EFFECT OF DECLUSTERING ALGORITHM IN PROBABILISTIC SEISMIC HAZARD ANALYSIS FOR KATHMANDU VALLEY

*Pawan Chhetri[1], Deepak Chamlagain[2], Ram Chandra Tiwari[1]

[1]Department of Civil Engineering, Pulchwok Campus, IOE, Tribhuvan University, Lalitpur, Nepal

[2]Department of Geology, Tri-Chandra Multiple Campus, Tribhuvan University, Kathmandu, Nepal

*Corresponding author's email: pawanchhetri5@gmail.com

Abstract

An earthquake is a random event with uncertainty on time of occurrence, size of events, and location of rupture. So earthquake phenomenon is a model based on Poisson's distribution. Thus all the dependent event like foreshock and aftershock has to be removed before performing any Probabilistic Seismic Hazard Analysis (PSHA). Among the number of methodologies proposed for declustering methods, the process proposed by Gardener and Knopoff (1974) and Reasenberg (1985) was mostly used due to the availability of source code and reliability of declustering work. In this study, an attempt has been made to compare the effect of the declustering process at hazard level for the scenario of Kathmandu Valley. Probabilistic seismic hazard analysis of Kathmandu valley is performed using RCRISIS software with different seismicity parameters calculated for without declustering, declustering using Gardener and Knopoff (1974), and declustering using Reasenberg (1985). Calculated PGA value at bedrock level for 760 years return period for three declustering models compared with the measured square root of the sum of square (SRSS) PGA by 2015 Gorkha earthquake at Kathmandu valley at KTP station. Obtained results highlighted the suitability of the Gardener and Knopoff source code for the study area.

Keywords: *Declustering, Poisson's distribution, PSHA, RCRISIS, Kathmandu Valley, 2015 Gorkha Earthquake*

1. INTRODUCTION

Earthquakes are natural hazards in which surface ground motion is observed due to the rupture of geological faults releasing strain energy in the form of seismic waves which travel outward from the focus in all directions. Earthquakes or Seismic hazards are sporadic events that can result in other devastating hazards such as ground shaking, landslides, liquefaction, surface rupture, and tsunamis which can ultimately lead to damage of all kinds of structures as well as loss of life.

During major earthquake events, numbers of earthquake swarms i.e. foreshock, aftershocks also occur near the mainshock location. Foreshocks and aftershocks are the dependent events that do not follow Poisson's distribution. These events are also very weak events that can't produce strong ground motion to impact the seismicity of the area. Hence the inclusion of such events misinterpreted the actual seismicity of the study area. So, while performing any seismic hazard analysis declustering is the compulsory step to be performed to prepare Poissonian residual catalog for probabilistic seismic hazard estimation (Talbi et al., 2013). Declustering is the process in which, dependent events like aftershock and foreshock in the originally downloaded catalog are removed using different well-developed declustering algorithms.

Based on confinement highlighted from characteristic spatiotemporal patterns of seismicity following major earthquake events, several studies have been developed to remove clusters from the original catalog. Utsu (1969); Gardner and Knopoff, (1974); Reasenberg (1985); Frohlich and Davis (1990); Davis and Frohlich (1991); Knopoff (2000) etc. are the major developed algorithms. Due to the availability of source code, Gardner and Knopoff (1974) and Reasenberg (1985) are the most adopted methodology for seismic hazard analysis. Gardner and Knopoff (1974) gave a declustering procedure that uses the proximity of earthquakes in space and time as an index of clustering. For a downloaded earthquake catalog, events are ordered in descending magnitude. Starting from the first event, space-time windows are measured around each event in the catalog. The size of bin N and duration D of each window change with the magnitude M of the possible mainshock. The highest magnitude event in each bin is identified as the mainshock, while the others dependent (foreshocks or aftershocks) events are identified and removed. The window parameters are estimated using the following regressions:

$$\mathrm{Log}(D)= a_1M+b_1 \tag{1}$$

$$\mathrm{Log}(N)=a_2M+b_2 \tag{2}$$

For a specific earthquake catalog, the parameters a1, b1, a2, and b2 can be estimated by interpolation of past aftershock zone extent and aftershock duration data.

2. LITERATURE REVIEW

Reasenberg (1985) suggests a static window test which states that "All events occurring within the 30 Km distance and 30 days' period are considered as related to an event and its foreshocks and aftershocks". Thus within a window, the event with the highest magnitude will be called the Main shock while lesser magnitude events will be called foreshocks and aftershocks. This study considers an effective zone entered for each earthquake. Earthquakes occurring inside the effective zone of a prior earthquake are considered aftershocks and following events are considered foreshocks.

