Earthquake Risk Assessment, Loss Estimation and Vulnerability Mapping for Dehradun City, India

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[March, 2014]

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Enschede, the Netherlands [March, 2014]

Thesis submitted to the Faculty of Geo-information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: Natural Hazards and Disaster Risk Management

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DISCLAIMER

Dedicated to my parents….

Abstract

Himalayan region is classified under high risk seismic zone of India. Dehradun is a city located at foothills of Himalayas which is surrounded by the Himalayan Frontal Thrust (HFT) and Main Boundary Thrust (MBT). This region has witnessed devastations due to two major earthquakes in the past namely the Uttarkashi (1991) and the Chamoli (1999) earthquake. This study focuses on seismic risk and vulnerability assessment of the Dehradun city using HAZUS-MH methodology.

HAZUS-MH is a software developed by FEMA, the official Federal Emergency Management Agency in the USA for loss estimation and risk assessment of hazards mainly like earthquake, flood and cyclone. This research considers its earthquake hazard application for assessing buildings at risk. The study is mainly divided into three parts as ward wise statistical sampling of buildings for complete city, damage assessment of buildings and risk mapping considering various scenarios. Reinforced concrete frame/shear wall with unreinforced masonry is major building type found for analysis and its corresponding building type is identified in HAZUS-MH. In total, around 11000 building blocks for 8 wards has been digitized using GEOEYE satellite data. Field survey for approximately 1800 number of buildings was carried out, classifying them into different building types.

Further, with the help of field survey data and household data, extrapolation is done for total 60 wards. These extrapolated values are then used to find the discrete and cumulative damage probability of buildings in terms of no, slight, moderate, extensive and complete damage using the capacity and demand spectrum curves.

Various parameters used for seismic hazard and risk mapping are seismic microzonation, soil class, liquefaction susceptibility and ground water depth details. All of these parameters as available are taken as input for generating the different earthquake scenarios in terms of magnitude of earthquake. Three scenarios are generated and risk maps are produced ward wise. Zones varying from high risk probability to low risk probability are identified and concluded with the help of results. However, the results obtained may be considered accurate to certain limited extent as the analysis demands presence of full inventory of buildings stock and also the missing parameter of landslide susceptibility.

Keywords:

Earthquake, Risk assessment, Loss estimation, Sampling, Vulnerability, Microzonation, HAZUS-MH, QuickBird.

Acknowledgments

Firstly I would like to thank Indian Institute of Remote Sensing, Dehradun, India and Faculty of Geo-information Science and Earth Observation, ITC, University of Twente, The Netherlands, for giving me an opportunity to study Master of Science course under joint education program.

I am sincerely and greatly thankful to my three supervisors Drs. M.C.J.Damen, Earth Systems Analysis Department from Faculty of Geoinformation Science and Earth Observation, ITC, University of Twente, The Netherlands, Dr. P.K.Champati Ray Head, Geo Sciences and Geo-Hazard Department and Mr. B.D.Bharath, Urban and Regional Studies Department from Indian Institute of Remote Sensing, Dehradun for their constant support and valuable time throughout the period of my research work.

I would also like to thank Dr. David Rossiter from ITC for his precious time and valuable comments in statistical sampling method and carrying out the field work efficiently.

I sincerely thank Dr. Y.V.N. Krishna Murthy, Director, Indian Institute of Remote Sensing, Dehradun for allowing me to use all the facilities required in completing research work successfully. I thank Dr. V.G.Jetten, Head, Earth Systems Analysis Department from ITC, The Netherlands for providing valuable comments and Dr. Nicholas Hamm, ITC for his constant support throughout the MSc course especially the three months period at ITC.

I am immensely grateful to Mr. Chris Stewart from FEMA Map Information Exchange for providing me free software HAZUS-MH 2.1 version as without it I wound not have succeeded in completing my research.

I am also thankful to Mr. Ashish Dhiman and Ms. Sushma Bhandari from Geo Sciences and Geo-Hazard Department, Indian Institute of Remote Sensing, Dehradun for all the help provided to me.

I also take this opportunity to thank my dear friends Ravisha, Ishaan, Kanishk, Shreya and Amreesh from IIRS for being there and helping me throughout.

Last but not the least and most important my closest friend Durgesh and my family members for bearing with me through all the good and bad times and being my constant support. Really thank you so much.

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1 Introduction

1.1 Background

Out of all the natural hazards counted, Earthquake is one of the most severe hazards which can neither be predicted nor be controlled. As noted from 1500's till date, millions of people have lost their lives and property worth billions of US dollars have been destroyed due to devastating earthquakes [1][2]. The only way out is preparedness which may reduce loss of life and money. There are various ways of preparedness such as capacity building, building of earthquake resistant structures, etc. One of the way is quantifying vulnerability of an area for seismic activity through risk assessment and loss estimation so as to minimize all type of losses mainly social, economic and environmental. For quantifying these losses, several types of loss estimation methodologies and software's are available like RADIUS, TELES and HAZUS-MH. HAZUS-MH is a software developed by FEMA, the official Federal Emergency Management Agency in the USA applicable for risk assessment and loss estimation of different facilities like building stock, emergency facilities, etc. for hazards mainly like earthquake, flood and cyclone.

As described in the disaster management process Figure 1-1 [3], more emphasis is now being given for the preparedness phase so that losses occurring due to disaster can be minimized and disaster recovery can easily be handled [4] [5]. This study aims at contributing in a small way in development of sustainable and resilient society.

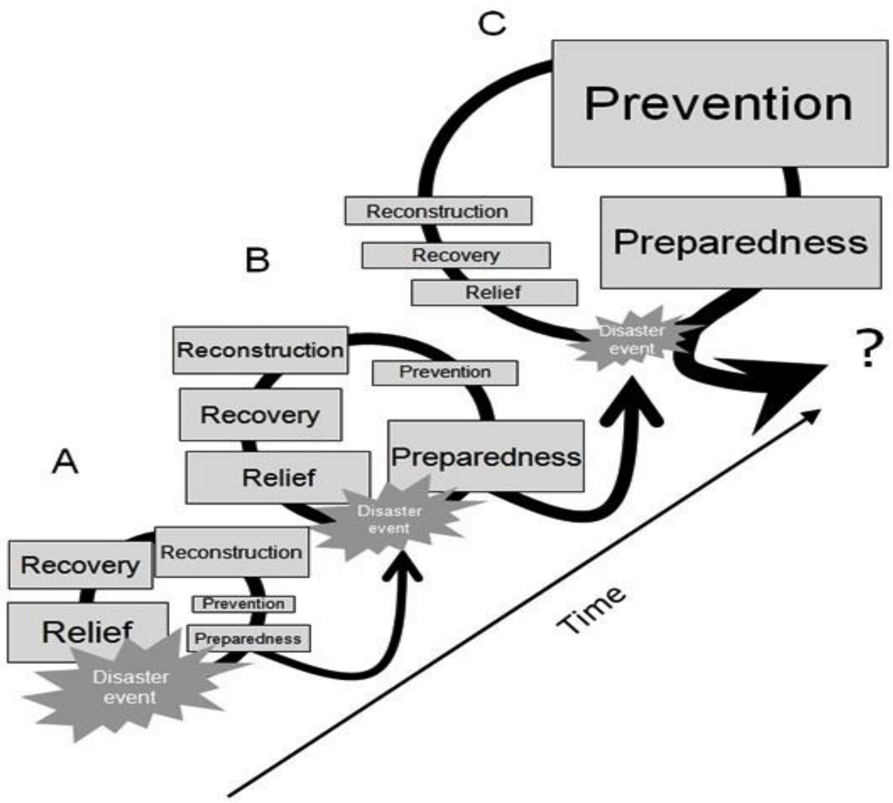


Figure 1-1 : Disaster Management Process

1.2 Earthquakes in India

India has a long history of disastrous earthquakes, majorly documented from 1800's [6].In last sixty years, population of India has doubled that has demanded growth in urbanization and safe human settlements. 59% of the land area of India is prone to seismic hazard damage [7]. 9 major earthquakes in past 40 years have resulted in life loss of more than 50,000 people with last as 2011 Sikkim earthquake [8][9]. Major earthquakes affecting this area as seen from Table 1-1 [10] are 1905 Kangra earthquake, 1975 Kinnaur earthquake , 1991 Uttarkashi earthquake and 1999 Chamoli earthquake.

Table 1-1 : List of significant earthquakes affected India in past 100 years

Date	Epicenter		Region	Magnitude in Richter scale
	Lat (^{0}N)	Long(^{0}E)		
1905	**32.3**	**76.3**	**Kangra, Himachal Pradesh**	**8.0**
1918	24.5	91.0	Srimangal, Assam	7.6
1930	25.8	90.2	Dhubri, Assam	7.1
1934	26.6	86.8	Bihar-Nepal Border	8.3
1941	12.4	92.5	Andaman Islands	8.1
1943	26.8	94.0	Assam	7.2
1950	28.5	96.7	Arunachal Pradesh-China Border	8.5
1956	23.3	70.2	Anjar, Gujarat	7.0
1967	17.4	73.7	Koyna, Maharashtra	6.5
1975	**32.4**	**78.5**	**Kinnaur, Himachal Pradesh**	**6.2**
1988	25.1	95.1	Manipur-Myanmar Border	6.6
1988	26.7	86.6	Bihar-Nepal Border	6.4
1991	**30.7**	**78.9**	**Uttarkashi, Uttarakhand**	**6.6**
1993	18.1	76.6	Latur-Osmanabad,Maharashtra	6.3
1997	23.1	80.1	Jabalpur, Madhya Pradesh	6.0
1999	**30.4**	**79.4**	**Chamoli, Uttarakhand**	**6.8**
2001	23.4	70.3	Bhuj, Gujarat	7.6
2011	27.8	88.1	Sikkim-Nepal Border	6.9

Major risk lies for more than 50 million people living near the seismically active Himalayan region. Due to the collision of Eurasian plate with the Indian plate , Himalayan region appears as one of the youngest and unstable region from geology point of view [11]. Active faults such as Himalayan Frontal Thrust, Main Boundary Thrust (MBT) and Main Central Thrust (MCT) exist in this region as seen in Figure 1-2 [12]. Based on the history of seismic activities in past 100 years and related scientific studies, Indian Meteorological Department (IMD) and Bureau of Indian Standards (BIS) have classified the country into four major seismic risk zones with the possible Modified Mercalli Intensity (MMI) as shown in Figure 1-3 where zone II is the lowest risk zone intensifying to zone V which is a very high risk zone. The area round the Himalayas is classified under zones IV and V, which are the highest seismic risk zones of India. Dehradun is a city located at the foothills of Himalayas and categorized under zone IV which is the second highest seismic risk zone. Maximum land area in India i.e., total 59% under zone III, IV and V is accountable to moderate or high seismic risk with remaining 41% under low risk zone.

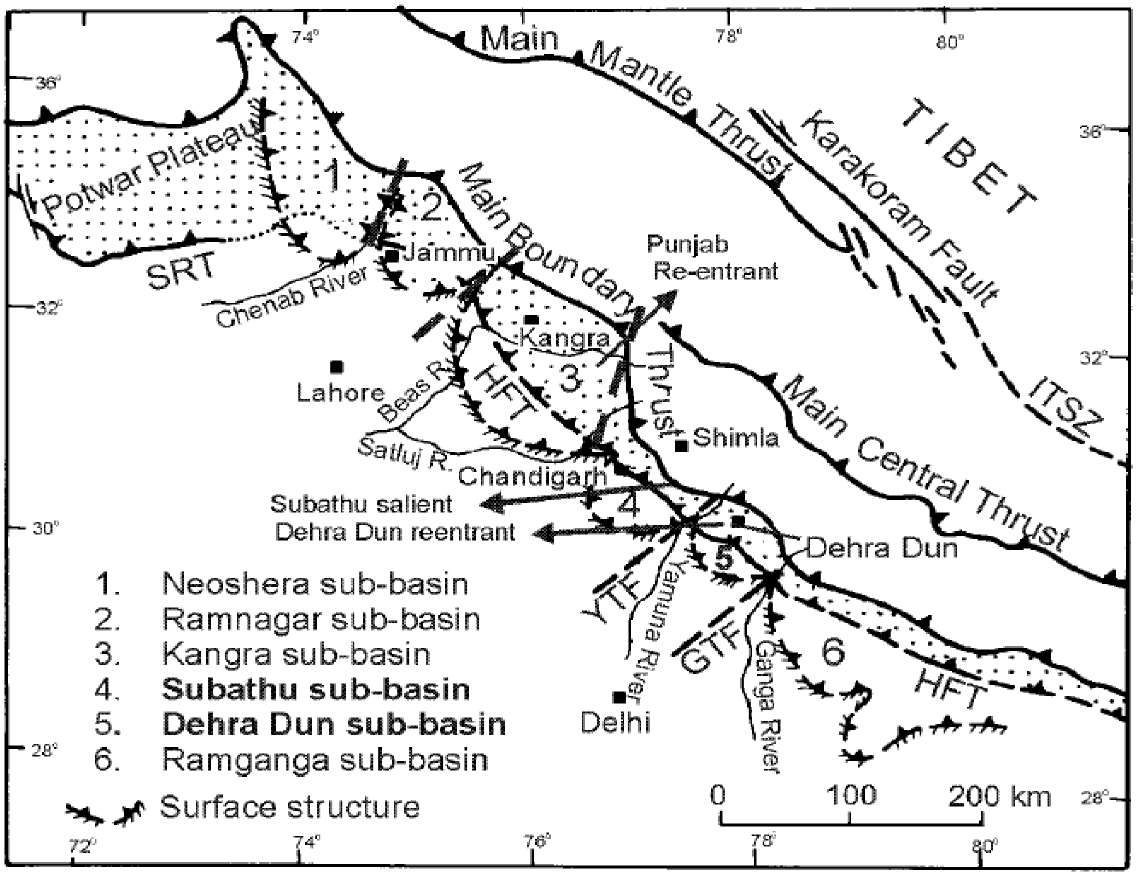


Figure 1-2 : Geological map showing various thrust lines shown on Himalayan basin

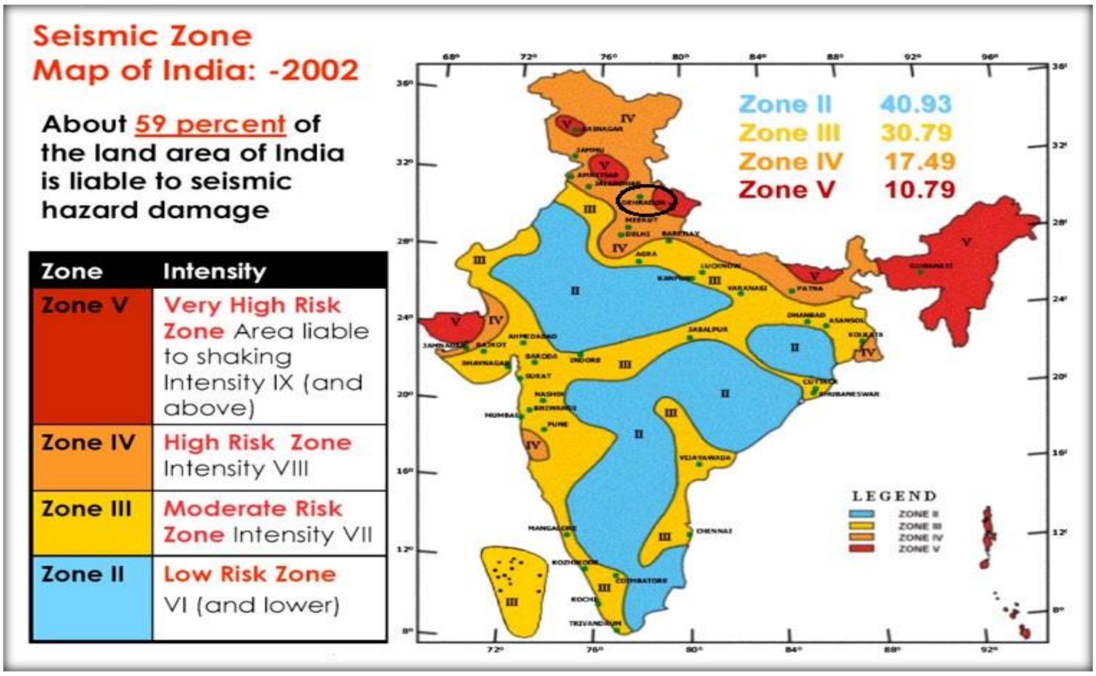


Figure 1-3 : Seismic Zonation and Intensity Map of India

1.3 Problem Statement

As no precise risk evaluation model for earthquake risk and damage assessment has been developed in India till date, the devastating effect of an earthquake can be minimized to a great extent by adopting risk models developed in other countries. HAZUS-MH is one of those tools developed in the United States, which assesses vulnerability and risk of earthquake. Its applicability to Indian sub-continent has been proved [13]. But HAZUS-MH only gives the loss estimation for the infrastructure facilities. There is a need to develop a risk map of the city for identifying the areas at risk .This can be achieved by combining the results of HAZUS-MH, liquefaction susceptibility, ground water depth and seismic microzonation details of Dehradun [14][15].

In past years, study has been done for Dehradun City using HAZUS-MH but they had limitations in terms of GIS & Remote Sensing data like building inventory, satellite image resolution and geological parameters. Moreover the study was done for a small part of the city [13]. This study aims at applying HAZUS-MH methodology for ward wise vulnerability and risk assessment of complete Dehradun city by making use of available parameters and data obtained through statistical sampling.

1.4 Research Identifications

1.4.1 Research Objectives

Main Objective:

The main objective is to prepare a geoinformation database for hazard and risk assessment using HAZUS for Dehradun city that will help to identify areas at risk for safe micro level planning of urban area. This database in the form of maps, tables and sampling method can be used for proper mitigation measures of earthquake.

Sub objectives:

1) To adopt a suitable statistical sampling method so that all construction types of buildings are covered in the selected wards of Dehradun city for vulnerability assessment.
2) Seismic hazard mapping to assess buildings at risk using various parameters in HAZUS.
3) To assess vulnerability of buildings for calculating earthquake loss estimation comprising of direct losses.
4) To produce a risk map considering various scenarios for earthquakes in terms of different magnitude.

1.4.2 Research Questions

1) Which statistical sampling method needs to be adopted so that all types of buildings are covered for vulnerability assessment in the selected wards for the field survey?
2) What are the various parameters required for generating a seismic hazard map in HAZUS? Comment on the seismic hazard map obtained by comparing the results with or without available parameters.
3) What are the different features that need to be considered for assessing vulnerability to calculate direct losses occurring due to earthquake?
4) What are the various scenarios to be considered in terms of different magnitudes of earthquake for risk mapping?

