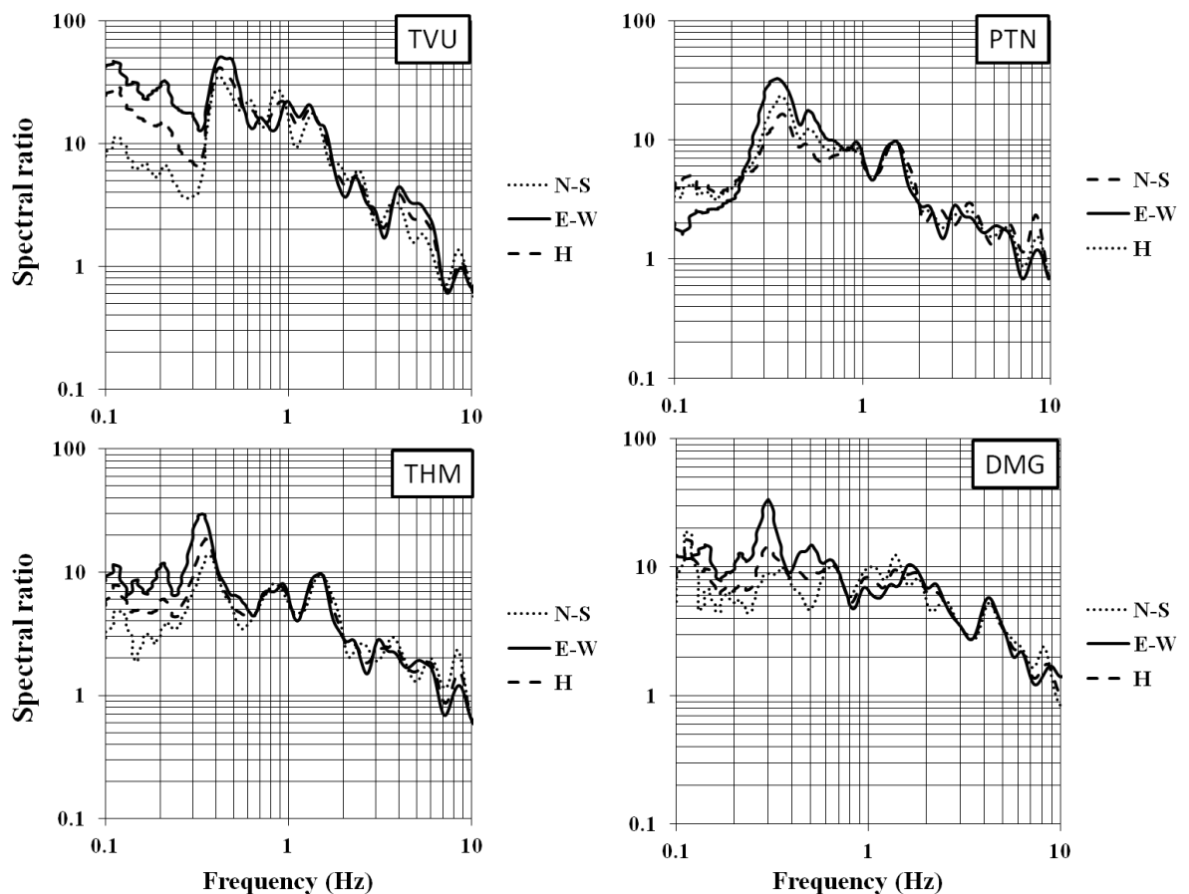


**Figure 56:** Location of the strong motion stations. KTP is a rock site and others are soil sites. The maximum PGA was recorded at DMG. (KTP: Kirtipur (rock site); TVU: Tribhuvan University, Central Department of Geology; PTN: Pulchowk Engineering Campus; THM: Sanothimi, University Grant Commission; DMG: Department of Mines and Geology; KATNP: Kantipath).



**Figure 57:** Peak ground acceleration (cm/sec<sup>2</sup>) recorded at five sites. DMG, which is a soil site, has recorded the largest PGA.

The site response functions were evaluated as the Fourier spectral ratios of the horizontal components on soil relative to the corresponding component on rock (Figure 58). The functions are remarkably similar in the low frequency range (<0.8 Hz) and reveal strong amplification that is possibly caused by basin effects. By contrast, the high frequency site response shows strong variability across the soil sites, which can be attributed to the underlying stratigraphy of the deeper and shallow soil layers of the valley. The most pronounced differences manifest in the frequency range > 2 Hz, which is consistent with the variability in PGA across the valley.

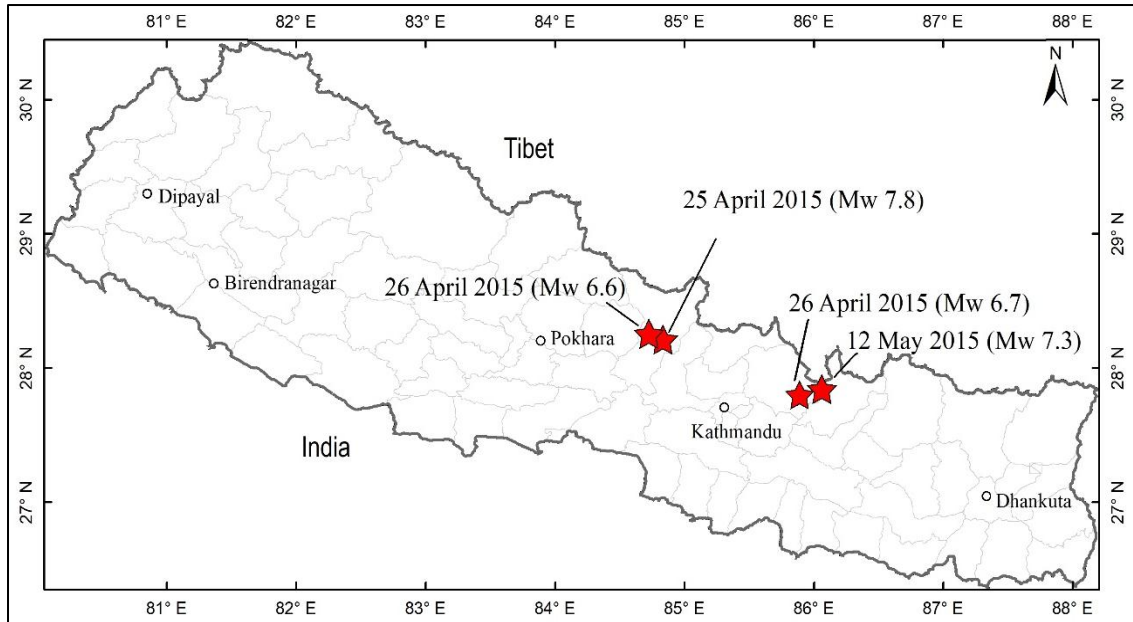


**Figure 58:** Spectral ratio at four soil sites relative to a rock site (KTP) (Rajaure *et al.*, 2014).

#### 4.9.2. April 25, 2015 Gorkha earthquake sequence

The Gorkha Earthquake occurred on 25<sup>th</sup> April of 2015. It rocked a large area in Nepal as well as the adjoining region in India and China. The Gorkha Earthquake and its three strong aftershocks ( $M_w > 6.5$ ) (Figure 59) were well recorded (Figure 60) by accelerometers deployed in Kathmandu sedimentary basin (Figure 56).





**Figure 59:** Location of four earthquakes, the strong motion records of which were utilized in this study.

Strong motion (ground acceleration) data (Figure 60) of Gorkha Earthquake and its three strong aftershocks (Figure 59; Table 12) were used to investigate response of the site to seismic ground motion.

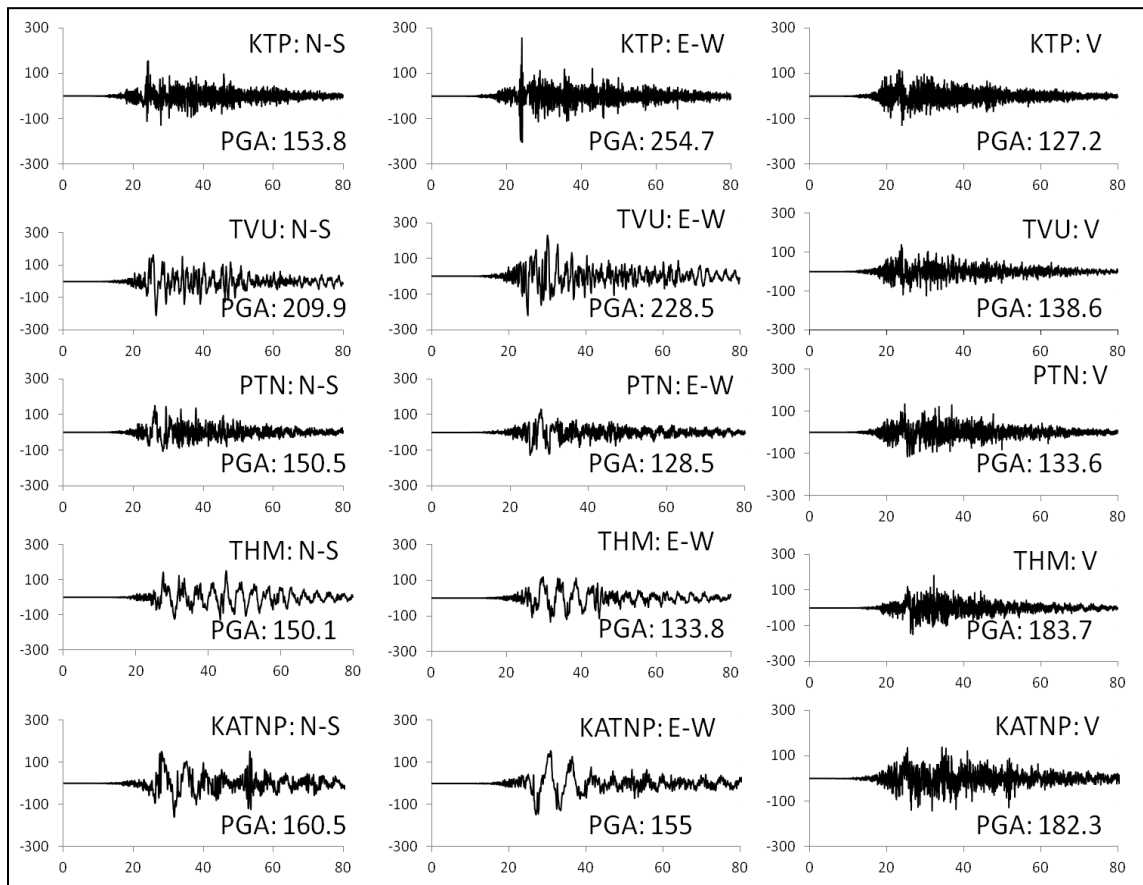
**Table 12:** List of Gorkha Earthquake and its strong aftershocks, which were used in this study.

Date	Mw	Latitude (°N)	Longitude (°E)
25 April 2015	7.8	28.13	84.71
25 April 2015	6.6	28.16	84.84
26 April 2015	6.7	27.73	85.97
12 May 2015	7.3	27.80	86.12

The signals were high passed at 0.1 Hz using fourth order Butterworth filter. This approach produces the maximized spectrum defined as the maximum amplitude of shaking at a given frequency in the horizontal plane, eliminates the need to rotate the component, and produces results similar to the standard averaging methods. Then, soil-to-bedrock amplification ratios of the soil sites relative to the reference (rock site) station for all four events are calculated.

The records depict that, the PGAs were smaller (Table 13, Figure 61) than expected, however the velocity were relatively large (Figure 62).

Figure 63 shows the Fourier spectrum of the data and it's very clear that the high frequencies ( $> 1.0$  Hz) are strongly damped at all the sites. The predominant period of the ground motion at soil sites varies between 3 and 5 s. The rock site (KTP) is dominated by high frequency energy, whereas the soil sites are dominated by low frequency energy (Figures 60 and Figure 63).



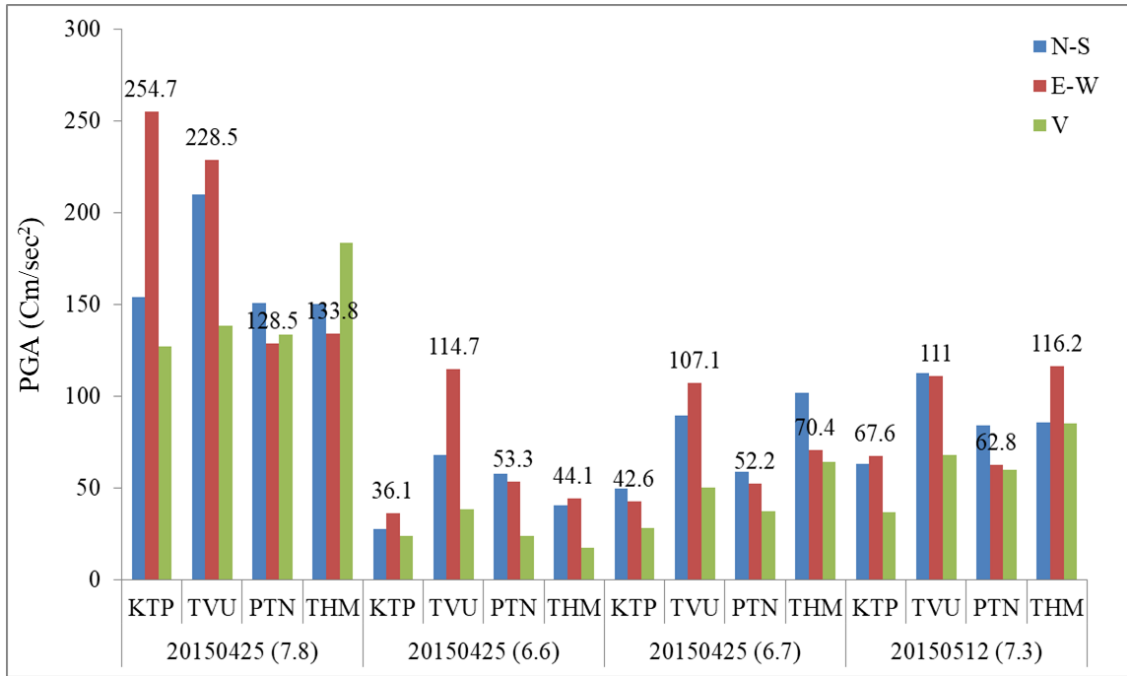
**Figure 60:** Acceleration time history recorded at five sites. KTP is a rock site and other are soil sites. E-W, N-S and V stand for east-west, north-south and vertical components. The maximum PGA is recorded by KTP (E-W component) (Rajaure *et al.*, 2017).

Peak ground acceleration is a high frequency characteristic of ground motion, which is an important parameter to rigid structures (small story structures). During the Gorkha Earthquake, the high frequencies were damped and therefore majority of the small story structures survived the ground shaking. On the other hand, the peak ground velocity is a low frequency characteristic of ground motion and is an

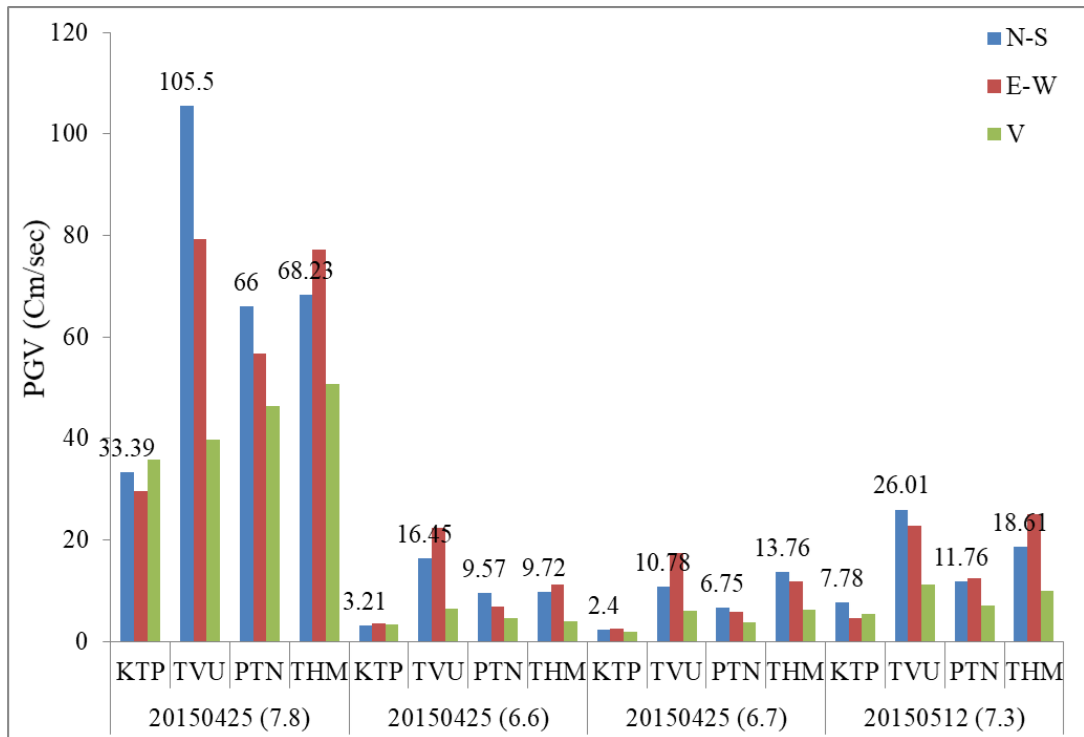
important parameter to the flexible structures (tall buildings). The damage to tall buildings correlates well with the large peak ground velocity.

**Table 13:** Peak ground acceleration (cm/sec<sup>2</sup>), peak ground velocity (cm/sec) and peak ground displacement of four earthquakes recorded at four sites. The largest PGA (254.7 cm/sec<sup>2</sup>) was recorded during the Mw 7.8 earthquake at rock site (KTP).

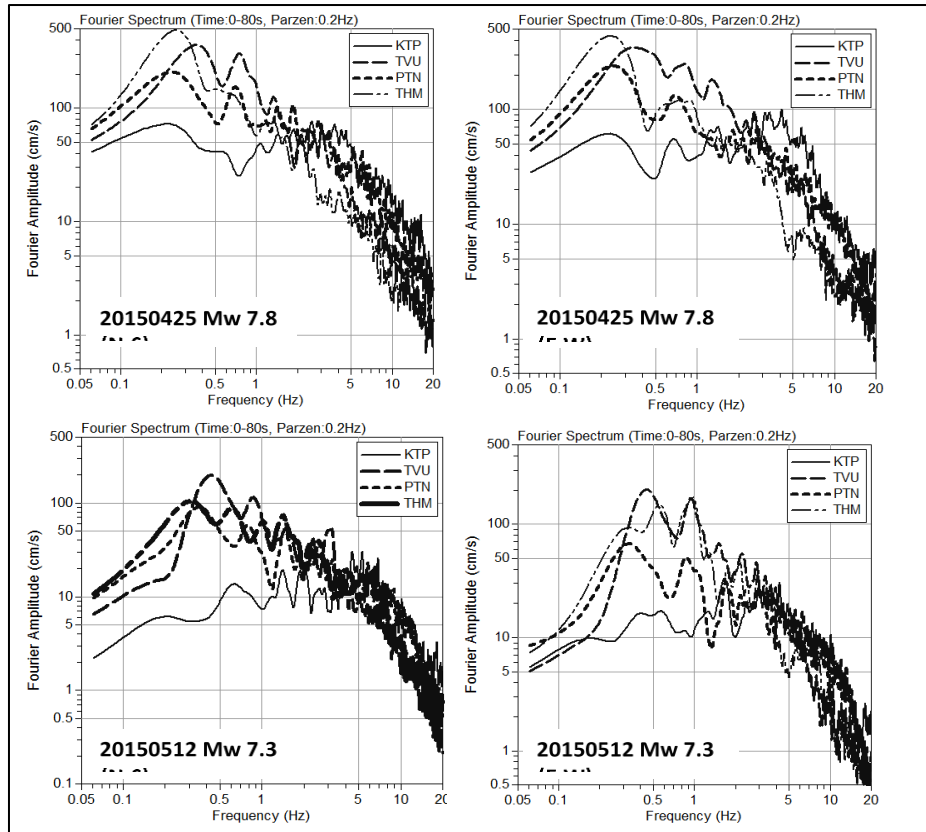
Earthquake		Acceleration (cm/sec <sup>2</sup> )			Velocity (cm/sec)			Displacement (cm)		
		N-S	E-W	V	N-S	E-W	V	N-S	E-W	V
20150425 (7.8)	KTP	153.8	254.7	127.2	33.39	29.74	35.88	35.64	25.5	31.9
	TVU	209.9	228.5	138.6	105.5	79.27	39.75	62.2	44.5	32
	PTN	150.5	128.5	133.6	66	56.69	46.37	65.57	55.68	46
	THM	150.1	133.8	183.7	68.23	77.15	50.84	64.7	68.6	31
20150425 (6.6)	KTP	27.7	36.1	23.8	3.21	3.54	3.28	1.6	1.2	2
	TVU	68	114.7	38.4	16.45	22.43	6.46	6.1	6.7	2.5
	PTN	58	53.3	24	9.57	6.82	4.58	4.6	3	2.8
	THM	40.5	44.1	17.6	9.72	11.31	4.02	5.2	3.8	1.7
20150426 (6.7)	KTP	49.8	42.6	28.1	2.4	2.5	1.96	0.39	0.6	0.4
	TVU	89.2	107.1	50.4	10.78	17.39	5.96	2.9	6.2	1.2
	PTN	58.6	52.2	37.2	6.75	5.9	3.76	2.75	2.43	1
	THM	101.6	70.4	64	13.76	11.81	6.18	5.9	3.3	2.2
20150512 (7.3)	KTP	63.2	67.6	36.7	7.78	4.57	5.47	2.3	2.5	2.48
	TVU	112.5	111	68.1	26.01	22.9	11.16	8.86	9.97	4.1
	PTN	84	62.8	60.1	11.76	12.54	7.11	6.2	5.3	4.9
	THM	85.7	116.2	85.1	18.61	25.08	10.04	10.36	8.94	4.88



**Figure 61:** Peak ground acceleration ( $\text{cm/sec}^2$ ) of the Gorkha Earthquake and its strong aftershocks recorded at four sites. Note that the maximum PGA was recorded at rock site (KTP).

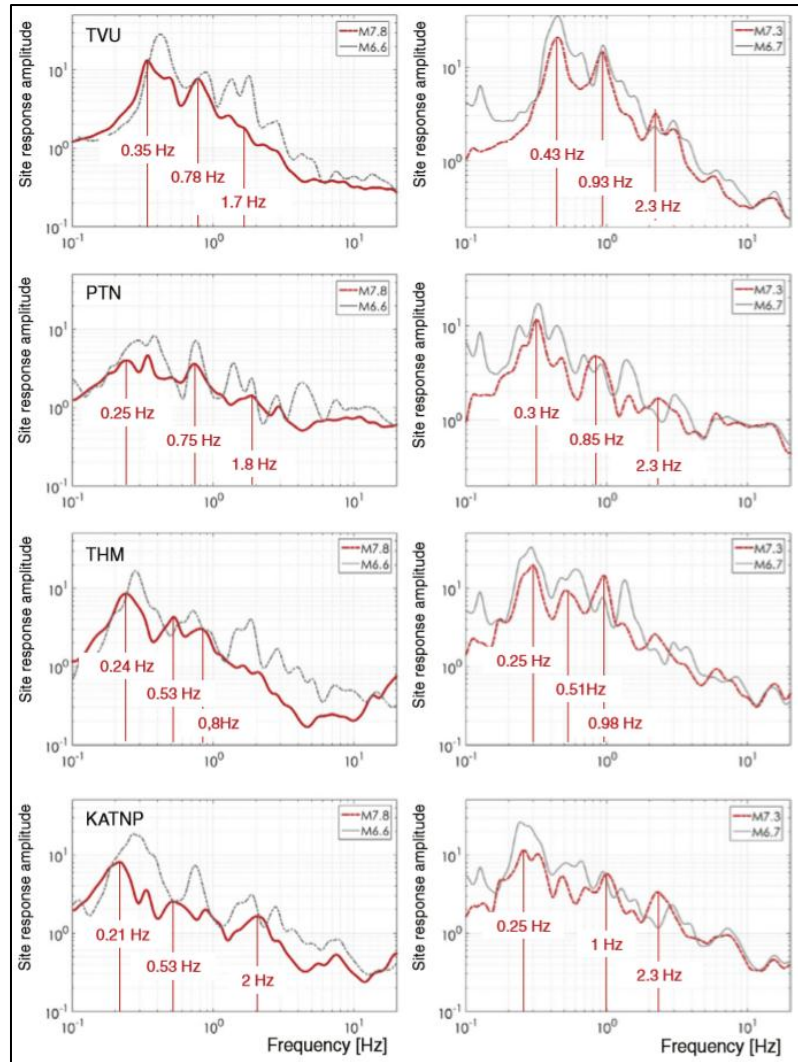


**Figure 62:** Peak ground velocity (cm/sec) recorded during the earthquakes at four sites. Note that the rock site has recorded the smallest PGV in all cases.



**Figure 63:** Fourier amplitude spectra of the earthquakes recorded at four sites. In all cases the lowest amplitude corresponds to the rock (KTP) site (Rajaure *et al.*, 2017).

Ratio of Fourier spectrum of ground motion at rock site to that at a soil site was used to investigate the amplification of seismic wave amplitude in Kathmandu valley during the Gorkha Earthquake sequence. In order to check the azimuthal influence of earthquakes, the earthquakes were grouped into two (Figure 64); two earthquakes in the west (Gorkha) and two earthquakes in the east (Dolakha). Figure 64 reveals the features of amplification in the Kathmandu valley during the Gorkha Earthquake sequence. The figures in the left column belong to the Mw 7.8 and Mw 6.6 earthquake which occurred in the west of Kathmandu at about 80 km; and the figures in the right hand column belong to the Mw 7.3 and Mw 6.7 earthquake which occurred in the east of Kathmandu at about 80 km. The results are grouped separately in order to check the azimuthal variation (if any). In the figures, it is clear that the amplification factor, which is a ratio of Fourier spectrum at soil site to that at the rock site (KTP) is smaller for the large earthquakes than the smaller ones. Similarly, the peak of amplification also moved towards high frequency during the smaller earthquakes. It clearly demonstrates that the sedimentary basin responded non-linearly during the earthquake sequence.



**Figure 64:** Ground response of the local geology of soil sites relative to rock site (KTP). This figure shows that amplification (ratio) during large magnitude earthquakes were comparatively smaller than during smaller earthquakes (Rajaure *et al.*, 2017).

## 4.10. Discussions

### 4.10.1. Seismic hazard in Nepal

Seismic hazard analysis of Nepal has been carried out incorporating the developments in the field of technology, improved knowledge of seismicity, seismotectonics, geodetic results, and impact of 2015 Gorkha Earthquake. Seismic hazard maps for five return periods have been prepared corresponding to 500, 1000, 2500, 5000 and 10000 year return periods.