Stevens et al. (2018) performed the comprehensive probabilistic seismic hazard analysis of Nepal with proper geometrical consideration of MHT, data highlighted by the 2015 Gorkha earthquake, paleoseismic studies, and geodetic based coupling model using Open Quake source code. They calculated the PGA value for a return period of 475 years and 2475 years. They found PGA for Nepal is more than 0.6g for most of the area considering local site effect. This study doesn't consider the declusturing phenomenon to remove the cluster events i.e. this PSHA was done without declustering of the original catalog.

Chamlagain et al. (2020) performed the probabilistic seismic hazard analysis of Nepal for the revision of NBC 105 after 2015, Gorkha event, and Niroula and Chamlagain (2020) performed probabilistic seismic hazard analysis for Kathmandu valley considering the effect of two contrasting model geometry of MHT (Single Ramp Model and Double ramp model). Both of the above studies were based on the declustering algorithm proposed by Gardener and Knopoff (1974). These studies considered the findings after the 2015 Gorkha earthquakes along with the next-generation attenuation relationship for the hazard estimation. Their results suggest the PGA value is in the range of 0.36g to 0.46g for 475 years return period and also compare PGA and Spectral Acceleration (SA) for both models with measured data at KTP station by 2015 Gorkha earthquake and declared the similarity of two models at hazard level. Although the above-mentioned Studies have similar types of source zones and the same Open Quake as the calculation code. PGA results obtained from non-cluster seismicity by Stevens et al. (2018) are on the higher side.

In this study, an attempt has been made to compare the effect of the declustering algorithm in hazard level for the case of Kathmandu valley. A total of 3 models were prepared for each unclustered catalog, Catalog developed by declustering using Gardner and Knopoff (1974) algorithm and catalog developed by Reasenberg (1985) declustering method using RCRISIS as the computing tool for probabilistic seismic hazard.

3. METHODOLOGY

3.1. Study Area

Nepal is one of the high seismic hazard nations, lying within the seismically active Himalayan range which is formed due to the continental collision of Indian and Eurasian plates. Hence lying in the seismically active Himalaya belt and also having fragile infrastructures, Nepal is prone to earthquake-related damages. Kathmandu basin is at high seismic risk also due to valley amplification properties, a thick succession of fluvial and lacustrine sediment deposit, poor construction practices, high population density, and its fragile geology. The effect of ground shaking in Kathmandu valley can be even more devastating as it may result in the risk of liquefaction as highlighted by many researchers. Kathmandu valley covers the Kathmandu, Lalitpur, and Bhaktapur districts in the study area of this research work. The selected study area covers the location of all existing seismic stations within the valley. The average elevation of the study area is 1400m above the mean sea level. The layout map of the study area is shown in figure 1

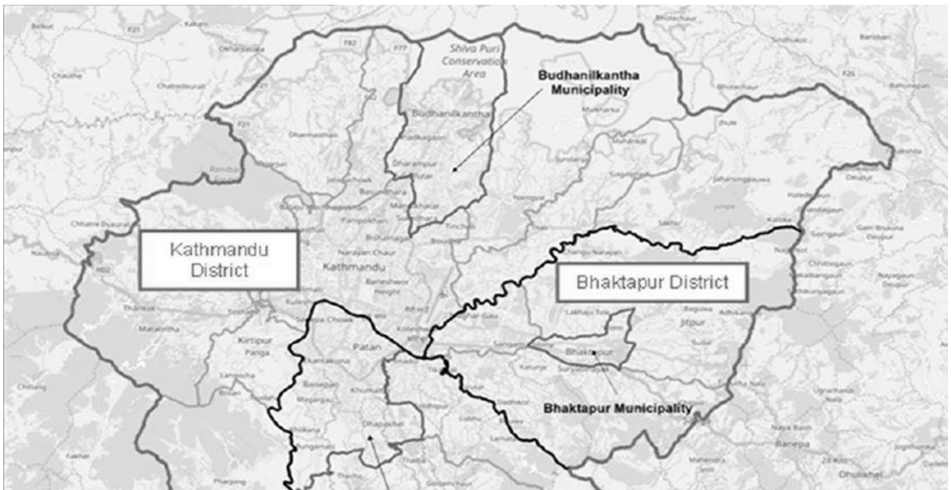

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Figure 1 Kathmandu Valley

3.2. Earthquake Catalog

Following the regulatory guide 1.165 (1997), the earthquake catalog was downloaded for the seismic study area of surrounding 350Km of our study area i.e. Kathmandu Valley. Earthquake catalog downloaded from the International seismological center (ISC), United States geological survey (USGS), and Global centroid moment tensor (GCMT) from the period of AD 1900 to AD 2021. Downloaded earthquake data consist of various types of magnitude data like local magnitude, body wave magnitude, moment magnitude, etc. So all types of magnitude have to be converted into the same common type of magnitude data (Moment magnitude). Several relations for magnitude conversion are available. Most of the previous researchers used correlation given by Scordilis (2006) but his correlation was developed considering global earthquake data with very less weightage number of data for south Asia and also gave the same relation for all data sources. So the correlation is given by Nath et al. (2017) used in this study. His method is updated and developed mainly by considering the seismicity of South Asia and also has a different range of correlation for different sources of data which is shown in table 1. Earthquake catalogs from different sources are merged into a single catalog giving priority orders as GCMT, USGS, and ISC respectively for repeated events. Total 2330 events are found to have occurred in these 121 years. These 2330 events are plotted in figure 2.