1.5 Expected Outcome

The final vulnerability and risk map generated for Dehradun City from the analysis will help to identify various areas at risk for micro level planning of urban area. Planners for planning the essential facilities like hospitals, fire brigade stations, etc. government local bodies like Mussoorie Dehradun Development Authority (MDDA) and Dehradun Nagar Nikam, nationalized bodies like National Institute of Disaster Management and private construction firms can use this map for building earthquake resistant structures at vulnerable areas, mitigation measures and rescue operations against earthquake to minimize elements at risk and to avoid losses occurring due to failure of building structures.

1.6 Structure of Thesis

Chapter 1: States introduction to earthquakes and its significance in Indian Context, problem statement and motivation behind the research, objectives and research questions to be achieved through this research.

Chapter 2: States about the background for the research, study of HAZUS-MH and its applicability to Indian region, Indian building types and related literature review.

Chapter 3: Gives detailed description about the study area and related general information.

Chapter 4: Provides details of fieldwork, database preparation and methodology adopted for carrying out study. It also provides details of the satellite data used for the database creation.

Chapter 5: States about the results obtained based on the analysis performed.

Chapter 6: States about the conclusions obtained from the results and recommendations for future work.

2 Literature Review

2.1 Hazard

Hazard is defined as "a potentially damaging physical event, phenomenon or human activity that may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation. This event has a probability of occurrence within a specified period of time and within a given area, and has a given intensity"[3].

2.1.1 Earthquake Hazard

An earthquake is sudden shaking of earth caused by waves moving below and on the ground surface due to release of large amount of stored strain energy. Ground shaking is the premium hazard seen due to earthquake. High intensity earthquakes results in partial or complete damage of buildings, dams, roads, bridges, etc. which concludes into loss of life and property. Effect of earthquake also depends on various factor like topography, epicenter, magnitude and location of fault rupture[16].

2.1.2 Earthquake Measurements

An earthquake is measured both in terms of intensity and magnitude. Energy released at the source is termed as magnitude and is generally measured in terms of Modified Mercalli Intensity scale (MMI). Richter scale is also one of the oldest and most popular used scale for measuring magnitude of an earthquake [13]. Intensity is determined based on the effects seen on environment, infrastructure and people. It is the shaking strength developed by an earthquake [17]. Table 2-1 shows the comparison between intensity and magnitude observed near the epicenter. Earthquake is also measured in terms of Peak ground acceleration (PGA) which unlike the energy released gives an impression of how hard the earth can shake. Peak ground acceleration value increases as we move from seismic risk zone II to zone V in India and is "fixed as 0.1g for Zone II, 0.16 g for Zone III , 0.24 g for Zone IV, and 0.36 g for Zone V" [18].

Table 2-1 : Comparison of Magnitude and Typical Maximum MMI [16]

Richter Magnitude	Typical Maximum MMI
1.0 – 3.0	I
3.0 – 3.9	II – III
4.0 – 4.9	IV – V
5.0 – 5.9	VI – VII
6.0 – 6.9	VII – IX
7.0 and Higher	VIII or Higher

2.2 Vulnerability

Vulnerability can be termed as "the degree of loss to a given element or set of elements at risk resulting from the occurrence of a natural phenomenon of a given magnitude. It is expressed on a scale from 0 (no loss) to 1 (total loss)"[3]. There are many dimensions of vulnerability like social, economic, geographical, political and environmental that implicates the intensity at which society is affected to hazard. Different communities have different exposure towards vulnerability [19].

2.2.1 Vulnerability Assessment

Vulnerability assessment is termed as calculating the extent of damage to a particular feature. Two main approaches towards vulnerability assessment are predicted vulnerability and observed vulnerability. Predicted vulnerability is concluded based on expected performance calculated using design specification and engineering computations. To find observed vulnerability, statistics from past earthquakes damages are used. Among both, predicted vulnerability seems to be more accurate as dependence on past data may not be reliable [20].

2.2.2 Earthquake Vulnerability of a Building

Earthquake vulnerability of a buildings can be termed as amount of damage induced in the building due to earthquake. " Vulnerability is expressed on a scale of 0 to 1, where 0 is no damage and 1 defines complete destruction" [21]. It can be expressed in various terms like vulnerability tables, vulnerability tables, fragility curve, response curves, etc.[22]. Vulnerability of a building is determined by factors like shape of building, type of building, its construction material, height, design and structure. A building behaves differently based on different intensities of ground motion.

2.3 Risk

Risk is defined as "The combination of the probability of an event and its negative consequences" [19]. It can be expressed mathematically as function of hazard, vulnerability and elements at risk. Elements at risk can be quantified to be used as a function of risk. Risk can be expressed as –

Risk = Hazard * Vulnerability * Elements at risk quantified

The above mentioned equation can be used spatially for quantifying risk and its mapping[22].

2.3.1 Elements at Risk

Primary elements at risk are buildings, dams, bridges and roads whereas secondary elements are Human life, environment and society. These elements can be quantified by various means and then can be used for vulnerability and risk assessment. For this study, the elements at risk are quantified in terms of number of buildings.

2.3.2 Earthquake Risk Assessment

For assessing the impact of earthquake, risk assessment is one of the most effective approach. It gives a combination of hazard and vulnerability with exposure to find out potential economic losses so that proper mitigation measures can be planned. While calculation, it also takes into account various factors like peak ground acceleration, ground shaking, ground failures, landslide susceptibility, liquefaction susceptibility and ground water depth so as to provide an account of direct and indirect losses occurring due to earthquake like fire, landslides and liquefaction. The results from risk assessment also help engineer's, scientist and urban planners for safe design of buildings against earthquakes [23]. Geological Survey of India and Indian Metrological Department are the prime organization monitoring the seismic hazard. The first vulnerability atlas of India was published by Ministry of Urban Department, Government of India. This atlas provides maps for various types of hazards. Also, with the development of Indian seismic code IS 1983, new risk mitigation strategy came into existence for India. Many organizations in India like National Information Centre for Earthquake Engineering (NICEE) IIT-Kanpur, National Geophysical Research Institute (NGRI) and Earthquake Engineering Department IIT-Roorkee are continuously working for advancements in risk assessment and mitigation methods.

2.4 Seismic Microzonation

Seismic microzonation is "the process of estimating the response of soil layers for earthquake excitations and thus the variation of earthquake characteristics is represented on the ground surface"[24].It is termed as the initial research step towards earthquake risk mitigation. A study using geophysical and geotechnical characteristics for seismic microzonation has been carried out for Dehradun city using geophysical and geotechnical parameters at the depth up to 30 m from ground of soil column at 5% damping condition giving the shear wave velocity map and spectral acceleration map of Dehradun at 1Hz, 3Hz, 5 Hz and 10Hz frequency[14][25].

2.5 Liquefaction Susceptibility and Groundwater Depth

Liquefaction of soil is its behavior, in which the saturated soil looses its substantial amount of strength due to high pore water pressure, generated or accumulated during strong earthquake ground shaking. Liquefaction susceptibility gives the extent as to which the soil is susceptible to liquefaction under ground shaking. It has been mapped for Doon valley in 2001 for earthquake magnitude 8 and considering parameters like geomorphological map, lineament map and digital elevation model using equation of peak ground acceleration given by Joyner and Boore, 1988. Also the ground water depth for this area is calculated [15]. The ground water depth for Dehradun city is also provided by Central Ground Water Board (CGWB) updated as on 2006 [26].

2.6 Statistical Sampling

Statistical sampling is mainly used for representing a large set of data in a short form. There are various types of sampling techniques available and is chosen based on the required output. Generally random sampling is widely used as safest option since not much resources in terms of time and material are required to carry out this kind of sampling[27]. For studying seismic risk assessment in terms of buildings, stratified random sampling is used as the collection of sample points is much easier for the study. Same technique has been used earlier for studying seismic risk assessment considering socio economic clustering for Dehradun city[28].

2.7 HAZUS - MH Methodology

HAZUS- MH is a nationally applicable standardized methodology that contains models for estimating potential losses from earthquakes, floods, and hurricanes [29]. HAZUS is a risk assessment software developed by Department of Homeland Security, Federal Emergency Management Agency (FEMA) in 1997.It uses ArcGIS as a supporting GIS software for usage.

What is HAZUS- MH?

1) It provides a platform of risk assessment for various hazards.
2) It calculates direct and indirect losses and suggests mitigation measures.
3) Identifies and visualizes hazards and vulnerabilities

This model requires an exhaustive data like general building stock, occupancy type, utilities and transport lifelines for database creation. General building stock inventory is formed by using census tract characteristics as the unit for grouping of buildings. Ultimate aim is to group the buildings into the pre-defined classes of buildings in HAZUS so that a seismic hazard map can be produced with the input of seismic microzonation details. Also the methodology helps to find damage probabilities under various ground shaking conditions as shown in Figure 2.2. Building types in HAZUS are basically classified into five frames such as unreinforced concrete frame, reinforced concrete frame, concrete frame, steel frame and wood frame. Further these are classified in total 37 buildings types based on number of stories as per HAZUS 2.1 (Annexure A). Figure 2.1 [13] shows the flow chart for HAZUS methodology. There are basically seven steps in calculating the damage functions.

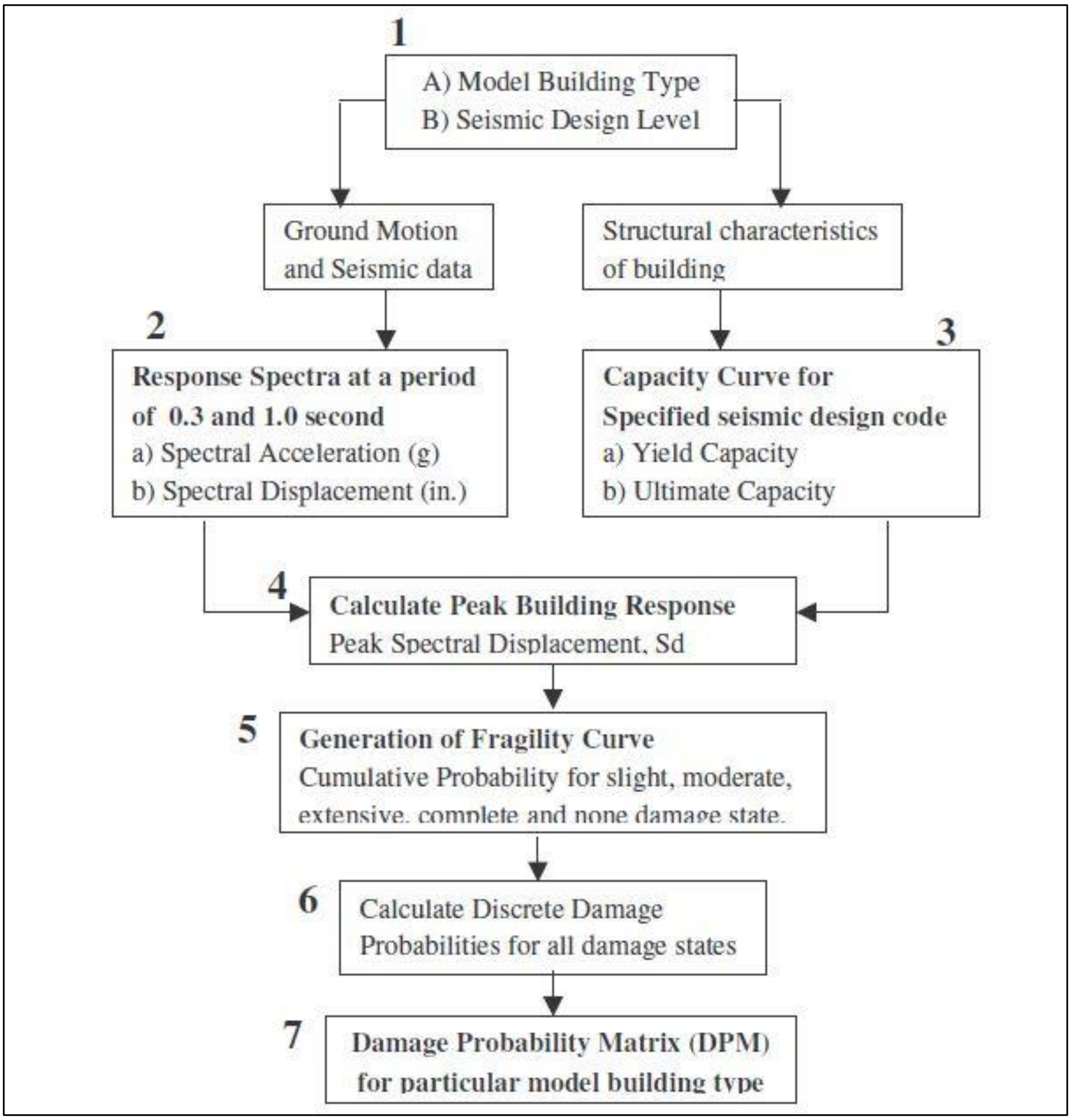


Figure 2-1 : Chart Showing HAZUS methodology

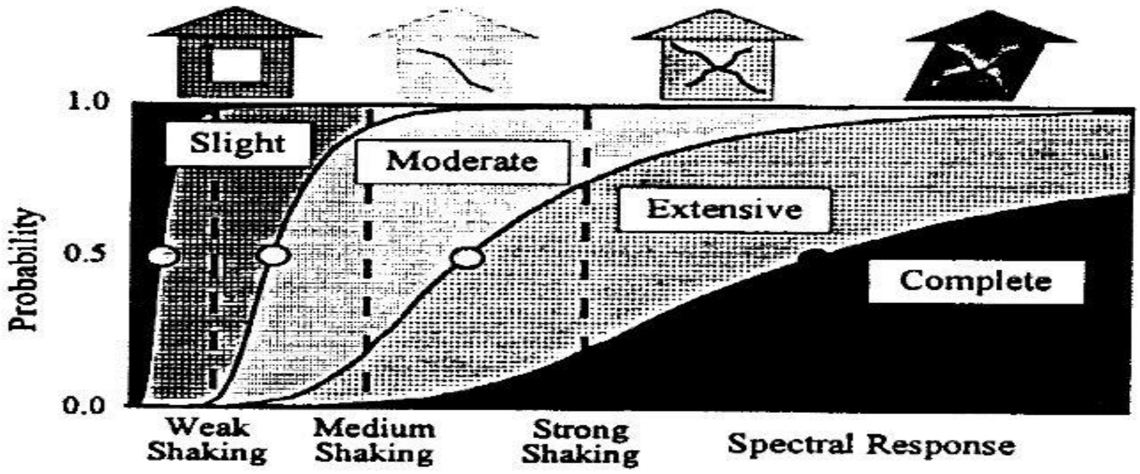


Figure 2-2 : Example fragility curves for different types of damages

2.8 Indian Building Types

Type of construction in India varies greatly from place to place. It mainly depends on the locally available construction materials, topography and the surrounding climatic conditions. Construction type and quality of building is also determined by the economic condition of the owner and influence of the society around. Hence, Indian Building codes are rarely followed for building construction. Also, strength characteristics data for existing buildings is not available. Following this scenario, Indian model building types are classified into 34 types as shown in Table 2-2 based on framing structure of the building and its performance analyzed from the past earthquake events [28].

Classification of existing construction is done in three classes. These are a) adobe and random rubble masonry, b) masonry wall construction using rectangular units and c) framed structures. Above three mentioned classes are further classified based on roof type and stories. Six different roof types are identified. Some classified building types can be compared with already existing building types in HAZUS except adobe and rubble masonry. Below mentioned Table 2-2 shows possible matches of Indian building types with HAZUS building types[28].

2.9 Use of Remote Sensing and GIS

High resolution remote sensing data like IKONOS and GEOEYE are very useful in preparation of database like building block map. Also, it can help in identifying various factors like texture, tone, height, color, etc. of the buildings. GEOEYE is a very high resolution data of 0.6 m pan resolution and 2.4 m multiresolution. Fusion needs to be done between same sensor pan and multiresolution so that in a single image, features of the both images are retained. This helps boundary delineations of buildings.

For enhancement of remote sensing data, processing like feature or boundary delineation, fusion techniques, feature masking and NDVI method is required which can be done through GIS software. GIS and Remote Sensing data can be used together in many ways for modelling, analysis, features extractions, etc. ArcGIS is an interim part of HAZUS model. HAZUS works only with ArcGIS and also the database creation is done through ArcGIS itself.

Table 2-2 : Indian Building Types and corresponding most likely HAZUS building types

Sr. No.	Label	Wall/Framing Type	Roof/Floor Type	Stories	HAZUS Label	Most likely HAZUS building type
Adobe and Random Rubble Masonry						
1	AM1	Rammed mud/ sun-dried bricks /rubble stone in mud mortar	R1, R2	1-2	Not Defined	Not Defined
2	AM2		R3	1-2		
3	AL1	Rubble stone in lime-surkhi mortar	R1, R2	1-2		
4	AL2		R3, R4	1-2		
5	AL3		R5	1-2		
6	AC1	Rubble stone in cement mortar	R1, R2	1-2		
7	AC2		R3, R4	1-2		
8	AC3		R5	1-2		
Masonry consisting of Rectangular units						
9	MM1	Burnt clay brick/ rectangular stone in mud mortar	R1, R2	1-2	Not Defined	Not Defined
10	MM2		R3, R4	1-2		
11	MM3		R5	1-2		
12	ML1	Burnt clay brick/ rectangular stone in lime-surkhi mortar	R1, R2	1-2		
13	ML2		R3, R4	1-2		
14	ML3		R5	1-2		
15	MC1	Burnt clay brick/ rectangular stone/ concrete blocks in Cement mortar	R1, R2	1-2		
16	MC2		R3, R4	1-2		
17	MC3L		R5,R6	1-2		
18	MC3M			3+		
19	ME1L	Burnt clay brick/ rectangular stone/ concrete blocks in cement mortar and provided with seismic bands and vertical reinforcement at corners and jambs	R5,R6	1-2		
20	ME1M			3+		
Framed Structures						
21	RC1L	RC frame/ shear wall with URM infill's – constructed without any consideration for earthquake forces	R6	1-3	C3L	Pre-code
22	RC1M			4-7	C3M	
23	RC2L	RC frame/ shear wall with URM infill's – earthquake forces considered in design but detailing of reinforcement and execution not as per		1-3	C3L	Pre-code/ Low-code
24	RC2M			4-7	C3M	

Sr. No.	Label	Wall/Framing Type	Roof/Floor Type	Stories	HAZUS Label	Most likely HAZUS building type
25	RC3L	earthquake resistant guidelines (Low-code / Moderate-code)		8+	C3H	
26	RC3L	RC frame/ shear wall with URM infill's - designed, detailed and executed as per earthquake resistant guidelines (Low-code/ Moderate-code/ High-code)		1-3	C3L	Pre-code/ Low-code/ Moderate-Code
27	RC3M			4-7	C3M	
28	RC3H			8+	C3H	
29	ST1L	Steel moment frames with URM infill's (Low-code/ Moderate-code/ High-code)		1-3	S5L	Pre-code/ Low-code/ Moderate-Code
30	ST1M			4-7	S5M	
31	ST1H			8+	S5H	
32	ST2L	Steel braced frames (Low-code/ Moderate -code/High-code)		1-3	S2L	Pre-code/ Low-code/ Moderate-Code
33	ST2M			4-7	S2M	
34	ST2H			8+	S2H	
35	MH	Manufactured Houses		1	MH	Pre-Code

* Roof/Floor types: R1 - Heavy sloping roofs-stones/burnt clay tiles/thatch on sloping rafters; R2 – Heavy Flat flexible heavy roof - wooden planks, stone/ burnt clay tiles supported on wooden/steel joists with thick mud overlay; R3 - Light sloping roofs - corrugated asbestos cement or GI sheets on sloping rafters without cross bracing; R4 - Trussed roof with light weight sheeting (without cross bracing); R5 - Trussed/hipped roof with light weight sheeting (with cross bracing); R6 - Flat rigid reinforced concrete or reinforced masonry slab

2.10 Previous Related Work

Many studies has been carried out using the HAZUS-MH methodology for different study areas. Study for similar region has been done using this methodology considering only one ward out of total 60 number of wards in 2005 in absence of various parameters [13]. Another study for Sikkim area, India for 2011 Sikkim earthquake is carried for finding the behavior of different building types and its structural properties [21]. Also the same methodology is applied for the study of Yogyakarta area, Indonesia where building replacement cost is calculated using the percentage of damage caused to a building under historic earthquake scenario [22].