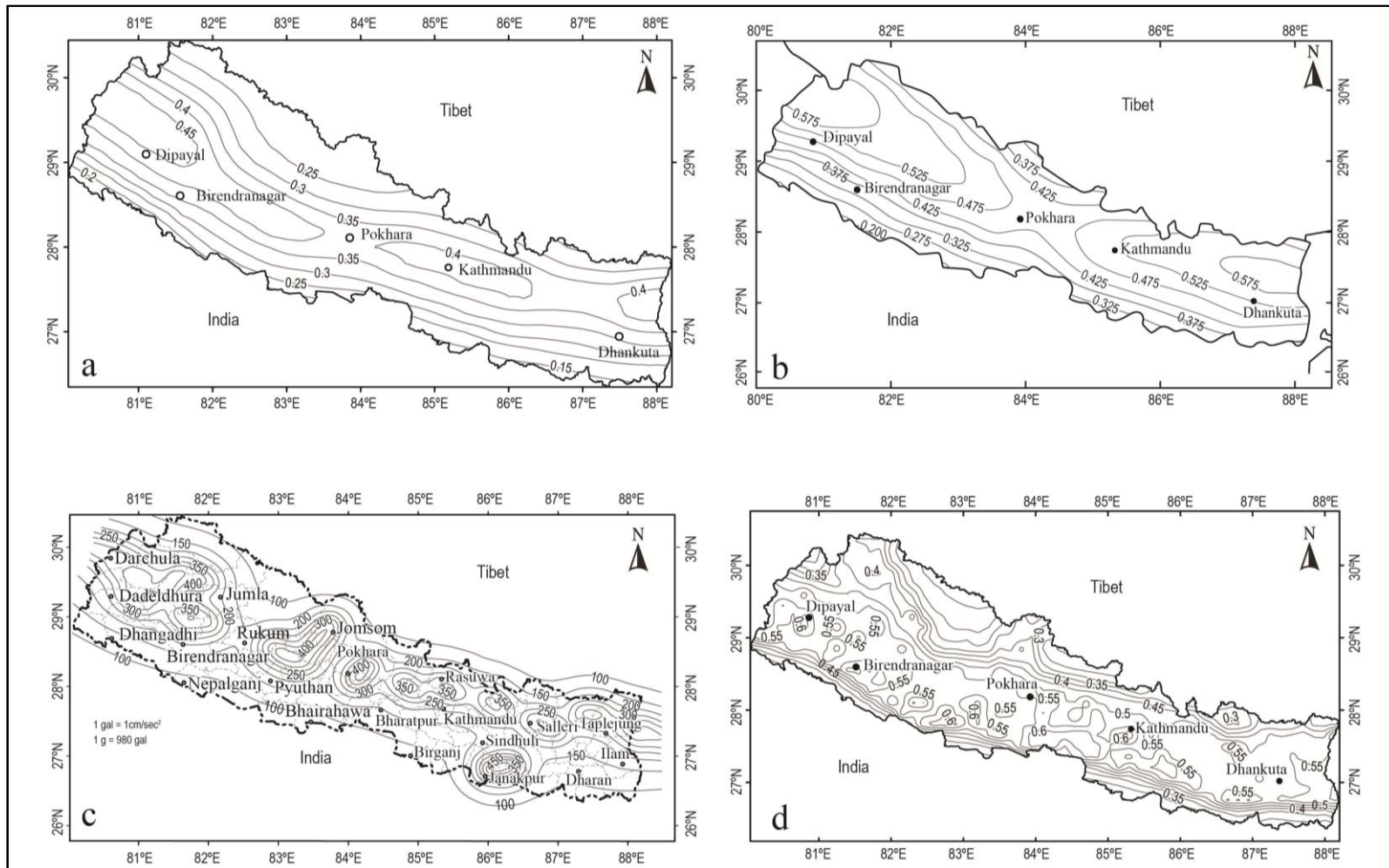
Multiple source models and multiple attenuation relations are used to evaluate seismic hazard in Nepal. Earthquake sources are considered both in Nepal and in the

surrounding areas of the region, which fall up to 250 km from the border of Nepal. The MHT is treated as a segmented source. Logic trees are used to incorporate uncertainties in source models and attenuation relations. Most of the previous works have prepared seismic hazard maps corresponding to 500 year return period, which is commonly used in building codes, therefore, further discussion is made on seismic hazard maps of 500 year return period only

The result (Figure 50) shows a belt of high hazard ( $PGA > 0.3$ ) in the middle part of Nepal parallel to the Himalaya. The maximum hazard ( $PGA > 0.45$ ) g is present in the far-western part of Nepal. The seismic hazard map (Figure 50) was prepared using attenuation relations (Appendix 18-1 and Appendix 18-2) described in 4.7.2. Among the relations, Young's *et al.* (1997) produces considerably large PGA (e. g. Appendix 19-1) in comparison to other relations. When Young's *et al.* (1997) relation is omitted for the subduction zone sources (MHT segments), the largest PGA is about 0.35 g (Appendix 21-2) in far-west and about 0.3 g in the Kathmandu Valley. As a local attenuation model is not available for Nepal and it is not known which specific model from other regions best fits the local attenuation pattern, Youngs *et al.* (1997) attenuation relation is continued to be used and the seismic hazard maps (Figure 50, Figure 51, Figure 52, Figure 53 and Figure 54) are adopted as the final seismic hazard maps corresponding to 500, 1000, 2500, 5000 and 10000 year return period.

A test is carried out to understand the major source of seismic hazard in the urban areas of Nepal. A seismic hazard map was prepared without considering the MHT sources, which shows considerably small PGA (Appendix 21-3) in the urban areas in Nepal. But the sources in the north (South-Tibet) have influence in the northern part reaching about 0.2 g Jomsom area. Evidently, the MHT is a major source of seismic hazard in the urban areas of Nepal.

The prepared seismic hazard map (Figure 50) is in a good agreement with frequently experienced and reported earthquakes in history, which have destroyed the northern part of Nepal many times (e.g. 1833 North Kathmandu Earthquake ( $M_w$  7.6) and 2015 Gorkha Earthquake ( $M_w$  7.8)). A comparison of the present result (Figure 50) with the results from three previous works (corresponding to 500 year return period) is presented in (Figure 65).



**Figure 65:** A comparison of the seismic hazard map (a) prepared in this study with other previous works by Thapa and Wang (2013) (b), Pandey *et al.* (2002) (c) and Stevens *et al.* (2018) (d). The depicted PGA corresponds to 10% probability of exceedance in 50 years at engineering rock site condition.



The result from this study (Figure 65(a)) agrees with the results obtained by Pandey *et al.*, (2002) in terms of the high hazard zone in the northern part of Nepal (Figure 65 (c)). The seismic hazard map (Figure 65(a)) was published using area sources and thrust faults as potential earthquake sources. The area sources are segments of the MHT and the thrusts are other geological faults. Young's *et al.* (1997) attenuation relation was used to derive the PGA. The PGA corresponds to 10% probability of exceedance in 50 years at the engineering bedrock. The pattern of large PGA distribution correlates with the pattern noticed in the present result. The PGA in this result varies between 0.1 and 0.4 g.

The seismic hazard map of Nepal (Figure 65 (b)) by Thapa & Wang (2013) shows PGA higher than in this result, which might have resulted from differently estimated earthquake recurrence parameters and the considered earthquake sources, which are not based on the geometry of the MHT. They have estimated b-value that is smaller (0.85) than estimated in this study for the region. They have followed the procedure developed by CEA (2005) to estimate seismic hazard using attenuation relation developed by CEA (2005) for western China. The smaller b-value might be responsible for the large PGA estimated. The large PGA in the north resulted on account of the division of MHT into two sources and possibly the recurrence parameters were estimated using data specific to the sources.

Stevens *et al.* (2018) prepared seismic hazard map of Nepal (Figure 65 (d)) using MHT as a single source with maximum potential magnitude up to Mw 9.0 and other faults in the north and northwest of Nepal. The researchers have used fixed b-value (1.0) in accordance with the worldwide observation of b-value in similar tectonic regions. The b-value (1.0) used by Stevens *et al.* (2018) is not small, however the predicted maximum PGA is relatively large (0.6 g). The large PGA possibly resulted from a very large single earthquake source (MHT). Present study considers segments of MHT, which have smaller maximum potential magnitude (up to 8.5) than considered by Stevens *et al.* (2018) (Mw 9.2). Additionally, Stevens *et al.* (2018) considered entire N-S rupture of the MHT, whereas weighted mean of three types of scenario rupture of MHT are considered in the present study, hence high hazard is estimated in the middle part of Nepal and the southern part has less hazard.

Seismic hazard analysis requires record of earthquakes recorded for long span of time and it should cover complete seismic cycles of large earthquakes. Systematic recording of earthquakes started very lately and therefore such a record does not extend back beyond 1900 AD. Records of the historical earthquakes have uncertainty in terms of their precise size and location. The presently prepared seismic hazard maps are prepared using instrumentally recorded data for the last 120 years and pre-instrumental data (before 1900 AD) which are available since 1100 AD. The earthquake recurrence parameters based on such a limited data were used to evaluate seismic hazard. The pre-instrumental data could have higher uncertainties because of their locations and magnitudes being estimated from the macroseismic data.

Furthermore, well established attenuation relations are not available for the region and Nepal particularly. Therefore, such relations have to be borrowed from other regions, which have similar tectonic environment. In addition to these uncertainties about attenuation relation, the scattering in attenuation relation, maximum potential magnitude of potential earthquake also influence the uncertainties in the result.

#### **4.10.2. Ground response of Kathmandu valley**

The results from seismic hazard analysis are calculated at the engineering rock site condition, where the shear wave velocity ( $V_s$ ) is larger than 760 m/s. However, the ground motions may be influenced by local geology and soft sediments.

Earlier reports on the 1934 Bihar-Nepal Earthquake ( $M_w$  8.2) and 1833 North Kathmandu Earthquake ( $M_w$  ~7.6) discuss localized massive destruction in the Kathmandu valley and attribute the massive destruction to local geology of the basin (Pandey and Molnar, 1988).

Present study utilized strong motion records of different earthquakes which occurred in and around Nepal to investigate the effect of local geology on ground shaking. The result depicts that the peak value of amplification increased gradually during the large-to-small earthquakes. The amplification was smaller during strong earthquakes ( $M_w$  7.8 and  $M_w$  7.3) in comparison to other strong aftershocks ( $M_w$  6.6 and  $M_w$  6.7) (Table 12). Apparent azimuthal effect was not noticed from the analysis of records, two of which occurred in the west of Kathmandu and two in the east. The soft

sediments of Kathmandu valley damped the frequencies above 2.5 Hz, which correspond to low rise buildings (up to 4 story), therefore the low rise buildings survived the shaking than was anticipated. Because of the amplification of motion at low frequency ( $<2.5$  Hz) the tall structures were affected considerably. Based on a few observations, it is too early to generalize the observations of Gorkha Earthquake to future strong earthquakes.

# CHAPTER 5

## CONCLUSIONS AND RECOMMENDATIONS

### 5.1 Conclusions

Probabilistic seismic hazard maps (Figure 50, Figure 51, Figure 52, Figure 53 and Figure 54) of Nepal have been prepared. The maps show PGA values for engineering soil site conditions corresponding to 10%, 5%, 2%, 1% probability of exceedance in 50 years and 1% probability of exceedance in 100 years ( approximately 500 year, 1000 year, 2500 year, 5000 year and 10000 year return period in their order).

The seismic hazard maps are prepared using two types of attenuation relations (Appendix 18-1 and Appendix 18-2). Among the relations, Young's *et al.* (1997) relation produces the largest PGA (Appendix 19-1) whereas the Atkinson and Boore (2003) relation produces the smallest. When Young's *et al.* (1997) relation is omitted for the subduction zone sources (MHT segments), the largest PGA, corresponding to ~500 year return period, is about 0.35 g in far-west and about 0.3 g in the Kathmandu Valley (Appendix 21-2). Considering the unavailability of a local attenuation model for Nepal, our knowledge on which model best fits the local attenuation model and the PGA recorded during 2015 Gorkha Earthquake, we chose to use Young's *et al.* (1997) attenuation relation also in all calculations.

The seismic hazard maps show the eastern Nepal (Taplejung and Terhathum), central Nepal (Kathmandu, Kavre, Sindhupalchok, Nuwakot, Dhading and Makawanpur) and far western Nepal (Jajarkot, Jumla, Kalikot, Dailekh, Achham, Bajura and Bajhang) have relatively high hazard.

The major conclusions on the seismic hazard analysis of Nepal are as follows.

- I. A comprehensive, magnitude-homogenized earthquake catalogue is prepared from catalogues collected from different sources. The catalogue contains independent earthquakes that are required in probabilistic seismic hazard analysis.
- II. Altogether nine earthquake source models are identified and delineated. Out of the nine models, six models are used in the preparation of seismic hazard maps.

- III. Peak ground acceleration is estimated at grid of ~20 km spacing. Probabilistic seismic hazard maps of Nepal have been prepared for 500, 1000, 2500, 5000 and 10000 year return periods.
- IV. The major source of seismic hazard in Nepal is the Main Himalayan Thrust.
- V. The region between MCT and MFT shows relatively high hazard.
- VI. The seismic hazard depends more on the maximum potential magnitude and earthquake recurrence parameters than on geometry of MHT.
- VII. The peak ground acceleration in major places are as follows. The PGA values correspond to 500 year return period for engineering rock site conditions.

Place	Latitude (°E)	Latitude (°N)	PGA (g)
Baglung	83.600	28.266	0.370
Bajhang	81.199	29.550	0.470
Bhairahawa	83.450	27.500	0.230
Biratnagar	87.283	26.467	0.150
Birgunj	84.867	27.017	0.160
Chaurjhari	82.193	28.626	0.420
Dadheldhura	80.567	29.300	0.400
Darchula	80.764	29.872	0.466
Dhankuta	87.340	26.970	0.300
Dipayal	80.930	29.243	0.448
Dunai	82.900	28.933	0.280
Gorkha	84.629	28.000	0.410
Hilsa	81.334	30.151	0.290
Ilam	87.910	26.910	0.330
Janakpur	85.917	26.733	0.160
Jiri	86.229	27.628	0.400
Jomsom	83.730	28.783	0.240
Jumla	82.193	29.274	0.320
Kathmandu	85.317	27.700	0.410
Mahendranagar	80.300	28.967	0.240
Mugu	82.085	29.502	0.330
Nepalgunj	81.617	28.067	0.200
Palpa	83.550	27.866	0.350
Pokhara	83.983	28.217	0.370
Pyuthan	82.853	28.101	0.400
Salyan	82.161	28.375	0.380
Simikot	81.819	29.968	0.270
Surkhet	81.600	28.600	0.360
Taplejung	87.650	27.370	0.410
Tumlingtar	87.193	27.314	0.370

Ground response of the Kathmandu valley sediments has been investigated utilizing strong motion records of the 2015 Gorkha Earthquake recorded in the Kathmandu sedimentary basin. The major observations on the ground response of the Kathmandu Valley are as follows.

- I. During the Gorkha Earthquake sequence, the PGA at soil sites were damped for frequencies larger than 2.5 Hz and amplified in the lower frequency (<2.5 Hz). Because of this reason, the small story buildings were less affected and the tall structures were affected more.
- II. The amplification factor was smaller during strong earthquake and was larger during smaller earthquakes. This is non-linear effect caused by the properties of soil in the Kathmandu Valley.
- III. The results on ground response are based on analysis of records recorded at a few places, therefore, should not to be generalized for other locations.
- IV. These results on ground response are based on strong motion records of a few earthquakes, therefore, should not be generalized for other future strong earthquakes.

## **5.2 Recommendations**

The followings are the main recommendations of this study:

- I. The prepared seismic hazard maps incorporate the experience of the 2015 Gorkha Earthquake and its different characteristics, multiple source models, multiple attenuation relations, different datasets and different earthquake recurrence parameters estimated using different methods. Additionally, three rupture scenarios of the sources from MHT were considered. The PGA values estimated for different part of Nepal in the present study are more realistic. Therefore, these findings should be considered in next revision of the Building code of Nepal
- II. The seismic hazard map and ground response results should be considered in policy making, planning, formulation and revision of building code, design of new infrastructures and retrofitting of existing infrastructures. It will facilitate the risk assessment, insurance policies and many others.

- III. Present study reveals that the effect of an earthquake in the Kathmandu valley is not uniform at all places. Therefore, a detailed study is required to completely understand the site characteristics in the Kathmandu sedimentary basin.
- IV. The Kathmandu valley sediments amplified low frequencies ( $<2.5$  Hz) and damped high frequencies ( $> 2.5$  Hz) during the 2015 Gorkha Earthquake. A dense network of strong motion instruments should be installed and operated continuously keeping always in mind that strong earthquakes are lessons to improve our understanding and move forward accordingly. Such a network will help in the derivation of local attenuation relation for Nepal that is not available to the date.
- V. Ground response of other major cities of Nepal where sediment cover is very thick such as Pokhara, cities at dun valleys and Terai etc, site characteristics is still unknown. Installation and operation of strong motion instruments is necessary for those cities also to better understand the ground response during earthquakes.

## **CHAPTER 6**

### **SUMMARY**

Nepal lies in the central part of the Himalaya which is one of the most seismically active zones in the world. The Himalaya is a converging zone, where the Indian Plate is continuously thrusting under the Eurasian Plate. The Main Himalayan Thrust (MHT) is the detachment surface, which separates these two plates. The Main Central Thrust (MCT), Main Boundary Thrust (MBT) and the Main Frontal Thrust are major thrust systems in Nepal. In addition to these thrust systems, there are several reverse faults in Nepal and normal faults in South Tibet.

Nepal has witnessed several mega-earthquakes and thousands of small earthquakes in the past. The 2015 Gorkha earthquake is one of the latest mega-earthquakes in Nepal, which resulted on account of the slip on the MHT. Large earthquakes ( $M_w > 7.5$ ), which are less frequent, are believed to occur at the depth of the MHT (~20 km). The consequences of occasional large earthquakes have remained very painful to the people, society, economy and the nation as a whole. The more frequent smaller earthquakes may occur off the MHT and could in particular be shallower. These smaller and shallow events being more frequent may impact in the hazard level significantly. The preparation of seismic hazard map and evaluation of site specific ground motion due to earthquake could be the basic steps of earthquake risk reduction. The policy making, planning, formulation/revision of building code, strengthening of existing structures and risk analysis all require the results from the seismic hazard analysis.

A number of attempts have been made to produce seismic hazard maps of Nepal in the past. However, in one hand, those maps prepared by different authors do not agree with each other. On the other hand preparation of a seismic hazard map is a dynamic process and the map evolves through time when there are new data, techniques and better understanding of geology, seismotectonics etc. Therefore, present study was undertaken to develop new seismic hazard maps of Nepal, corresponding to different return periods, using multiple dataset, multiple source models, and multiple attenuation and recurrence relations. Seismic hazard maps of different return periods



have been prepared so that they would be helpful in planning and in the design of different kinds of hydropower projects as well as other development infrastructures

A comprehensive, magnitude-homogenized earthquake catalogue is prepared from earthquake catalogues collected from different sources. The prepared catalogue can serve as an input in further seismic hazard analysis.

Three rupture scenarios of the MHT were used with different weight factors to account for uncertainty in the dimension of rupture, as revealed by 2015 Gorkha Earthquake, possibly the 1833 North Kathmandu Earthquake and other rupture areas revealed by paleoseismic investigations carried out in Nepal. Further, 2015 Gorkha Earthquake and its aftershock area (rupture area) have been used in the present study to prepare the seismic hazard map of Nepal and analyze the ground response of the Kathmandu valley.

In this study, the Probabilistic Seismic Hazard Analysis (PSHA) technique developed by Cornell (1968) and Algermissen *et al.* (1982) was used to evaluate seismic hazard in Nepal. The prepared seismic hazard maps depict seismic hazard expressed in terms of PGA (g) across the country. The maps show a belt of relatively high hazard in the middle part of Nepal that runs parallel to the Himalaya. The belt of high hazard correlates with the location of the MHT, often felt earthquakes and the rupture area of the 2015 Gorkha Earthquake. Relatively high hazard is depicted in the far-western part of Nepal. The hazard strongly drops in the southern part of Nepal (in the south of the MFT) because of the boundary of major source of earthquakes (MHT) ends there. The MHT is the major contributor of seismic hazard in Nepal.

Characteristics of ground motion may be influenced by local geology. Local geology can bring changes in amplitude, duration and frequency content of ground motion. Variable destruction pattern was reported during 1934 Bihar-Nepal Earthquake (Mw 8.2). Strong motion records of earthquakes recorded in the Kathmandu Valley were used to investigate characteristics of the ground motion and amplification in the valley. Local geology of Kathmandu sedimentary basin responded non-linearly to the ground motions during the Gorkha Earthquake and its three strong earthquakes. The amplification was small during strong earthquakes in comparison the smaller earthquakes. The amplitudes at frequencies larger than 2.5 Hz were strongly damped

and those smaller than 2.5 Hz were amplified. Because of damping of high frequencies, the small storied buildings were less affected than was anticipated initially. Similarly, the tall buildings were severely affected because of amplification of frequencies smaller than 2.5 Hz.

The result of seismic hazard analysis is important for a nation like Nepal which is pursuing to accelerate its development works. The result can help in policy making, planning, formulation and revision of building code, design of new infrastructures and strengthening of existing ones. Similarly, it can help in risk assessment, insurance policies and many others. The result of ground response in Kathmandu Valley are based on acceleration data of a very few earthquakes recorded at six locations. The results from these limited number earthquakes, recorded at a few sites should not be generalized for entire Kathmandu Valley.

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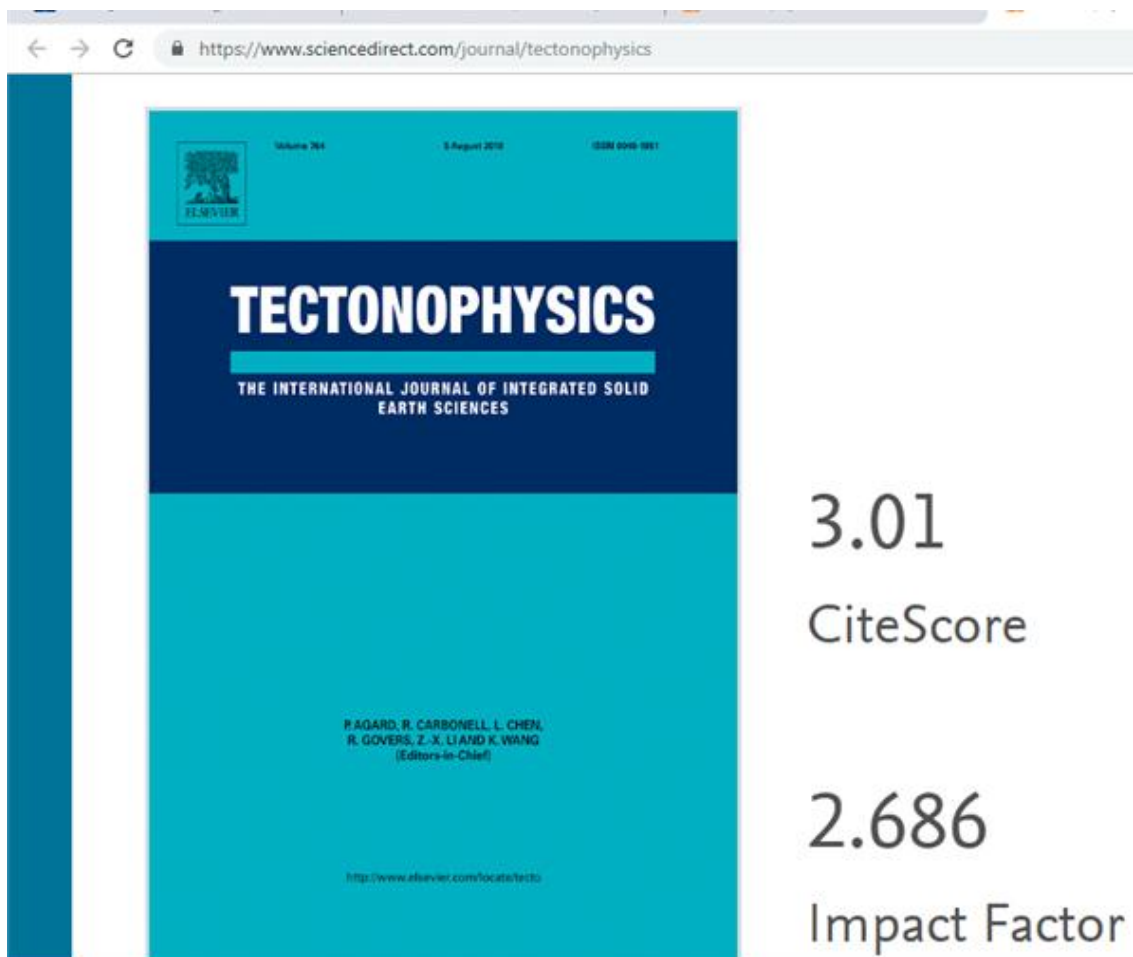
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# APPENDIX 1

## LIST OF PUBLICATIONS RELATED TO PHD RESEARCH

**Appendix 1.1.** International Journal with impact factor (Impact factor 2017/2018=2.686; 5-Year Impact Factor: 3.200)

Rajaure S., D. Asimaki, E. M. Thompson, S. Hough, S. Martin, J.P. Ampuero, A. Inbal, M. Dhital, L. Paudel (2017). "Characterizing the Kathmandu Valley sediment response through strong motion recordings of the 2015 Gorkha Earthquake sequence", *Tectonophysics*, 714-715, pp. 146-157.doi: 10.1016/j.tecto.2016.09.030.



The image shows a screenshot of a web browser displaying the cover of the journal *Tectonophysics*. The browser's address bar shows the URL <https://www.sciencedirect.com/journal/tectonophysics>. The journal cover features the Elsevier logo in the top left corner, the title "TECTONOPHYSICS" in large white letters on a dark blue background, and the subtitle "THE INTERNATIONAL JOURNAL OF INTEGRATED SOLID EARTH SCIENCES" below it. The cover also lists the Editors-in-Chief: P. AGARD, R. CARBONELL, L. CHEN, R. GOVERS, Z.-X. LI AND K. WANG. At the bottom of the cover, the URL <http://www.elsevier.com/locate/tecto> is provided. To the right of the journal cover, two citation metrics are displayed: a CiteScore of 3.01 and an Impact Factor of 2.686.

Metric	Value
CiteScore	3.01
Impact Factor	2.686

## Appendix 1.2. Indexed Journal

1. Rajaure, S., Koirala, B., Pandey, R., Timsina, C., Jha, M., Bhattarai, M., Dhital, M., Paudel, L., & Bijukchhen, S. (2014). Ground response of the Kathmandu Sedimentary Basin with reference to 30 August 2013 South-Tibet Earthquake. *Journal of Nepal Geological Society*, 47(1), 23-34. <https://doi.org/10.3126/jngs.v47i1.23101>


The screenshot shows a web browser window displaying the Nepal Journals Online (NepJOL) website. The browser's address bar shows the URL: <https://www.nepjol.info/index.php/JNGS/article/view/23136>. The website header includes the title "Nepal Journals Online" and navigation links for "Home", "About", "Site search", "Register", and "Login". Below the header, the "Journal of Nepal Geological Society" logo is visible, along with a "WORKING TOWARDS JOL STARS" badge. The main navigation bar includes "Current", "Archives", and "About" with a search icon. The article page content includes a breadcrumb trail: "Home / Archives / Vol 49 No 1 (2015) / Articles". The article title is "The 2015 Gorkha Earthquake and response of the Kathmandu Valley sediments". The authors listed are Sudhir Rajaure (Department of Mines and Geology), Megh Raj Dhital (Central Department of Geology, Tribhuvan University), and Lulu Prasad Paudel (Central Department of Geology, Tribhuvan University). A "pdf" icon is present next to the authors' names. The publication date is "Published 2015-12-31". The "How to Cite" section provides the citation: "Rajaure, S., Dhital, M., & Paudel, L. (2015). The". On the right side of the page, there is a section for "JOL" established by INASP in 2007, managed by Tribhuvan University Central Library. It describes NepJOL as a service for online publication of Nepalese journals and provides an "About page" link. At the bottom right, there is a "Activate Windows" notification.

2. Rajaura, S., Dhital, M., & Paudel, L. (2015). The 2015 Gorkha Earthquake and response of the Kathmandu Valley sediments. *Journal of Nepal Geological Society*, 49(1), 1-5. <https://doi.org/10.3126/jngs.v49i1.23136>

PKP The 2015 Gorkha Earthquak PKP Ground response of the × + ▾

ps://www.nepjol.info/index.php/JNGS/article/view/23101

About Site search

**Journal of Nepal Geological Society** 

Current Archives About ▾ Search

Home / Archives / Vol 47 No 1 (2014) / Articles

**Ground response of the Kathmandu Sedimentary Basin with reference to 30 August 2013 South-Tibet Earthquake**

**S. Rajaura**  
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**R. Pandey**  
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**S. Bijukchhen**  
Hokkaido University, Sapporo, Japan

 pdf

Published  
2014-06-30

How to Cite  
Rajaura, S., Koirala, B., Pandey, R., Timsina, C., Jha, M., Bhattarai, M., Dhital, M., Paudel, L., & Bijukchhen, S. (2014). Ground response of the Kathmandu Sedimentary Basin with reference to 30 August 2013 South-Tibet Earthquake. *Journal of Nepal Geological Society*, 47(1), 23-34. <https://doi.org/10.3126/jngs.v47i1.23101>

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Issue  
[Vol 47 No 1 \(2014\)](#)

Section

**JOL** Established by INASP in 2007. Managed by Tribhuvan University Central Library.  
*Nepal Journals Online (NepJOL)* is a service to provide online publication of Nepalese journals. For more information about NepJOL and how to join the service, see the [About page](#).

**Information**  
[For Readers](#)  
[For Authors](#)

Acti

3. Rajaure, S., & Paudel, L. (2018). A comprehensive earthquake catalogue for Nepal and its adjoining region. *Journal of Nepal Geological Society*, 56(1), 65-72. <https://doi.org/10.3126/jngs.v56i1.22747>

The screenshot shows a web browser window displaying the article page on the Nepal Journals Online (NepJOL) website. The browser's address bar shows the URL: <https://www.nepjol.info/index.php/JNGS/article/view/22747>. The website header includes 'Nepal Journals Online' with navigation links for 'Home', 'About', and 'Site search', and user options for 'Register' and 'Login'. The main header features the 'Journal of Nepal Geological Society' logo and a 'Search' button. Below the header, a breadcrumb trail reads 'Home / Archives / Vol 56 No 1 (2018) / Articles'. The article title is 'A comprehensive earthquake catalogue for Nepal and its adjoining region'. The authors listed are 'Sudhir Rajaure' (Department of Mines and Geology, Lainchaur, Kathmandu) and 'Lalu Prasad Paudel' (Central Department of Geology, Tribhuvan). A 'pdf' icon is visible next to the authors' names. The publication date is 'Published 2018-06-28'. On the right side, there is a 'JOL' logo and text stating it was established by INASP in 2007 and managed by Tribhuvan University Central Library. A small watermark 'Activate Windows' is visible in the bottom right corner of the browser window.

## APPENDIX 2

### Participation in International Conferences

**Appendix 2-1:** The 10th ASC General Assembly (ASC 2014) Makati City, Philippines 17-20 November 2014- Conference



**Appendix 2-2:** The 11th Asian Regional Conference of International Association of Engineering Geology and Environment (IAEG), November 28–30, 2017, Kathmandu, Nepal.