Table 1: Formula for the homogenization of original catalog (Nath et al., 2017)

Catalogue accessed	Magnitude scales	Min. Mag.	Max. Mag.	Converted to	Magnitude range	Equations
ISC	m_b	3	9	$M_{W,GCMT}$	3.8-7.0	$M_{W,GCMT}$=1.168X$m_{b,ISC}$-0.663
	M_L	3	8	$M_{W,GCMT}$	3.5-7.3	$M_{W,GCMT}$=0.499X$m_{L,ISC}$+2.88
	M	3	7.5	$M_{W,GCMT}$	4.7-7.2	$M_{W,GCMT}$=0.978Xm_{ISC}+0.1634
	M_N	3	5.7	$M_{L,ISC}$	3.6-5.3	$M_{L,ISC}$=1.219X$M_{N,ISC}$-0.972
	M_D	3	7.4	$m_{b,ISC}$	4.0-6.2	$m_{b,ISC}$=1.428X$M_{D,ISC}$-2.182
	M_{LV}	3	8.1	$m_{b,ISC}$	2.0-4.5	$m_{b,ISC}$=0.962X$M_{LV,ISC}$-0.0009
					4.6-7.6	$m_{b,ISC}$=1.177X$M_{LV,ISC}$-1.393
USGS	m_{pv}	3	7.2	$m_{b,ISC}$	3.4-6.6	$m_{b,ISC}$=1.337X$M_{PV,ISC}$-1.625
	m_b	3	7.5	$M_{W,GCMT}$	4.6-6.4	$M_{W,GCMT}$=1.082X$m_{b,USGS}$-0.413
	M_S	4	7.5	$M_{W,GCMT}$	4.5-5.6	$M_{W,GCMT}$=1.15X$M_{s,USGS}$-0.628
					5.7-7.0	$M_{W,GCMT}$=1.21X$M_{s,USGS}$-1.45
					7.1-7.5	$M_{W,GCMT}$=$M_{s,USGS}$
	uk	5.6	7.1	$M_{S,ISC}$	6.5-6.8	$M_{S,ISC}$=uk_{USGS}+0.2
	m_w	3.9	9.1	$M_{W,GCMT}$	5.1-7.0	$M_{W,GCMT}$=1.017X$m_{w,USGS}$-0.118
					7.1-7.8	$M_{W,GCMT}$=$m_{w,USGS}$

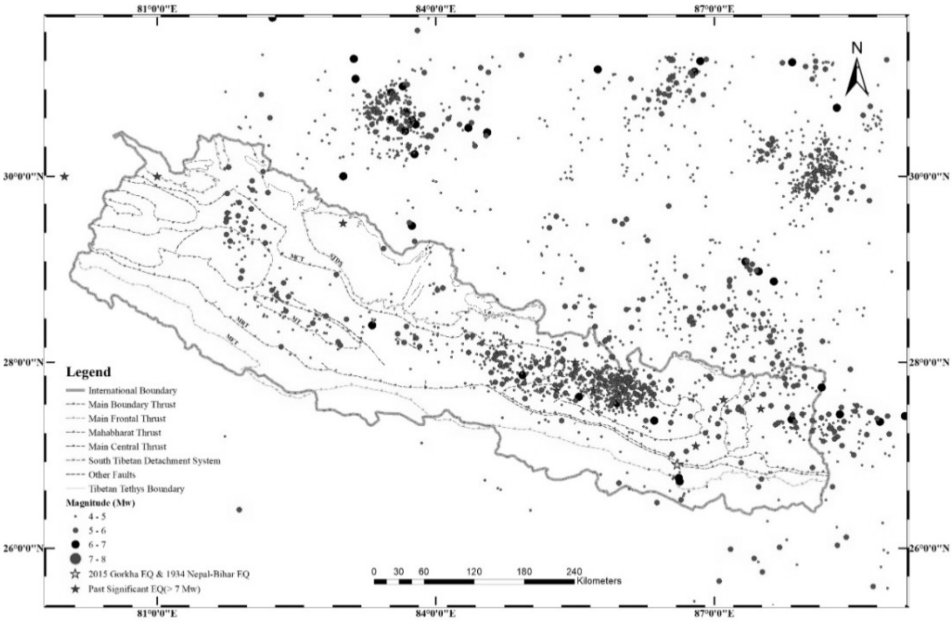

Figure 2 : Collected homogenized catalog plotted in digitized fault map of Nepal

3.3. Declustering

For this study, three models of seismicity parameters were developed using three different conditions of declustering. At first, non-clustered data from the downloaded catalog were proceeds further for source characterization and G-R parameter calculation step. In this study, the Z-map tool developed for seismological analysis is used for declustering work and found 1044 events are independent events using Gardner and Knopoff (1974) and 1328 events are Poissonian events using Reasenberg (1985) methodology. These declustered catalogs were used for further seismic hazard analysis