3 Study Area

3.1 Introduction

Dehradun is located in the Doon valley on the foothills of the Himalayas. Active faults such as Himalayan Frontal Thrust, Main Boundary Thrust (MBT) and Main Central Thrust (MCT) exist in this region. It has a history of being one of the most important places from tourism as well as from education point of view. It is a gateway to many beautiful hill stations like Mussorie – Queen of Mountains and Garwal Himalayas of Uttarakhand state. Also Dehradun city is very well connected to some of the important cities such as New Delhi, Chandigarh, Lucknow and Haridwar through air, road and rail. The city houses some of the renowned educational institutes of the country since 1900's. In 2000, it has been declared as capital of Uttarakhand state, resulting in increase of population and rapid urbanization. Being of capital importance, industries have started venturing into this area. There is a demand in growth of infrastructure to meet the public expectations. Construction of various types of household and industrial buildings is on the rise.

3.2 Earthquakes History

Major earthquakes in these areas were 1991 Uttarkashi earthquake having magnitude 6.8 which killed over thousands of people with a significant amount of property damage, to be exact "population of about 307,000 in 1,294 villages were effected, 768 persons died while 5,066 were injured. In addition the earthquake claimed 3,096 head of livestock and as many as 42,400 houses were damaged" [30] and 1999 Chamoli earthquake of magnitude 6.8 killing approximately 103 people with a large amount of infrastructure damage [31]. Both of these earthquakes occurred at the foothills of Himalayas affecting Dehradun and nearby region significantly.

3.3 General Information about Dehradun City

3.3.1 Geographical Location

Dehradun is located between 30° 15' 58" N to 30° 24' 16" N latitude and 77° 58' 56" E to 78° 06' 05" E longitude. The local bodies Dehradun Municipal Corporation and Mussoorie Dehradun Development Authority (MDDA) have divided the city into 60 wards for administrative functions. It is located at altitude of 640 meters above sea level and is bordered by Rispana River and Bindal River from eastern and western part respectively. Dehradun city covers approximate area of 350 sq. kms. [32]. Below figures show the location of Dehradun City.

Figure 3-1 : Map of India [33]

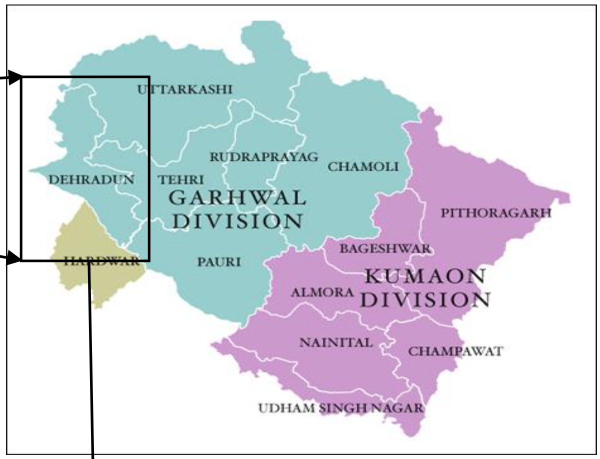


Figure 3-2 : Map of Uttarakhand State[33]

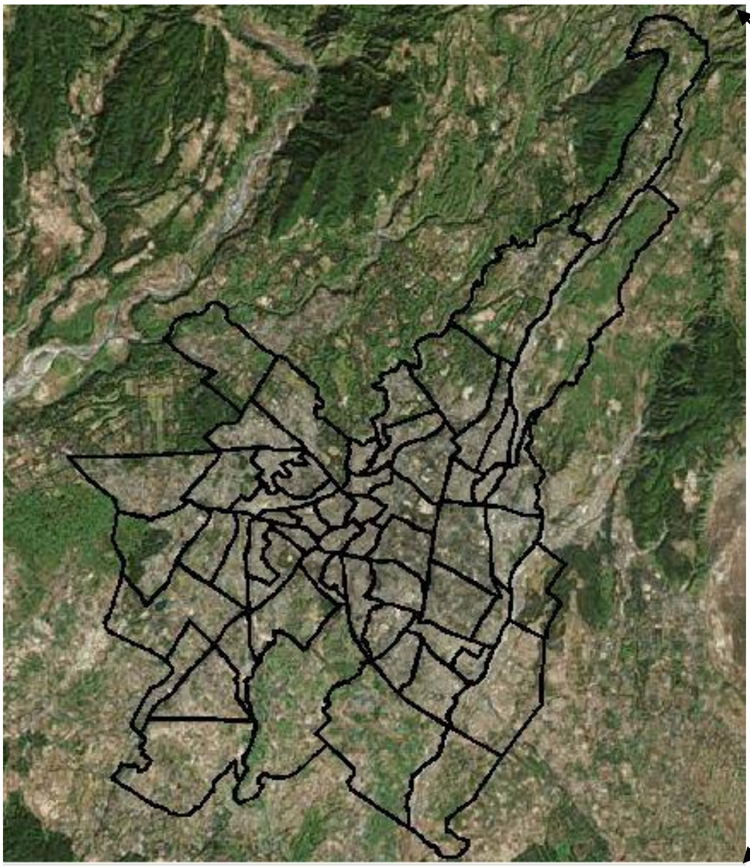


Figure 3-3 : Geoeye satellite image of Dehradun with outline ward map

Figure 3-4 : Dehradun district map[33]

3.3.2 Climatic Conditions

Dehradun climate generally varies from tropical to temperate. Three main seasons ranges as summer season from March to June, rainy from July to September and then follows winter season from October to February. In summers, the maximum temperature reaches around 40^0 and average temperature is around 27^0 whereas winters witness a minimum temperature around $2^0$and average temperature of 13^0. Precipitation received during rainy season is around 2025 mm. Relative Humidity is around 76% during rainy season.

3.3.3 Landuse Pattern

After declaration of Dehradun as capital of Uttarakhand State, the city has seen tremendous growth in terms of population as well as infrastructure. To meet the demand of this growing population and for building a sustainable environment, MDDA has proposed following landuse plan as shown in Table 3-1 [34].

Table 3-1: Existing and Proposed landuse pattern of Dehradun City

Sr. No.	Landuse Pattern	Existing Area (Ha) 2001	Existing Area (%) 2001	Proposed Area (Ha) 2025	Proposed Area (%) 2025
1	Residential	2989.3	8.33	5325.65	14.84
2	Commercial	298.52	0.832	423.32	1.18
3	Industrial	40.50	0.113	331.67	0.52
4	Govt. and Semi Govt. offices	470.59	1.312	925.97	2.58
5	Utilities and Services	289.02	2.979	1030.49	2.88
6	Public and Semi Public offices	NA	NA	132.92	0.37
7	Tourism and Recreation	NA	NA	202.16	0.56
8	Parks and Open Space	NA	NA	978.88	2.73
9	Transportation and Circulations	425.1	1.186	1517.80	4.23
10	Miscellaneous	NA	NA	24998.34	69.71
	Total	9686.87	27.04	35867.2	100

3.3.4 Building Types and Urban Settlement Pattern

Many old and beautiful buildings are situated in Dehradun. Starting from British Colonial era to Modern Indian period, Dehradun has witnessed transition in type of buildings construction. Some of the noteworthy structures are Clock Tower, Forest Research Institute, Indian Military Academy, Morrison Memorial Church, etc. Nowadays, construction in the city is mainly RC framed structure and load bearing structure [35]. As reinforced buildings against earthquake are not in practice here it may result in failure during a moderate to high earthquake as it has been concluded that the valley is highly exposed to the seismic hazard [36].Therefore it can be said that the whole Doon valley is tectonically unstable, there is possibility of one or more great earthquakes in the area in near future [37].

Urban settlement is spread over the whole city unevenly in 60 wards as created by local government bodies for administration. Some wards situated in the middle of the city are highly crowded with a mix type of building construction i.e., old and new while the wards towards the outskirts has seen the recent developments. Figure 3-5 shows the 60 wards by Dehradun Municipal Corporation.

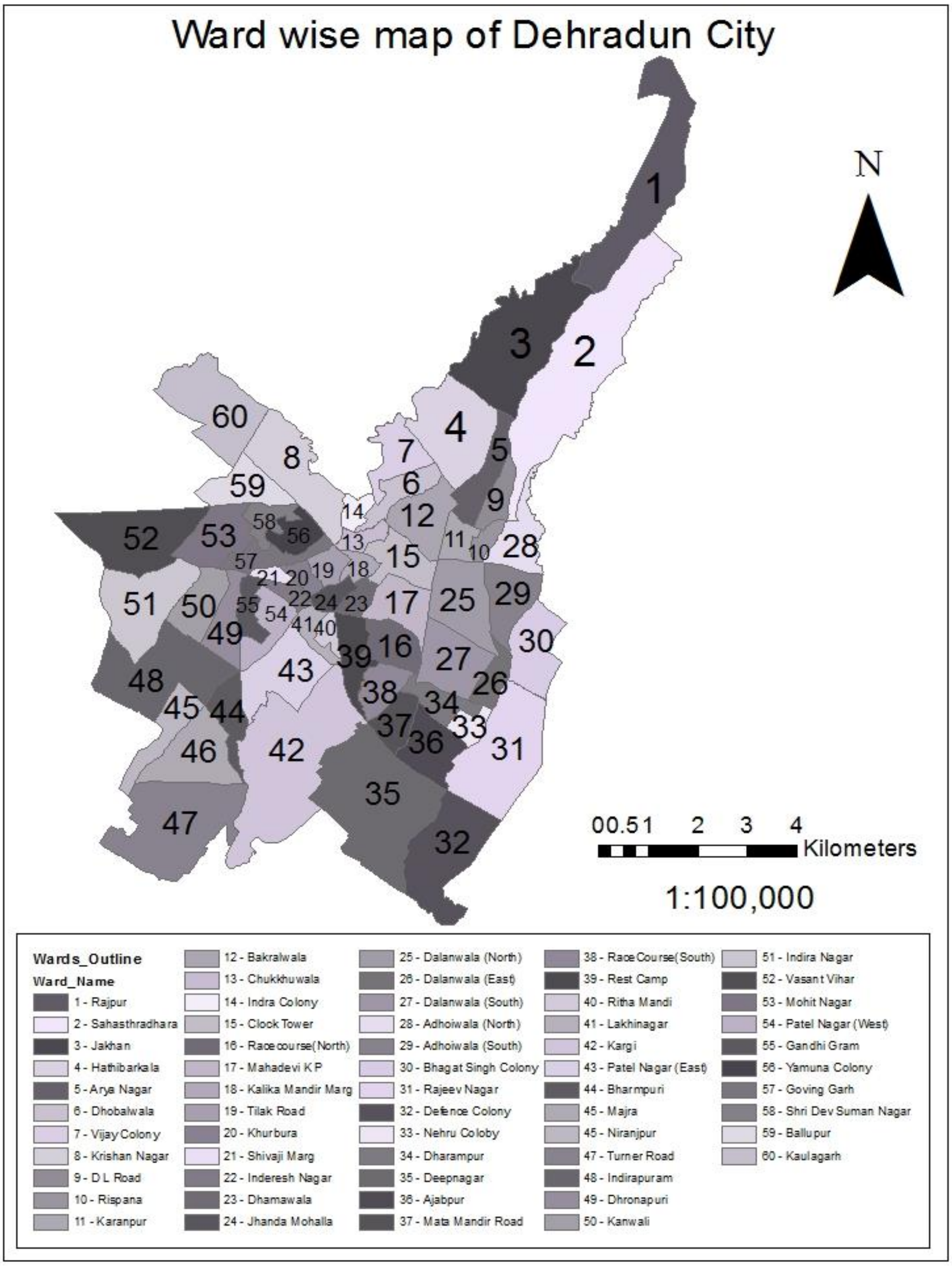


Figure 3-5 : Ward wise map of Dehradun city

3.3.5 Demographics

Uttarakhand is one of the newly formed state with total population around 10 million as per 2011 census. It is divided into 13 districts. Dehradun is one of the highest populated district with total population of 1,695,860. Population of the city as per 2011 census India is 578,420 out of which 303,411 are males and 275,009 are females. Population density of Dehradun city is around 500 /km^2. Rise in population of the city is significant as the total population in 2001 was 426,674. Households have also increased considerably since last decade. In 2001, total households were 84,012 against population of 426,674 with household size of 5.1 persons. According to 2011 census, total households are 124,059 against population of 578,420 with household size of 4.7 persons [38].

3.3.6 Dehradun Local Authorities

Dehradun local authorities are Dehradun Municipal Corporation (DMC) and Mussoorie Dehradun Development Authority (MDDA). These authorities are local governing bodies deciding the rules and regulations for the city. These authorities with other national and international bodies like National Disaster Management Center (NDMA), Asia Disaster Preparedness Center (ADPC), etc. decides the disaster management plans and mitigation measures for the city. Various studies are being carried out for earthquake risk assessment, vulnerability, capacity building and preparedness.

4 Methodology and Database Preparation

4.1 Introduction

This chapter basically deals with the methodology adopted for the research and the database preparation for the analysis. The Research Methodology is divided into three stages i.e., pre field work, field work and post field work. These three stages are further divided into many steps for achieving the objectives as shown in below figure 4.1.

Sampling, HAZUS geodatabase creation, building damage probability and risk map generation are some of the key steps of the research methodology. Main part of the research lies in creation of seismic hazard map and damage assessment for the development of final risk map.

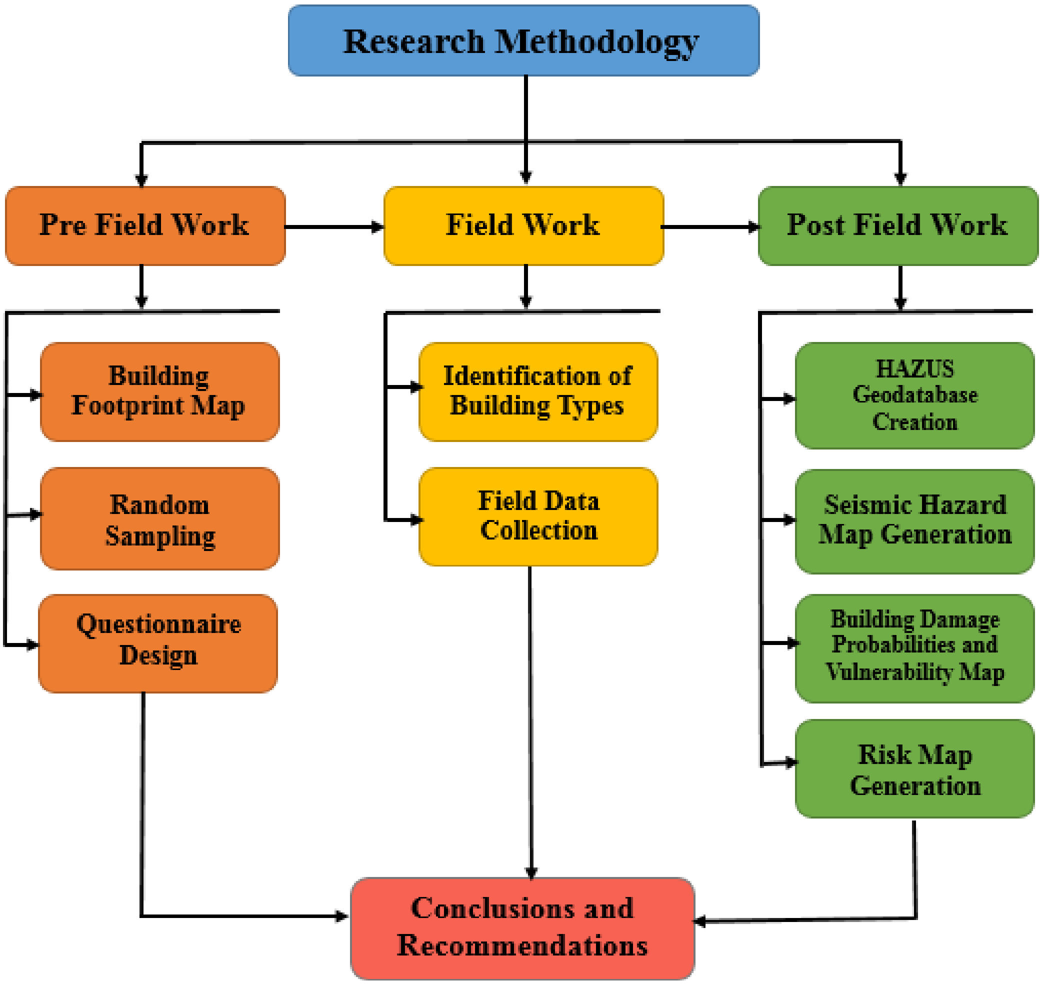


Figure 4-1 : Flowchart showing Research Methodology

4.2 Pre Field Work

4.2.1 Building Footprint Map

Building footprint map for 8 wards is generated out of total 60 wards present in Dehradun city. These 8 wards are selected from preliminary field survey so that a maximum number of different building types are covered during actual field survey. The data used for digitization of footprint map is as shown in table 4.1. Around 11000 number of building blocks have been digitized for 8 wards using ArcGIS software. Figure 4.2 shows the building footprint map for selected wards with ward numbers.