### APPENDIX 3

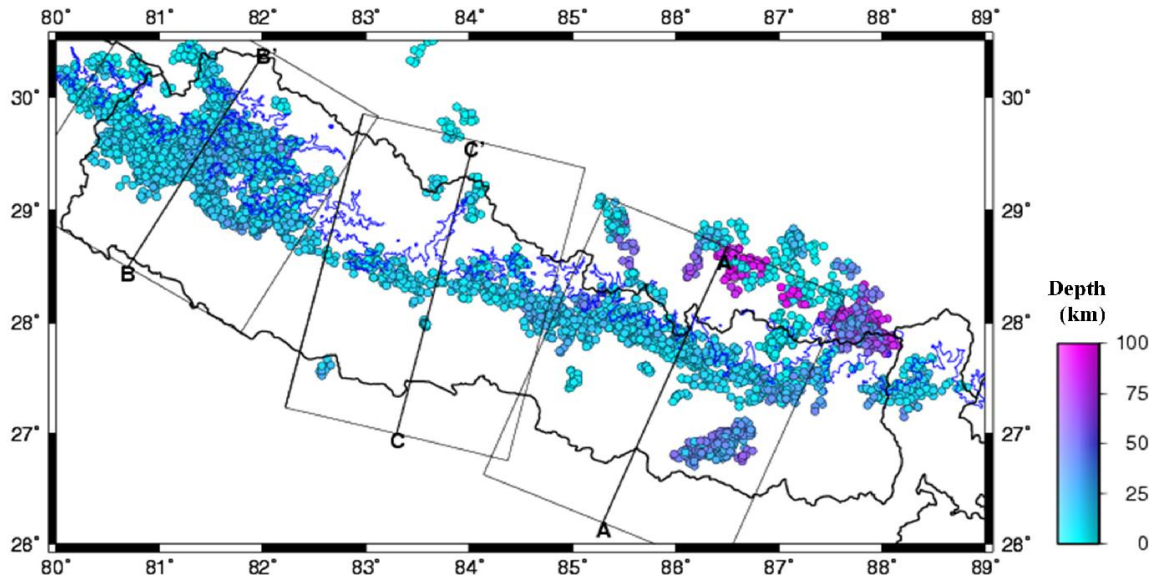
National earthquake hazards reduction program (NEHRP) ([www.nehrp.gov](http://www.nehrp.gov)) soil classification system. Where  $V_{s30}$  stands for shear-wave velocity of upper 30 m thick soil profile.

NEHRP Class	Soil description	Shear-wave velocity
A	Hard rock	$V_{s30} > 1500$
B	Firm to hard rock	$760 < V_{s30} < 1500$
C	Dense soil and soft rock	$360 < V_{s30} < 760$
D	Stiff soil	$180 < V_{s30} < 360$
E	Soft soil	$V_{s30} < 180$
F	Soil requiring site-specific evaluations	----



## APPENDIX 4

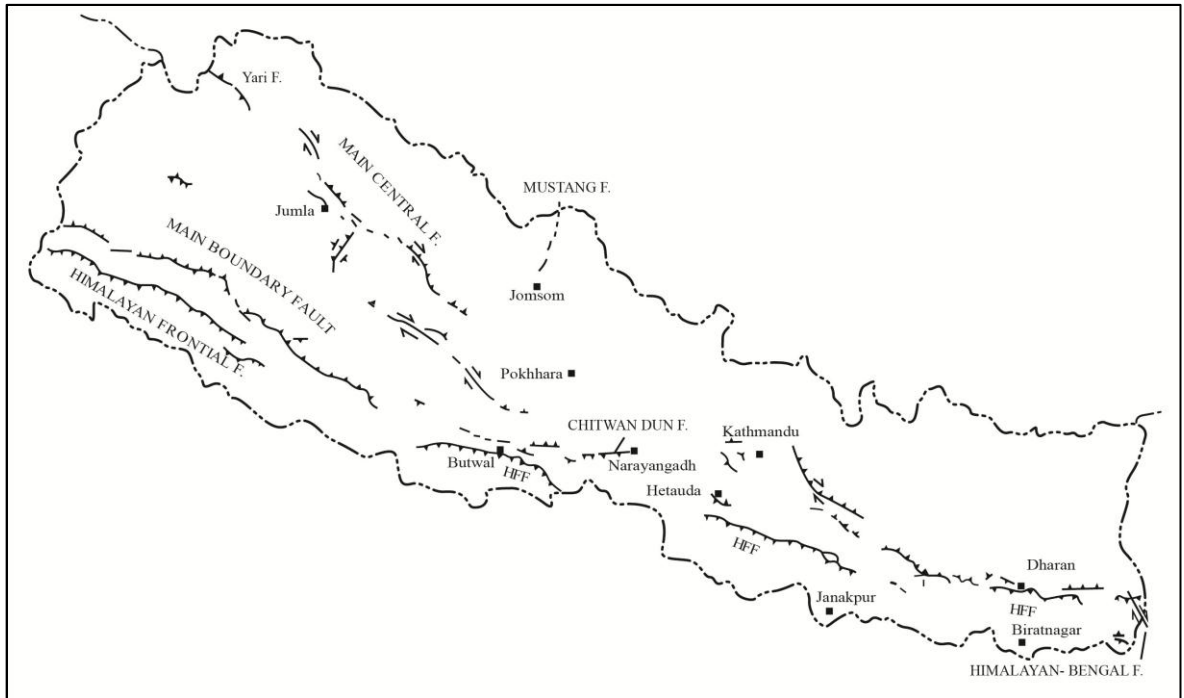
Local earthquakes relocated using double difference relocation technique (Waldhauser and Wellsworth (2000), (Rajaure *et al.*,2013). There are noticeable lateral variations in the seismicity belt. These variations correlate with geological structures (Appendix 8).





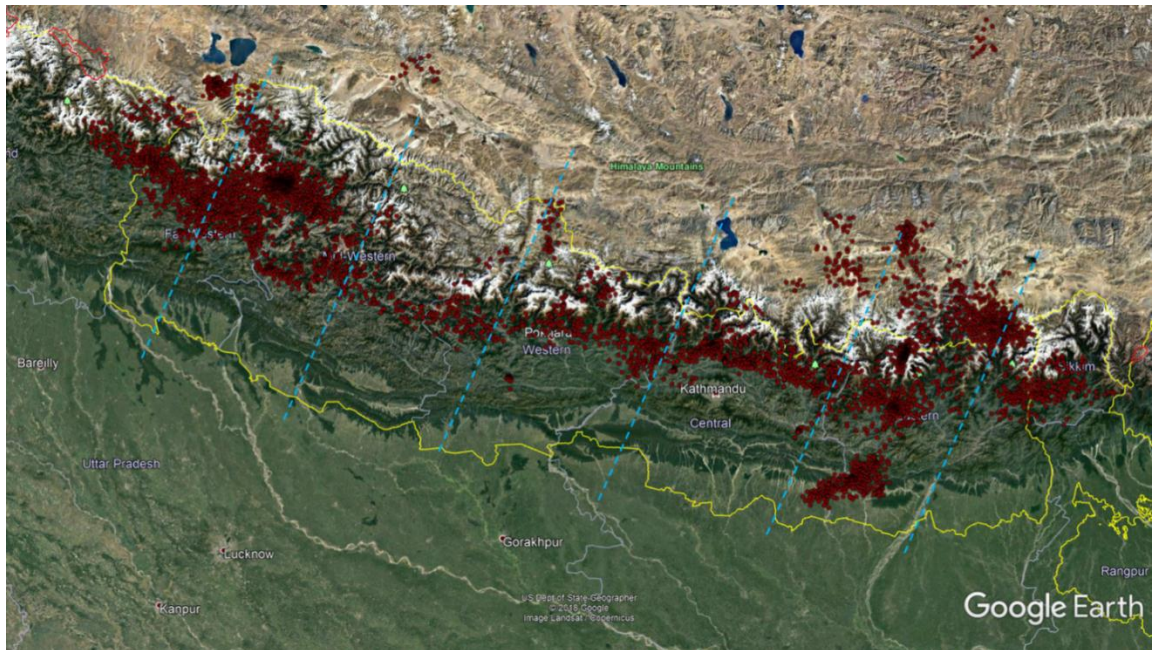
## APPENDIX 6

Active fault distribution in Nepal (based on the work of Nakata, 1982, Nakata *et al.*, 1984 and Nakata & Kumahara, 2000)



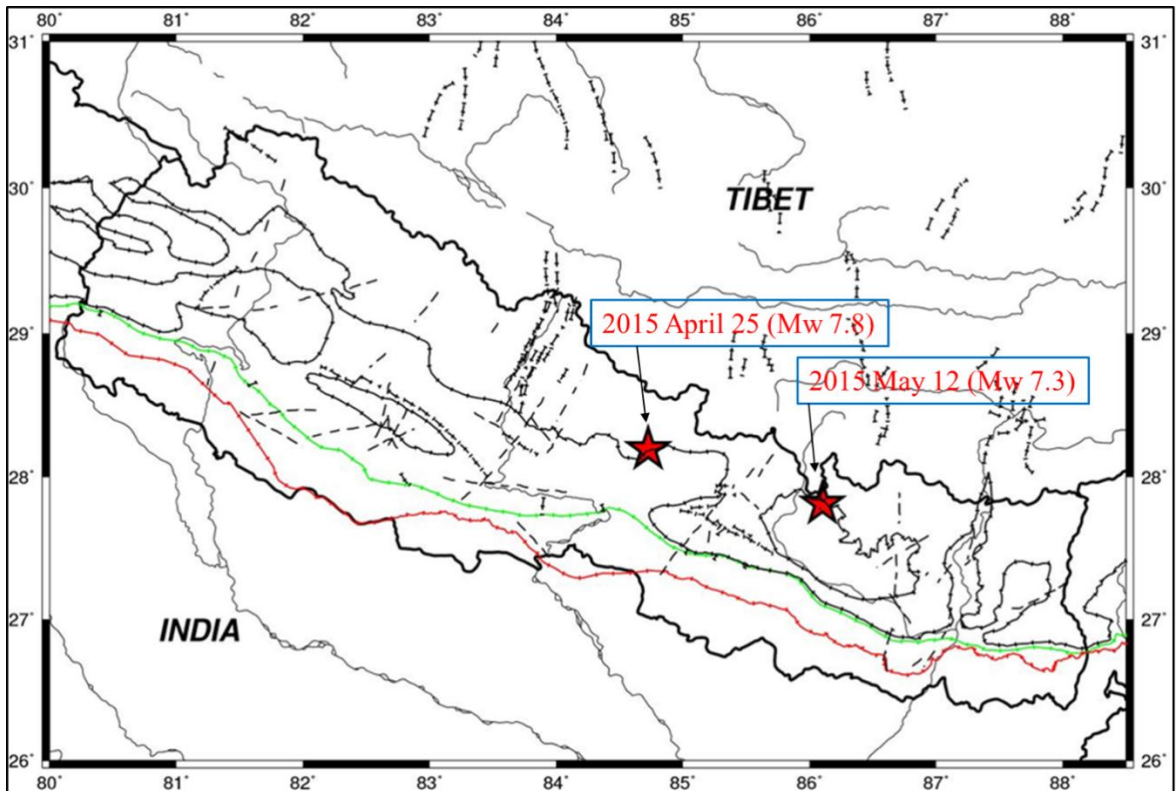
## APPENDIX 7

Google Earth image of Nepal and surrounding region with relocated seismicity by Rajaure et al. (2013). Lineaments and some of the faults can be identified in this image. Lateral variation (demarcated by NE-SW blue dashed line) in seismicity belt is very interesting and was used in the delineation of earthquake sources.



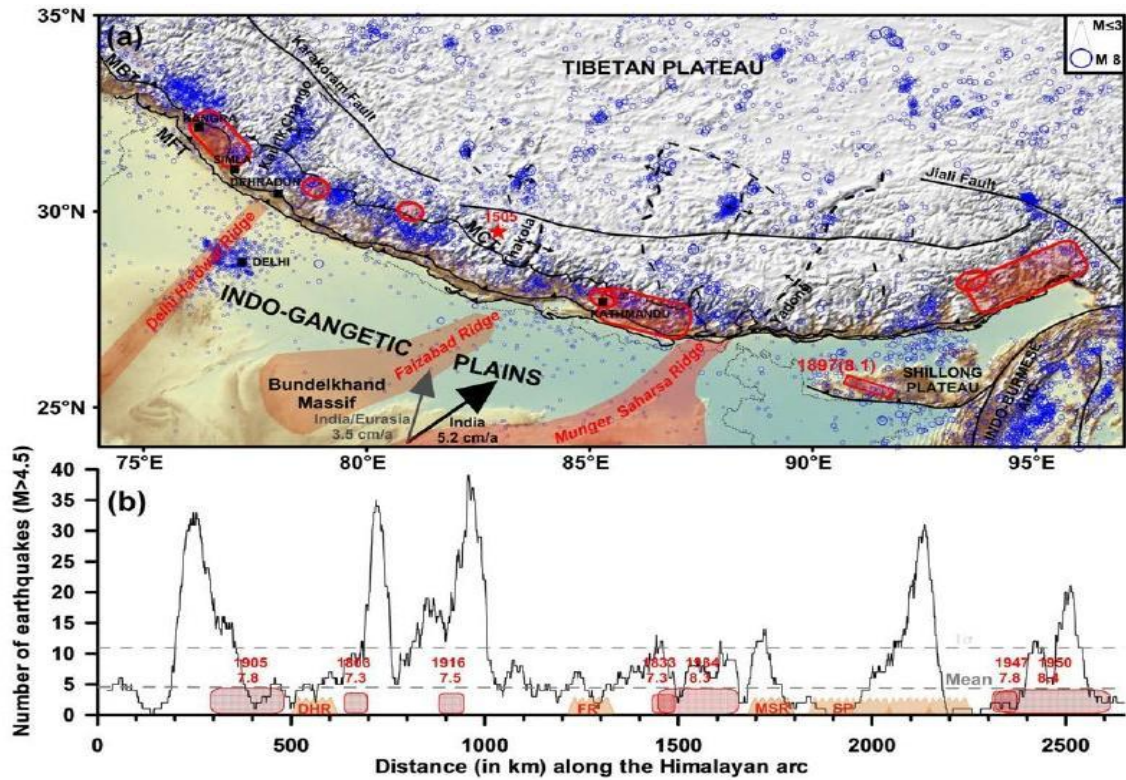
## APPENDIX 8

Geological structures, fold axis and lineaments in the region, compiled by the author from different sources. The two stars are the 2015 Gorkha Earthquake (left) and Dolakha Earthquake (right). (Modified from Rajaure et al., 2013)



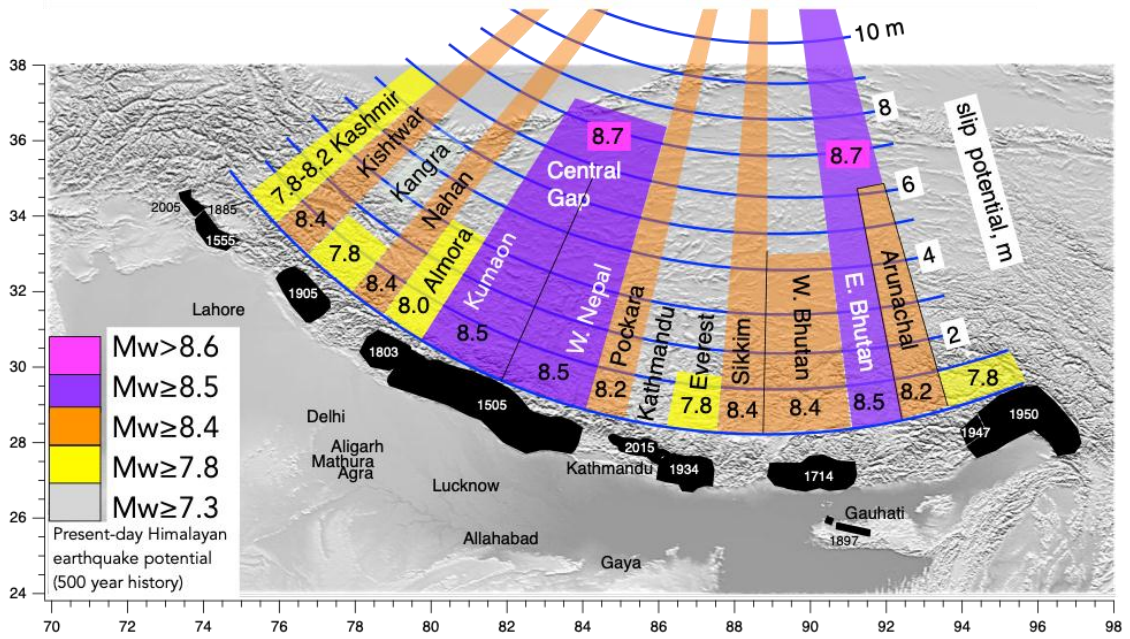
## APPENDIX 9

Subsurface ridges in north India. These ridges are supposed to control the rupture size and maximum magnitude of earthquakes in the Himalaya (Gahalaut V. K. and Kundu B., 2012)



# APPENDIX 10

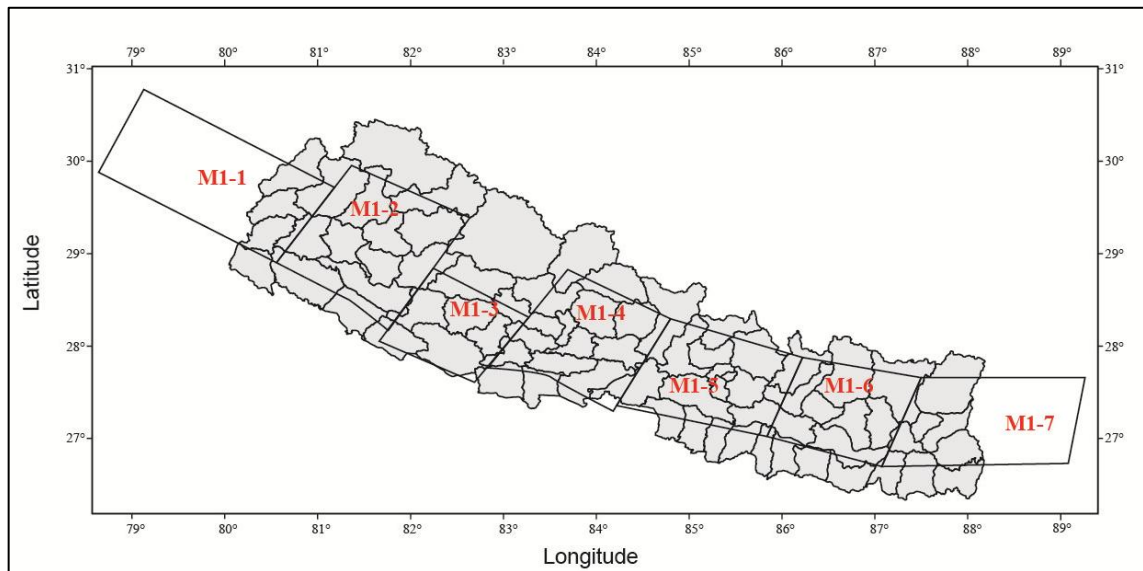
Possible segments along the Himalaya and their potential magnitudes at the present (Bilham, 2019)



## APPENDIX 11

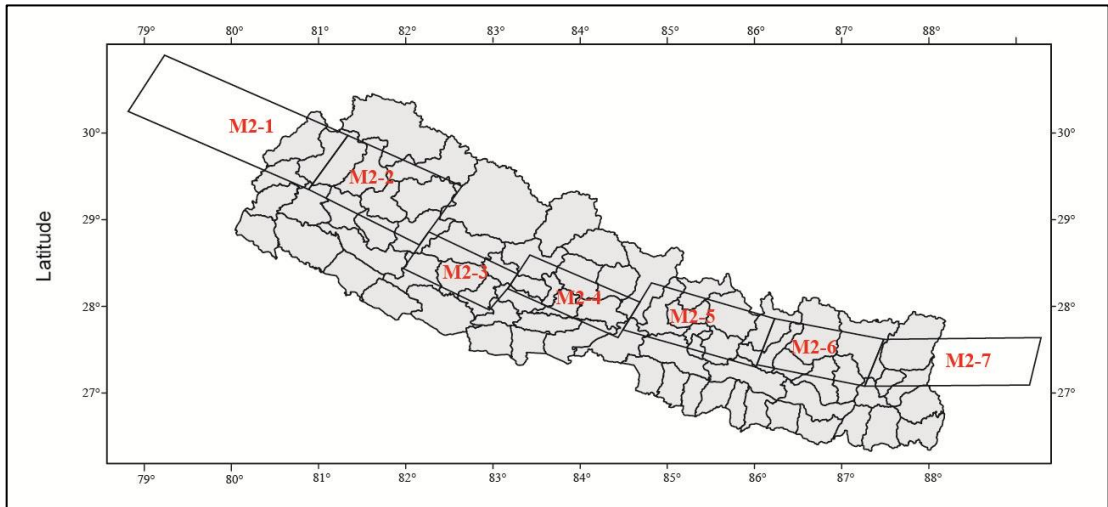
Potential earthquake sources, identified in the present study. There are altogether nine source models (Appendix 11-1 to 11-9).

**Appendix 11-1:** This model (Model-1) contains segments of the MHT only. The northern border corresponds to the seismicity belt in Nepal Himalaya, which correlates with the boundary between locked part of MHT in the south and aseismically creeping part in the north. The model has seven sources, with maximum potential magnitude ( $M_w$ ) between 8.0 and 8.2.

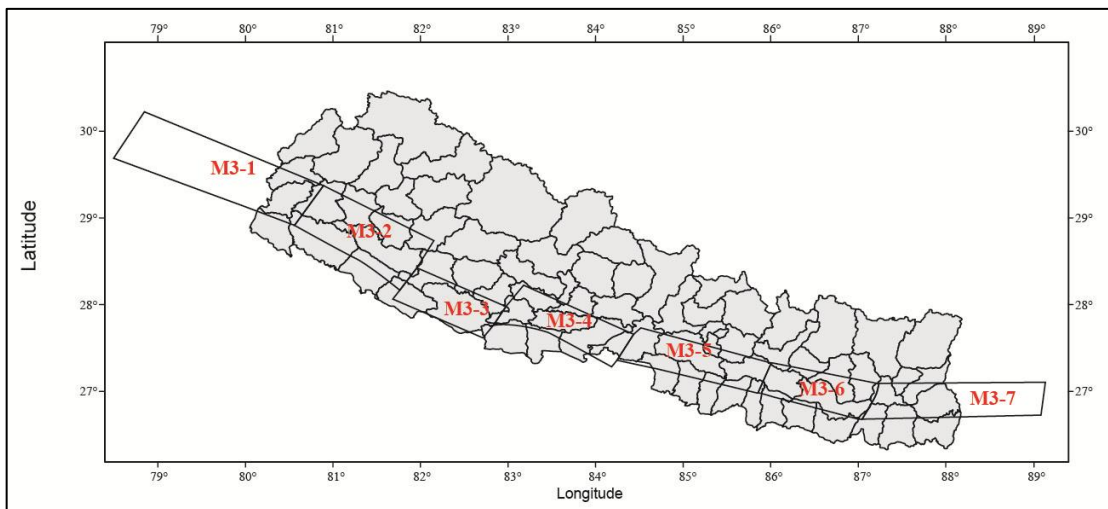




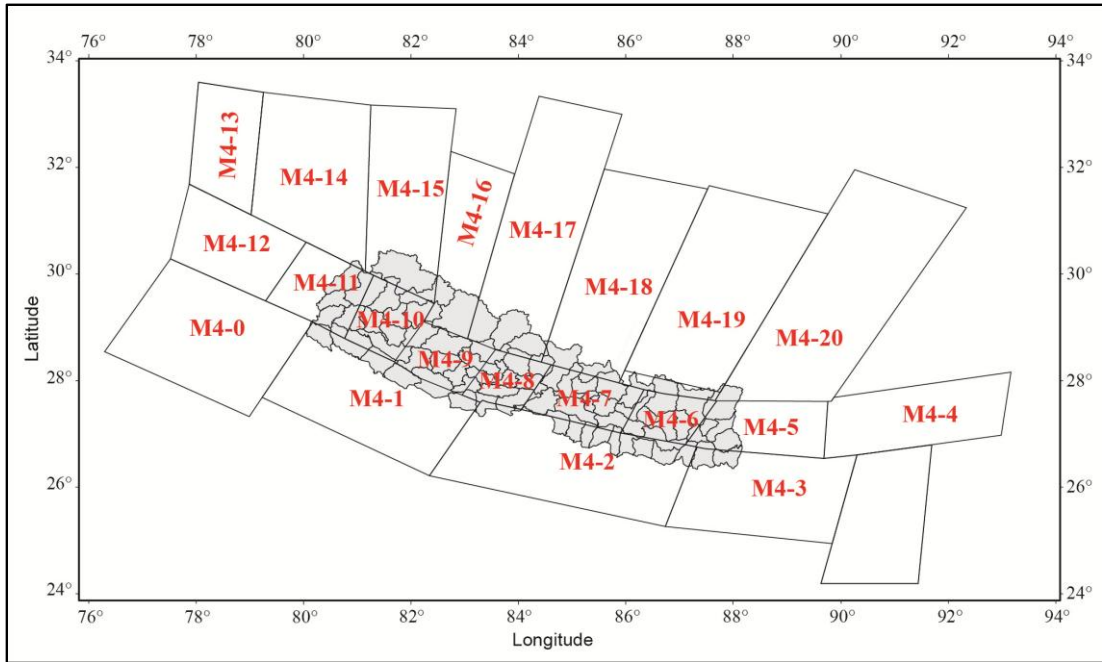
**Appendix 11-2:** This model (Model-2) also consists of seven sources. These sources represent the northern (half) rupture of Model-1. This model has been considered because earthquakes of Gorkha Earthquake size and rupture are believed to be common than Model-1. The maximum potential magnitude ( $M_w$ ) ranges between 7.8 and 8.0.



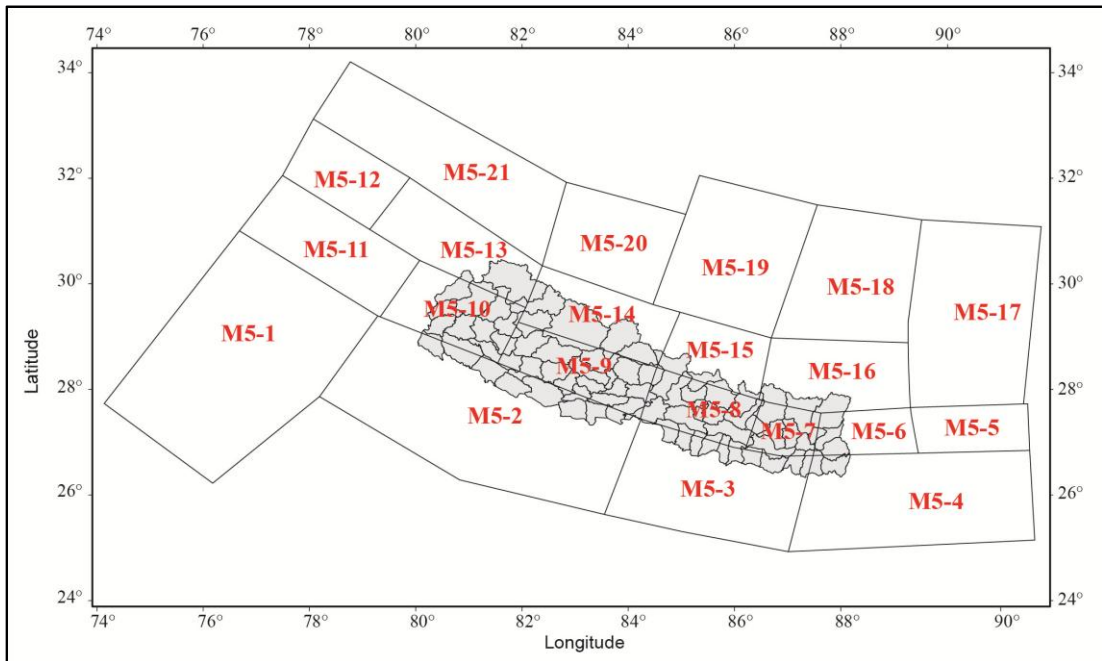
**Appendix 11-3:** This model (Model-3) also has seven sources. This model is considered to represent the southern rupture of the sources in Model-1, which did not rupture during the 2015 Gorkha Earthquake. This model has 20 km depth in the northern border and 10 km in the south. The maximum potential magnitude of the sources ranges between  $M_w$  7.8 and 8.0.