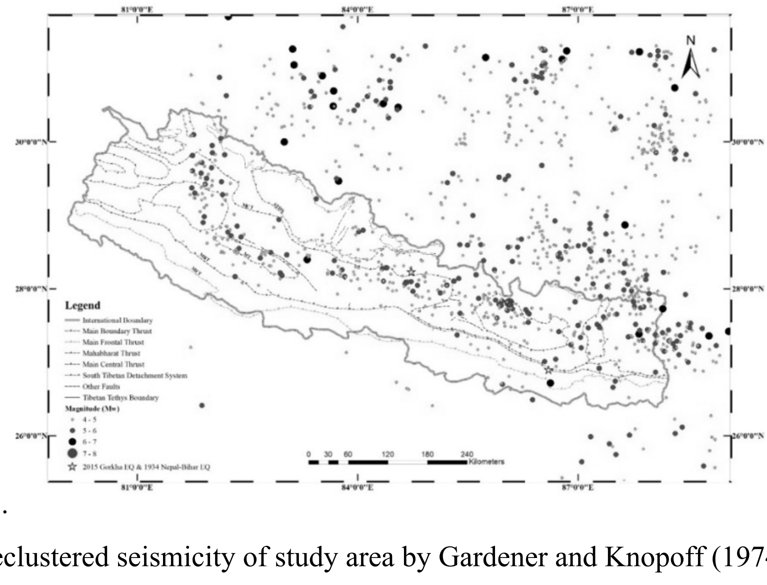

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Figure 3: Declustered seismicity of study area by Gardener and Knopoff (1974) algorithm

3.4.Source Characterization

This study follows a similar source characterization model as suggested by Stevens et al. (2018) and Niroula and Chamlagain (2020). Within the developed seismotectonic map a total of Six source zones were delineated considering tectonics, fault geometry, neotectonic deformation, and earthquake type and pattern. Source geometry, depth, and properties other than seismicity were kept constant for all three models of analysis. To use the modified G-R model, estimation of maximum magnitude for each source model is also a must. Theoretically, maximum magnitude is estimated using possible rupture length, which is very difficult to calculate using short-term data and proper data sources regarding rupture length. Different literature and past study are considered to approximate the maximum magnitude for each source zone and are shown in table 2.

Table 2: Maximum magnitude approximation

	Maximum magnitude			
Source Zone	Our catalog	From a,b graph	Purposed	Source for maximum magnitude
SZ 1	5.6	7.9	7.5	Stevens (2018)
SZ 2(MHT)	8.1	8.5	9	Stevens and Avouac(2016)
SZ 3	6.9	8	6.9	Kumar et al (2012)
SZ 4	6.9	7.8	7.1	Elliot et al (2010)
SZ 5	8.2	7.6	8.2	Ambraseys and Douglas (2004)
SZ 6	8.2	9.5	8.2	Ambraseys and Douglas (2004)

3.1. Completeness analysis and Earthquake recurrence model

The downloaded catalog is for 121 years only. Due to the short span nature of the catalog, the completeness of the data is always questionable. To assess the completeness of different magnitude classes, this study follows the Stepp (1972) technique. This method relies on the statistical property of the Poisson distribution that highlights time intervals during which the recorded earthquake occurrence rate does not change. The length of the time interval for which the standard deviation does not vary from the straight line is the time interval of completeness for that particular magnitude class. The complete time interval of each magnitude class can be visually determined from the plots. Results of completeness analysis are vital for the calculation of G-R parameter and minimum magnitude of completeness for each source zone which has a significant effect on the seismic hazard analysis. Z-map tool was used for the completeness analysis and to calculate a, b value of G-R parameter by maximum likelihood method (Kijko, 1988) for each source zone. Sample calculation for each declustered model is shown in Figures 4, 5, and 6 for SZ 2 (MHT).