Table 4-1: Satellite Data Used

Sr. No.	Satellite Image	Acquisition Date	Ground Resolution	Projection System
1	GEOEYE PAN	07-Dec-2006	0.6m	UTM , WGS 1984
2	GEOEYE MS	07-Dec-2006	2.4m	UTM , WGS 1984
3	GEOEYE (Bing Maps)	Updated till 2011	0.6m	UTM , WGS 1984

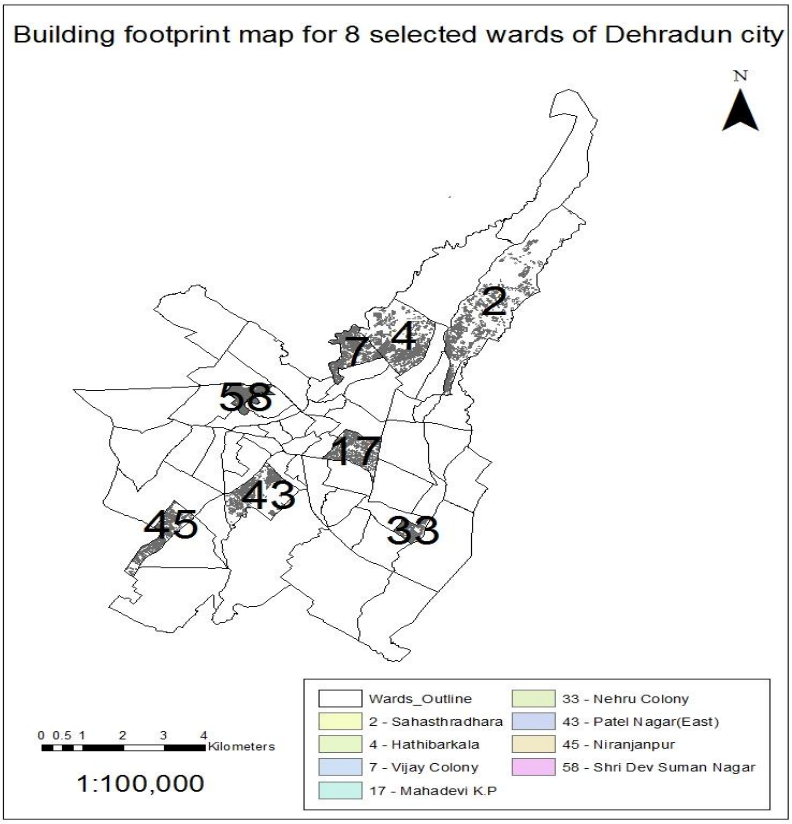


Figure 4-2 : Building footprint map for 8 selected wards of Dehradun city

4.2.2 Random Sampling:

As the area is large and buildings are also high in number, random statistical sampling method has been adopted for the collecting the samples with the intention that the sample points have a good spread over the complete ward. 50 sample points from each ward has been selected and survey has been done for the building type at particular point. Figure 4-3 shows digitized building blocks on GEOEYE image for ward number 43 and Figure 4-4 shows the distribution of sample points over complete ward number 43. The black colored cross represents the points collected through GPS.

Figure 4-3 : Digitized building blocks of ward number 43 on GEOEYE Image

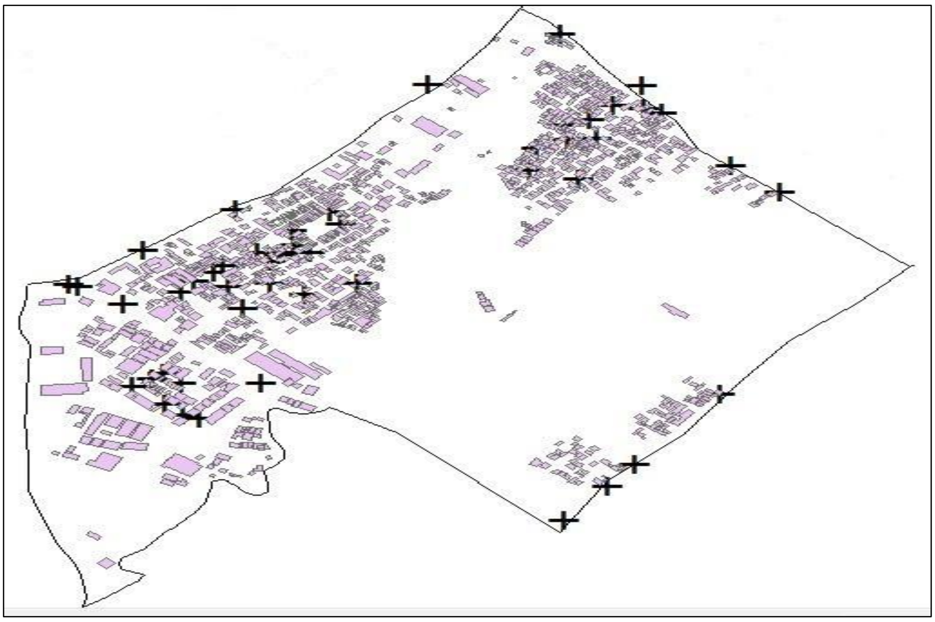


Figure 4-4 : Building blocks of ward number 43 with distributed sample points

4.2.3 Checklist Design

A good checklist in seismic risk assessment study would definitely be helpful in collecting the information in an organized way. Keeping this in mind, the checklist is designed that maximum usable information about the building is collected in stipulated time. There is no standard format available for checklist of pre earthquake risk assessment and it depends upon the purpose to be fulfilled from the information adopted. As this study revolves around HAZUS methodology, the checklist designed basically provides input for the study. The main aim is to understand the type of building, its utility, its approximate age and present condition of the building. The structure of the checklist used for this study is shown in Appendix B.

4.3 Field Work

4.3.1 Identification of Building Types

Extensive field work was carried in three stages. Firstly a preliminary of 2 days in October’14 for selecting the wards to be digitized so that a good variety of building type with different ages is recorded. Then the main field work was carried out for 7 days in Novmeber’14 for 400 number of buildings across 8 wards selected after random sampling. Along with collection of GPS points, photographs of each and every building type was clicked for reference. Thirdly, a complete ward was surveyed comprising of 1400 for 12 days for validation of values obtained through surveyed samples. Identification of building type is based on HAZUS methodology and Indian building types[28] [39]. Classification is based on the type of building construction and number of floors. One more important factor is the type of roof of the building. All the wards have mixture of residential, commercial, institutional, etc. with 5 types of building i.e., RC1L, RC1M, RC2L, RC2M and MH described in detail in Table 2-2 and short description in Table 4-2. Some of the typical examples of building types seen in 8 different wards with its satellite image are given in Figure 4-5 to Figure 4-14.

Table 4-2 : Short description of 5 building types

Building Type	Description
RC1L	Reinforced Concrete category 1 with Low-rise (1-3)
RC1M	Reinforced Concrete category 1 with Mid-rise (4-7)
RC2L	Reinforced Concrete category 2 with Low-rise(1-3)
RC2M	Reinforced Concrete category 2 with Mid-rise(4-7)
MH	Manufactured Home

Figure 4-5 : Building type RC1L of ward no. 4 on GEOEYE image

Figure 4-6 : Building type RC1L of ward no. 4 on ground

Figure 4-7 : Building type RC1M of ward no. 33 on GEOEYE image

Figure 4-8 : Building type RC1M of ward no.33 on ground

Figure 4-9 : Building type RC2L of ward no. 43 on GEOEYE image

Figure 4-10 : Building type RC2L of ward no.43 on ground

Figure 4-11 : Building type RC2M of ward no. 02 on GEOEYE image

Figure 4-12 : Building type RC2M of ward no. 02 on ground

Figure 4-13 : Building type MH of ward no. 07 on GEOEYE image

Figure 4-14 : Building type MH of ward no. 07 on ground

4.3.2 Field Data Collection

Building samples from 8 selected wards is surveyed to collect all the information necessary for the analysis and results. Table 4-3 depicts the distribution of different building types from 50 samples collected from each ward. This results is further used for extrapolation. Apart from this, other field data like visual characteristics of building like age of building, its utility and building appearance are recorded for reference. For validation of distribution of buildings over surveyed samples, an extensive detailed field survey is carried out for ward number 4 having total of 1396 number of buildings .Table 4-4 shows the distribution over detailed surveyed ward. As seen from table 4-3 and 4-4, there is little difference in the two distribution percentages. Table 4-5 shows the household data collected by local authorities of the city i.e., Dehradun Nagar Nikam. This household data is used for extrapolating the total number of houses in the city across different wards.

Table 4-3 : Surveyed samples with building type distribution

Sr. No.	Ward Name	Ward No.	Number of sample buildings surveyed	RC1L		RC1M		RC2L		RC2M		MH	
				No.	%	No.	%	No.	%	No.	%	No.	%
1	Sahastradhara	2	50	39	78%	1	2%	2	4%	5	10%	3	6%
2	Hathibarkala	4	50	48	96%	1	2%	0	0%	0	0%	1	2%
3	Vijay Colony	7	50	43	86%	0	0%	1	2%	2	4%	4	8%
4	M.K.P	17	50	45	90%	1	2%	2	4%	2	4%	0	0%
5	Nehru Colony	33	50	49	98%	0	0%	0	0%	1	2%	0	0%
6	Patel Nagar (East)	43	50	47	94%	0	0%	0	0%	2	4%	1	2%
7	Niranjanpur	45	50	47	94%	0	0%	0	0%	1	2%	2	4%
8	Shri Dev Suman Nagar	58	50	49	98%	0	0%	1	2%	0	0%	0	0%

Table 4-4 : Distribution of building types over detailed field surveyed ward

Sr. No.	Ward Name	Ward No.	Total number of buildings	RC1L		RC1M		RC2L		RC2M		MH	
				No.	%	No.	%	No.	%	No.	%	No.	%
1	Hathibarkala	4	1396	1284	92%	42	3%	14	1%	14	1%	42	3%

Table 4-5 : Ward wise household data for Dehradun city

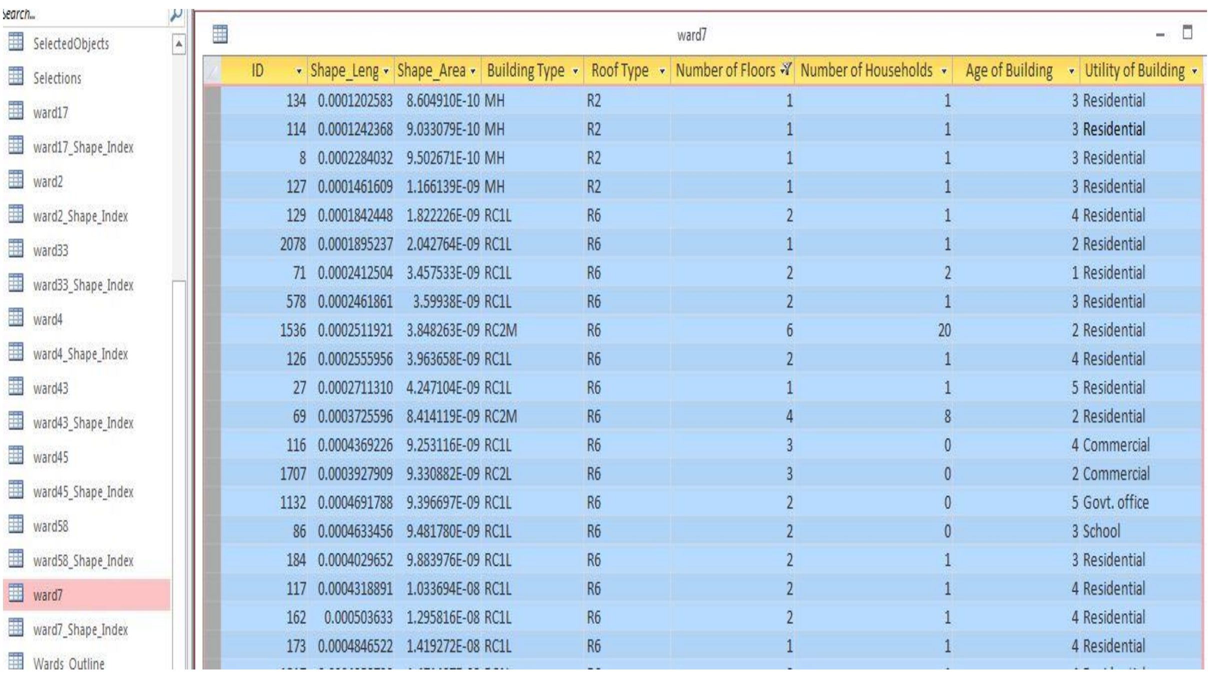
Sr. No.	Ward Nos.	Number of Households	Sr. no.	Ward Nos.	Number of Households
1	Ward Number 1	2392	31	Ward Number 31	3618
2	Ward Number 2	3308	32	Ward Number 32	3032
3	Ward Number 3	2852	33	Ward Number 33	1546
4	Ward Number 4	1704	34	Ward Number 34	1921
5	Ward Number 5	1785	35	Ward Number 35	3406
6	Ward Number 6	1934	36	Ward Number 36	2598
7	Ward Number 7	1868	37	Ward Number 37	2862
8	Ward Number 8	2182	38	Ward Number 38	1609
9	Ward Number 9	1496	39	Ward Number 39	2316
10	Ward Number 10	1505	40	Ward Number 40	1351
11	Ward Number 11	1571	41	Ward Number 41	1160
12	Ward Number 12	1595	42	Ward Number 42	3496
13	Ward Number 13	1354	43	Ward Number 43	1897
14	Ward Number 14	1759	44	Ward Number 44	3005
15	Ward Number 15	1240	45	Ward Number 45	1483
16	Ward Number 16	1417	46	Ward Number 46	2344
17	Ward Number 17	1370	47	Ward Number 47	2458

Sr. No.	Ward Nos.	Number of Households	Sr. no.	Ward Nos.	Number of Households
18	Ward Number 18	1190	48	Ward Number 48	2315
19	Ward Number 19	1926	49	Ward Number 49	2140
20	Ward Number 20	1612	50	Ward Number 50	2124
21	Ward Number 21	2044	51	Ward Number 51	3128
22	Ward Number 22	1731	52	Ward Number 52	3260
23	Ward Number 23	1111	53	Ward Number 53	1989
24	Ward Number 24	1472	54	Ward Number 54	2232
25	Ward Number 25	1895	55	Ward Number 55	2122
26	Ward Number 26	1788	56	Ward Number 56	1554
27	Ward Number 27	1776	57	Ward Number 57	2208
28	Ward Number 28	1692	58	Ward Number 58	1854
29	Ward Number 29	2836	59	Ward Number 59	2119
30	Ward Number 30	2357	60	Ward Number 60	2150

4.4 Post Field Work

4.4.1 HAZUS Geodatabase Creation

For working with building inventory in HAZUS, creation of geodatabase is required. A geodatabase with all the building type and other information like utility of building and its age is created in MS-Access for analysis. Figure 4-15 shows a screen capture of database created for ward number 7 in MS-Access. This database is created with the help of existing database provided with the HAZUS software. Further it helps in preparing seismic hazard and risk maps.



ID	Shape_Leng	Shape_Area	Building Type	Roof Type	Number of Floors	Number of Households	Age of Building	Utility of Building
134	0.0001202583	8.604910E-10	MH	R2	1	1	3	Residential
114	0.0001242368	9.033079E-10	MH	R2	1	1	3	Residential
8	0.0002284032	9.502671E-10	MH	R2	1	1	3	Residential
127	0.0001461609	1.166139E-09	MH	R2	1	1	3	Residential
129	0.0001842448	1.822226E-09	RC1L	R6	2	1	4	Residential
2078	0.0001895237	2.042764E-09	RC1L	R6	1	1	2	Residential
71	0.0002412504	3.457533E-09	RC1L	R6	2	2	1	Residential
578	0.0002461861	3.59938E-09	RC1L	R6	2	1	3	Residential
1536	0.0002511921	3.848263E-09	RC2M	R6	6	20	2	Residential
126	0.0002555956	3.963658E-09	RC1L	R6	2	1	4	Residential
27	0.0002711310	4.247104E-09	RC1L	R6	1	1	5	Residential
69	0.0003725596	8.414119E-09	RC2M	R6	4	8	2	Residential
116	0.0004369226	9.253116E-09	RC1L	R6	3	0	4	Commercial
1707	0.0003927909	9.330882E-09	RC2L	R6	3	0	2	Commercial
1132	0.0004691788	9.396697E-09	RC1L	R6	2	0	5	Govt. office
86	0.0004633456	9.481780E-09	RC1L	R6	2	0	3	School
184	0.0004029652	9.883976E-09	RC1L	R6	2	1	3	Residential
117	0.0004318891	1.033694E-08	RC1L	R6	2	1	4	Residential
162	0.000503633	1.295816E-08	RC1L	R6	2	1	4	Residential
173	0.0004846522	1.419272E-08	RC1L	R6	1	1	4	Residential

Figure 4-15 : HAZUS geodatabase creation in MS-Assess

4.4.2 Seismic Hazard Map Generation

As per HAZUS-MH methodology, seismic hazard calculation includes ground motion and ground failure (i.e., landslide, liquefaction and surface fault rupture). Seismic hazard map shows the probability of occurrence of these ground motion and ground failure over the area. Methodology can be explained as:

4.4.2.1 Ground motion

Ground motion estimation is done by three parameters namely as standard spectrum shape, peak ground acceleration and peak ground velocity [39]. Its spatial distribution can be determined by any of the following methods:

- Deterministic ground motion analysis
  The analysis is done for user specific defined earthquake scenarios. For an assumed earthquake scenario, ground shaking demand is calculated using attenuation relationships for defined soil class.

- Probabilistic ground motion analysis
  Probabilistic ground motion analysis is done for user defined earthquake scenario with the ground shaking probability of return period varying from 50 years to 2500 years.

- User provided ground motion maps
  It can either be deterministic or probabilistic or a combination of both analysis as it depends on user provided ground motion and contour maps.

For this study, maps required for ground motion analysis are provided. Parameters required for earthquake scenario generation is as per Table 4-6 [13][40] . Input maps required for analysis are as mentioned below.

Table 4-6 : Parameters assumed for risk map generation

Characteristics	Parameters
Epicentre	78° 5’ 52”E 30°23’57”N
Major Thrust	MBT
Moment magnitude (M_w)	8
Fault Type	Strike Slip
Fault Depth	15 Km
Fault Length	30 Km
Dip Angle	9

4.4.2.2 Peak Ground Acceleration and Peak Ground Velocity

Peak ground acceleration is concluded form spectral acceleration response and peak ground velocity is calculated from 1-second spectral acceleration response[25] [39].

4.4.2.3 Spectral Acceleration response

Spectral acceleration response is a necessary parameter for hazard mapping as it provides the ground shaking response at different time periods. The spectral acceleration at periods of 0.3 second and 1.0 second at 5% damping is provided for analysis as the response parameter is available at frequencies 1Hz, 3Hz, 5 Hz, 10Hz for Dehradun city[25].