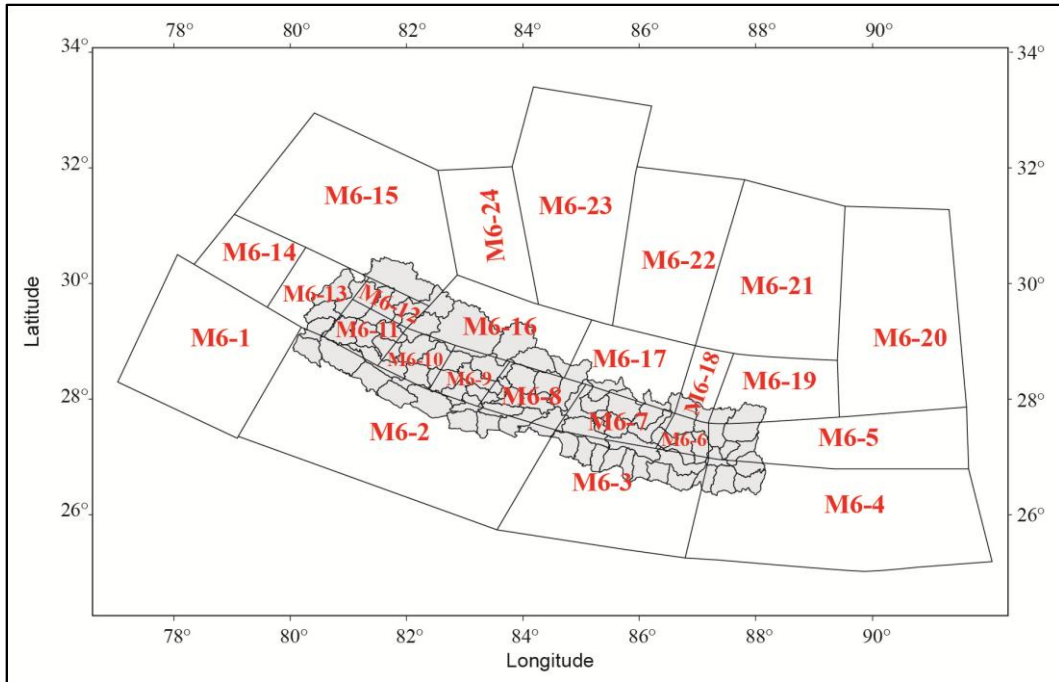
**Appendix 11-4:** This model (Model-4) has twenty sources. The depth of northern border of the sources (M4-4 to M4-12) is 10 km and 0 km in the south. The maximum potential magnitudes of the sources ranges between Mw 7.5 and 8.2.



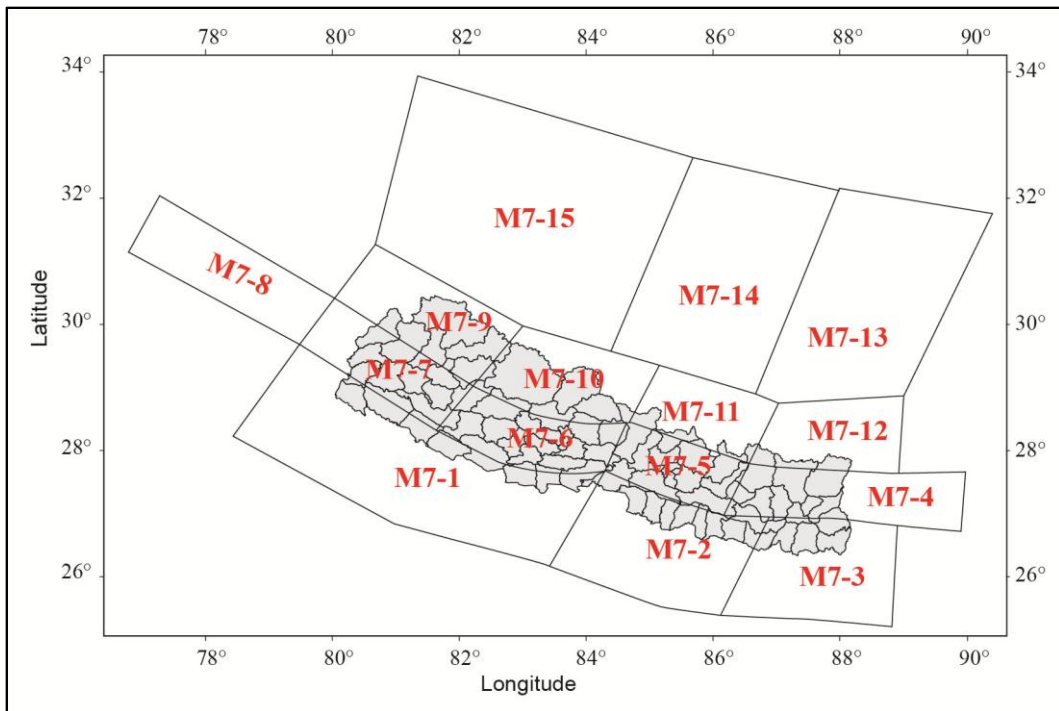
**Appendix 11-5:** This model (Model-5) considers sources from the Himalaya (MHT) as well as the surrounding region. There are altogether 21 sources with maximum potential magnitude between Mw 7.5 and 8.2.



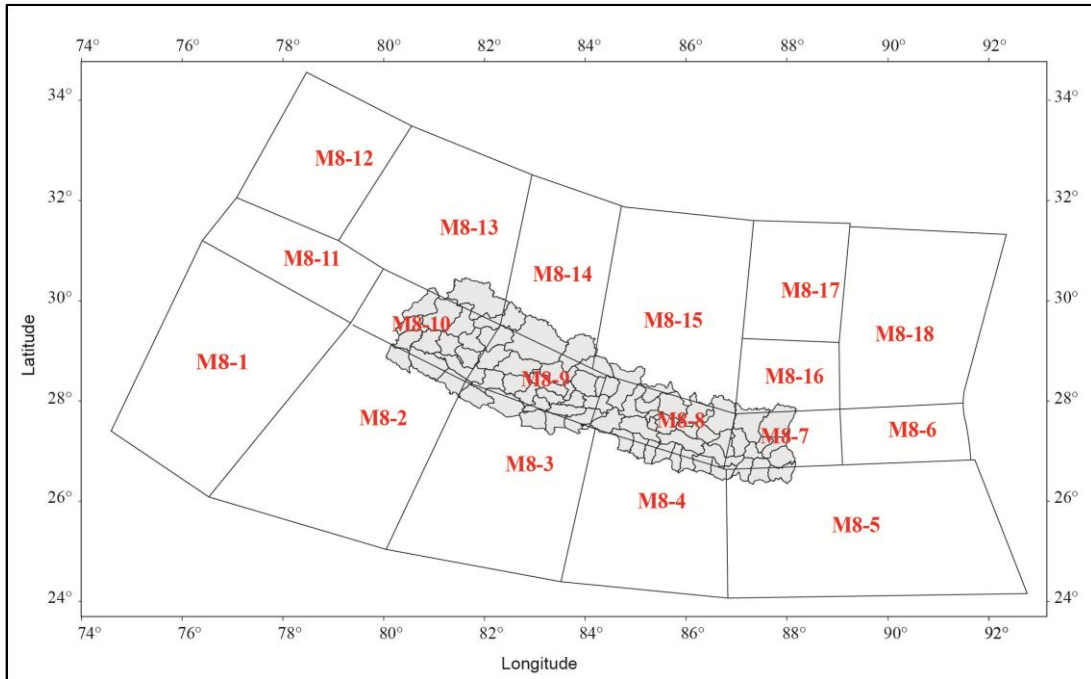
**Appendix 11-6:** This model (Model-6) has 24 potential sources from Himalaya and the surrounding region. The maximum potential magnitude of the sources is between 7.5 and 8.4.



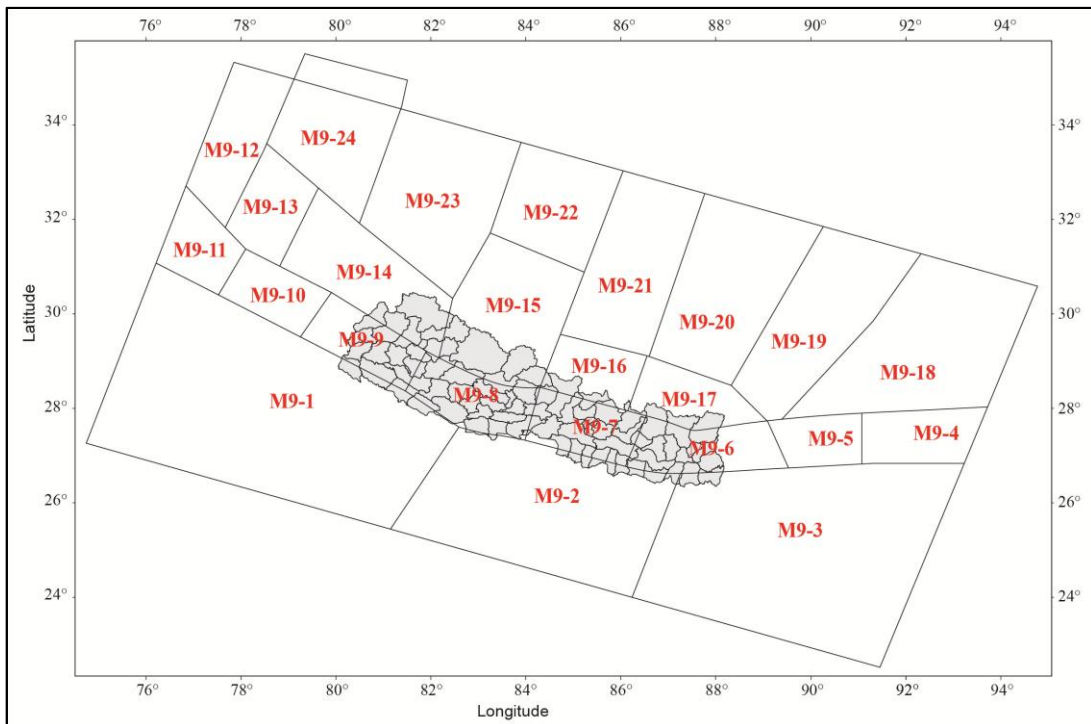
**Appendix 11-7:** There are altogether 15 sources in this model (Model-7). The maximum potential magnitude of the sources ranges between 7.5 and 8.3.



**Appendix 11-8:** This model (Model-8) has 18 sources from the Himalaya and the adjoining region. The maximum potential magnitude of the sources ranges between 7.5 and 8.5.

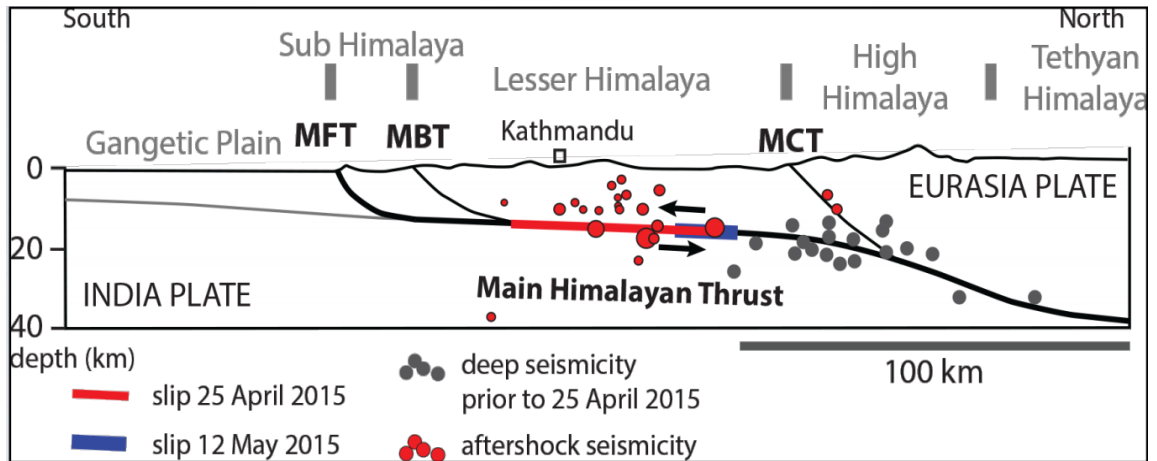


**Appendix 11-9:** This model (Model 9) has 24 earthquake sources. The maximum potential magnitude of the sources ranges between 7.5 and 8.5.



## APPENDIX 12

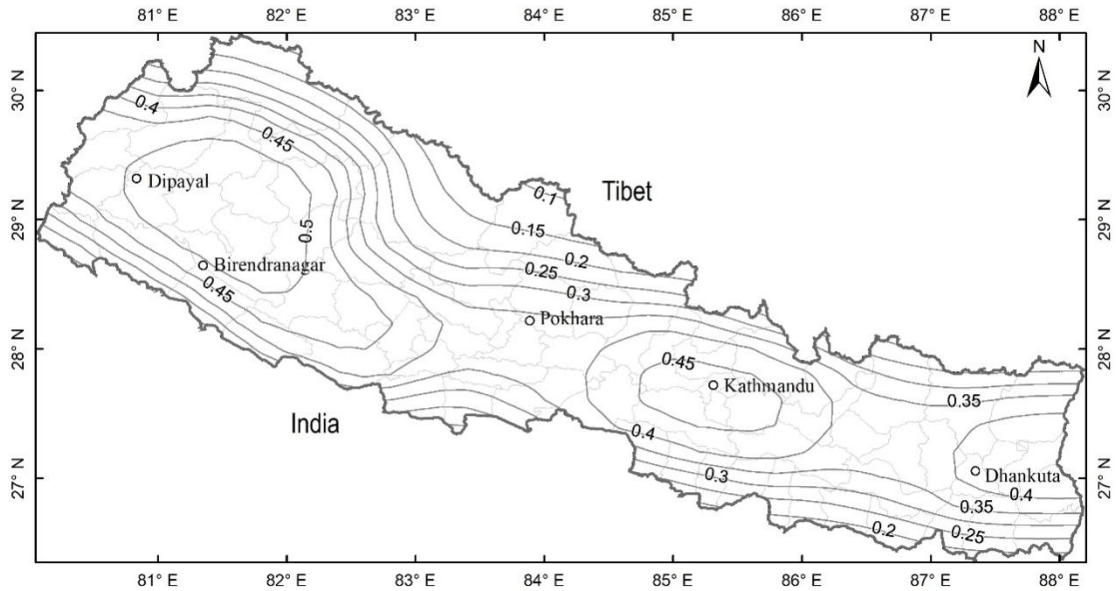
Generalized section across the Himalaya (USGS poster). The Main Himalayan Thrust (MHT) is the detachment surface (MHT) on which slip occurs during earthquakes. The red line on MHT is the slip that occurred during Gorkha Earthquake. In the source models a simple model is assumed, where the depth of the source (segment of MHT) in the north correlates with the cluster of earthquakes and in the south it joins the MFT.



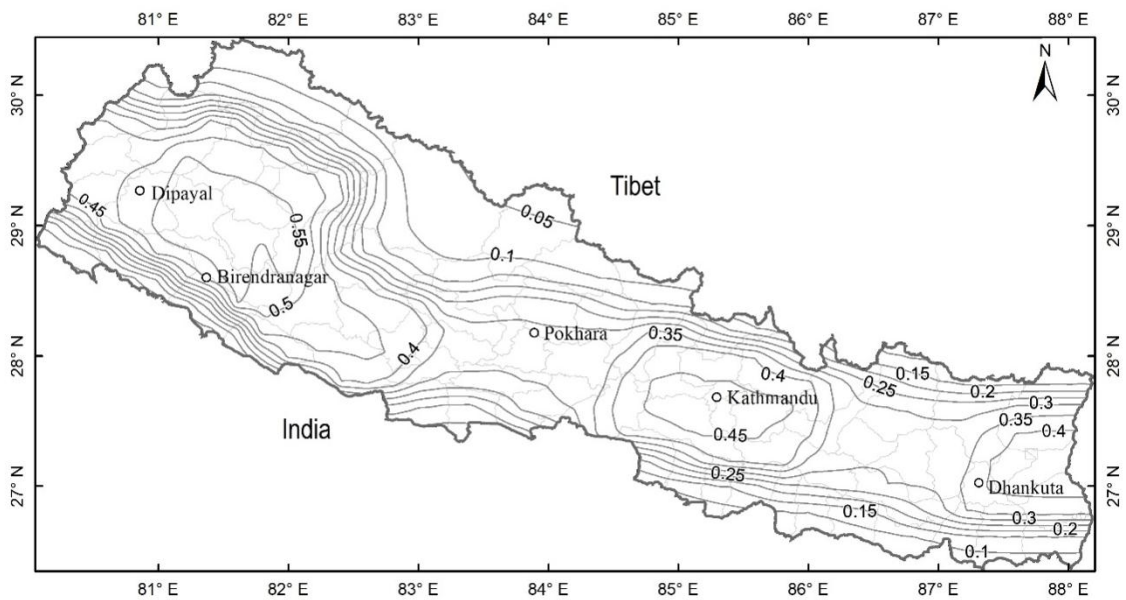
## APPENDIX 13

Variation in PGA with variation in depth of source plane. Common source model, common attenuation relation, common earthquake recurrence parameters were used in this test.

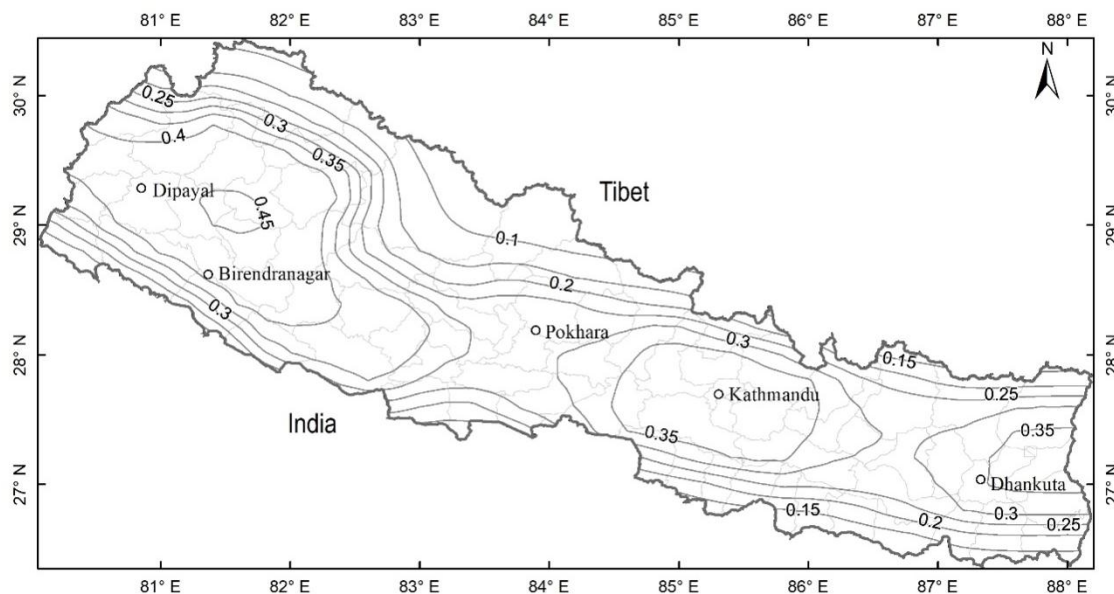
**Appendix 13-1:** Seismic hazard map with 20 km depth fixed to all vertices of the sources in Model-1 (Appendix 11-1). The maximum PGA is about 0.5 g in the far-west.



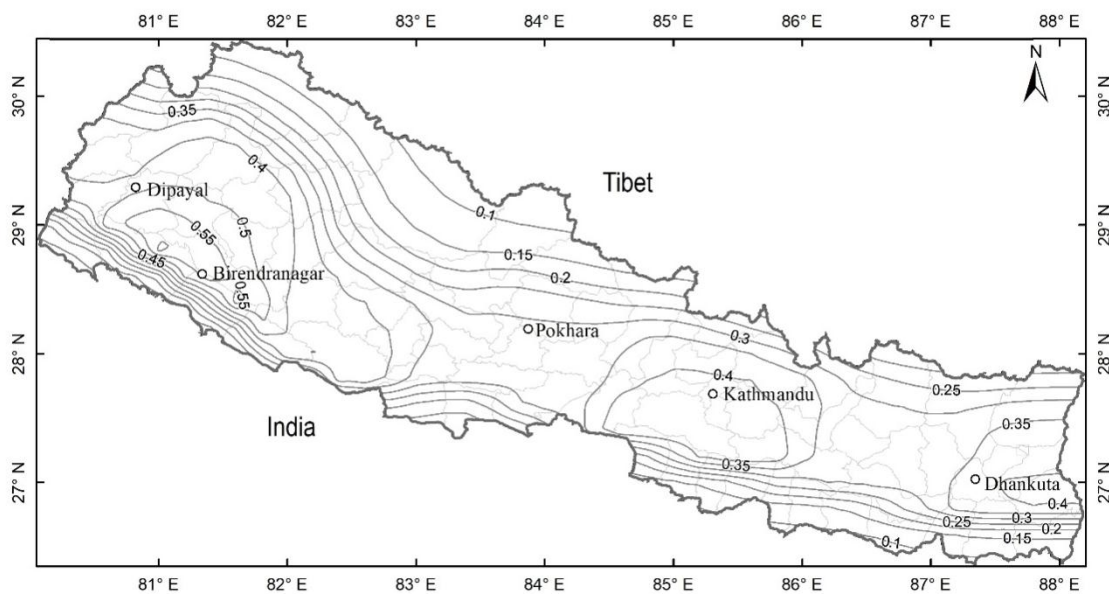
**Appendix 13-2:** Seismic hazard map with 5 km depth fixed to northern vertices of Model-1 (Appendix 11-1). The maximum PGA is about 0.55 g in the far-west and the shapes of zones are in the middle of north-south stretch.



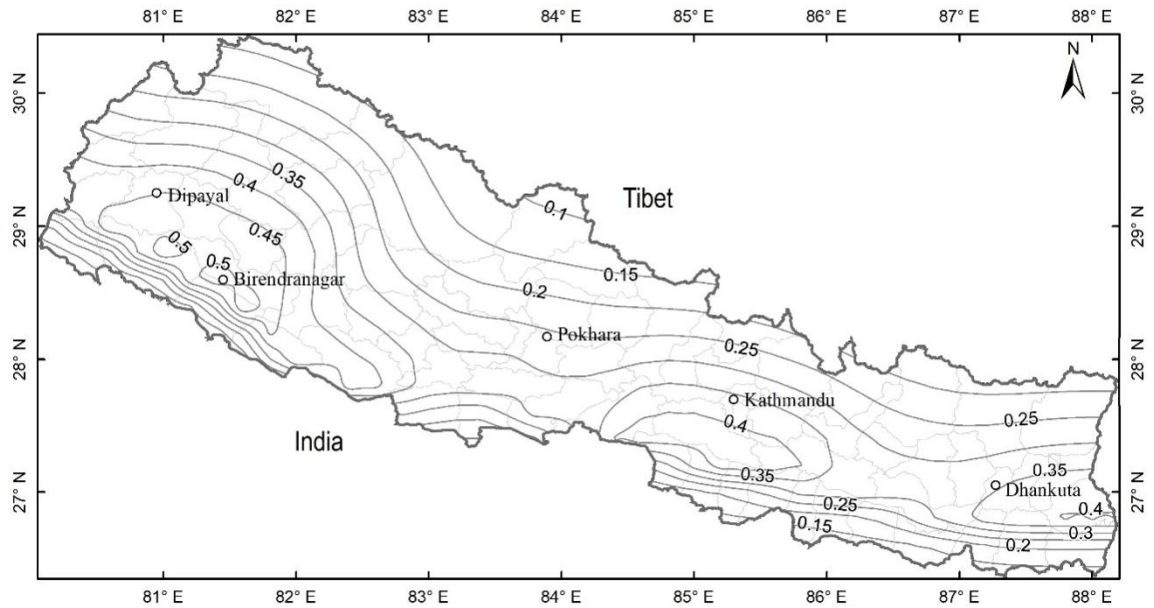
**Appendix 13-3:** Seismic hazard map with 10 km fixed depth to all vertices of the sources in Model-1 (Appendix 11-1). The maximum PGA is about 0.55 g. The shape of the PGA values got denser in the south on account of the hanging wall effect because of the geometry of the MHT.



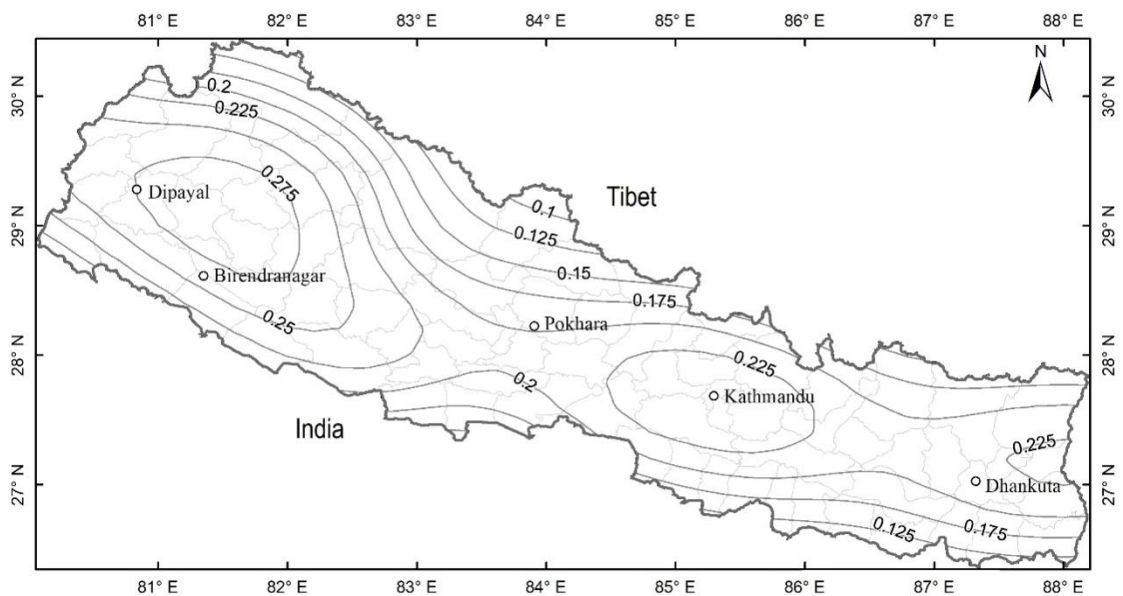
**Appendix 13-4:** Seismic hazard map with 20 km depth fixed to the vertices in the north of the sources in Model-1 (Appendix 11-1) and 0 km in the south. The maximum PGA is about 0.55 g in the far-west and the oval shapes of zones are getting shorter in the N-S direction because of hanging wall effect of the sources.



**Appendix 13-5:** Seismic hazard map with 50 km depth fixed to the vertices in the north. Model-1 (Appendix 11-1). The maximum PGA is about 0.5 g in the southern part of far-west. The change in the shape of the contours can be noticed between this map and the previous one. Because of hanging wall effect and depth > 50 km north, the higher PGA contours are concentrated in the southern part of Nepal.



**Appendix 13-5:** Seismic hazard map with 50 km depth fixed to all vertices of the sources in Model-1 (Appendix 11-1). The maximum PGA is about 0.27 g in the southern part of far-west. The change in the shape of the contours can be noticed between this map and the previous one. Because of hanging wall effect and depth > 50 km north, the higher PGA contours are concentrated in the southern part of Nepal.

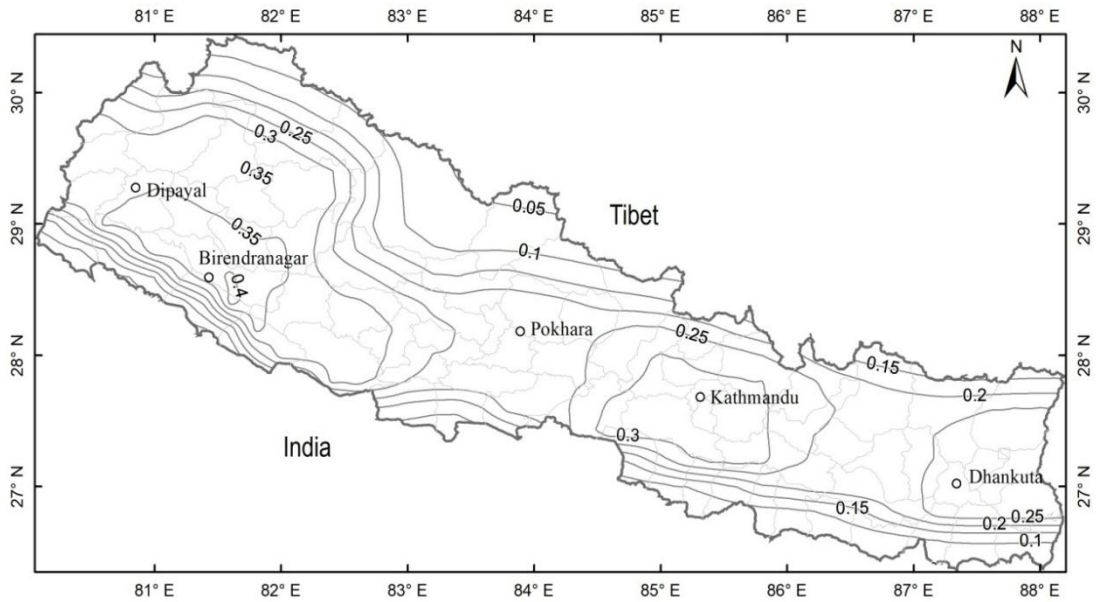




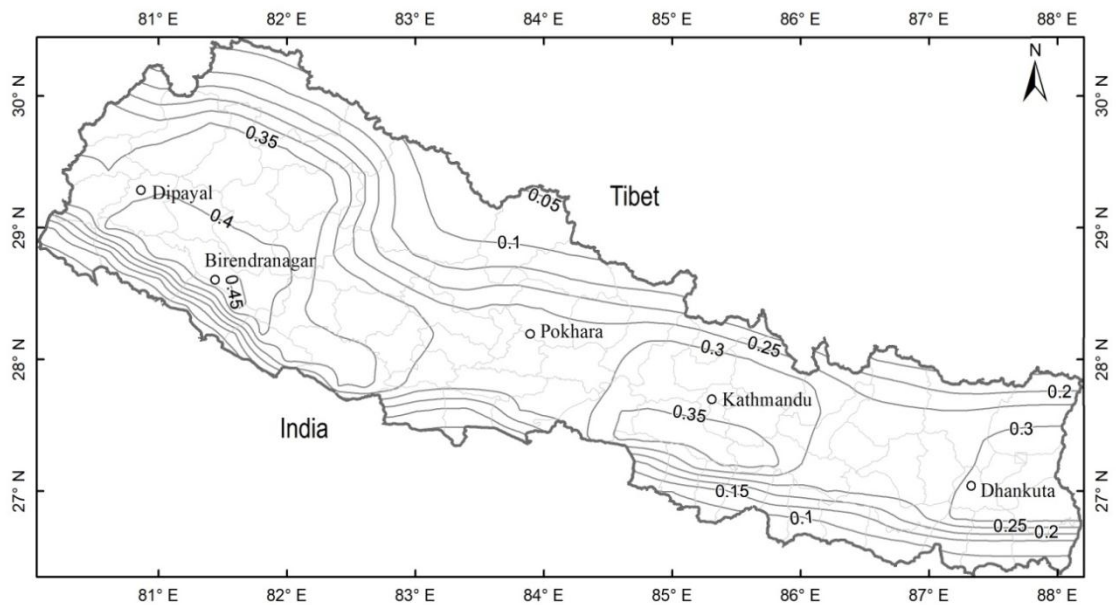
## APPENDIX 14

Variation in seismic hazard with variation in maximum potential magnitude. Common model (Appendix 11-1), common attenuation relation and common recurrence parameters were used in this test.