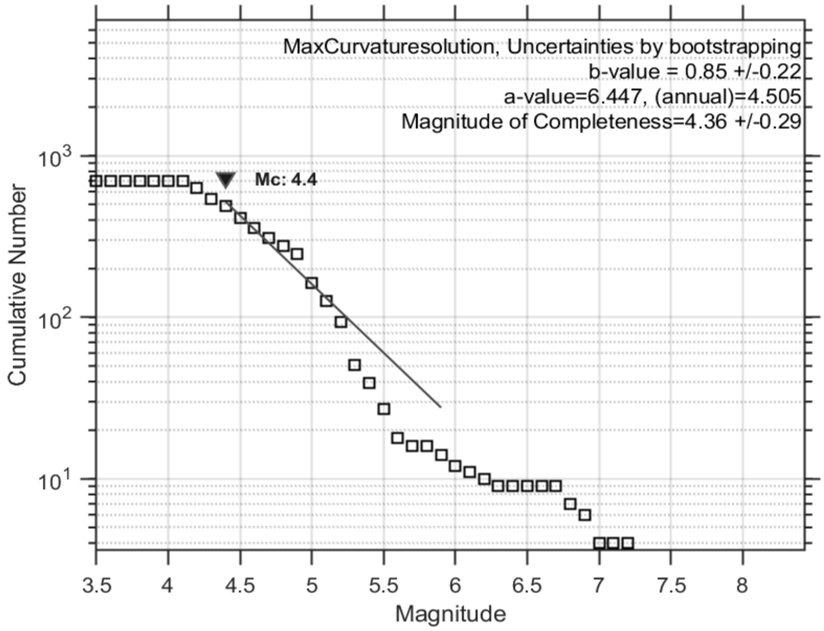

Figure 4: G-R Parameter without declustering

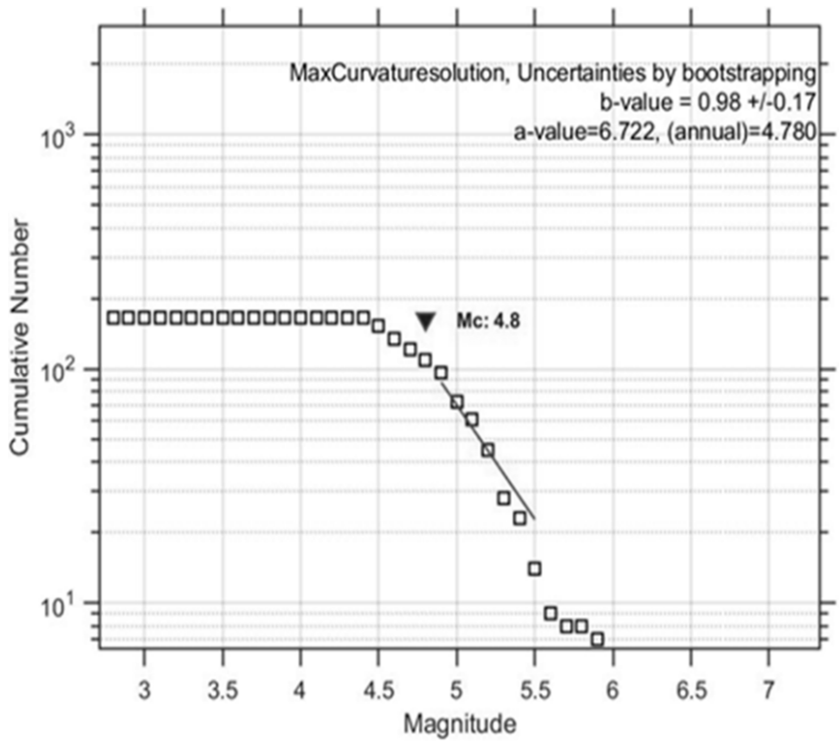

Figure 5 : G-R Parameter with Declustering using G and K (1974)

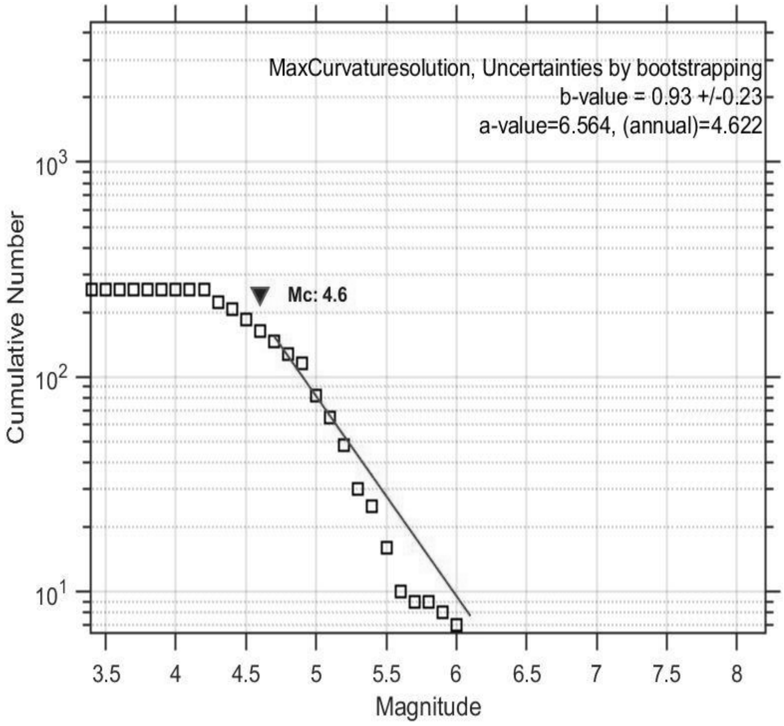

Figure 6: Parameter calculated using Reasenberg (1985)

Summary of calculated a, b value for each source zone for different declustering data model is shown in table 3.