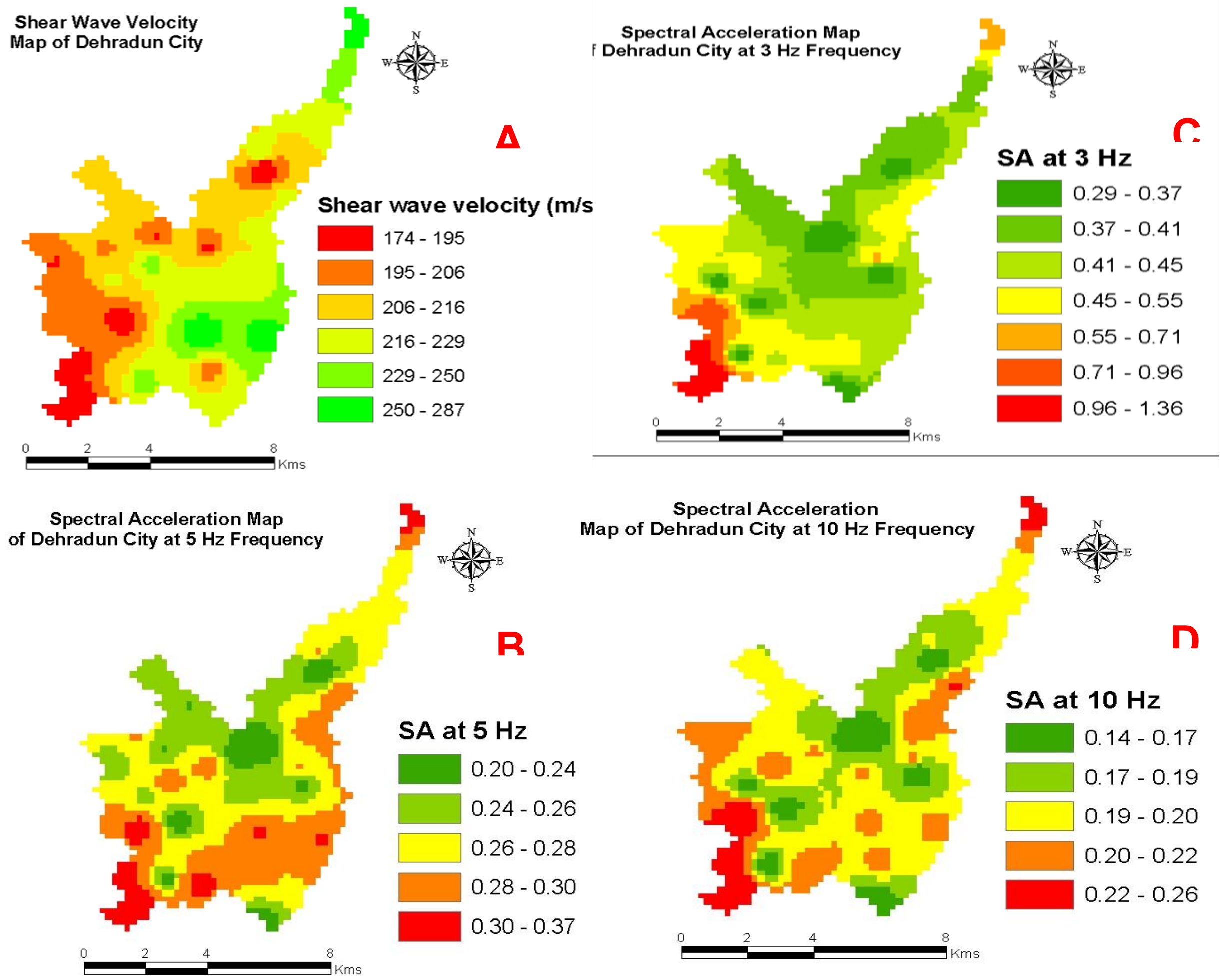


Figure 4-16 : Seismic Microzonation details of Dehradun City

4.4.2.4 Soil Class

HAZUS-MH takes into soil classification according to NEHRP provisions. As seen from Figure 4-16, the shear wave velocity lies between the range of 180- 360 m/sec. c [25] and as per Table 4-7[41], it is concluded that soil class D is the appropriate soil class for this study.

Table 4-7 : Soil class classification according to NEHRP provisions

Soil Profile Type	Soil/Rock Description	Average Shear wave Velocity for upper 30 m (in m/sec)
A	Hard Rock	>1500
B	Rock	760-1500
C	Very Dense soil/Soft soil	360-760
D	Stiff soil	180-360
E	Soft soil	<180
F	Special soils requiring site specific evaluation	

4.4.2.5 Liquefaction Susceptibility Map

Liquefaction is primarily accessed by duration and amplitude of ground shaking, soil susceptibility and groundwater depth. The liquefaction susceptibility map was prepared for Doon valley in 2001. The map is created at assumption of Moment magnitude 8 which also matches the criteria of earthquake magnitude for this study [39].

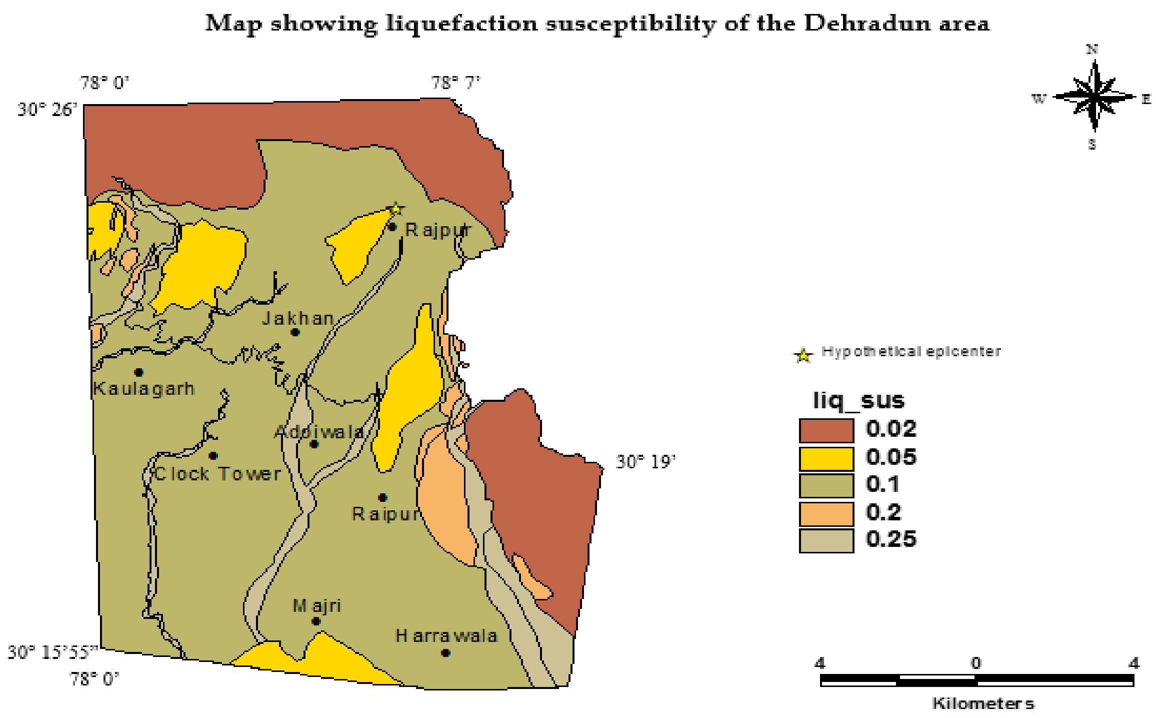


Figure 4-17 : Map showing liquefaction susceptibility of the Dehradun area

4.4.2.6 Depth to Water Level

In HAZUS, depth to water level parameters is defined in feet's. As seen from the Figure 4-18 [26], depth to water level vary for different parts of the city. A common value of 10 m i.e., approximately 30 feet over the entire city is taken for analysis.

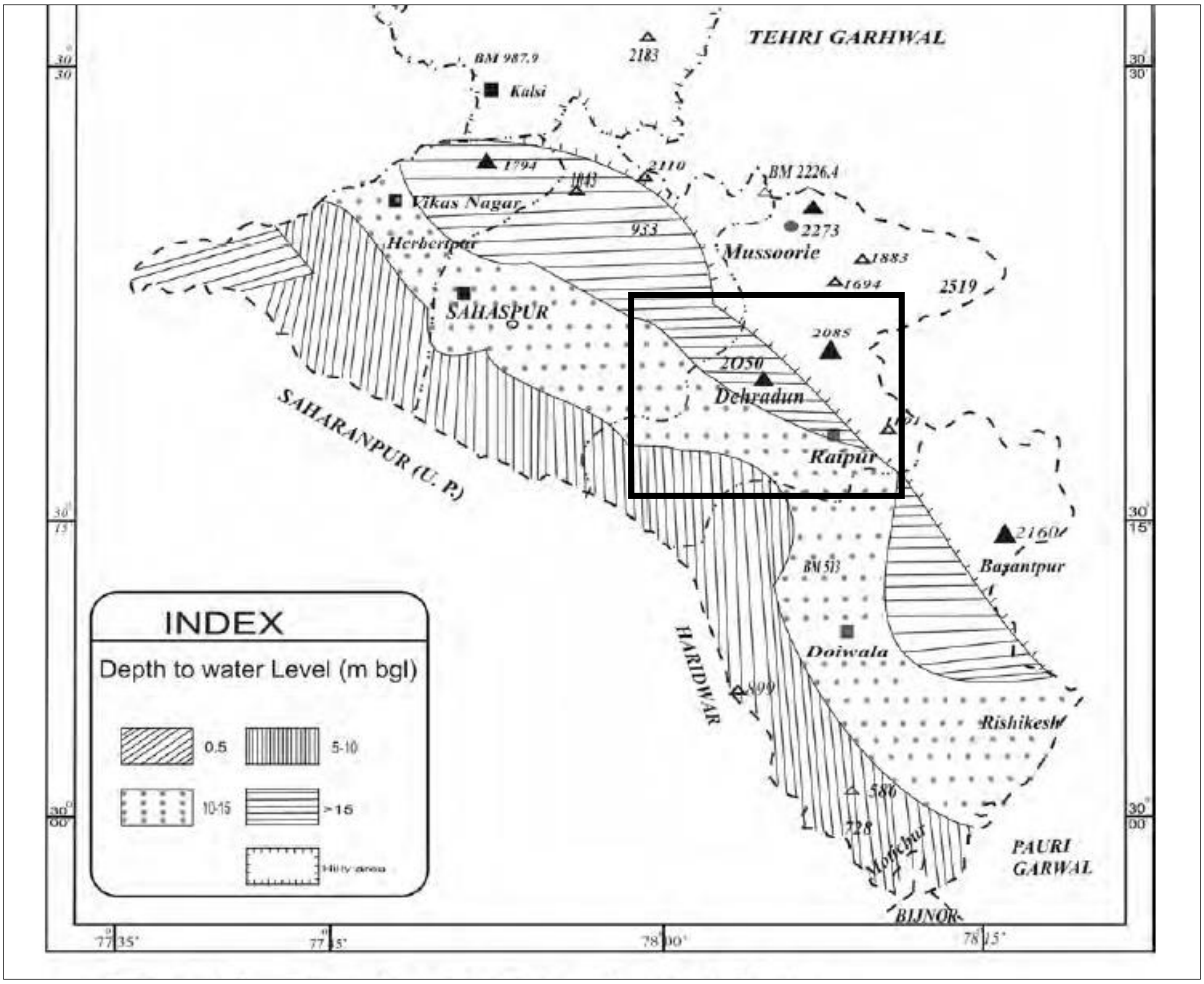


Figure 4-18 : Depth to water level of Dehradun city by Central Ground Water Board (CGWB)

4.4.2.7 Landslide Susceptibility Map

Landslide susceptibility of a region is categorized by the geological map, critical acceleration and slope angle of the region. In absence of the susceptibility map, the value is set to zero.

4.4.3 Building Damage Probabilities Calculations

Building damage probabilities are calculated under various available parameters like soil class, liquefaction probability, spectral acceleration and ground water depth with geological parameters mentioned in Table 4-6 at scenario with maximum earthquake magnitude of 8.

4.4.3.1 Demand Spectrum Curve

Demand spectrum curve is a plot of spectral acceleration and spectral displacement. This format of plot of demand spectrum is used for damage assessment of buildings. As per the methodology, relationship is given as:

$$S_D = 9.8 * S_A * T^2 \tag{4.1}$$

where S_D is the spectral displacement
S_A is the spectral acceleration
T is time period in seconds

Spectral displacement is calculated from the spectral acceleration values against frequency as given in table 5-3.

4.4.3.2 Capacity Curve

Capacity curve represents the true lateral strength of a building. It is given by three parameters namely design capacity, yield capacity and ultimate capacity. For this study, two parameters i.e., yield capacity and ultimate capacity values are taken from HAZUS technical manual for different building types under various seismic design codes.

4.4.3.3 Peak Building Response

Peak building response is derived from the intersection point of the demand spectrum curve and capacity curve for different building types. The value obtained in term of peak spectral displacement is used for cumulative damage probability calculation for different building types.

4.4.3.4 Cumulative Damage Probability

Cumulative damage probability is calculated with the help of below mentioned equation[39]. The parameters namely median spectral displacement and beta is obtained form given values in HAZUS technical manual for different building types. Standard normal cumulative distribution function is obtained from z-distribution table of function (0, 1). Output is in the form of 4 types i.e., slight, moderate, extensive and complete damage of buildings.

$$P(d_s|S_d) = \Phi\left[\frac{1}{\beta_{ds}}\ln\left(\frac{S_d}{\bar{S}_{d,ds}}\right)\right] \tag{4-2}$$

where: $P(d_s|S_d)$ is the probability of reaching the slight damage state for a given peak building response S_d
$\bar{S}_{d,ds}$ is the median value of spectral displacement at which the building reaches the threshold of damage state
β_{ds} is the standard deviation of the natural logarithm of spectral displacement for damage state d_s
Φ is the standard normal cumulative distribution function

4.4.3.5 Discrete Damage Probability

Discrete damage probability is calculated as per below given probability functions. These functions require cumulative damage probability as an input.

Table 4-8 : Discrete Damage Probability equations

Probability		
Complete Damage	$P(C) =$	$P(C\|S_d)$
Extensive Damage	$P(E) =$	$P(E\|S_d) - P(C\|S_d)$
Moderate Damage	$P(M) =$	$P(M\|S_d) - P(E\|S_d)$
Slight Damage	$P(S) =$	$P(S\|S_d) - P(M\|S_d)$
No Damage	$P(N) =$	$1 - P(E\|S_d)$

4.4.4 Vulnerability Map

Considering the above earthquake scenario with moment magnitude 8 and damage probabilities of different building types, ward wise vulnerability map is generated. Vulnerability is mapped and classified in three zones namely low, moderate and high vulnerable zones. The scale varies from 0 i.e., no damage to 1 i.e., complete damage.

4.4.5 Risk Maps Generation

Risk is expressed as = Hazard * Vulnerability * buildings at risk

For this study risk maps are generated considering three scenarios in terms of earthquake moment magnitude of 6, 7 and 8 with all the other conditions as same. Hazard map obtained from defined parameters and various characteristics maps is crossed with the vulnerability map generated considering the probable damage of buildings at risk.

5 Results and Discussions

5.1 Field Work Output

The distribution percentage of type of buildings out of 50 samples surveyed is then extrapolated to total number of building present in that particular ward. Table 5-1 shows the distribution of building types for total number of buildings across 8 wards. Number of household to number of houses ratio is calculated for the surveyed sample and by **averaging the value found out is 1.4**. This value along with the household data from table 4-4 is used to calculate number of houses i.e., buildings in each ward as shown in table 5-2 with the same distribution of different building types for extrapolation.

Table 5-1 : Total Number of buildings distributed in selected wards

Sr. No.	Ward Name	Ward No.	Total number of buildings	RC1L		RC1M		RC2L		RC2M		MH	
				No.	%	No.	%	No.	%	No.	%	No.	%
1	Sahastradhara	2	2345	1829	78%	47	2%	94	4%	235	10 %	141	6%
2	Hathibarkala	4	1396	1340	96%	28	2%	0	0%	0	0%	28	2%
3	Vijay Colony	7	1332	1146	86%	0	0%	27	2%	53	4%	107	8%
4	M.K.P	17	1021	919	90%	20	2%	41	4%	41	4%	0	0%
5	Nehru Colony	33	966	947	98%	0	0%	0	0%	19	2%	0	0%
6	Patel Nagar (East)	43	1285	1208	94%	0	0%	0	0%	51	4%	26	2%
7	Niranjanpur	45	1074	1010	94%	0	0%	0	0%	21	2%	43	4%
8	Shri Dev Suman Nagar	58	1295	1269	98%	0	0%	26	2%	0	0%	0	0%

Table 5-2 : Total number of buildings distributed ward wise by average percentage

Sr. No.	Ward Number	Number of Households	Number of Buildings	RC1L	RC1M	RC2L	RC2M	MH
1	Ward Number 1	2392	1709	1568	13	26	56	47
2	Ward Number 2	3308	2345	2152	18	35	76	64
3	Ward Number 3	2852	2037	1869	15	31	66	56
4	Ward Number 4	1704	1396	1281	10	21	45	38
5	Ward Number 5	1785	1275	1170	10	19	41	35
6	Ward Number 6	1934	1381	1267	10	21	45	38
7	Ward Number 7	1868	1332	1222	10	20	43	37
8	Ward Number 8	2182	1559	1430	12	23	51	43
9	Ward Number 9	1496	1069	980	8	16	35	29
10	Ward Number 10	1505	1075	986	8	16	35	30
11	Ward Number 11	1571	1122	1030	8	17	36	31
12	Ward Number 12	1595	1139	1045	9	17	37	31
13	Ward Number 13	1354	967	887	7	15	31	27
14	Ward Number 14	1759	1256	1153	9	19	41	35
15	Ward Number 15	1240	886	813	7	13	29	24
16	Ward Number 16	1417	1012	929	8	15	33	28