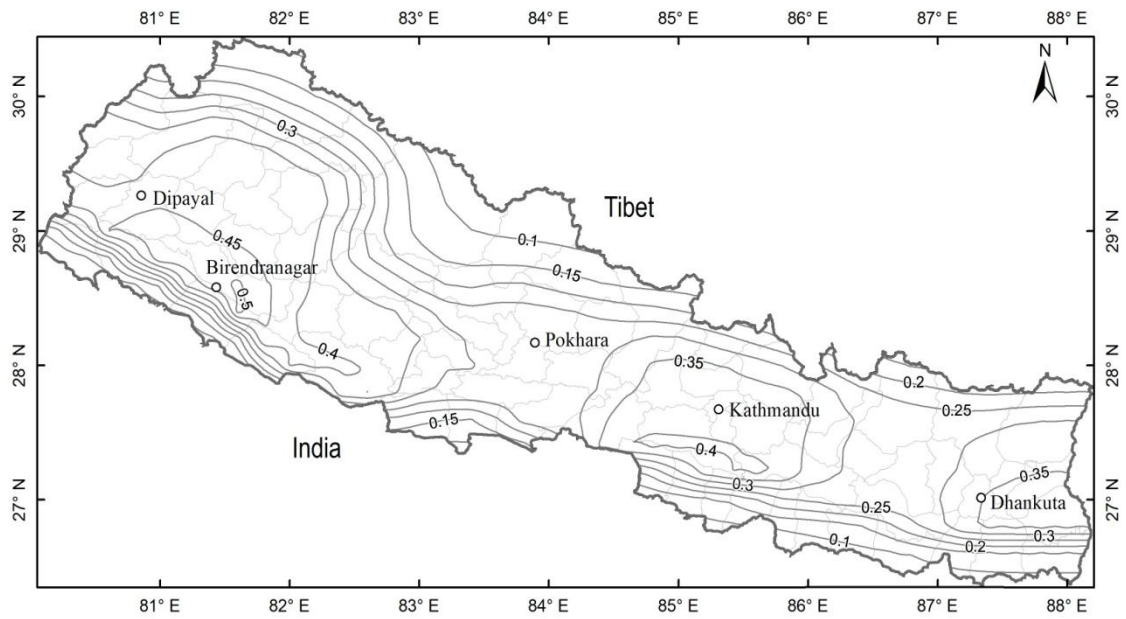
**Appendix 14-1:** Seismic hazard map using maximum potential magnitude ( $M_w$ ) 6.5. The maximum PGA is about 0.4 g in far-west and 0.3 g in Kathmandu Valley.



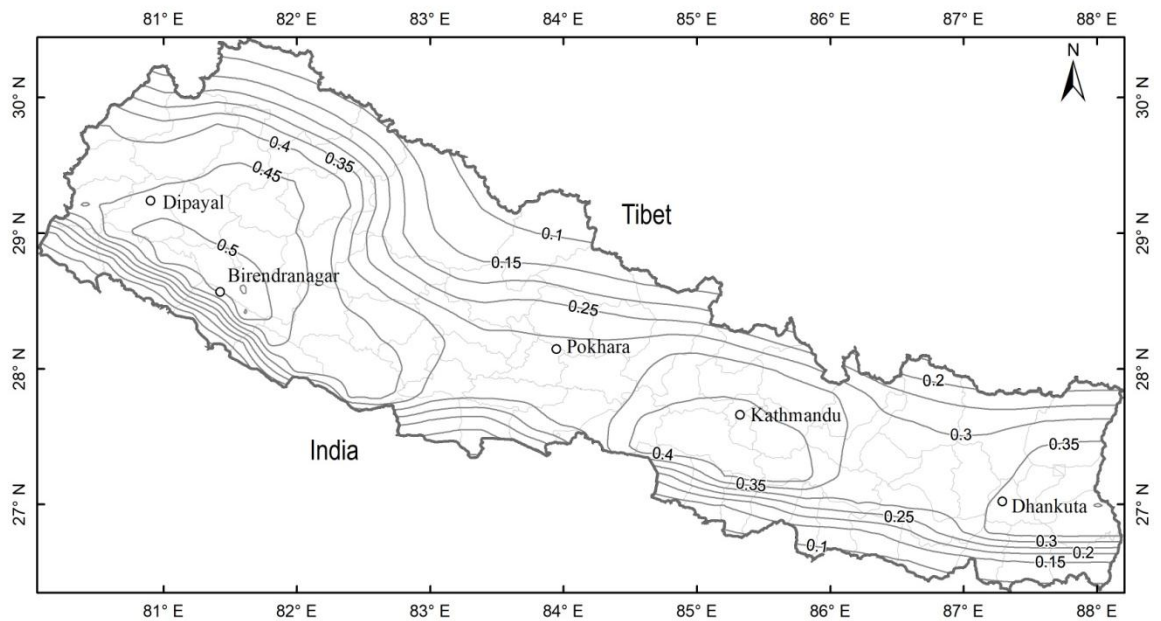
**Appendix 14-2:** Seismic hazard map using ( $M_w$ ) 7.0 as maximum potential magnitude. The maximum PGA is about 0.45 g in a small area in far-west and 0.3 g in Kathmandu Valley.



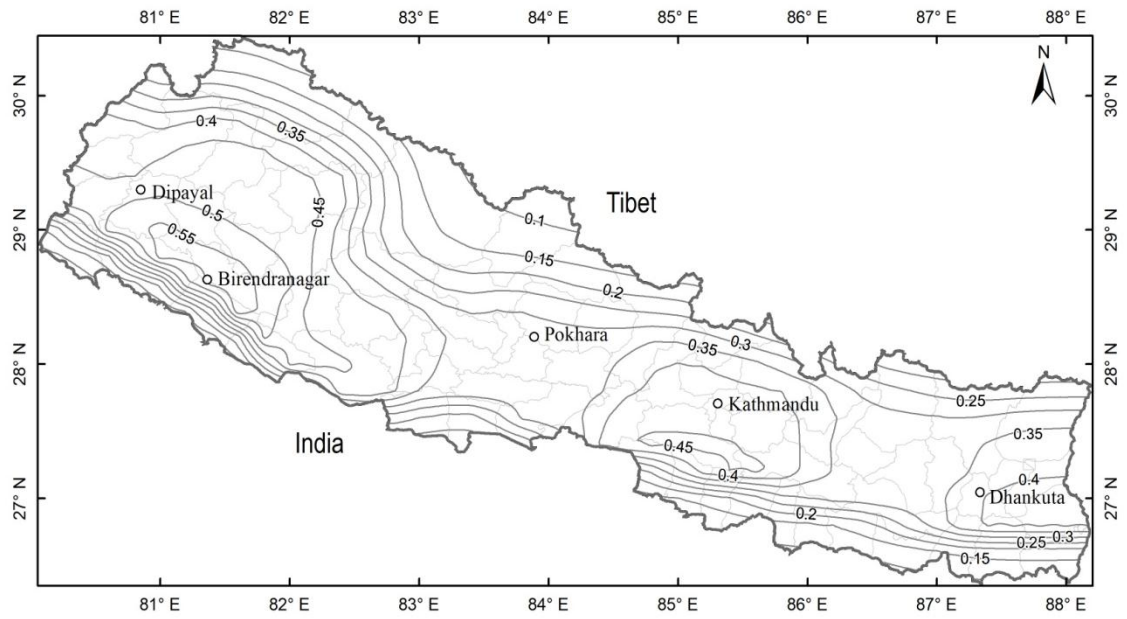
**Appendix 14-3:** Seismic hazard map using (Mw) 7.5 as maximum potential magnitude. The maximum PGA is about 0.5 g in a small area in far-west and 0.35 g in Kathmandu Valley.



**Appendix 14-4:** Seismic hazard map using (Mw) 8.0 as maximum potential magnitude of sources. The maximum PGA is about 0.5 g in a small area in far-west and 0.4 g in Kathmandu Valley.



**Appendix 14-5:** Seismic hazard map using (Mw) 8.5 as maximum potential magnitude. The maximum PGA is about 0.55 g in a small area in far-west and 0.4 g in Kathmandu Valley.



## APPENDIX 15

Maximum potential magnitude and earthquake recurrence parameters of identified earthquake sources. The magnitudes of the earthquake sources, which are segments of the MHT were calculated using Equations 1, 2, 3, and 4. The magnitudes of other sources from South Tibet and north India were fixed to Mw 7.5 as we don't have data of large earthquakes and experience in those regions.

**Appendix 15-1:** Maximum potential magnitude and earthquake recurrence parameters of sources in Model-1 (Appendix11-1). The maximum potential magnitude of Model-2 and Model-3 were estimated assuming half rupture area of the corresponding sources in Model-1.

Source	a-value	b-value	$\lambda$	$\beta$	Max Mw
M1-1	4.3	0.95	0.37	2.19	8.2
M1-2	3.9	0.95	0.14	2.19	8.2
M1-3	4.2	0.95	0.27	2.19	8.2
M1-4	4.4	0.95	0.45	2.19	8.1
M1-5	4.4	0.95	0.40	2.19	8.2
M1-6	4.1	0.95	0.22	2.19	8.1
M1-7	4.1	0.95	0.23	2.19	8.3

**Appendix 15-2:** Maximum potential magnitude and earthquake recurrence parameters of sources in Model-2 (Appendix 11-2).

Source	a-value	b-value	$\lambda$	$\beta$	Max Mw
M2-1	4.3	0.95	0.37	2.19	7.9
M2-2	3.9	0.95	0.14	2.19	7.9
M2-3	4.2	0.95	0.27	2.19	7.9
M2-4	4.4	0.95	0.45	2.19	7.8
M2-5	4.4	0.95	0.40	2.19	8.0
M2-6	4.1	0.95	0.22	2.19	7.8
M2-7	4.1	0.95	0.23	2.19	8.0

**Appendix 15-3:** Maximum potential magnitude and earthquake recurrence parameters of sources in Model-3 (Appendix 11-3).

Source	a-value	b-value	$\lambda$	$\beta$	Mmax
M3-1	4.3	0.95	0.37	2.19	7.9
M3-2	3.9	0.95	0.14	2.19	7.9
M3-3	4.2	0.95	0.27	2.19	7.9
M3-4	4.4	0.95	0.45	2.19	7.8
M3-5	4.4	0.95	0.40	2.19	8.0
M3-6	4.1	0.95	0.22	2.19	7.8
M3-7	4.1	0.95	0.23	2.19	8.0

**Appendix 15-4:** Maximum potential magnitude and earthquake recurrence parameters of sources in Model-4 (Appendix 11-4).

Source	a-value	b-value	$\lambda$	$\beta$	Mmax
M4-1	4.2	1.1	0.05	2.53	7.5
M4-2	4.2	1.1	0.13	2.53	7.5
M4-3	4.9	1.1	0.26	2.53	7.5
M4-4	4.3	0.95	0.32	2.19	8.4
M4-5	4.3	0.95	0.39	2.19	8.2
M4-6	3.9	0.95	0.15	2.19	8
M4-7	4.2	0.95	0.30	2.19	8.2
M4-8	4.0	0.95	0.16	2.19	8
M4-9	4.2	0.95	0.25	2.19	8.1
M4-10	4.5	1	0.34	2.30	7.5
M4-11	4.5	0.95	0.60	2.19	5.2
M4-12	4.4	0.95	0.50	2.19	8.3
M4-13	5.3	1.1	0.64	2.53	7.5
M4-14	5.1	1.1	0.44	2.53	7.5
M4-15	4.9	1.1	0.28	2.53	7.5
M4-16	5.1	1.1	0.44	2.53	7.5
M4-17	5.3	1.1	0.59	2.53	7.5
M4-18	5.2	1.1	0.50	2.53	7.5
M4-19	5.1	1.1	0.40	2.53	7.5
M4-20	5.0	1.1	0.32	2.53	7.5

**Appendix 15-5:** Maximum potential magnitude and earthquake recurrence parameters of sources in Model-5 (Appendix 11-5)

Source	a-value	b-value	$\lambda$	$\beta$	Mmax
M5-1	4.4	1.1	0.07	2.53	7.5
M5-2	4.5	1.1	0.11	2.53	7.5
M5-3	4.6	1.1	0.11	2.53	7.5
M5-4	5.0	1.1	0.32	2.76	7.5
M5-5	3.7	0.95	0.09	2.19	8.3
M5-6	4.4	0.95	0.48	2.19	8.2
M5-7	3.8	0.95	0.11	2.19	7.9
M5-8	4.0	0.95	0.20	2.19	8.1
M5-9	4.8	1	0.56	2.53	8.1
M5-10	4.3	0.95	0.35	2.19	7.9
M5-11	4.1	0.95	0.20	2.19	7.9
M5-12	4.4	0.95	0.50	2.19	7.5
M5-13	4.2	0.95	0.28	2.19	7.7
M5-14	4.6	1	0.44	2.19	8.2
M5-15	4.9	1.1	0.26	2.53	7.5
M5-16	5.2	1.1	0.50	2.53	7.5
M5-17	4.9	1.1	0.23	2.53	7.5
M5-18	4.9	1.1	0.27	2.53	7.5
M5-19	4.7	1.1	0.14	2.53	7.5
M5-20	5.0	1.1	0.29	2.53	7.5
M5-21	5.2	1.1	0.51	2.53	7.5

**Appendix 15-6:** Maximum potential magnitude and earthquake recurrence parameters of sources in Model-6 (Appendix 11-6).

Source	a-value	b-value	$\lambda$	$\beta$	Mmax
M6-1	3.3	1.1	0.04	2.53	7.5
M6-2	3.7	1.1	0.08	2.53	7.5
M6-3	3.8	1.1	0.13	2.53	7.5
M6-4	4.6	1.1	0.72	2.53	7.5
M6-5	4.1	0.95	0.21	2.19	8.2
M6-6	4.2	0.95	0.30	2.19	8.1
M6-7	3.9	0.95	0.13	2.19	8
M6-8	4.2	0.95	0.30	2.19	8.3
M6-9	4.0	0.95	0.18	2.19	8.1
M6-10	4.1	0.95	0.20	2.19	8
M6-11	4.5	0.95	0.56	2.19	8.4
M6-12	4.4	0.95	0.49	2.19	8.5
M6-13	3.9	1.1	0.14	2.53	7.5
M6-14	4.6	1.1	0.14	2.53	7.5
M6-15	4.2	1.1	0.05	2.53	7.5
M6-16	4.1	1.1	0.04	2.53	7.5
M6-17	4.5	1.1	0.10	2.53	7.5
M6-18	4.5	1.1	0.09	2.53	7.5
M6-19	4.7	1.1	0.17	2.53	7.5
M6-20	4.6	1.1	0.13	2.53	7.5
M6-21	4.6	1.1	0.14	2.53	7.5
M6-22	3.9	1.1	0.03	2.53	7.5
M6-23	4.5	1.1	0.17	2.53	7.5
M6-24	4.1	1.1	0.16	2.53	7.5

**Appendix 15-7:** Maximum potential magnitude and earthquake recurrence parameters of sources in Model-7 (Appendix 11-7).

Source	a-value	b-value	$\lambda$	$\beta$	Mmax
M7-1	3.8	0.95	0.12	2.19	7.5
M7-2	4.0	0.95	0.20	2.19	7.5
M7-3	3.9	0.95	0.15	2.19	7.5
M7-4	4.5	0.95	0.54	2.19	8.2
M7-5	4.0	0.95	0.17	2.19	7.9
M7-6	4.4	0.95	0.42	2.19	8.2
M7-7	4.4	0.95	0.50	2.19	8.2
M7-8	4.8	1	0.57	2.30	8.3
M7-9	4.5	0.95	0.61	2.19	8.3
M7-10	4.8	1.1	0.19	2.53	7.5
M7-11	4.2	1.1	0.05	2.53	7.5
M7-12	4.3	1.1	0.07	2.53	7.5
M7-13	4.6	1.1	0.12	2.53	7.5
M7-14	5.0	1.1	0.28	2.53	7.5
M7-15	5.0	1.1	0.28	2.53	7.5



**Appendix 15-8:** Maximum potential magnitude and earthquake recurrence parameters of sources in Model-8 (Appendix 11-8).

Source	a	b	$\lambda$	$\beta$	Mmax
M8-1	3.5	0.95	0.06	2.19	7.5
M8-2	2.7	0.95	0.01	2.19	7.5
M8-3	2.7	0.95	0.01	2.19	7.5
M8-4	2.6	0.95	0.01	2.19	7.5
M8-5	4.8	0.95	1.19	2.19	7.5
M8-6	4.3	0.95	0.40	2.19	8.4
M8-7	4.4	0.95	0.54	2.19	8.4
M8-8	4.4	0.95	0.51	2.19	8.5
M8-9	4.4	0.95	0.56	2.19	8.5
M8-10	4.9	0.95	1.45	2.19	8.5
M8-11	4.5	0.95	0.62	2.19	8.6
M8-12	4.1	0.95	0.22	2.19	7.5
M8-13	5.3	1.1	0.79	2.53	7.5
M8-14	5.6	1.1	1.47	2.53	7.5
M8-15	5.7	1.1	1.87	2.53	7.5
M8-16	5.3	1.1	0.67	2.53	7.5
M8-17	5.6	1.1	1.42	2.53	7.5
M8-18	4.8	1.1	0.5	2.53	7.5

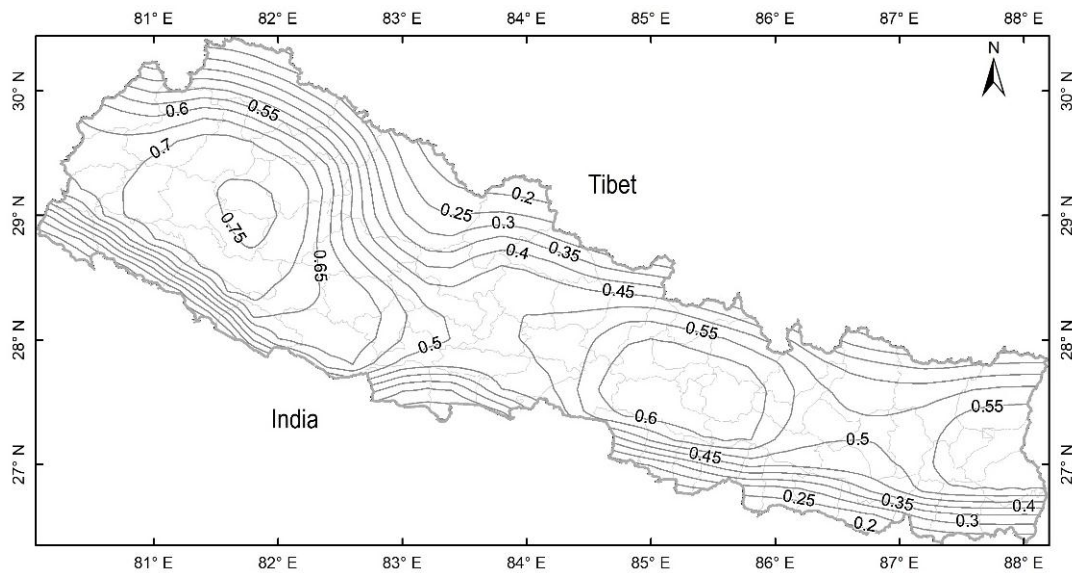
**Appendix 15-9:** Maximum potential magnitude and earthquake recurrence parameters of sources in Model-9 (Appendix 11-9).

Source	a	b	$\lambda$	$\beta$	Mmax
M9-1	4.3	0.95	0.34	2.18	8.4
M9-3	4.7	1.10	0.18	2.53	7.5
M9-4	4.3	1.10	0.06	2.53	7.5
M9-5	3.6	1.00	0.04	2.303	7.5
M9-6	4.3	0.95	0.35	2.18	8.3
M9-7	4.8	1.10	0.22	2.53	7.0
M9-8	4.8	1.10	0.2	2.53	7.5
M9-9	4.8	1.10	0.2	2.53	7.5
M9-10	4.0	0.95	0.2	2.18	8.1
M9-11	4.6	1.10	0.14	2.53	7.5
M9-12	4.7	1.10	0.16	2.53	7.5
M9-14	4.2	1.10	0.05	2.53	7.5
M9-15	4.7	1.10	0.15	2.53	7.5
M9-16	5.6	1.20	0.38	2.76	7.5
M9-17	3.8	0.95	0.12	2.18	8.0
M9-18	4.2	0.95	0.31	2.18	8.2
M9-19	5.6	1.20	0.39	2.76	7.5
M9-20	4.3	0.95	0.39	2.18	8.3
M9-21	4.3	0.95	0.4	2.18	8.4
M9-22	5.0	1.20	0.1	2.76	7.5
M9-23	4.5	1.10	0.1	2.53	7.5
M9-24	4.0	0.95	0.2	2.18	8.3

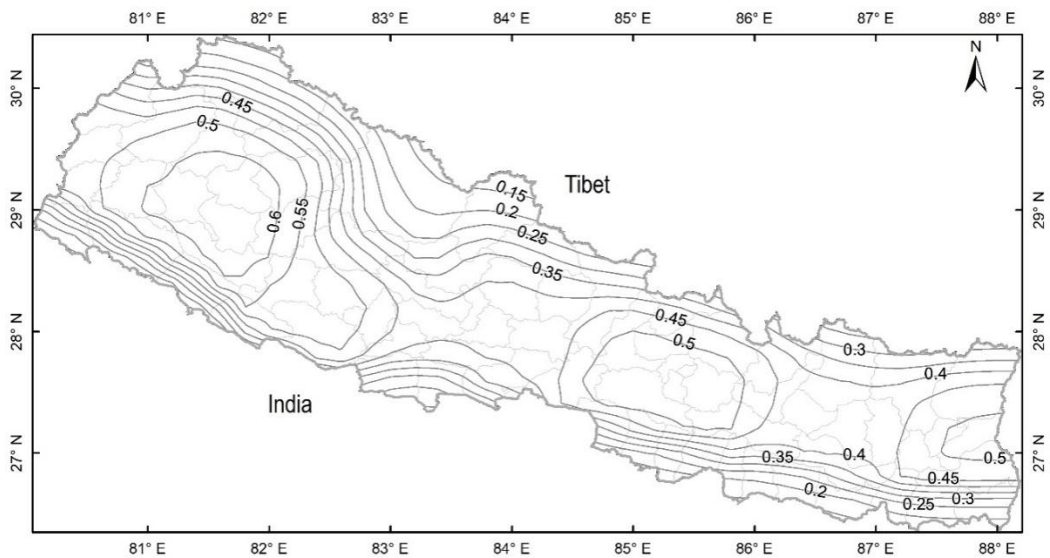
## APPENDIX 16

Variation of seismic hazard with variation in b-value. The b-value was changed from 0.7 to 1.2 successively with the increment of 0.1. Common attenuation relation, common source model (Model-1) and common earthquake recurrence parameters were used in the following tests.

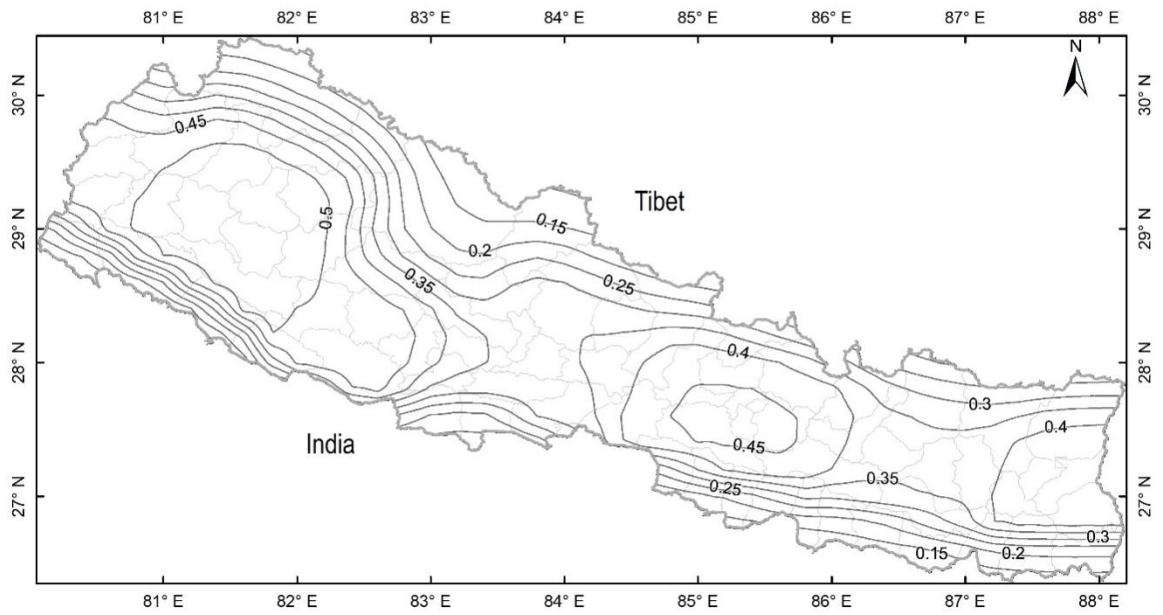
**Appendix 16-1:** Seismic hazard map prepared using b-value 0.7. The PGA is as high as 0.75 in the far-west and 0.6 in the Kathmandu Valley.



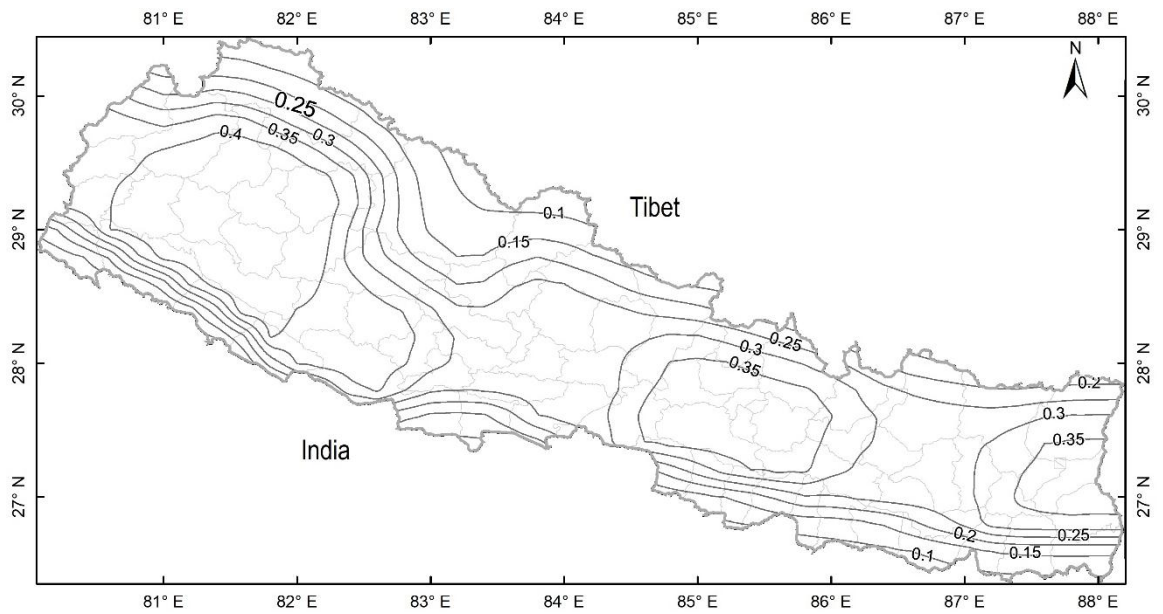
**Appendix 16-2:** Seismic hazard map prepared using b-value 0.8. The PGA is as high as 0.6 g in the far-west and 0.5 g in the Kathmandu Valley.