Table 3 : Summary of G-R parameter calculation

Source Zone	Value of G-R parameter					
	Without Declustering		Declustering by Gardener and Knopoff		Reasenberg	
	a	b	a	b	a	b
SZ 1	5.4	1	5.4	1	5.4	1
SZ 2(MHT)	6.45	1.07	6.7	1.15	6.56	1.16
SZ 3	4.59	0.79	4.73	0.91	4.59	0.81
SZ 4	5.75	0.77	5.69	1.04	5.58	0.78
SZ 5	5.26	0.75	5.1	0.79	5.19	0.78
SZ 6	5.36	0.74	4.61	0.69	4.59	0.64

3.2. Ground Motion Prediction equations (GMPEs) and Hazard estimation

There is no defined ground motion prediction equation derived for the scenario of Nepal. This study considers subduction Zone for source zone 2 (MHT), active shallow crust for SZ 1, SZ 4, SZ 5, and SZ 6 for both models of sources, and stable continental area for SZ 3. R-CRISIS version 20.1.1. was used for the hazard calculation. R-CRISIS is a Windows-based software with the capability of performing probabilistic seismic hazard analysis (PSHA) using a fully probabilistic approach, allowing the calculation of results in terms of outputs with different characteristics (i.e. exceedance probability curves, stochastic event sets). There are various inbuilt GMPEs for such zones in R-CRISIS software, so to incorporate them GMPEs were chosen to calculate for best-suited equations in terms of weightage approach. The weighted approach by Niroula & Chamlagain (2020) is used to combine the number of models with suitable weightage. Instead of the logic tree approach, the hybrid model approach is adopted to consider earthquakes as random variables.3 hybrid models are selected using inbuilt GMPE available in R-CRISIS. Adopted ground motion prediction model along with their weightage in hybrid model is expressed in terms of the flowchart in figure 6

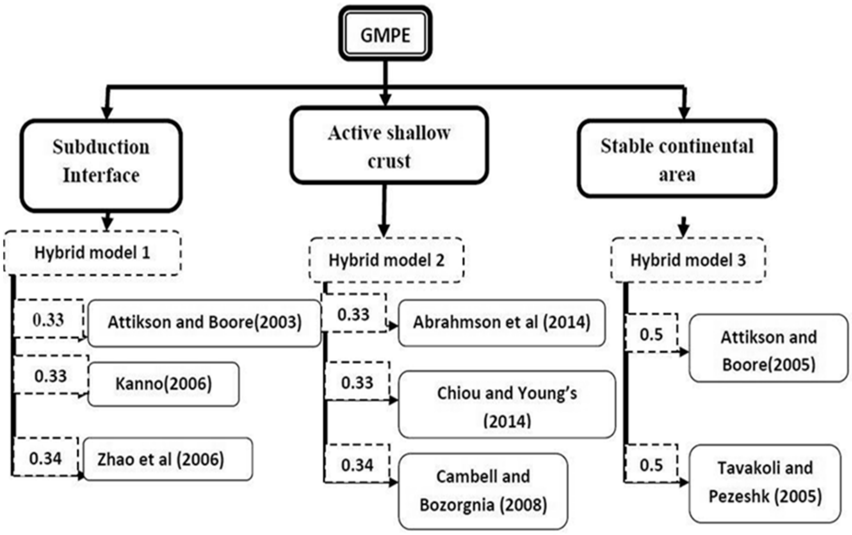

Figure 7: Hybrid GMPEs model

4. RESULTS AND DISCUSSION

Hazard calculation is done for three different models based on the declustering algorithm for Kathmandu valley. PGA value across the valley calculated for a total of 826 locations at 0.010*0.010 grid for 760 years return period. Sapkota et al (2013) and Rajendran et al. (2015) suggested that the return period of major earthquakes is more than 700 years. This consideration is also adopted by Stevens et al. (2018) and Niraula and Chamlagain (2020), in their seismic hazard analysis. So, the results of 760 years were used for the validation of the calculation of our PSHA.

Value of PGA range is 0.336g to 0.327g, 0.265g to 0.257g, and 0.219g to 0.214g for the unclustered model, declustering with Gardener and Knopoff (1974) model and Reasenberg (1985) model respectively at bedrock level. There are a total of 6 seismic stations inside the Kathmandu valley. But only the KTP station (85.27259E, 27.68216N) at Kirtipur is at bedrock level. So in this study, measurement of KTP station by 2015 Gorkha earthquake is used to validate and compare this analysis. PGA maps developed using different source models for 6.37% probability of exceedance in

50 years (760 years return period) at bedrock level for Kathmandu Valley are shown in Figures 8, 9, and 10.