Sr. No.	Ward Number	Number of Households	Number of Buildings	RC1L	RC1M	RC2L	RC2M	MH
17	Ward Number 17	1370	1021	937	8	15	33	28
18	Ward Number 18	1190	850	780	6	13	28	23
19	Ward Number 19	1926	1376	1262	10	21	45	38
20	Ward Number 20	1612	1151	1056	9	17	37	32
21	Ward Number 21	2044	1460	1340	11	22	47	40
22	Ward Number 22	1731	1236	1134	9	19	40	34
23	Ward Number 23	1111	794	728	6	12	26	22
24	Ward Number 24	1472	1051	965	8	16	34	29
25	Ward Number 25	1895	1354	1242	10	20	44	37
26	Ward Number 26	1788	1277	1172	10	19	42	35
27	Ward Number 27	1776	1269	1164	10	19	41	35
28	Ward Number 28	1692	1209	1109	9	18	39	33
29	Ward Number 29	2836	2026	1859	15	30	66	56
30	Ward Number 30	2357	1684	1545	13	25	55	46
31	Ward Number 31	3618	2584	2371	19	39	84	71
32	Ward Number 32	3032	2166	1987	16	32	70	60
33	Ward Number 33	1546	966	886	7	14	31	27
34	Ward Number 34	1921	1372	1259	10	21	45	38
35	Ward Number 35	3406	2433	2232	18	36	79	67
36	Ward Number 36	2598	1856	1703	14	28	60	51
37	Ward Number 37	2862	2044	1876	15	31	66	56
38	Ward Number 38	1609	1149	1054	9	17	37	32
39	Ward Number 39	2316	1654	1518	12	25	54	45
40	Ward Number 40	1351	965	885	7	14	31	27
41	Ward Number 41	1160	829	760	6	12	27	23
42	Ward Number 42	3496	2497	2291	19	37	81	69
43	Ward Number 43	1897	1285	1179	10	19	42	35
44	Ward Number 44	3005	2146	1969	16	32	70	59
45	Ward Number 45	1483	1074	985	8	16	35	30
46	Ward Number 46	2344	1674	1536	13	25	54	46
47	Ward Number 47	2458	1756	1611	13	26	57	48
48	Ward Number 48	2315	1654	1517	12	25	54	45
49	Ward Number 49	2140	1529	1402	11	23	50	42
50	Ward Number 50	2124	1517	1392	11	23	49	42
51	Ward Number 51	3128	2234	2050	17	34	73	61
52	Ward Number 52	3260	2329	2136	17	35	76	64
53	Ward Number 53	1989	1421	1304	11	21	46	39
54	Ward Number 54	2232	1594	1463	12	24	52	44
55	Ward Number 55	2122	1516	1391	11	23	49	42
56	Ward Number 56	1554	1110	1018	8	17	36	31
57	Ward Number 57	2208	1577	1447	12	24	51	43
58	Ward Number 58	1854	1295	1188	10	19	42	36
59	Ward Number 59	2119	1514	1389	11	23	49	42
60	Ward Number 60	2150	1536	1409	12	23	50	42
	Total	**124059**	**88592**	**81283**	**664**	**1329**	**2879**	**2436**

5.2 Seismic Hazard Map

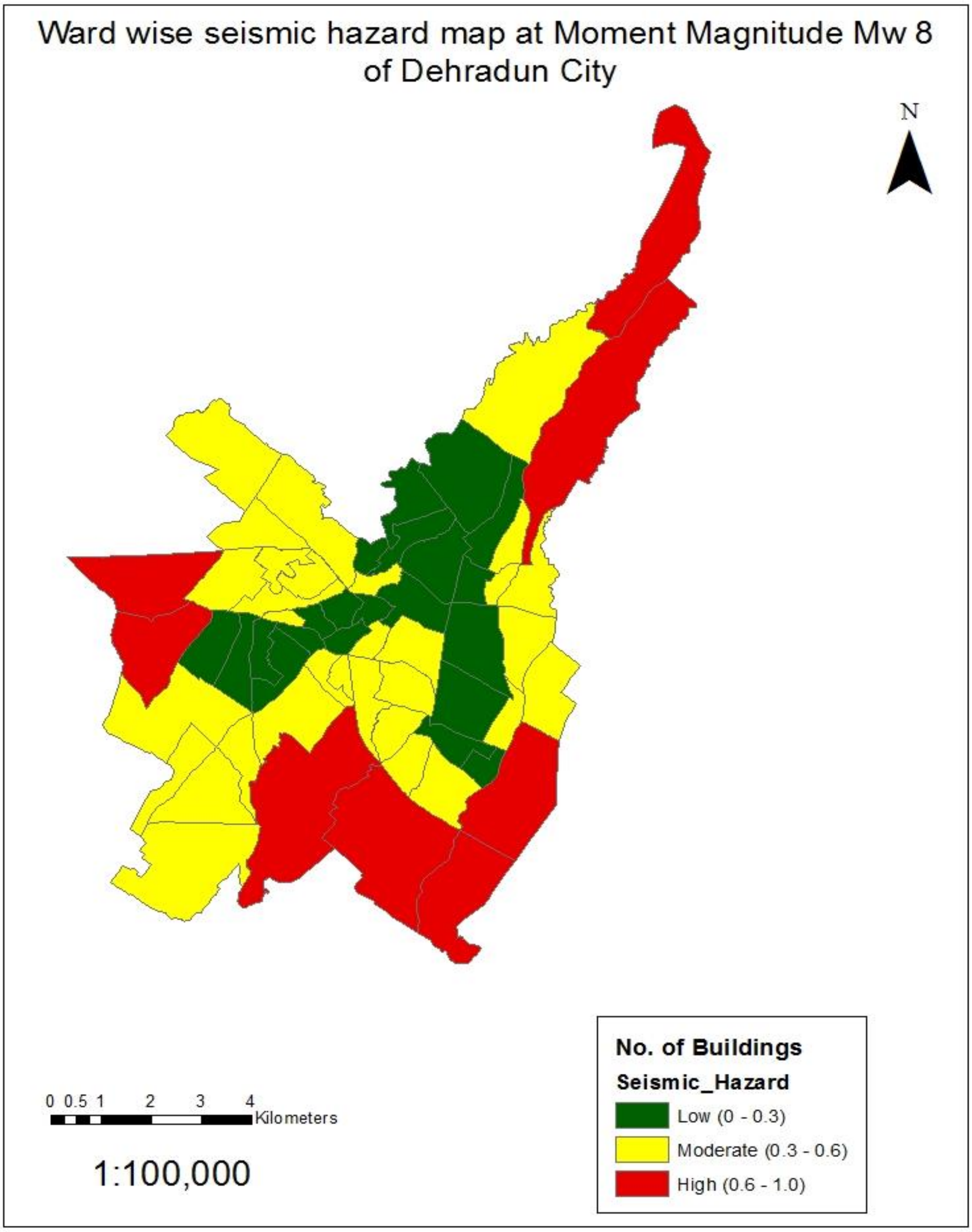


Figure 5-1 : Ward wise seismic hazard map of Dehradun city

Discussion

Figure 5-1 represents the ward wise seismic hazard probability across complete city. Map shows that some wards at outskirts of the city i.e., north-east and south-west part have high probability of hazard while some wards in north-west side have low probability of hazard. Major number of wards lies in moderate hazard zone having spread all over the ward. This shows that the probability of hazard varies all across the ward from low to high in the probability scale 0 to 1.

5.3 Demand Spectrum Curve

Spectral acceleration with 5% damping level at frequencies 1Hz, 3Hz, 5Hz, 10Hz are taken for calculating different values of spectral displacement over complete Dehradun area. By average of S_A over total region of Dehradun at different frequencies in Table 5-3.

Table 5-3 : Spectral Acceleration with corresponding Spectral Displacement

Frequency (Hz)	Time Period – T (sec)	Spectral Acceleration – S_A (g)	Spectral Displacement – S_D (inches)
1	1.00	0.08	0.78
3	0.33	0.50	0.53
5	0.20	0.27	0.11
10	0.10	0.20	0.02

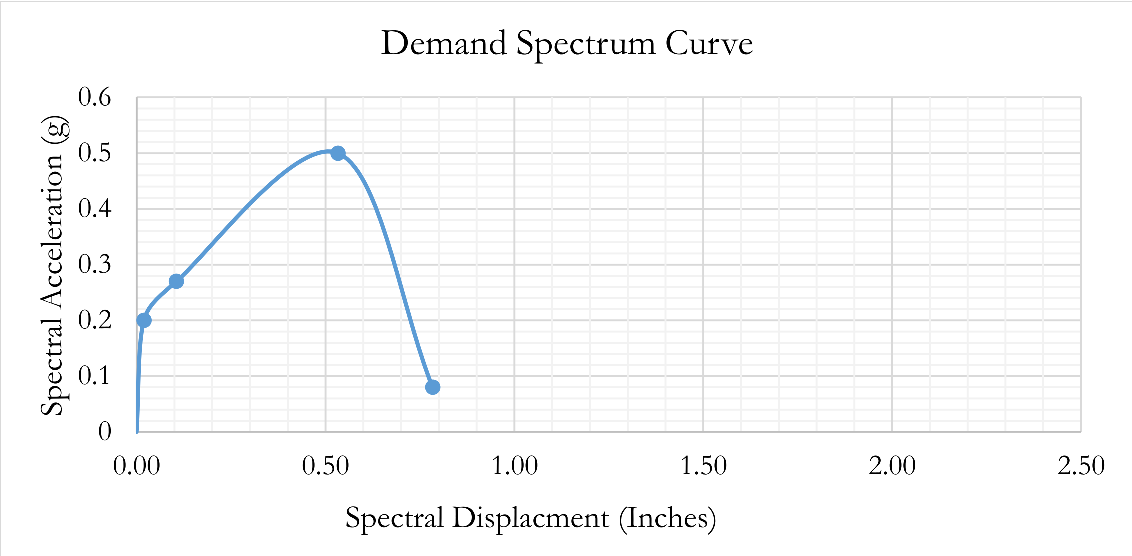


Figure 5-2 : Demand Spectrum Curve

Discussion

Figure 5-2 shows that for given time period, spectral acceleration increases with spectral displacement except at one point where time period is 1 second. At 1s, as the spectral acceleration decreases with increase in spectral displacement. This is because at 1 Hz, the value of shear wave velocity is low with small variation[25]. Also for soil class D, the shear wave velocity is low resulting in low spectral acceleration.

5.4 Capacity Curve

Capacity curve is generated by yield capacity point and ultimate capacity point of a particular type of building. Material and weight of the building are the deciding factors of these values. These values given in HAZUS technical manual for each model building type[39]. Table 5-4 represents the yield and ultimate capacity point values at pre-code and low-code seismic design table. It is also seen that values of building type RC1L and RC2L at pre-code and low code seismic design level are same and also building type RC1M and RC2M have same values. Hence, three curves are generated as one for RC1L and RC2L, one for RC1M and RC2M and one for building type MH.

Table 5-4 : Yield and Ultimate capacity points under different conditions

Building Type	HAZUS Building Type	Yield Capacity Point		Ultimate Capacity Point	
		D_y(in)	A_y(g)	D_u(in)	A_u(g)
Pre-code seismic design					
RC1L	C3L	0.120	0.100	1.350	0.225
RC1M	C3M	0.260	0.083	1.950	0.188
MH	MH	0.180	0.150	2.160	0.300
Low-code seismic design					
RC2L	C3L	0.120	0.100	1.350	0.225
RC2M	C3M	0.260	0.083	1.950	0.188

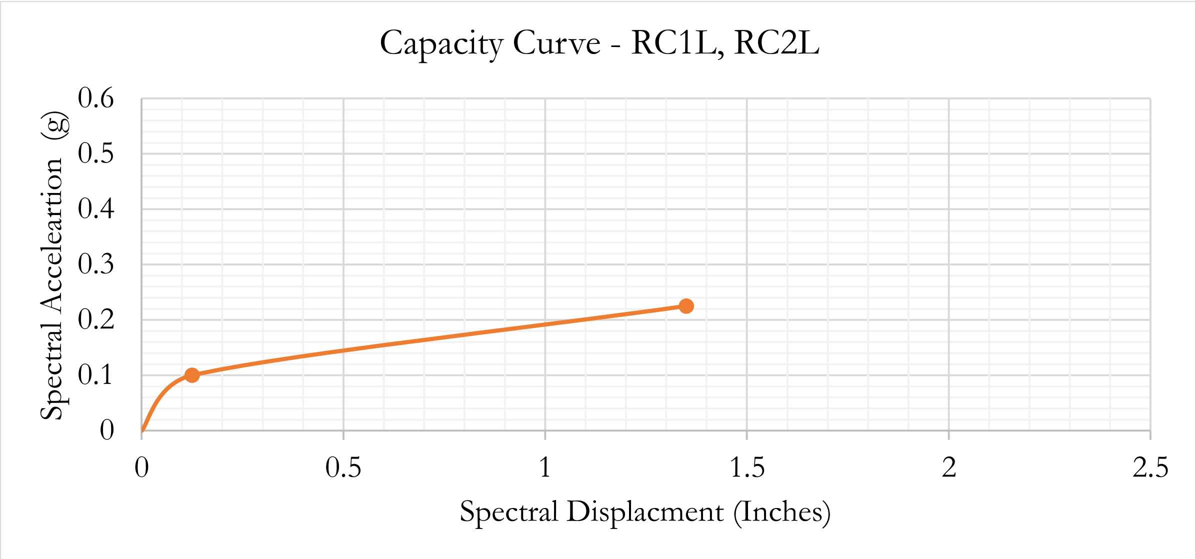


Figure 5-3 : Capacity curve for building type RC1L and RC2L

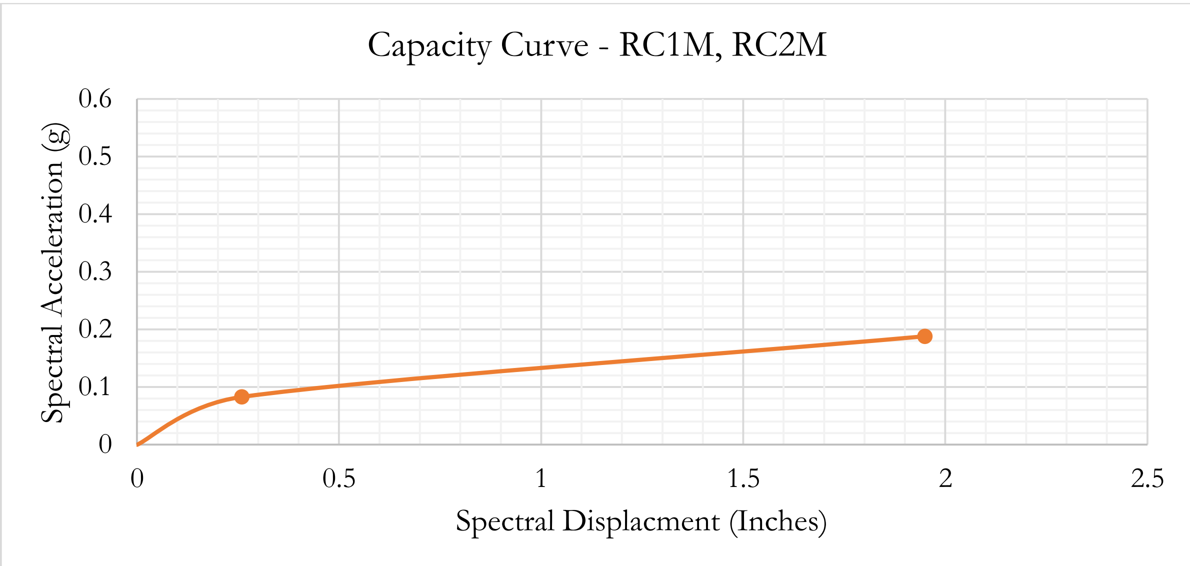


Figure 5-4 : Capacity curve for building types RC1M and RC2M

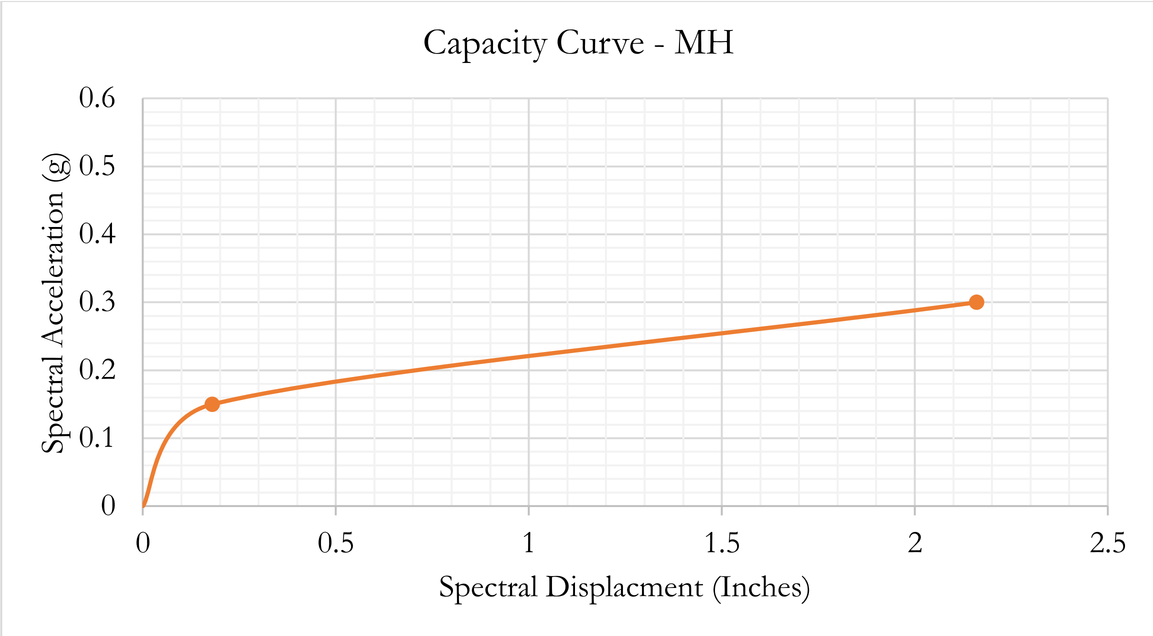


Figure 5-5 : Capacity curve for building type MH

Discussion

All the three plots of Figure 5-3, 5-4 and 5-5 show a common trend of increase spectral acceleration with increase in spectral displacement. Basically capacity curves represents true lateral strength of corresponding building types.

5.5 Peak Building Response

Peak Building Response or Peak Spectral displacement is obtained by the intersection point of demand spectrum curve and capacity curve. It actually means that shaking is experienced by building till the peak building response point is achieved. Maximum damage in a building is seen when it reaches or crosses the peak building response point. The two curves i.e., demand spectrum curve and capacity curve are overlaid to achieve peak building response.