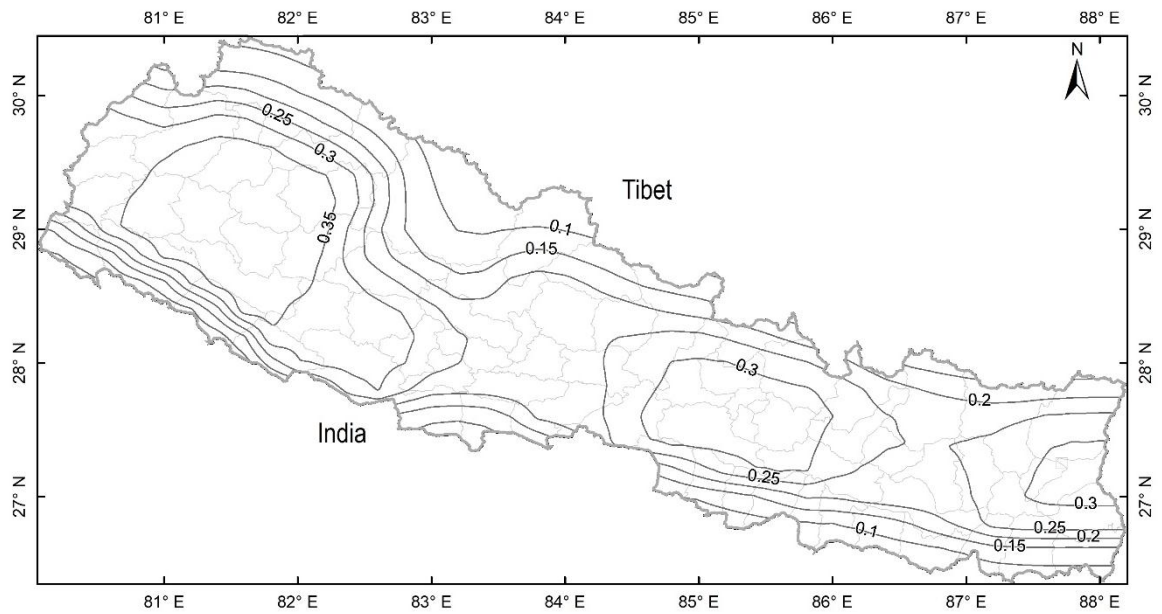
**Appendix 16-3:** Seismic hazard map prepared using b-value 0.9. The PGA is as high as 0.5 g in the far-west and 0.45 g in the Kathmandu Valley.



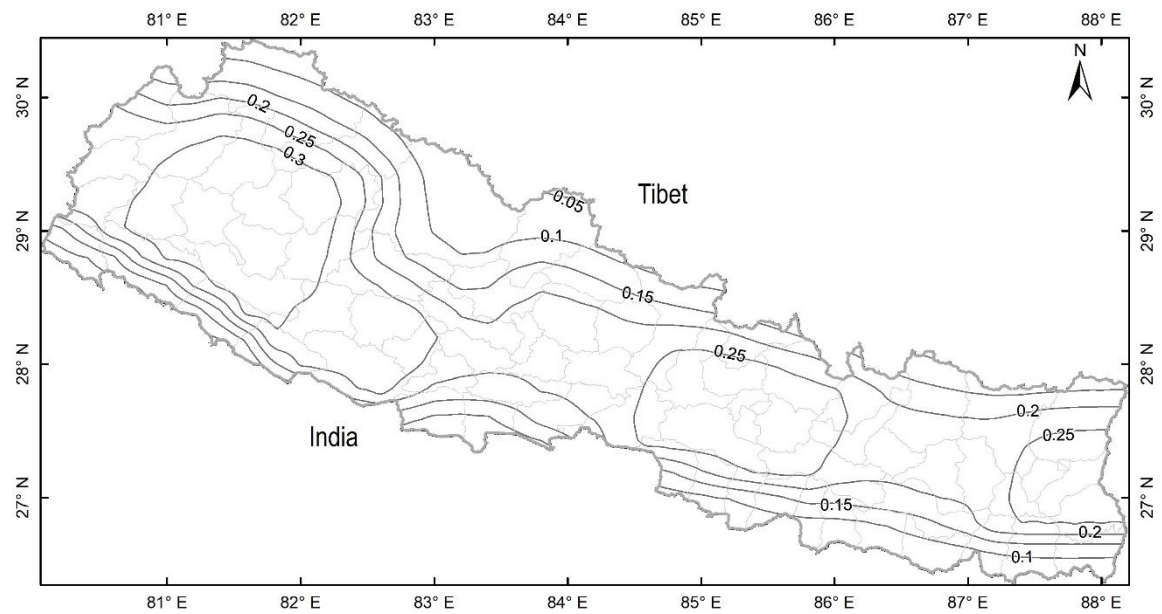
**Appendix 16-4:** Seismic hazard map prepared using b-value 1.0. The PGA is as high as 0.4 g in the far-west and 0.35 g in the Kathmandu Valley.



**Appendix 16-5:** Seismic hazard map prepared using b-value 1.1. The PGA is as high as 0.35 g in the far-west and 0.3 g in the Kathmandu Valley.



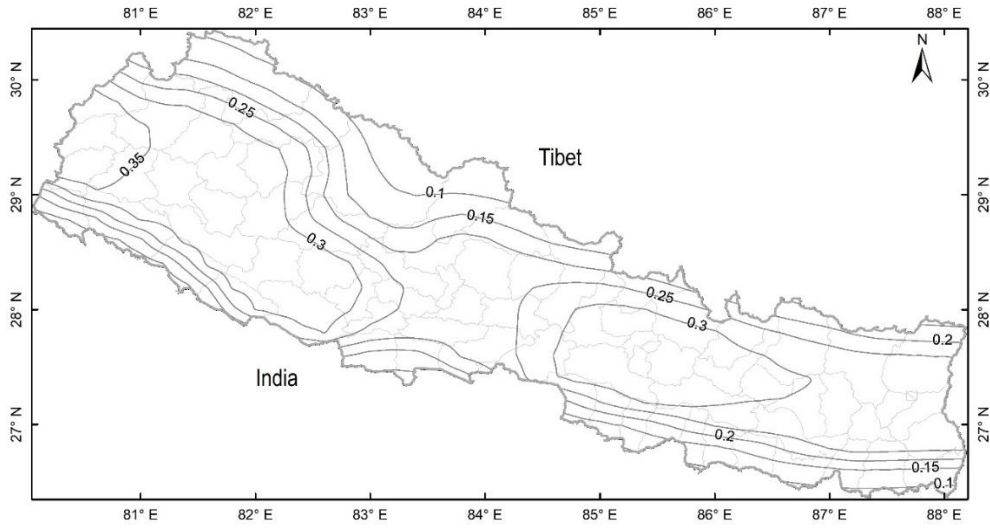
**Appendix 16-6:** Seismic hazard map prepared using b-value 1.2. The PGA is as high as 0.3 g in the far-west and 0.25 g in the Kathmandu Valley.



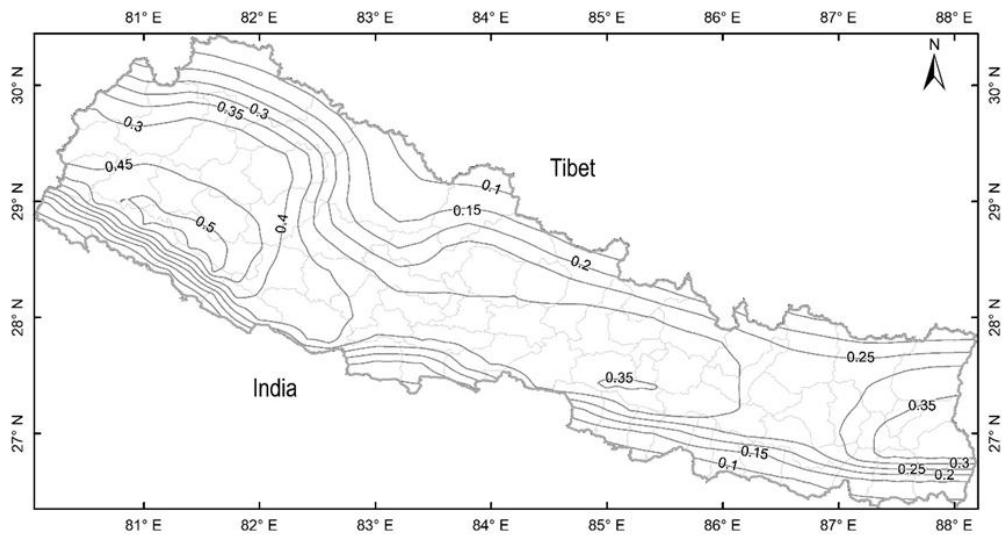
## APPENDIX 17

Variation in seismic hazard with different catalogues and differently estimated a- and b-values.

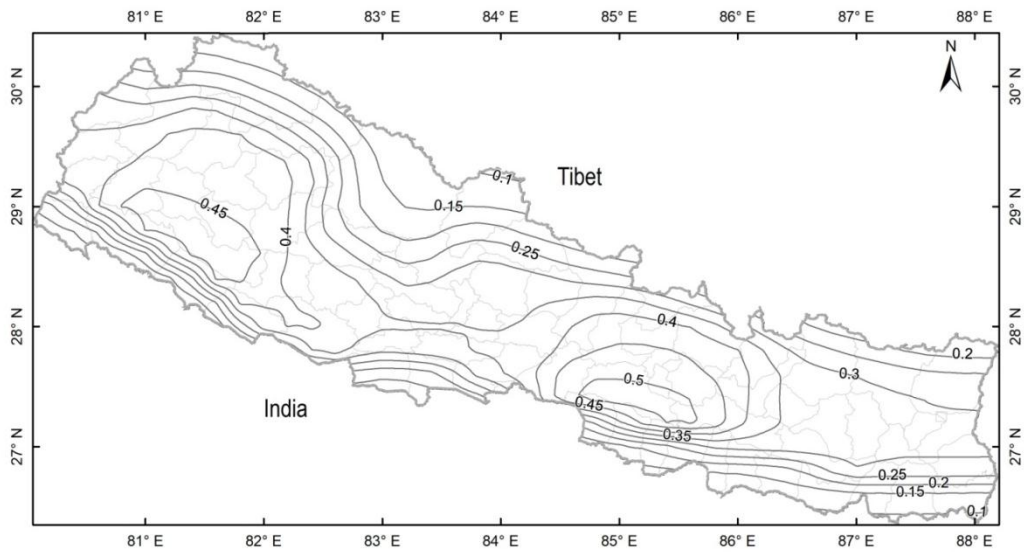
**Appendix 17-1:** Seismic hazard map prepared using an earthquake catalogue, which contains data since 1900 AD. The a- and b-values of the sources (Appendix 11-1) were calculated applying least square method.



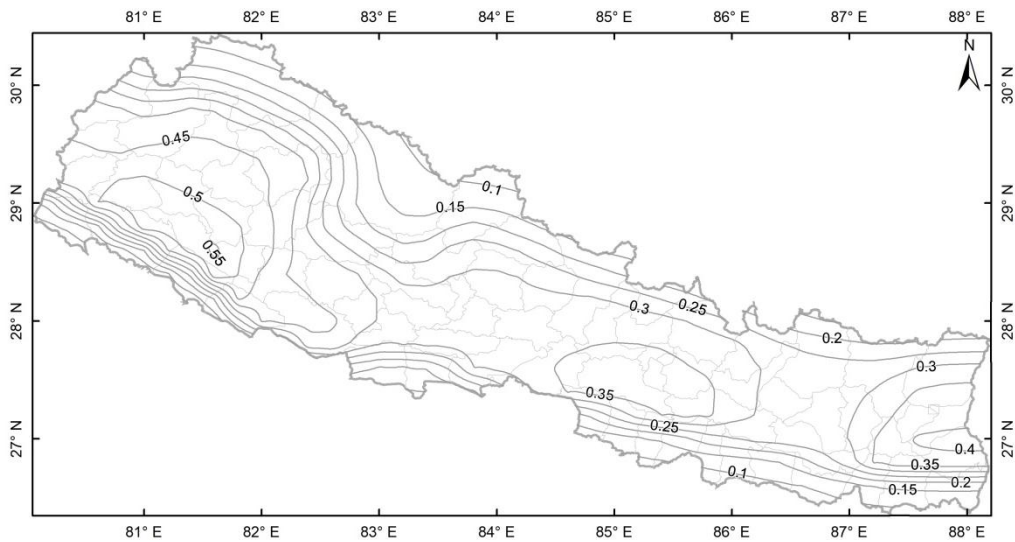
**Appendix 17-2:** Seismic hazard map prepared using data since 1900 AD. A fixed b-value of (0.95) was applied to all sources (Appendix 11-1) and a-values were calculated from the data.



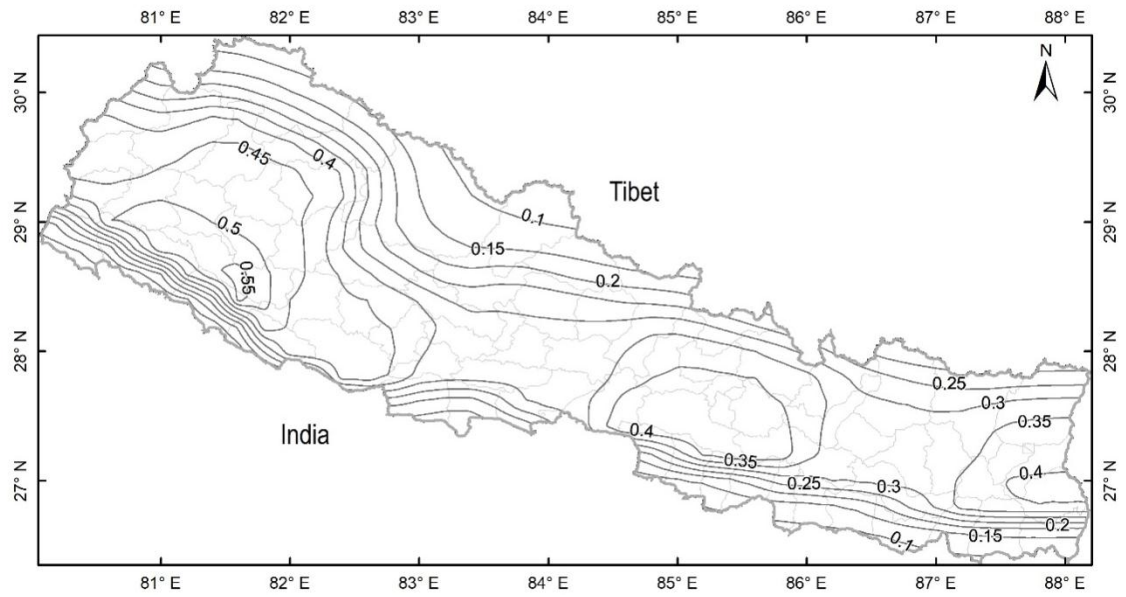
**Appendix 17-3:** Seismic hazard map prepared using data since 1100 AD. The a- and b-values of the sources (Appendix 11-1) were calculated applying least square method. The maximum PGA is larger than that in Appendix 17-2.



**Appendix 17-4:** Seismic hazard map prepared using earthquake parameters from the instrumental data available since 1100. A fixed b-value (0.95) was used to recalculate the a-values of the sources (Appendix 11-1). The maximum PGA is larger than that in Appendix 17-3.



**Appendix 17-5:** Seismic hazard map prepared using data since 1964. After 1964, there is regular reporting of earthquakes up to Mw 4.0. The b-value was fixed to 0.95 and a-values were recalculated from data. The maximum PGA is comparable to Appendix 17-4.

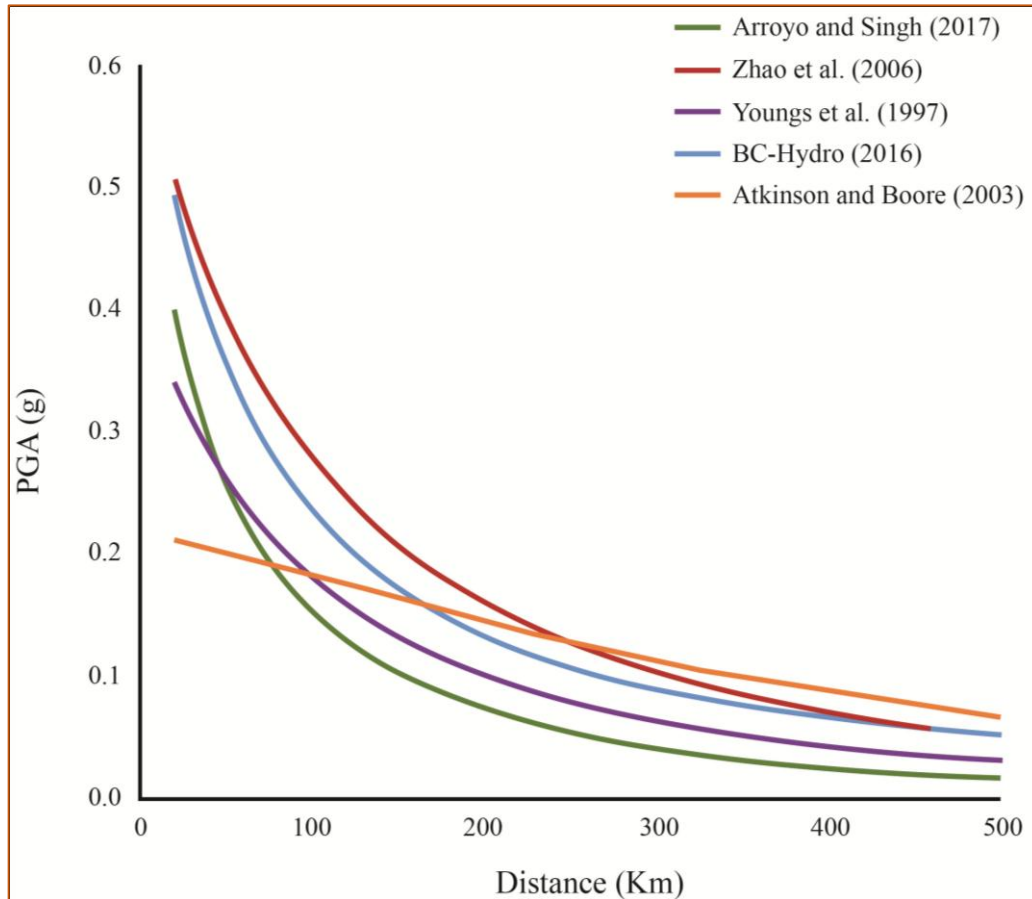




## APPENDIX 18

Attenuation relations (also called ground motion prediction equation (GMPE)), which were used in this study.

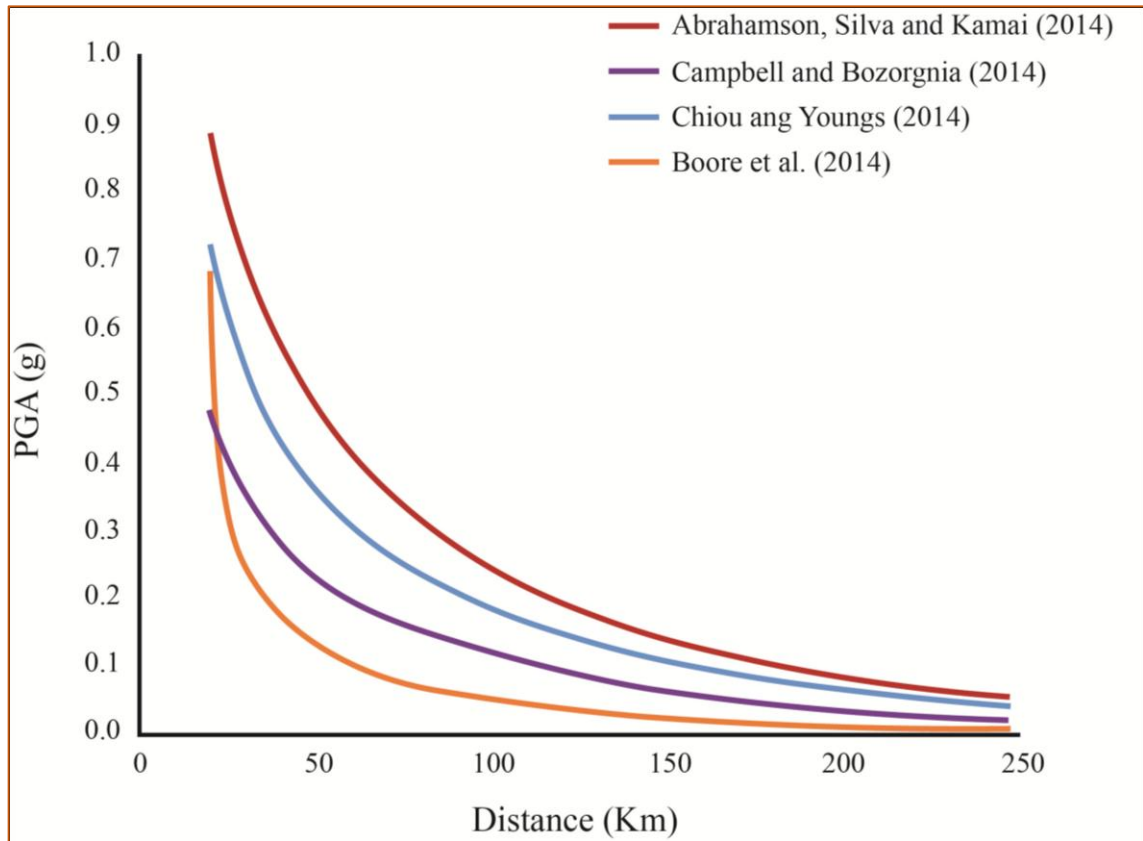
**Appendix 18-1:** Attenuation relations for subduction zone. The Atkinson and Boore (2003) relation was not used in hazard calculations because it produces considerably small hazard (Appendix 19-2)



**Appendix 18-2:** Description of attenuation relations for subduction zone.

Features	Attenuation relations				
	Zhao <i>et al.</i> (2006)	Young's <i>et al.</i> (1997)	BcHydro(2016)	Atkinson And Boore (2003)	Arroyo and Singh (2017)
Database	USA and Iran	Global	NGA-West2	Cascadia, Japan, Mexico, Central America	India and Nepal
Valid Distance (Km)	0-300	10-500	10-300	1-300	0-1000
Distance metric	Rrup	Rrup	Rrup	Rup	Rrup
Spectral Period (s)	0-5	0-5	0-10	0-3	0.01-6
Magnitude (Mw)	5-8.3	5-8.5	6-8.4	5-8.5	5-8.0
Unit	gal	gal	g	gal	gal

**Appendix 18-3:** Attenuation relation for shallow-active crustal earthquakes (normal fault earthquakes).



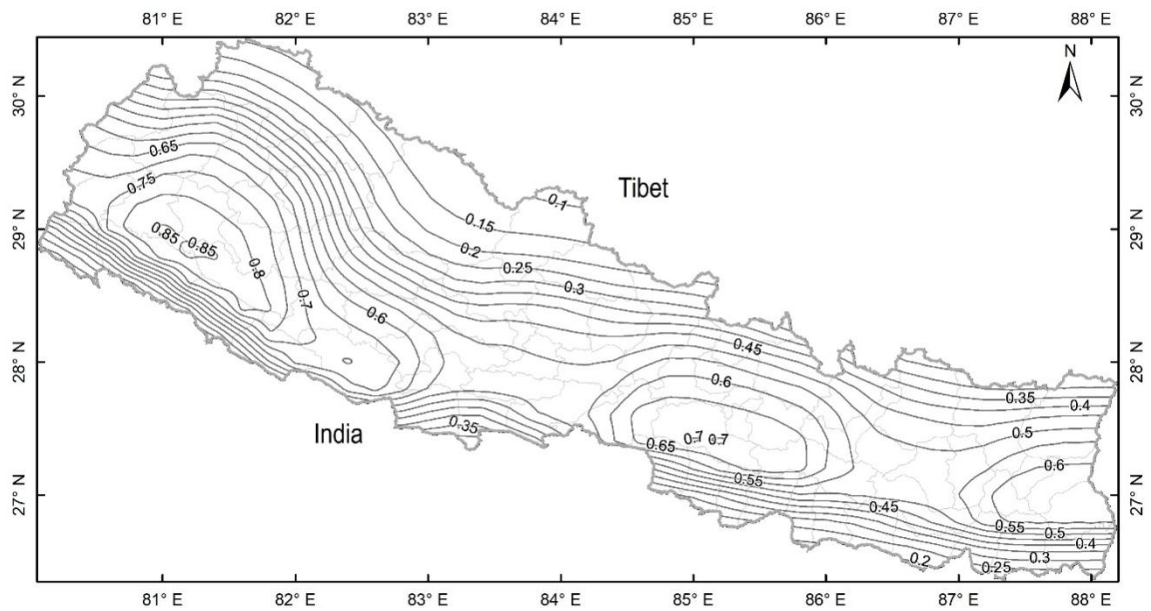
**Appendix 18-4:** Attenuation relations for subduction zone. The Atkinson and Boore (2003) relation produces the smallest PGA, therefore was not used. The other four relations were used in this study using a logic tree with equal weight for earthquake sources in the Himalaya (MHT).

Features	Attenuation relations			
	Abrahamson, Silva and Kamai (2014)	Boore <i>et al.</i> (2014)	Chiou and Youngs (2014)	Campbell and Bozorgnia (2014)
Database	NGA-West-2	NGA-West-2	NGA-West-2	NGA-West-2
Valid Distance (Km)	0-300	0-400	0-300	0-300
Distance metric	Rrup	Jyb	Rrup	Rup
Spectral Period (s)	0-10	0-10	0-10	0-10
Magnitude (Mw)	3-8.5	3-8.5	3.5-8	3-8.5
Unit	g	g	g	g

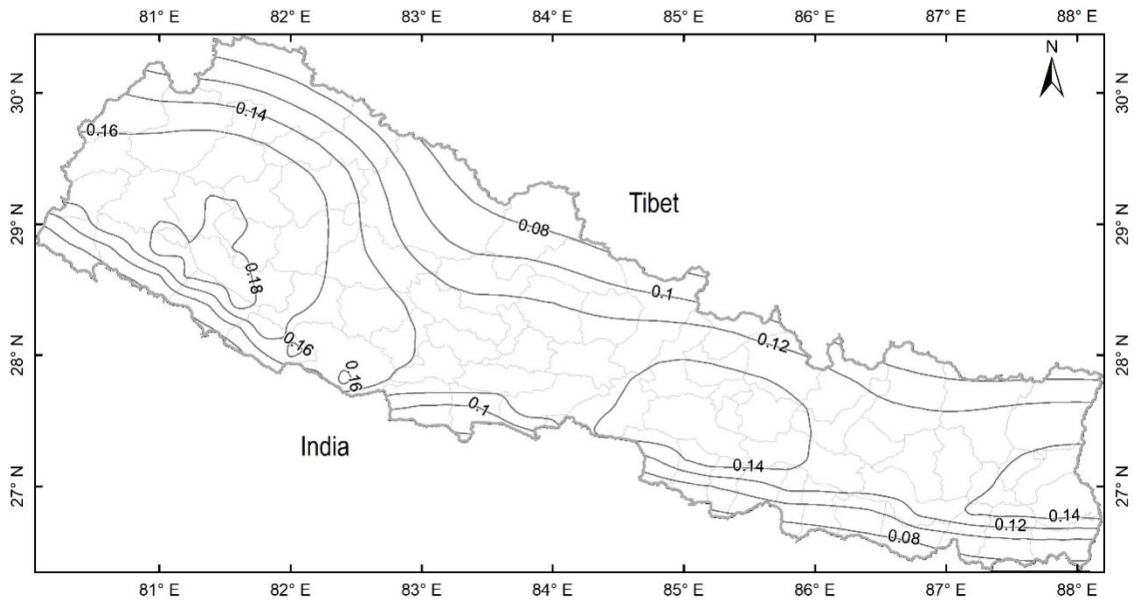
## APPENDIX 19

Common earthquake recurrence parameters to different attenuation relations, common attenuation relation and common source models were applied to different attenuation relations.

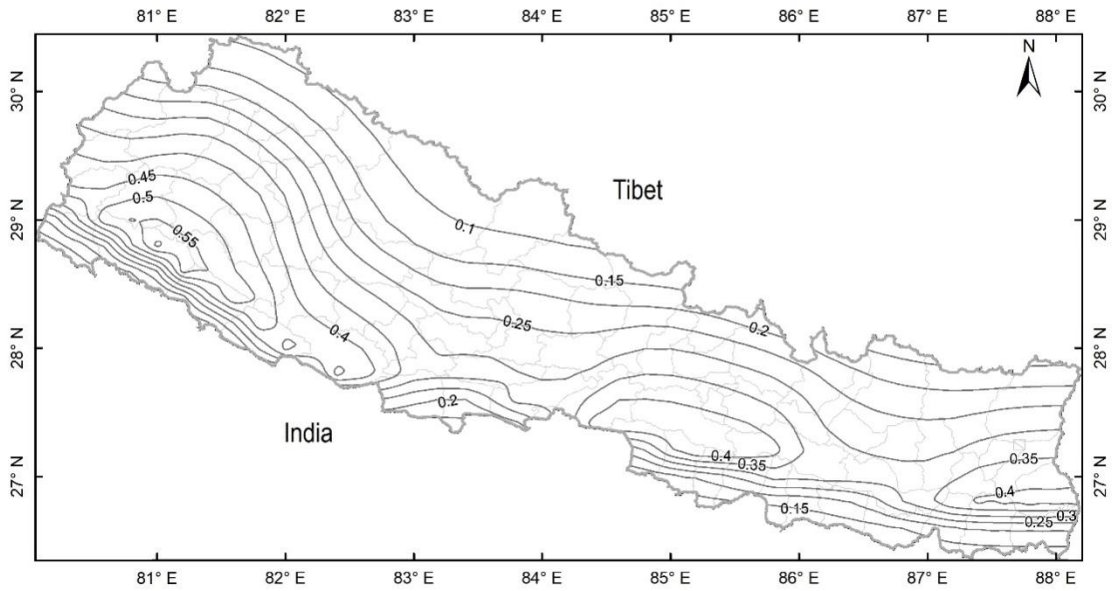
**Appendix 19-1:** Seismic hazard map prepared using Youngs *et al.* (1997) attenuation relation. This relation is for subduction region. The maximum PGA is larger than 0.85 g in the far-west and over 0.6 g in the Kathmandu Valley.