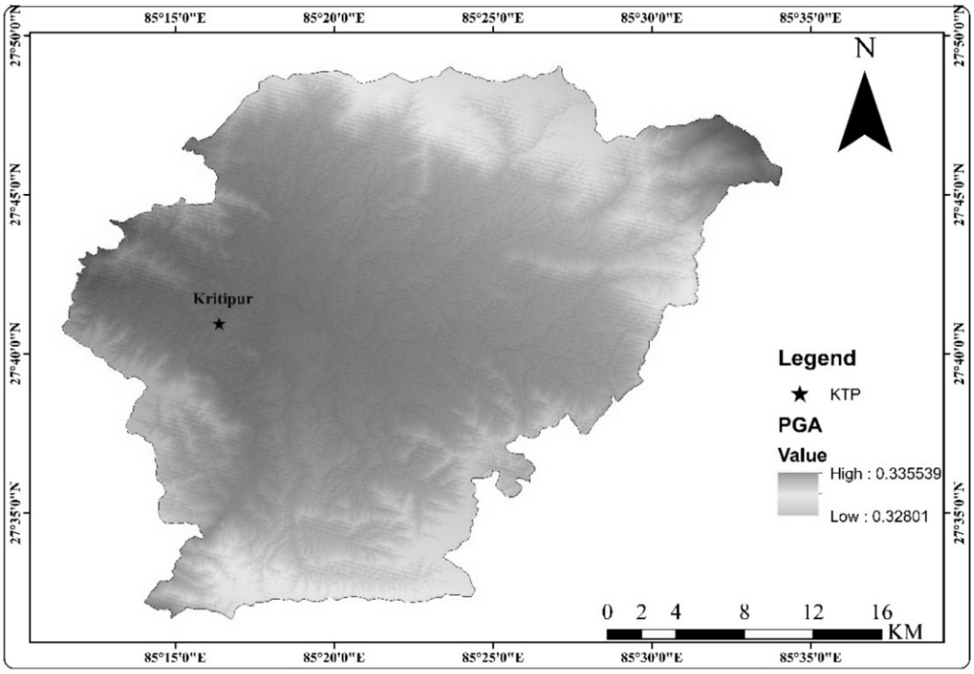

Figure 8 : PGA map of Kathmandu valley without declustering of catalog

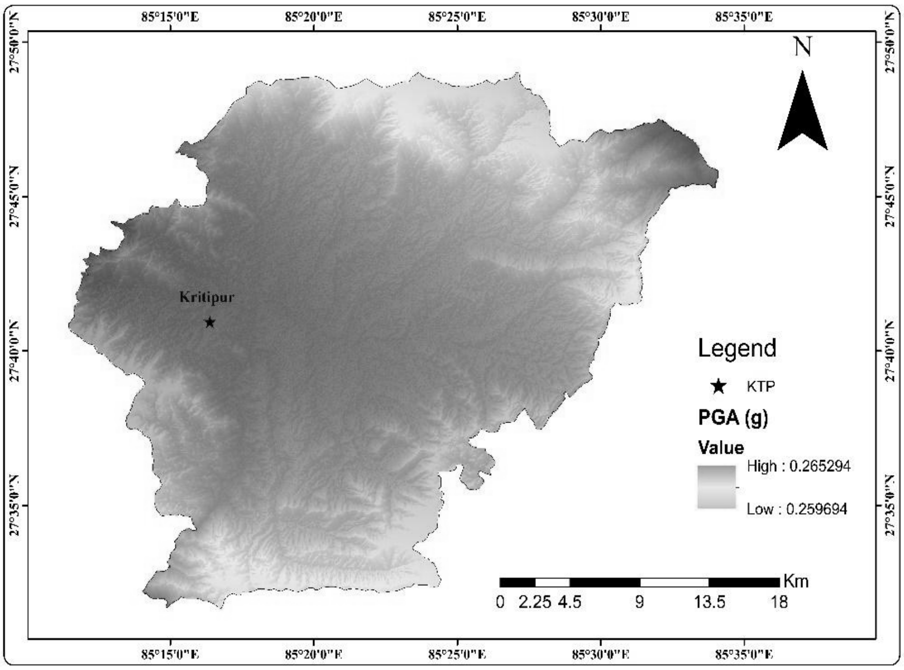

Figure 9 : PGA map of Kathmnadu valley using Gardener and Knopoff declustering algorithm