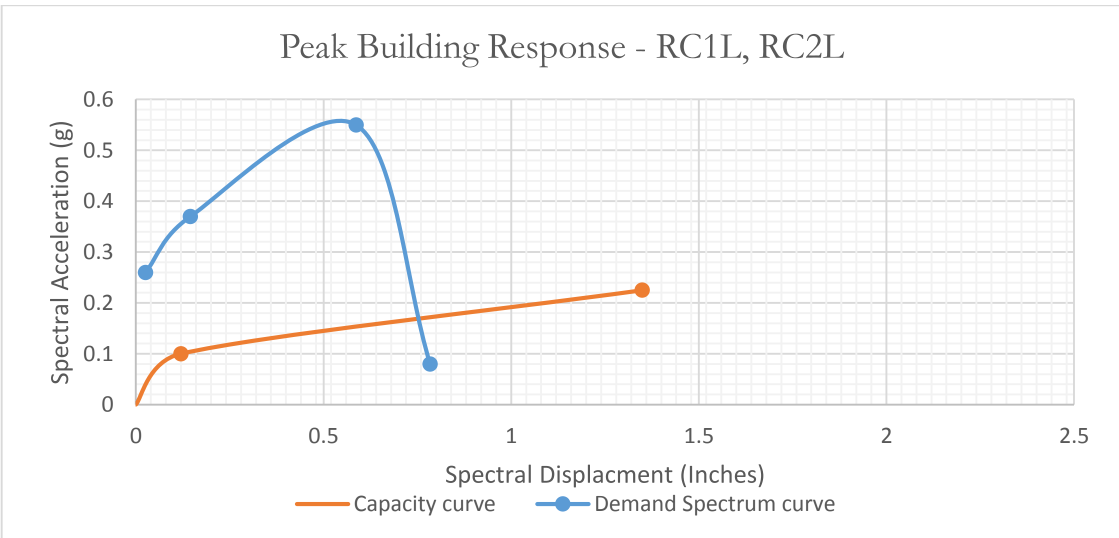


Figure 5-6 : Peak building response for building type RC1L and RC2L

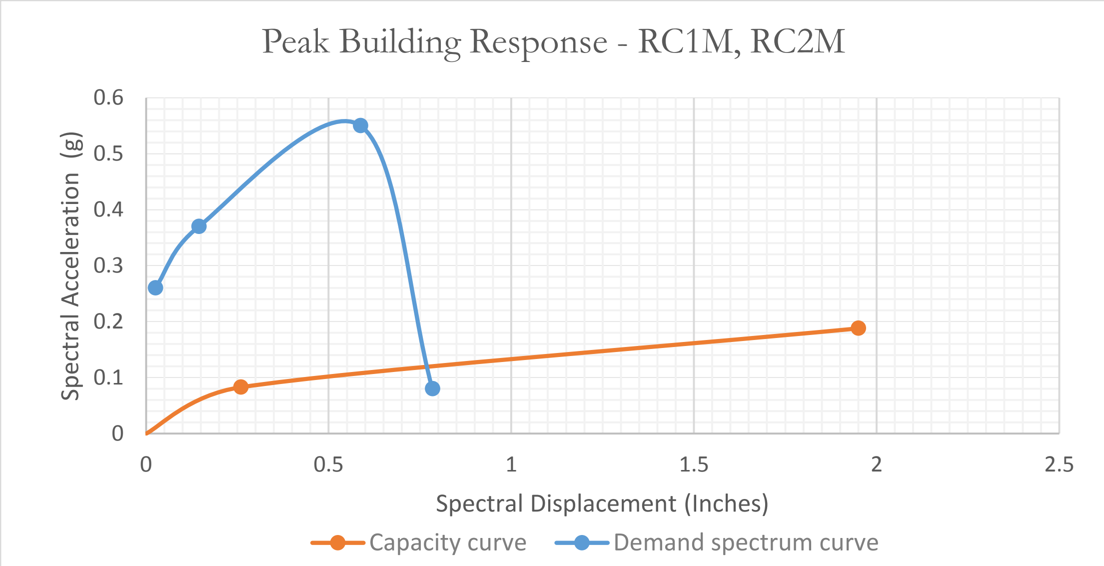


Figure 5-7 : Peak building response for building type RC1M and RC2M

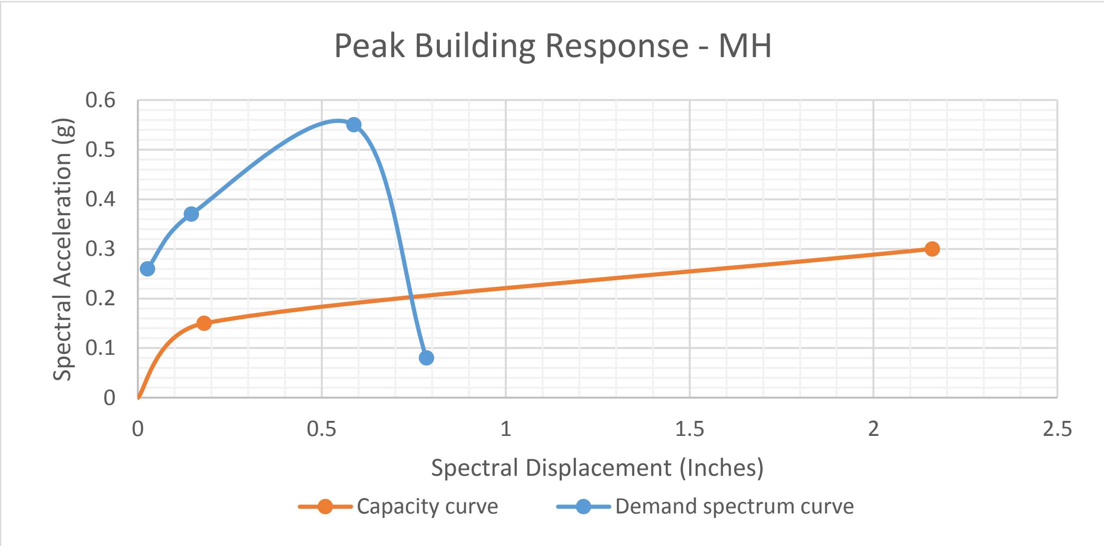


Figure 5-8 : Peak building response for building type MH

Discussion

From the three different peak building response plots, three peak response point in terms of spectral displacement are obtained. These are shown in Table 5-5. These values are further used in damage probability calculations.

Table 5-5 : Peak building response values for different building types

Building Type	Peak Building Response (S_D in Inches)
RC1L, RC2L	0.75
RC1M, RC2M	0.77
MH	0.74

5.6 Cumulative Damage Probabilities

Cumulative damage probability is calculated for five building types for four damage types namely slight damage, moderate damage, extensive damage and complete damage. The parameters for calculating these damage probabilities is taken from HAZUS technical manual[39]. Table 5-6 shows the two parameters i.e.., Median Spectral Acceleration and Log standard Deviation (Beta) taken for 4 types of damages respectively. Table 5-7 represents the cumulative damage probabilities calculated using above mentioned parameters. Table 5-8 represents the cumulative damage probabilities for different building types in percentage.

Table 5-6 : Parameters of fragility curves for different building types

Building Type	Slight		Moderate		Extensive		Complete	
	$S_{d.S/S}$	β_S	$S_{d.S/M}$	β_M	$S_{d.S/E}$	β_E	$S_{d.S/C}$	β_C
Pre code seismic design								
RC1L	0.43	1.19	0.86	1.15	2.16	1.15	5.04	0.92
RC1M	0.72	0.90	1.44	0.86	3.60	0.90	8.40	0.96
MH	0.38	1.11	0.77	1.10	2.30	0.95	6.72	0.97
Low code seismic design								
RC2L	0.54	1.09	1.08	1.07	2.70	1.08	6.30	0.91
RC2M	0.90	0.85	1.80	0.83	4.50	0.79	10.50	0.98

Table 5-7 : Cumulative probabilities for different building types

Building Type	Slight- $P(S/S_d)$	Moderate- $P(M/S_d)$	Extensive – $P(E/S_d)$	Complete- $P(C/S_d)$
Pre code seismic design				
RC1L	0.564	0.213	0.090	0.019
RC1M	0.528	0.233	0.044	0.006
MH	0.589	0.289	0.058	0.012
Low code seismic design				
RC2L	0.552	0.239	0.063	0.010
RC2M	0.472	0.154	0.013	0.004

Table 5-8 : Cumulative probabilities for different building types in percentage

Building Type	Slight- $P(S/S_d)$	Moderate- $P(M/S_d)$	Extensive – $P(E/S_d)$	Complete- $P(C/S_d)$
Pre code seismic design				
RC1L	56.40%	21.30%	9.01%	1.92%
RC1M	52.79%	23.27%	4.36%	0.64%
MH	58.90%	28.90%	5.82%	1.16%
Low code seismic design				
RC2L	55.17%	23.90%	6.30%	0.96%
RC2M	47.21%	15.39%	1.29%	0.38%

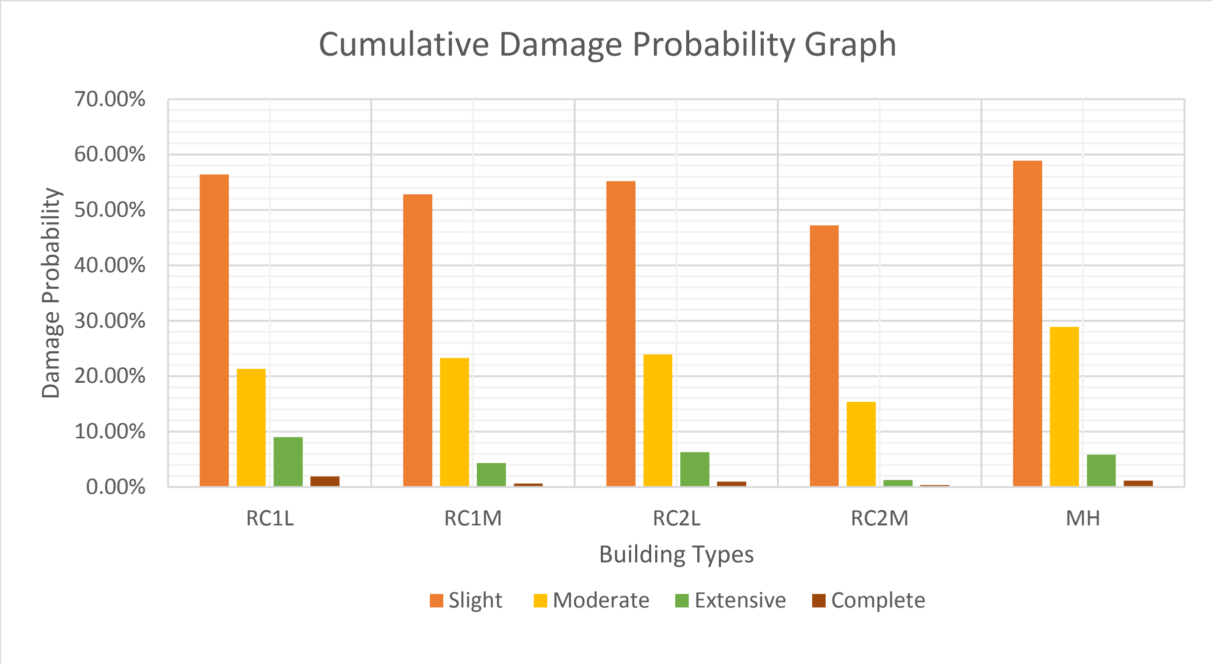


Figure 5-9 : Graph of percentage cumulative probabilities damage for different building types

Discussion

Figure 5-9 shows the graph of cumulative probabilities of 5 building types for each type of damage. It is seen that there is uniformity across all type of buildings where the percentage of slight damage is highest, followed by moderate damage then by extensive damage and the lowest percentage is of complete damage.

5.7 Discrete Damage Probabilities

Discrete Damage probabilities are calculated again for 5 building types with 5 types of damage probabilities namely no damage, slight damage, moderate damage, extensive damage and complete. Table 5-9 shows the calculated discrete damage probabilities for 5 building types whereas same is shown in percentage in table 5-10.

Table 5-9 : Discrete damage probabilities for different building types

Building Type	No Damage - P(N)	Slight - P(S)	Moderate - P(M)	Extensive - P(E)	Complete - P(C)
Pre code seismic design					
RC1L	0.436	0.351	0.123	0.071	0.019
RC1M	0.472	0.295	0.189	0.037	0.006
MH	0.411	0.300	0.231	0.047	0.012
Low code seismic design					
RC2L	0.448	0.313	0.176	0.053	0.010
RC2M	0.528	0.318	0.141	0.009	0.004

Table 5-10 : Discrete damage probabilities for different building types in percentage

Building Type	No Damage - P(N)	Slight - P(S)	Moderate - P(M)	Extensive - P(E)	Complete - P(C)
Pre code seismic design					
RC1L	43.60%	35.10%	12.29%	7.09%	1.92%
RC1M	47.21%	29.52%	18.91%	3.72%	0.64%
MH	41.10%	30.00%	23.08%	4.66%	1.16%
Low code seismic design					
RC2L	44.83%	31.27%	17.60%	5.34%	0.96%
RC2M	52.79%	31.82%	14.10%	0.91%	0.38%

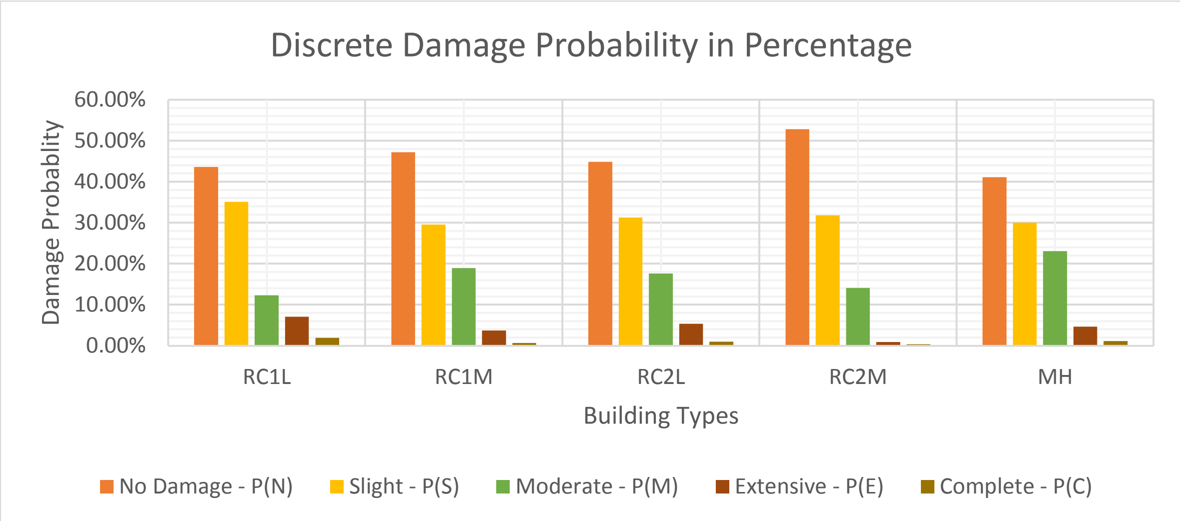


Figure 5-10 : Discrete damage probabilities of different building types in percentage

Discussion

Figure 5-10 represents graph of discrete damage probabilities for 5 types of buildings. As seen no damage probability is highest for all building types. The trend is common for all building type as seen by percentage decreases from no damage probability to complete damage probability.

5.8 Discrete Damage Probabilities for 60 wards

The damage probabilities calculated for 5 types of buildings are scaled up for total 60 wards present in Dehradun city. These probabilities are calculated with the help of extrapolation done as shown in Table 5-2. The sum total of buildings from this table and discrete damage probabilities from Table 5-10 are used to find out the number of buildings in each ward that fall under different categories of damages. Details of all the values is shown in appendix B and C. These values in terms of number of buildings and percentage are then averaged to find final discrete damage probabilities across whole Dehradun city. Table 5-11 shows the final damage probabilities. These are also shown in terms of number buildings in table 5-12.

Table 5-11 : Final damage probability distribution in percentage

No Damage	Slight Damage	Moderate Damage	Extensive Damage	Complete Damage
43.88%	34.75%	12.78%	6.78%	1.82%

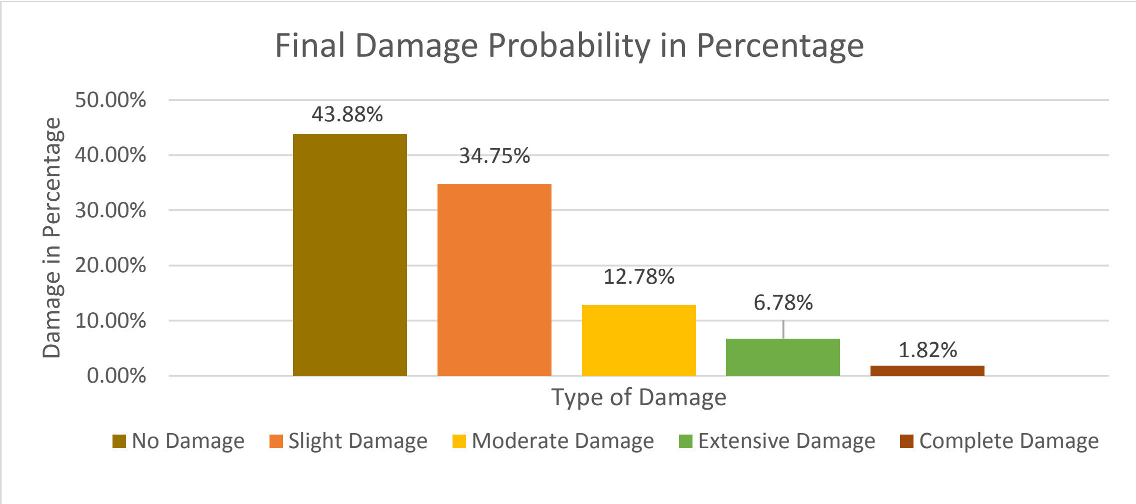


Figure 5-11 : Final damage probability in percentage

Table 5-12 : Final damage probability in number of buildings

No Damage	Slight Damage	Moderate Damage	Extensive Damage	Complete Damage
38878	30684	11299	6041	1703