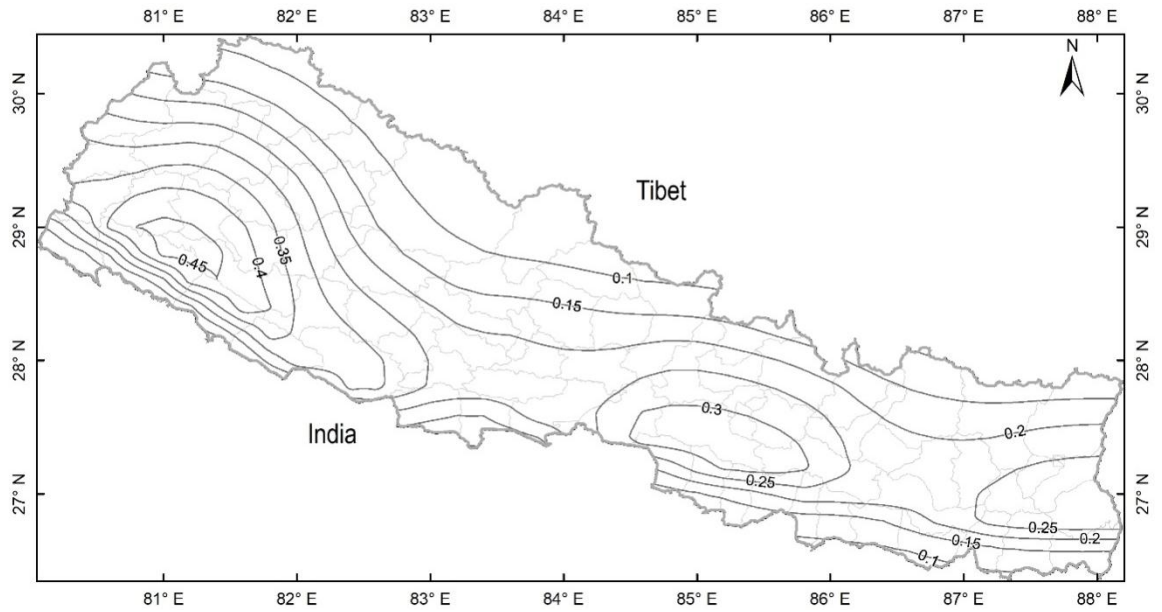
**Appendix 19-2:** Seismic hazard map prepared using Atkinson and Boore (2003) attenuation relation. This relation is for subduction region. The maximum PGA is very small (0.8 g) in the far-west and 0.14 g in the Kathmandu Valley in comparison to other relations.



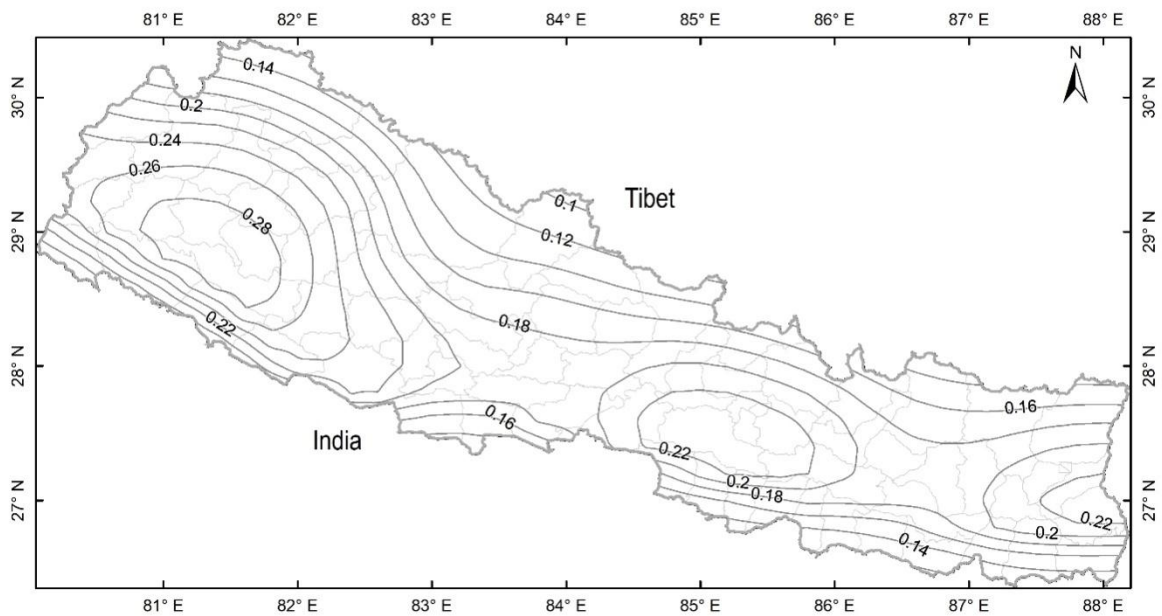
**Appendix 19-3:** Seismic hazard map prepared using Zhao *et al.* (2006) attenuation relation. The maximum PGA is larger than 0.5 g in the far-west and over 0.3 g in the Kathmandu Valley.



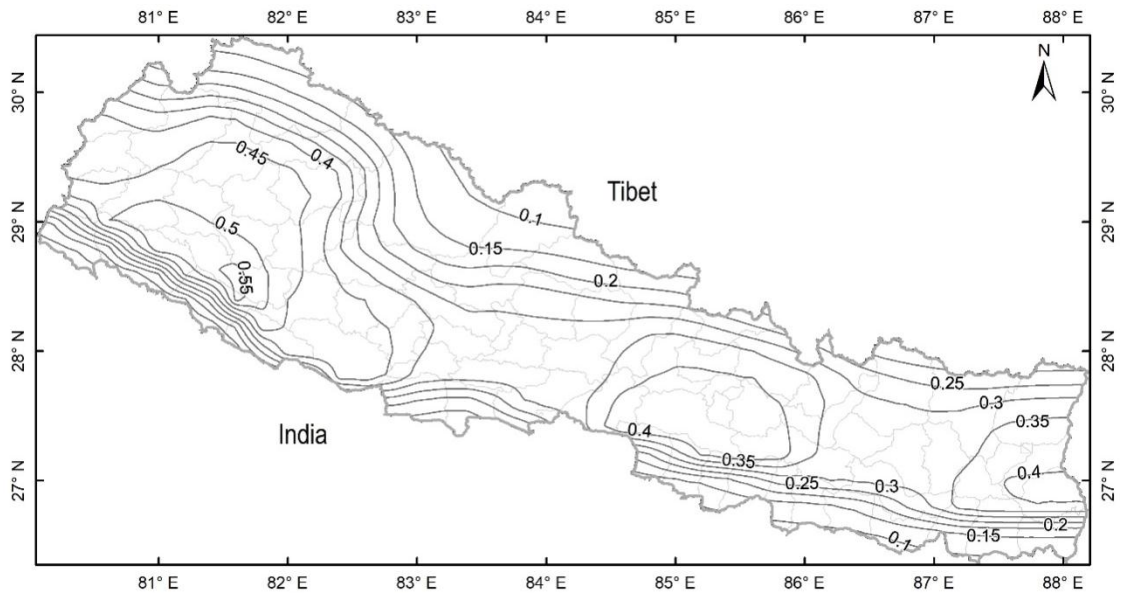
**Appendix 19-4:** Seismic hazard map prepared using BC-Hydro (2016) attenuation relation. The maximum PGA is larger 0.4 g than in far-west and over 0.25 g in the Kathmandu Valley.



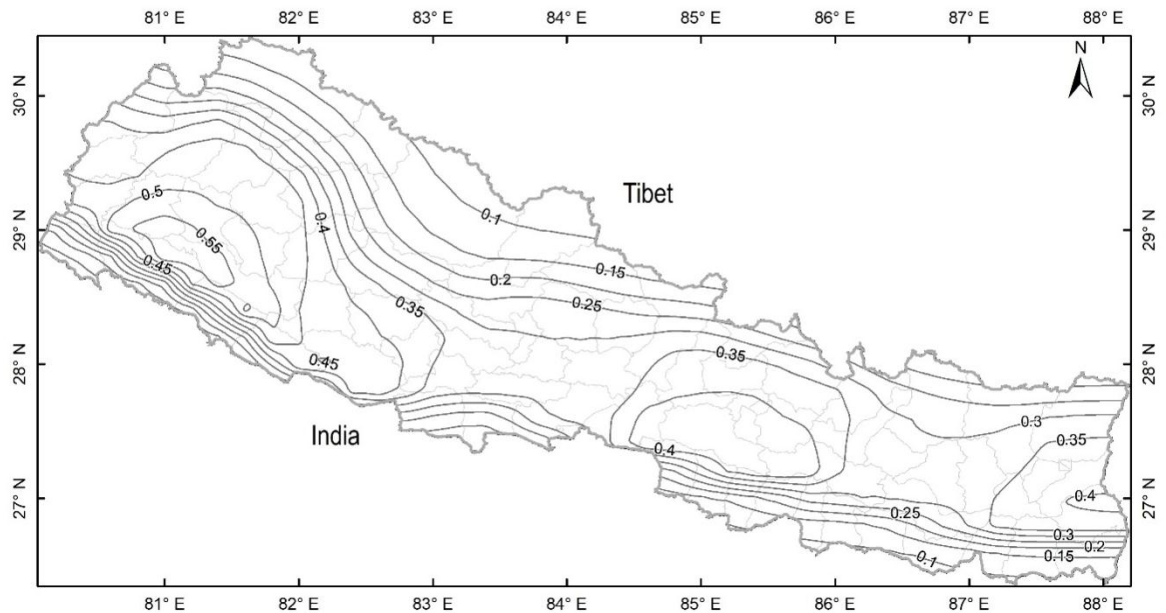
**Appendix 19-5:** Seismic hazard map prepared using Arroyo and Singh (2017) attenuation relation. The maximum PGA is larger than 0.28 g in the far-west and over 0.22 g in the Kathmandu Valley.



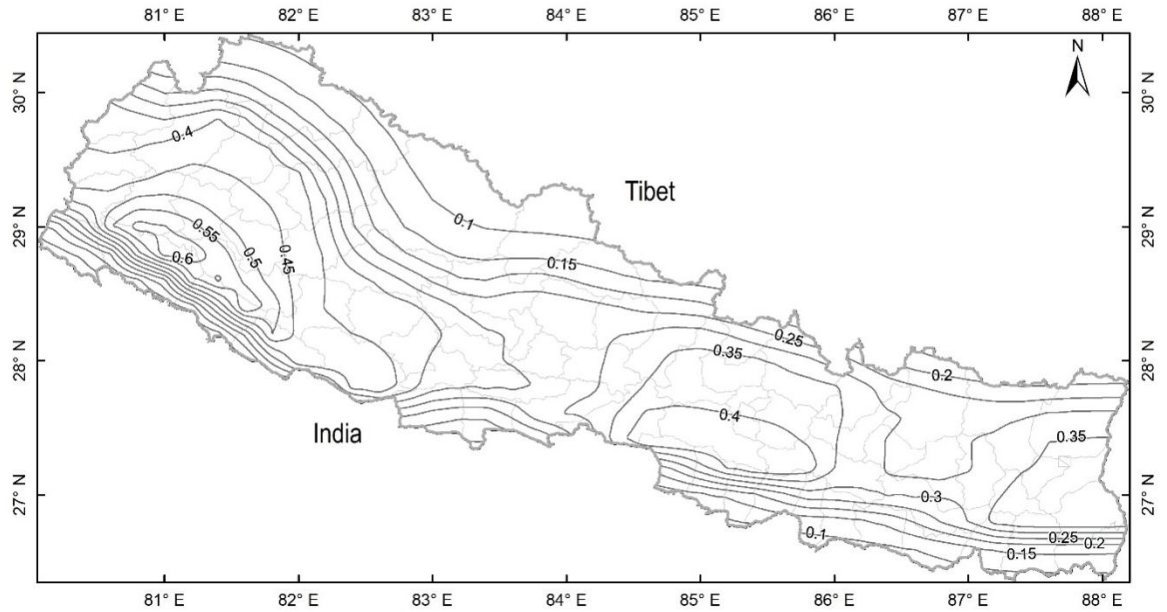
**Appendix 19-6:** Seismic hazard map prepared using Atkinson, Silva and Kamai (2014) attenuation relation. This relation and other relations onwards are for active shallow crustal earthquakes. The maximum PGA is larger than 0.5 g in the far-west and over 0.4 g in the Kathmandu Valley.



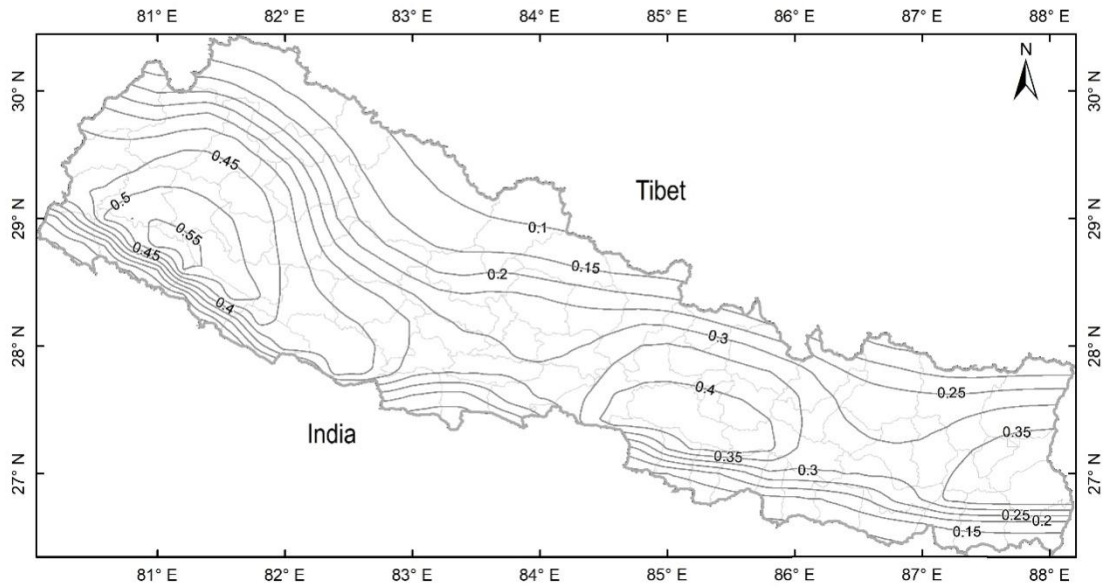
**Appendix 19-7:** Seismic hazard map prepared using Boore *et al.* (2014) attenuation relation. The maximum PGA is larger than 0.55 g in the far-west and over 0.35 g in the Kathmandu Valley.



**Appendix 19-8:** Seismic hazard map prepared using Campbell and Bozorgnia (2014) attenuation relation. The maximum PGA is larger than 0.55 g in the far-west and over 0.35 g in the Kathmandu Valley.



**Appendix 19-9:** Seismic hazard map prepared using Chiou and Youngs (2014) attenuation relation for active shallow crustal earthquakes. The maximum PGA is larger than 0.5 g in the far-west and over 0.35 g in the Kathmandu Valley.

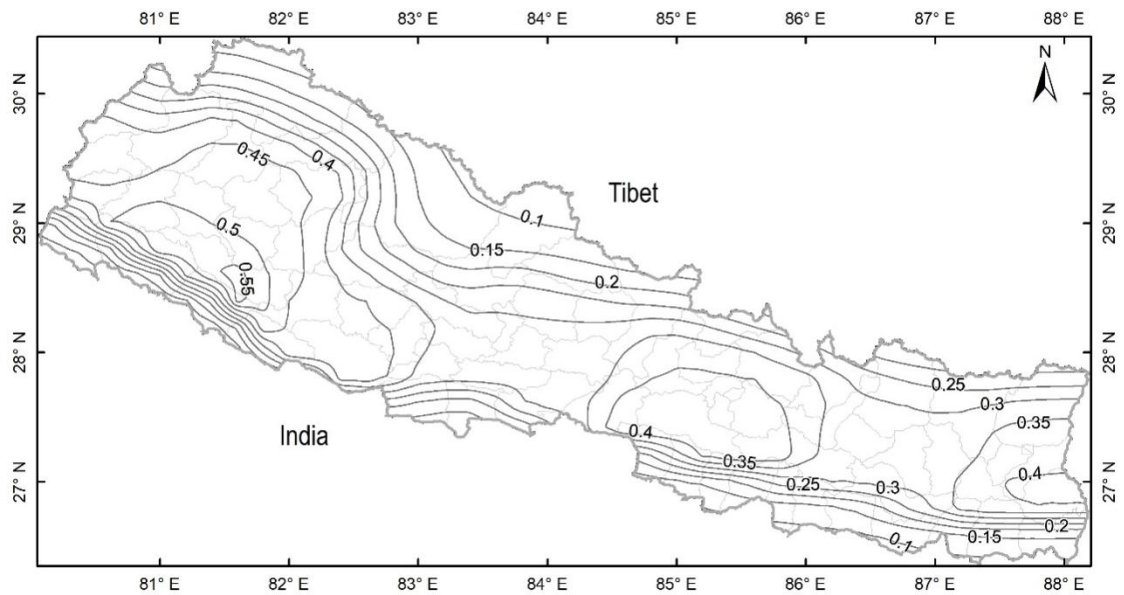




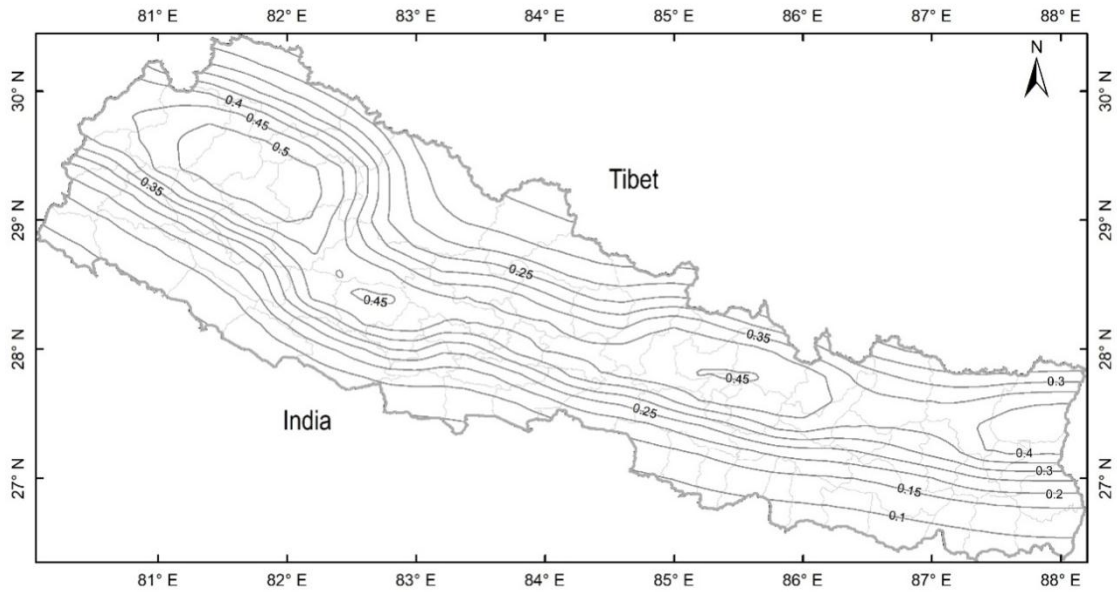
## APPENDIX 20

Seismic hazard maps prepared using different source models. Nine different source models were used with common attenuation relation and common earthquake recurrence parameters.

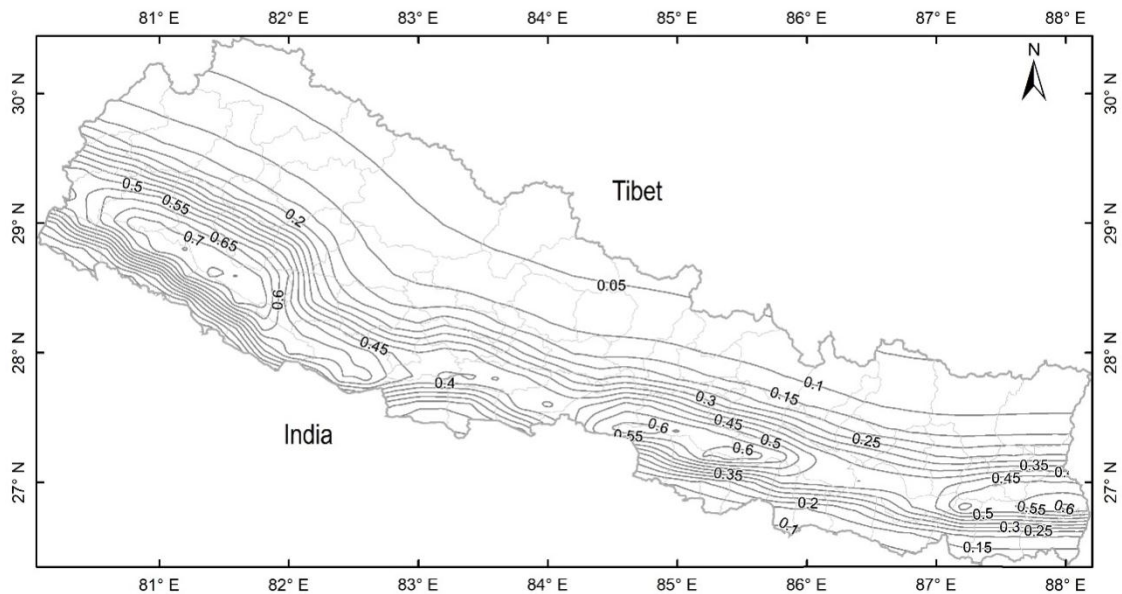
**Appendix 20-1:** Seismic hazard map prepared using Model-1 (Appendix 11-1).. The largest PGA is 0.55 g in the far-west.



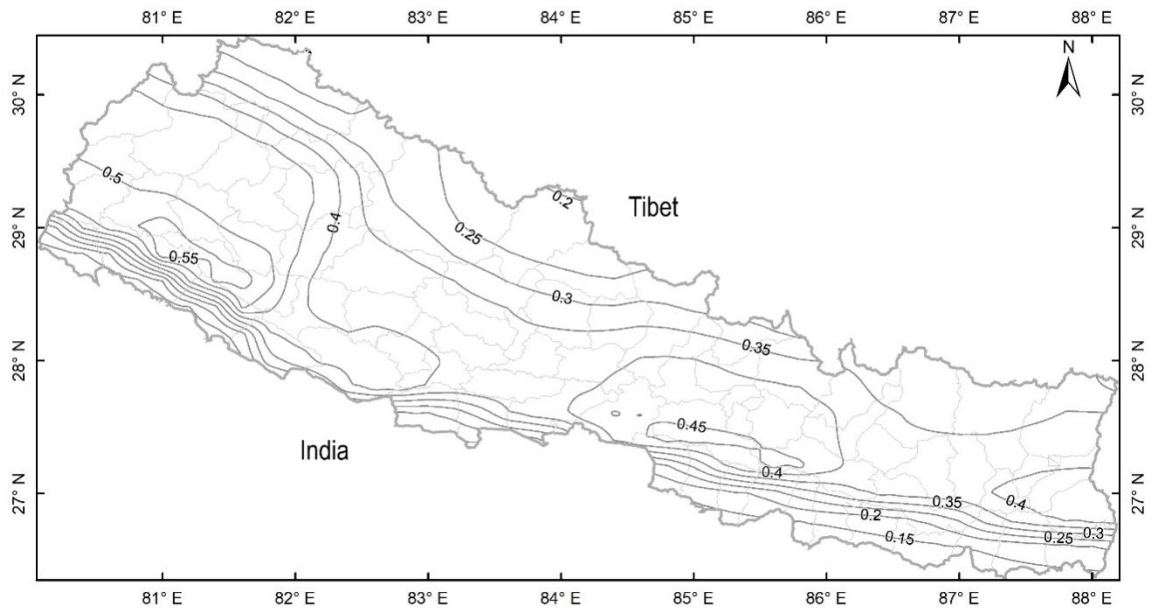
Appendix 20-2: Seismic hazard map prepared using Model 2 (Appendix 11-2). The high hazard is in the middle part because northern half area (rupture scenario) of Model-2 (Appendix 11-2) was used as a source. The sources have 20 km fixed depth in the north and 10 km in their southern part. The largest PGA is 0.5 g in the far-west and larger than 0.4 in the Kathmandu Valley.



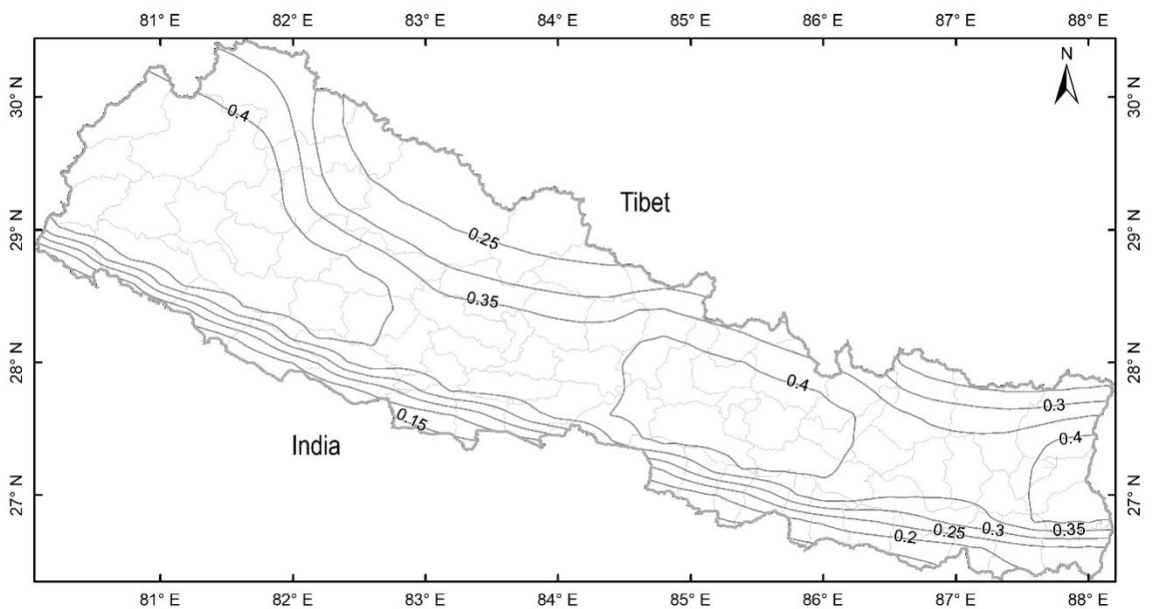
**Appendix 20-3:** Seismic hazard map prepared using Model-3 (Appendix 11-3). The sources have 10 km fixed depth in the north and 0 km in their southern border, where MHT emerges to the surface along MFT. The largest PGA is 0.7 g in the far-west and larger than 0.3 in the Kathmandu Valley.



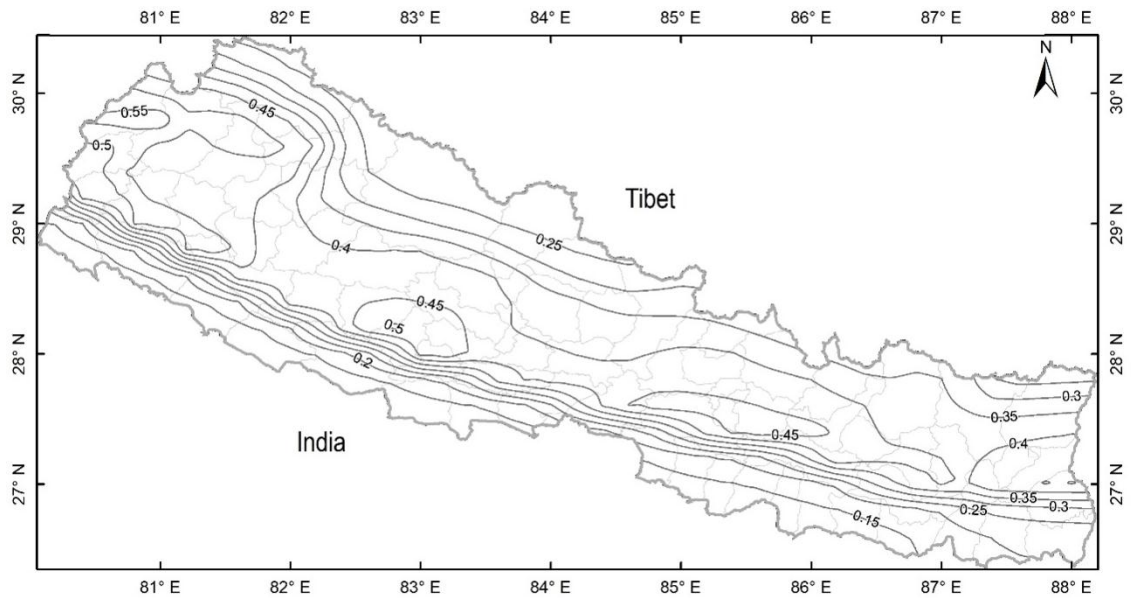
**Appendix 20-4:** seismic hazard map prepared using Model 4 (Appendix 11-4). The high hazard is in the southern part because of the geometry of the earthquake sources. The largest PGA is larger than 0.5 g in the far-west and larger than 0.4 in the Kathmandu Valley.