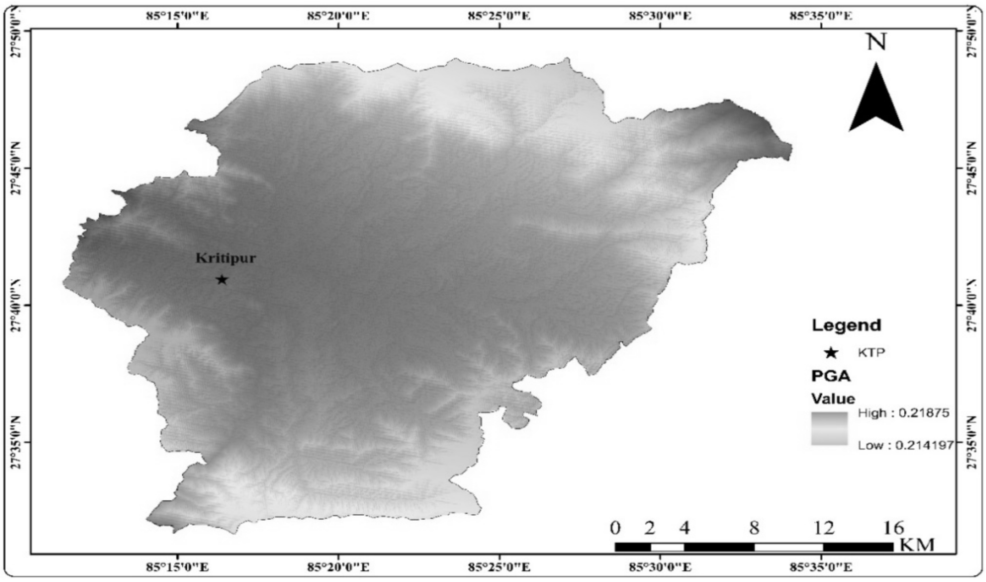

Figure 10: PGA map of Kathmandu valley using Reasenberg algorithm

Recorded PGA value at bedrock level at KTP station in 2015 Gorkha earthquake is 0.2599g. In this study, the calculated PGA for 760 years return period at bedrock level at KTP station is 0.2602g with 0.115% error by using Gardener and Knopoff (1974). This value is closer to the measured PGA value at KTP than the other two source models.

Spectral acceleration value was also compared for the KTP station. Calculated SA value for 760 years return period at bedrock level for different source model is compared with measured SA at KTP for EW direction and the square root of the sum of the squares (SRSS). Comparison plots in normal graphs are shown in figure 11 and comparison in semi-log graphs is shown in figure 12. Both comparisons suggest the closeness of Gardener and Knopoff (1974) methodology with recorded results.

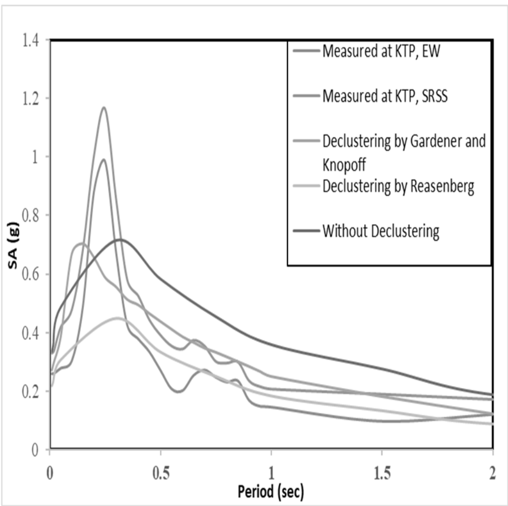

Figure 11: Comparison in normal graph

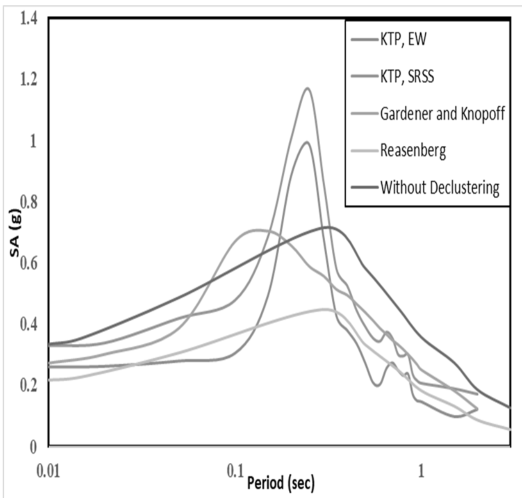

Figure 12: Comparison in Semi-log graph

5. SUGGESTION AND RECOMMENDATION

Calculated PGA value for each type of source model is consistent with the previous PSHA study with a similar source characterization approach and variation across the Kathmandu valley also satisfy the coupling interlocking zonation suggested by Stevens et al. (2015). Among the three source model, PGA results from the Gardner and Knopoff (1974) algorithm model gives more accurate results. Based on this PSHA for Kathmandu valley. Due to the availability of source code for calculation and with help of this study, it is suggested to use Gardener and Knopoff (1974) algorithm to remove dependent clusters for PSHA

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