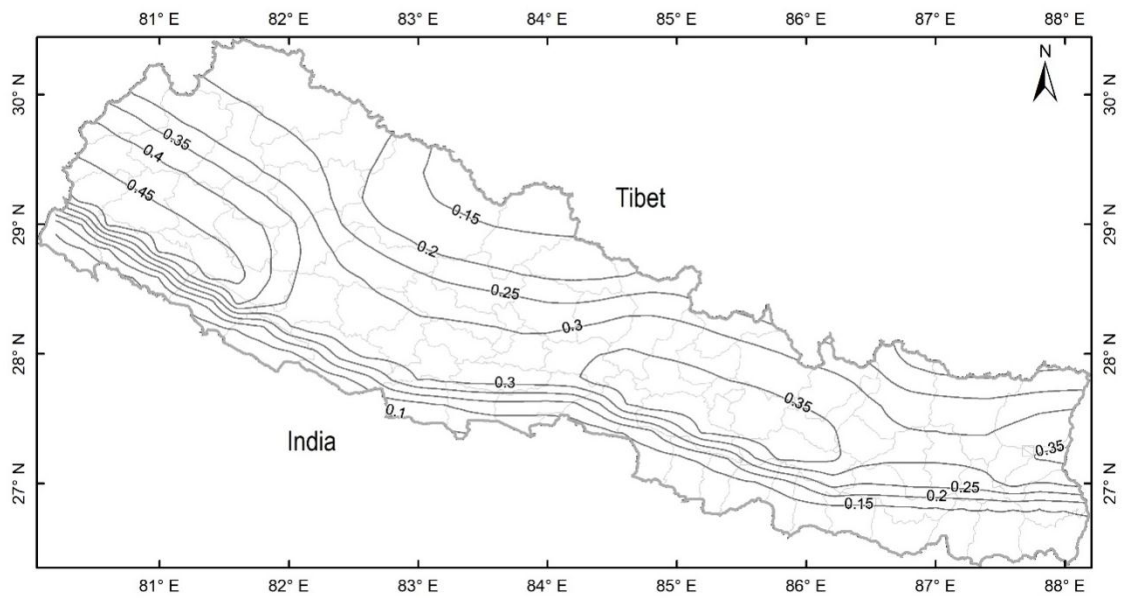
**Appendix 20-5:** seismic hazard map prepared using Model 5 (Appendix 11-5). The largest PGA is 0.4 g in the far-west and larger than 0.4 in the Kathmandu Valley.



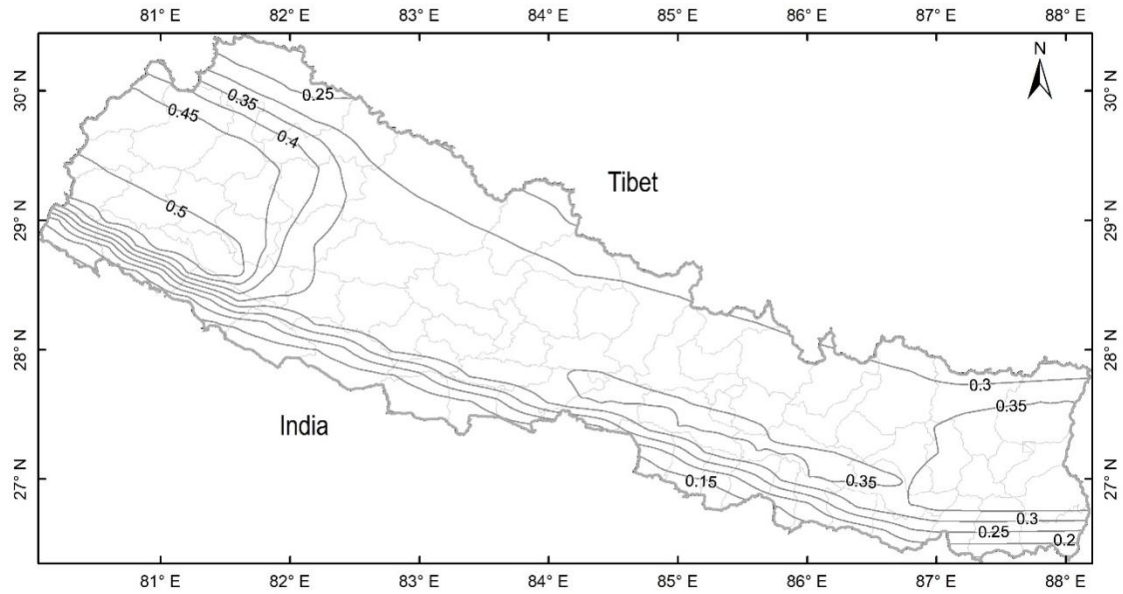
**Appendix 20-6:** seismic hazard map prepared using Model 6 (Appendix 11-6). The largest PGA is larger than 0.5 g in the southern part of far-west and larger than 0.4 in the Kathmandu Valley.



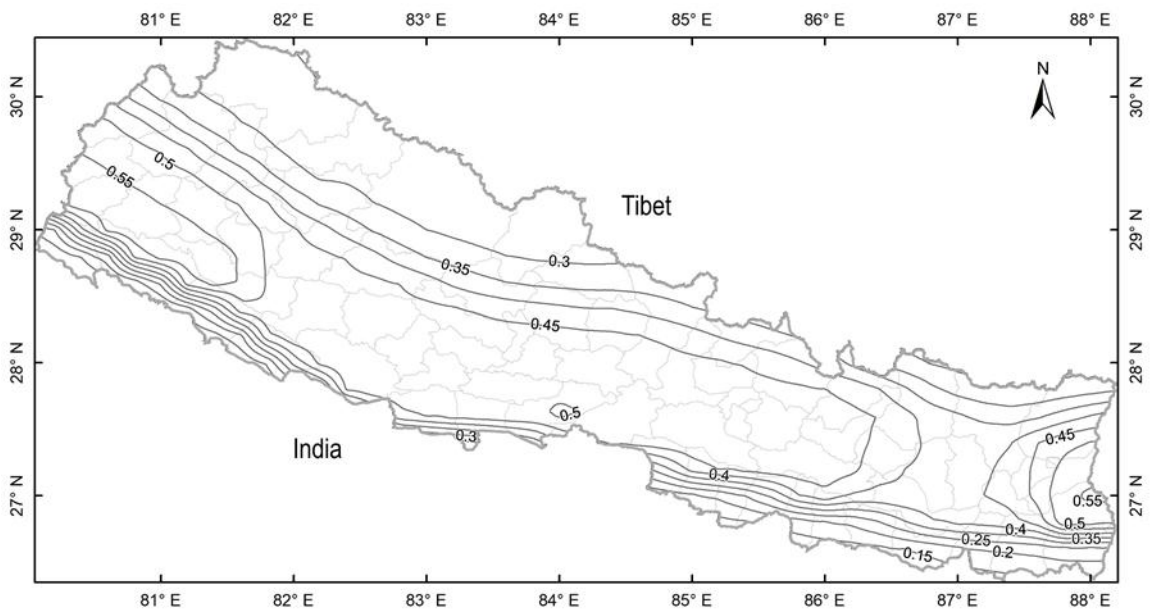
**Appendix 20-7:** seismic hazard map prepared using Model 7 (Appendix 11-7). The largest PGA is larger than 0.45 g in the southern part of far-west and larger than 0.35 in the Kathmandu Valley.



**Appendix 20-8:** Seismic hazard map prepared using Model 8 (Appendix 11-8). The high hazard is in the southern part because of hanging wall effect. The sources have 20 km fixed depth in the north and 10 km in their southern border. The largest PGA is 0.5 g in the far-west and larger than 0.4 in the Kathmandu Valley.



**Appendix 20-9:** seismic hazard map prepared using Model-9 (Appendix 11-9). The high hazard is in the southern part because of hanging wall effect. The largest PGA is 0.5 g in the far-west and larger than 0.4 in the Kathmandu Valley.



## APPENDIX 21

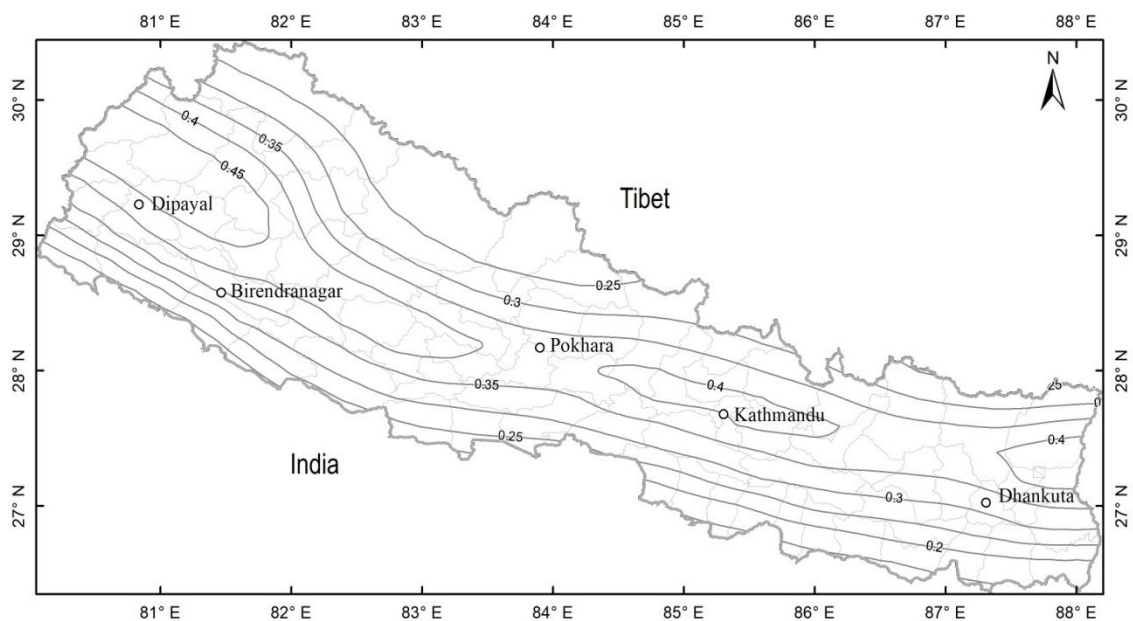
Seismic hazard maps prepared using logic tree method.

The seismic hazard map (Appendix 21-1) was prepared using two sets of attenuation relations (Appendix 18-1 and 18-2). Attenuation relations as described in Appendix 18-1 were applied to segments of the MHT and its adjacent area in the south. The sources in South Tibet were applied the second sets of attenuation relation (Appendix 18-2). The six source models and two sets of attenuation relations, each were given equal weight to produce the final map (Figure 50). Fixed b-value and recalculated a-value were applied to prepare Appendix 21-1 utilizing earthquake catalogue since 1100 AD.

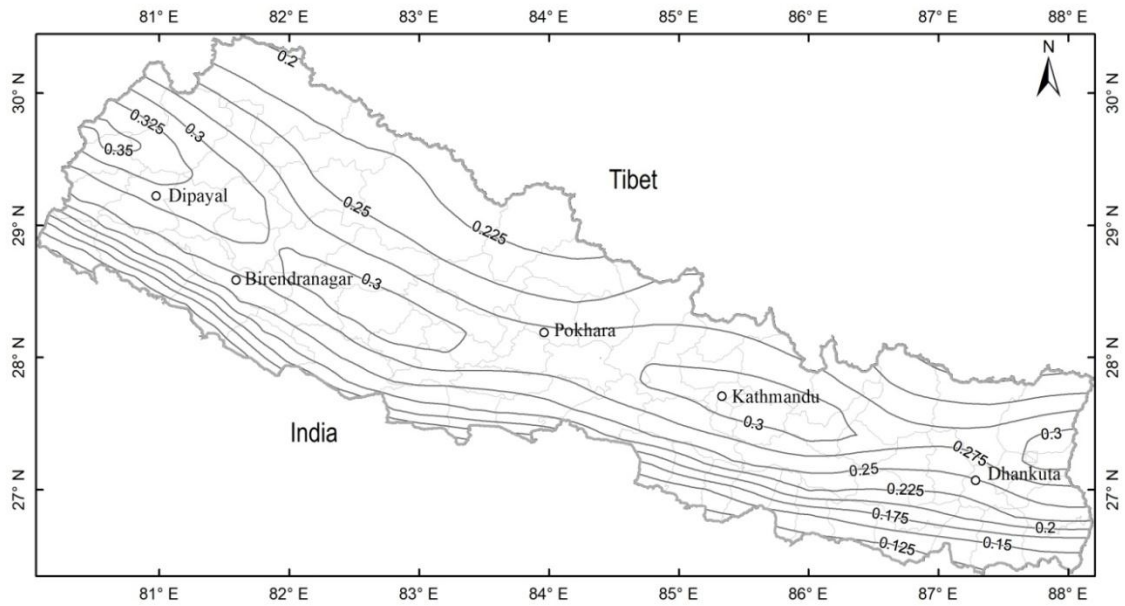
Appendix 21-2 is an example of seismic hazard map prepared ignoring Young's 1997 attenuation relation in Appendix 21-1.

Appendix 21-3 is another example of seismic hazard map, which was prepared using earthquake sources in South Tibet and North India. In this map the sources from the MHT were not used.

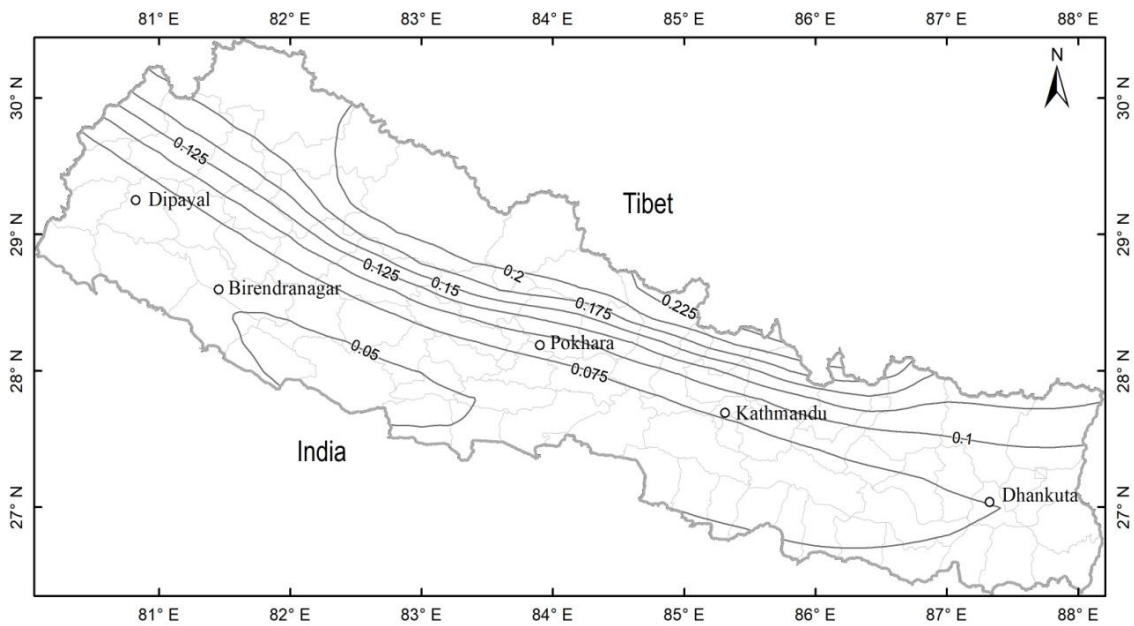
**Appendix 21-1:** Seismic hazard map applying logic tree method as mentioned above. The maximum PGA reaches 0.45 g in the far-west.



**Appendix 21-2:** Seismic hazard map applying logic tree method as mentioned above. This map was prepared following the process explained in Appendix 21-3, using Zhao *et al.* (2006) and BcHydro (2016) attenuation relations (Young's *et al.*, 1997 attenuation relation was not used). The largest PGA is smaller than that in Appendix 21-3.



**Appendix 21-3:** Seismic hazard map applying logic tree method as mentioned above. This map was prepared without considering the sources from MHT in order to check the influence of other sources in Nepal.



## APPENDIX 22

Earthquake catalogue ( $M_w \geq 5.5$ ) compiled in this study

Year	Month	Day	Hour	Minute	Second	Latitude	Longitude	Depth	Mw
1100	1	15	8	43	25.6	26.885	86.589	NA	8.5
1255	6	7	NA	NA	NA	27.77	85.3	NA	7.8
1344	9	14	NA	NA	NA	27.5	87.5	NA	7
1408	8	0	NA	NA	NA	27.9	86	NA	6.5
1411	9	29	NA	NA	NA	30	90.2	NA	7.7
1681	1	0	NA	NA	NA	27.6	87.1	NA	8
1505	6	6	NA	NA	NA	29.5	83	NA	8.5
1664	0	0	NA	NA	NA	25	90	NA	7.8
1720	7	25	NA	NA	NA	30	80	NA	7.5
1751	0	0	NA	NA	NA	31.3	80	NA	7
1767	7	0	NA	NA	NA	28	85.5	NA	7.9
1803	9	1	NA	NA	NA	31.5	79	NA	8.1
1803	9	4	NA	NA	NA	29.6	87.8	NA	6
1819	6	27	NA	NA	NA	30.5	80.5	NA	6.2
1833	8	26	NA	NA	NA	27.7	85.7	NA	7.7
1845	8	6	NA	NA	NA	26.09	90.89	NA	7.1
1846	10	18	NA	NA	NA	25.07	90.37	NA	6.2
1849	1	22	NA	NA	NA	25.97	90.07	NA	6.1
1852	3	31	NA	NA	NA	28.09	79.17	NA	7
1866	5	23	NA	NA	NA	27.12	85.26	NA	7.4
1869	7	7	NA	NA	NA	27.7	85.3	NA	6.5
1869	1	9	NA	NA	NA	25.5	91.5	NA	7.1
1885	5	14	NA	NA	NA	30.5	91	NA	6.2
1897	6	12	NA	NA	NA	25.5	91	NA	8
1897	8	2	NA	NA	NA	25	90	NA	6.3
1944	10	29	NA	11	35	31.051	83.135	20	6.8
1945	6	4	12	8	59.7	30.218	80.082	15	6.4
1947	2	10	4	2	3.7	31.537	85.278	15	6.6
1951	5	28	15	59	23.7	28.926	86.685	15	5.9
1951	11	17	4	46	2.7	30.908	91.498	15	6.1
1951	11	18	9	26	37.3	30.799	91.413	15	6.8
1951	11	18	9	35	54.7	31.056	91.261	30	7.7
1951	12	26	10	7	0.4	31.244	90.784	15	6.3
1952	6	15	15	16	3.3	31.373	90.919	15	5.9
1952	8	17	16	2	14.5	30.648	91.601	25	7.5
1952	10	7	18	2	19.9	31.464	87.446	15	5.7
1952	11	19	10	23	32	29.682	86.506	15	5.8



1953	2	23	0	46	10.8	29.529	81.382	10	5.8
1953	8	29	1	58	29.2	28.168	82.333	15	5.8
1953	12	3	14	54	11.4	31.151	85.743	30	6.5
1954	2	23	6	40	35.9	27.672	91.605	15	6.2
1954	9	4	6	43	49.4	28.169	83.825	15	5.9
1955	3	27	14	38	48.2	29.671	90.166	15	5.9
1955	8	4	6	40	49.5	30.675	86.43	15	5.7
1955	9	20	20	21	13	27.5	90	15	5.9
1955	12	29	8	25	35.4	29.845	90.189	15	6
1956	6	12	3	12	30.4	25.029	90.853	15	6
1957	4	14	7	11	58	30.521	84.348	15	6.5
1957	4	22	1	42	22.9	30.841	84.297	15	5.9
1958	1	23	5	30	13.4	30.622	84.133	15	6
1958	10	28	10	46	33.7	30.472	84.553	15	6.2
1958	11	3	14	31	39.3	30.44	84.54	15	5.6
1958	12	28	5	34	41	29.926	79.9	15	6
1959	2	22	3	30	44.6	28.949	91.925	20	5.9
1960	7	29	10	42	47.6	26.488	90.297	15	5.7
1960	8	21	3	29	4.9	27	88.5	29	5.7
1961	12	24	7	13	27.6	29.512	80.806	15	5.9
1963	4	12	0	41	29.3	31.885	78.781	30	6
1963	11	27	21	10	25	30.8	80.5	33	5.5
1964	2	18	3	48	34.4	27.4	91.18	22	5.5
1964	4	13	3	19	57.3	27.52	90.17	1	5.5
1964	9	26	0	46	2.6	29.96	80.46	50	6
1964	10	6	20	19	32.1	29.4	80.98	11	5.5
1964	12	20	3	31	32.1	29.35	81.1	9	5.5
1965	1	12	13	32	24.1	27.4	87.84	23	6
1965	6	1	7	52	25.1	28.59	83.06	20	5.5
1966	3	6	2	10	52	31.51	80.55	5	5.6
1966	3	6	2	15	57.2	31.49	80.5	50	6.1
1966	6	27	10	41	8.1	29.62	80.83	33	6.1
1966	6	27	10	47	45.1	29.55	80.99	43	5.5
1966	6	27	10	49	51	29.5	80.9	72	5.6
1966	6	27	10	59	18.1	29.71	80.89	36	6.1
1966	6	27	13	55	49.3	29.62	80.93	18	5.5
1966	8	15	2	15	28	28.67	78.93	5	5.8
1966	12	16	20	52	16.3	29.62	80.79	19	5.9
1966	12	21	22	10	59.3	29.65	80.79	21	5.5
1967	9	15	10	32	44.2	27.42	91.86	19	6
1969	2	11	22	9	57	28.1	82.7	33	6.3
1969	2	13	10	23	54	28.2	81.8	33	5.5

1969	6	22	1	33	23	30.5	79.4	15	5.5
1970	2	12	1	51	48.4	29.24	81.57	25	5.5
1971	5	3	0	33	24.6	30.789	84.328	27.1	5.5
1972	7	22	16	41	2.1	31.377	91.414	17.3	5.6
1974	3	3	4	53	17.3	30.745	86.318	28.6	5.6
1974	3	24	14	16	1.1	27.664	86.003	20.4	5.6
1974	9	27	5	26	33.6	28.594	85.512	19.9	5.7
1975	1	19	8	12	9.8	31.937	78.525	48.6	6
1976	9	14	6	43	51.6	29.808	89.568	75.4	5.6
1977	2	19	6	15	25	31.797	78.432	40	5.6
1978	2	10	17	29	47.1	28.033	84.698	0	5.5
1979	5	20	22	59	11.6	29.932	80.27	15.8	5.9
1980	2	22	3	2	44.8	30.552	88.646	14.2	5.9
1980	7	29	12	23	7.7	29.339	81.214	3	5.9
1980	7	29	14	58	41.6	29.628	81.091	23.3	6.2
1980	11	19	19	0	44.6	27.402	88.797	1.3	6.1
1982	1	22	4	29	55.9	30.891	89.867	2.6	5.5
1982	1	23	17	37	29.2	31.675	82.284	25	6.1
1982	1	23	17	48	1.9	31.563	82.208	30.9	5.5
1984	5	18	4	28	52.2	29.52	81.793	0	5.8
1984	11	18	22	4	35.5	28.674	83.319	0	5.6
1985	1	7	16	13	5.4	27.14	91.958	12	5.6
1986	1	10	3	46	30.9	28.653	86.563	63.4	5.7
1986	6	20	17	12	47.2	31.216	86.824	33	6
1986	7	16	22	3	6.5	31.051	78.002	4.4	5.8
1986	9	9	16	24	21.8	31.54	85.046	0	5.6
1987	8	9	21	15	2.7	29.465	83.739	73.6	5.7
1988	4	20	6	40	25.8	27.017	86.721	55	5.6
1988	8	20	23	9	10.1	26.72	86.626	64.6	6.5
1988	10	29	9	10	52.7	27.866	85.637	18	5.7
1989	2	3	17	50	0.2	30.187	89.944	18.7	5.6
1990	1	9	2	29	21.8	28.154	88.108	35.5	5.9
1991	10	19	21	23	14.8	30.77	78.791	13.2	6.5
1991	12	9	1	2	42.5	29.512	81.611	2.9	5.8
1992	7	30	8	24	49.2	29.566	90.18	31.4	6
1993	1	18	12	42	4.5	30.844	90.378	10	5.9
1993	3	20	14	51	59.7	29.027	87.328	12.2	5.9
1993	3	20	18	13	26.4	25.88	90.68	19	5.9
1996	7	3	6	44	41.5	30.106	88.191	8.2	5.8
1997	1	5	8	47	24.5	29.874	80.565	24.9	5.6
1997	11	3	2	29	48.1	29.036	85.392	8.3	5.6
1998	7	20	1	6	1.1	30.175	88.245	57.9	5.5

1998	9	3	18	15	52.1	27.863	86.95	2.6	5.8
1999	3	28	19	5	12.3	30.511	79.421	22.9	6.4
1999	10	5	17	4	48	26.26	91.926	33	5.5
1999	10	8	14	52	12.9	31.286	79.437	15	5.5
2001	11	27	7	31	51.6	29.691	81.716	22.6	5.7
2001	11	27	8	53	53.8	29.641	81.704	25.7	5.5
2002	6	4	14	36	2.6	30.566	81.42	10	5.6
2004	7	11	23	8	41.8	30.719	83.666	8.1	5.8
2004	10	26	2	11	31	31.036	81.082	4	6
2005	4	7	20	4	40.2	30.517	83.655	14.7	6
2006	2	14	0	55	24.8	27.387	88.416	28.7	5.5
2006	2	23	20	4	54.5	26.958	91.712	14.9	5.6
2008	8	25	13	22	1.5	31.061	83.652	25.5	6.1
2008	9	25	1	47	12.2	30.84	83.586	10	5.6
2008	10	6	8	30	45	29.844	90.379	6.4	6.1
2008	10	8	14	7	15.4	29.768	90.336	2.4	5.5
2008	12	8	8	59	8.8	29.99	82.085	15.3	5.5
2009	7	24	3	11	57	31.169	85.963	13.3	6
2009	9	21	8	53	6.2	27.369	91.46	16.1	6.1
2009	11	7	20	8	49.2	29.539	86.045	21.4	5.8
2009	12	31	9	57	31	27.332	91.48	18.5	5.6
2010	2	26	4	42	38.1	28.507	86.776	79	5.7
2010	11	30	8	39	57.5	29.797	90.317	13.8	5.6
2010	11	30	12	40	27.6	29.688	91.248	0	5.6
2011	4	4	11	31	41.1	29.626	80.729	17.4	5.8
2011	9	18	12	40	49.6	27.804	88.154	29.6	6.6
2014	3	30	17	10	14.7	31.345	86.472	12.6	5.5
2014	3	30	17	17	23.8	31.518	86.585	0	5.5
2014	3	30	17	40	31.4	31.294	86.269	10	5.5
2015	4	25	6	11	26.3	28.28	84.79	15	7.8
2015	4	25	6	11	33	27.794	85.339	8	6.8
2015	4	25	6	15	3.1	27.443	85.074	0	6
2015	4	25	6	15	22.9	27.628	85.54	10	6.2
2015	4	25	6	17	57.4	27.641	85.758	0	5.5
2015	4	25	6	18	10.9	27.686	86.021	10	5.8
2015	4	25	6	20	40.3	28.205	84.492	10	5.6
2015	4	25	6	45	22.1	28.39	84.83	15	7.1
2015	4	25	6	45	29.3	27.86	84.93	21	6.7
2015	4	25	6	56	33.9	27.882	85.751	10	5.7
2015	4	25	8	55	56	27.587	85.506	10	5.5
2015	4	25	9	17	2.3	28.39	87.317	10	5.9
2015	4	25	17	42	50.9	28.238	85.829	10	5.6

2015	4	25	23	16	15.5	27.82	84.89	9	5.7
2015	4	26	7	9	10.7	27.771	86.017	22.9	6.7
2015	4	26	7	9	24.2	26.923	87.064	10	6.2
2015	4	26	16	26	5	27.856	85.753	17	5.9
2015	5	12	7	5	19.7	27.809	86.065	15	6.8
2015	5	12	7	5	34.2	26.861	87.136	10	6.6
2015	5	12	7	17	20.6	27.714	86.218	13	5.7
2015	5	12	7	34	22.6	27.746	86.245	10	5.6
2015	5	12	7	36	54.5	27.625	86.162	15	6.3
2015	5	12	7	37	5.1	26.917	86.895	10	6
2015	5	16	11	34	10	27.56	86.073	7	5.9
2015	5	16	11	34	24	26.696	87.031	10	5.6
2015	6	28	1	5	28.6	26.638	90.41	26	5.7
2015	9	8	13	27	19.6	26.485	85.964	326	5.6
2015	12	18	22	16	56.5	29.399	81.654	10	5.6
2016	11	27	23	35	21	27.802	86.532	10	5.6