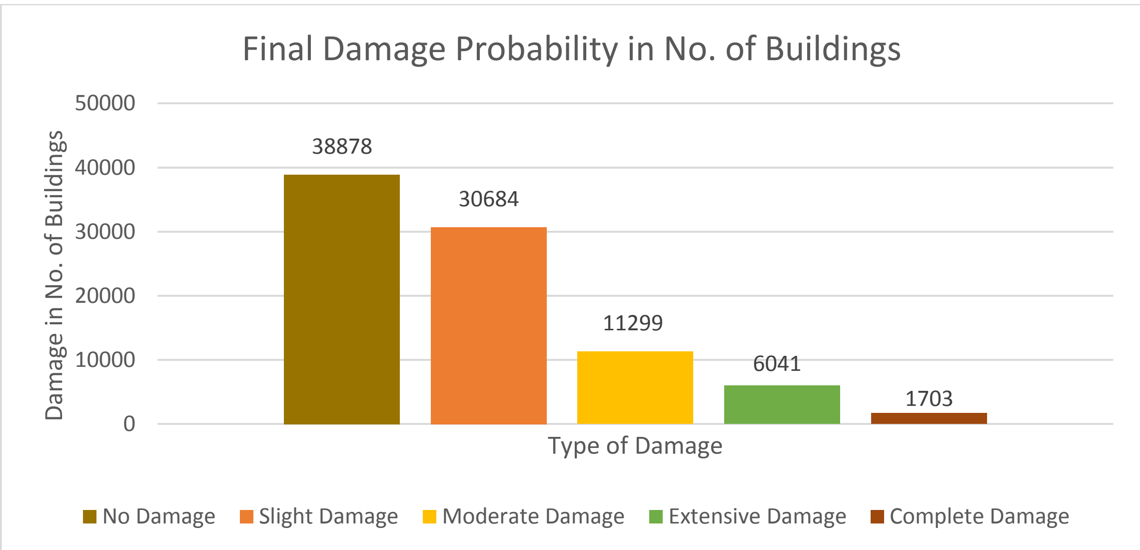


Figure 5-12 : Final damage probability in number of building

5.9 Final Damage Probability Maps

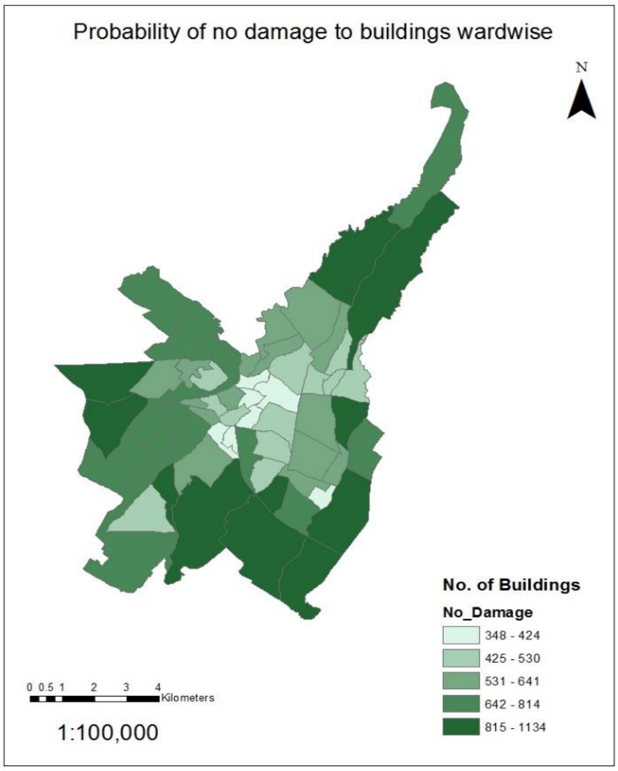


Figure 5-13 : Ward wise Dehradun city map showing number of building with no damage

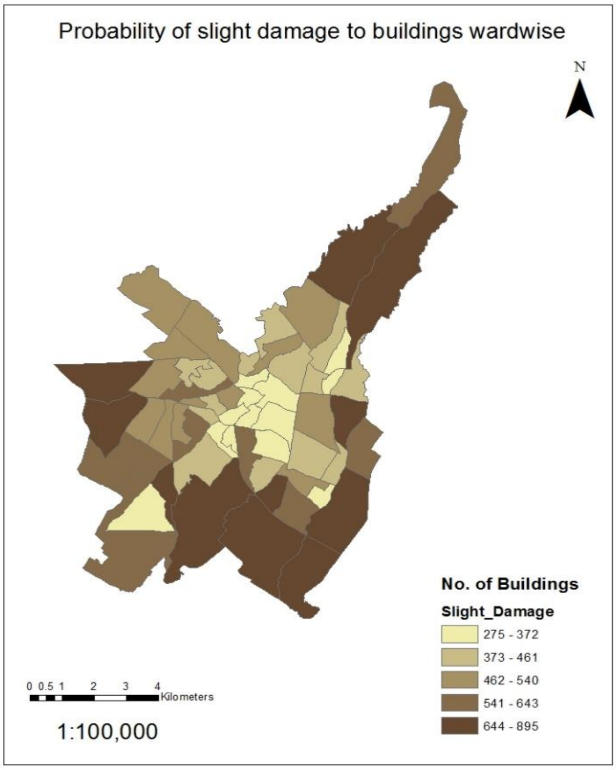


Figure 5-14 : Ward wise Dehradun city map showing number of building with slight damage

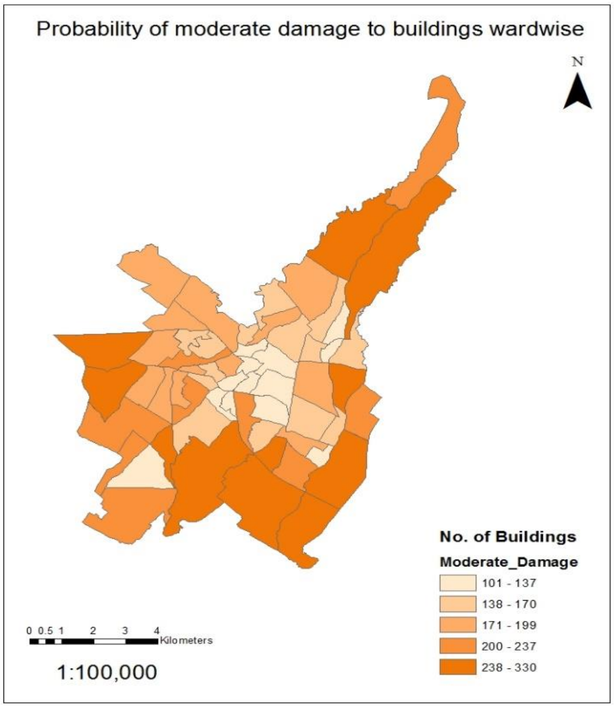


Figure 5-15 : Ward wise Dehradun city map showing number of building with moderate damage

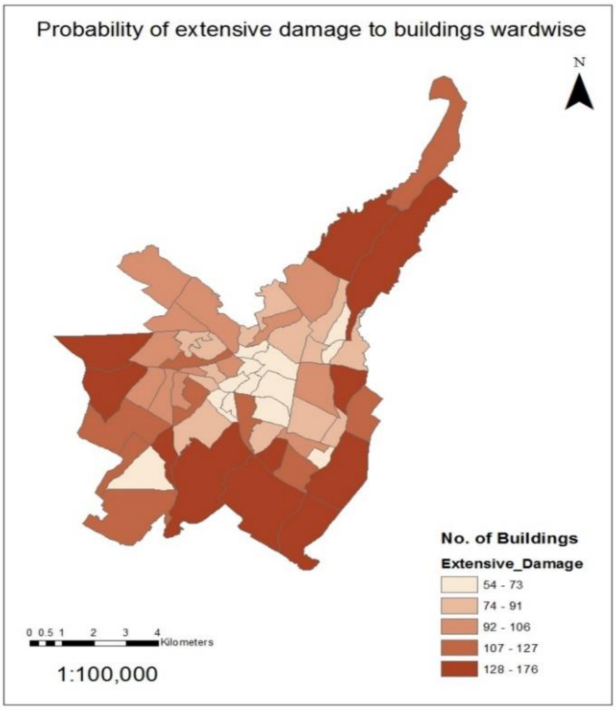


Figure 5-16 : Ward wise Dehradun city map showing number of building with extensive damage

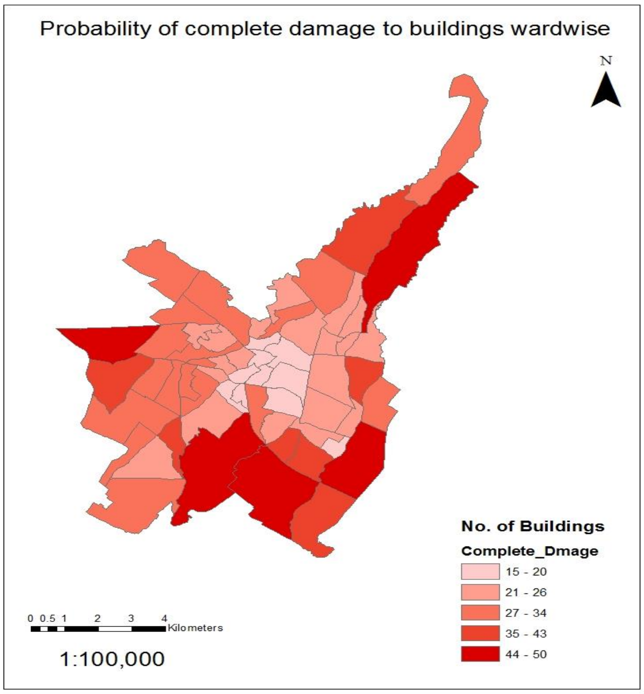


Figure 5-17 : Ward wise Dehradun city map showing number of building with complete damage

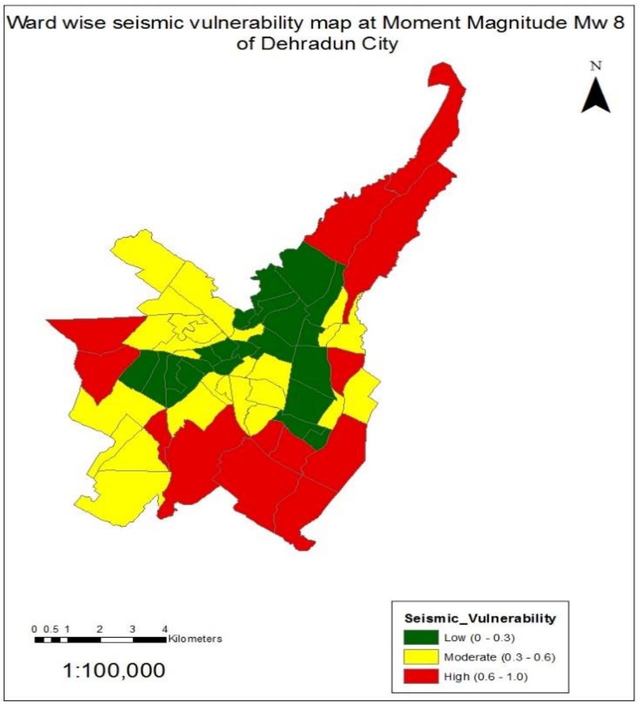


Figure 5-18 : Ward wise seismic vulnerability map at Moment Magnitude Mw 8 of Dehradun city

Discussion

Figure 5-13 to 5-17 gives ward wise number of buildings under different state of damages. Figure 5-18 shows the ward wise seismic vulnerability by all damage states counted together. It is concluded that the wards at the outskirts shows higher probability of damage as compared to the wards inside the city.

5.10 Risk Maps

Scenario with earthquake Moment Magnitude Mw 6

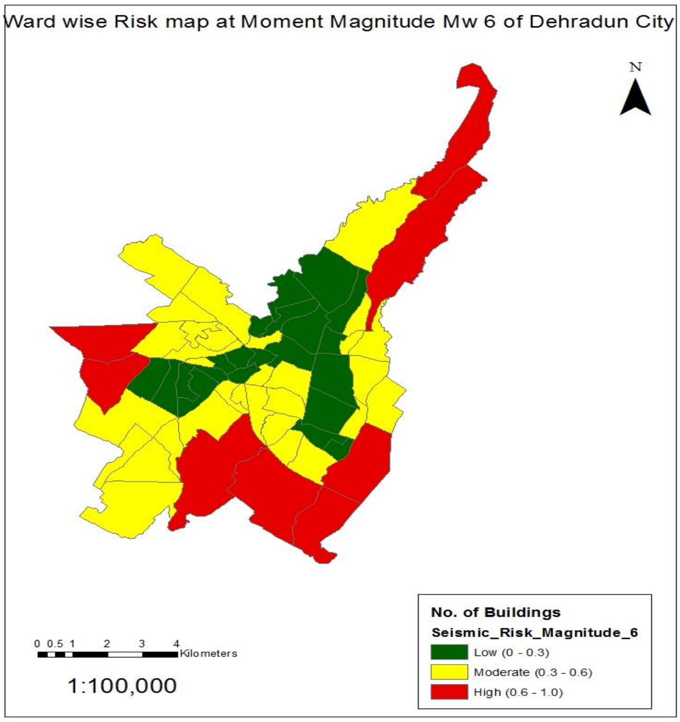


Figure 5-19 : Ward wise seismic risk map at Moment magnitude Mw 6 of Dehradun city

Scenario with earthquake Moment Magnitude Mw 7

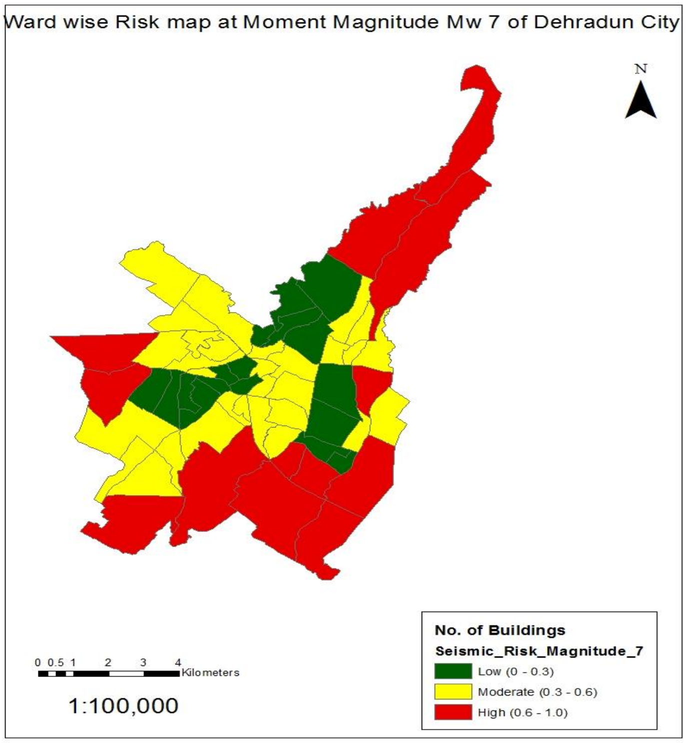


Figure 5-20 : Ward wise seismic risk map at Moment magnitude 7 of Dehradun city

Scenario with earthquake Moment Magnitude Mw 8

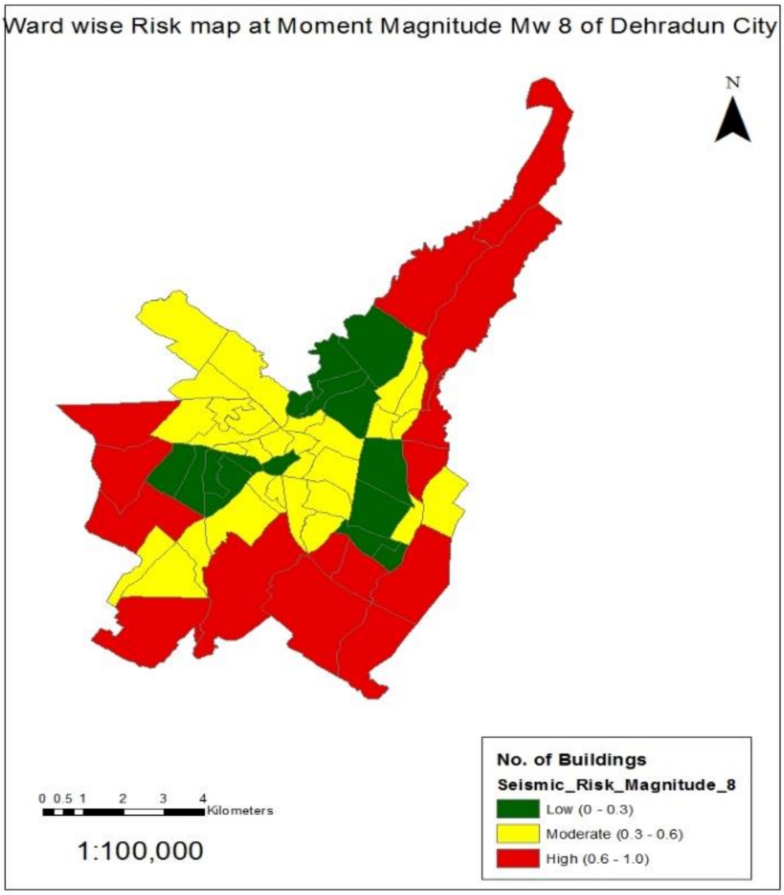


Figure 5-21 : Ward wise seismic risk map at Moment magnitude Mw 8 of Dehradun city

Discussion

Figure 5-19, 5-20 and 5-21 shows the ward wise seismic risk map at earthquake moment magnitude 6, 7 and 8 respectively. The probability of risk varies from 0 to 1 and is classified into low, moderate and high risk zones. As the magnitude increases the number of wards under high risk zones increases. Also it is observed that wards towards the outskirts of the city are under high risk. The reason might be the increase in spectral acceleration towards the outskirts as seen from Figure 4-16. Also another reason may be the liquefaction susceptibility criteria as its probability is high at southeast and northern part of the city. Total 15 wards are under high risk zone following 30 wards under moderate risk zone and remaining 15 wards under low risk zone.

6 Conclusions and Recommendations

This chapters aims at concluding the study by answering the research questions mentioned at the start of the study with the recommendations for future research work.

6.1 Research Conclusions

1) Which statistical sampling method needs to be adopted so that all types of buildings are covered for vulnerability assessment in the selected wards for the field survey?

Statistical sampling was so chosen such that it serves the purpose of the study and also the samples collected should have uniform representation of study area. Keeping this in account, random statistical sampling method is adopted for this research study. 50 samples from each wards are chosen random such that the sample points are distributed over complete wards so that a good collection of different building type is collected during field survey. These sample points from the selected 8 wards are then used for extrapolating the values for total 60 wards so that complete damage assessment of buildings in whole Dehradun area can be done effectively.

2) What are the various parameters required for generating a seismic hazard map in HAZUS? Comment on the seismic hazard map obtained by comparing the results with or without available parameters.

Various parameters required in HAZUS for generating seismic hazard map are soil class, spectral acceleration response, liquefaction susceptibility map, landslide susceptibility map and water depth input. In this study seismic hazard map is generated considering 4 available parameters. They are soil class, spectral acceleration response, liquefaction susceptibility map and water depth input. It can be concluded from seismic hazard map that wards towards outskirts i.e., ward numbers 1,2,31,32,35,42,51 and 52 are under high seismic hazard zone while around 30 wards lie under moderate hazard zone and 12 wards are under low hazard seismic zone.

3) What are the different features that need to be considered for assessing vulnerability to calculate direct losses occurring due to earthquake?

Different features that count under direct losses calculations for earthquake vulnerability assessment are general building stock, essential facilities, transportation lifelines, utility lifelines, high potential loss facilities and human life. In this study, the only feature considered for seismic vulnerability assessment is general building stock. Enormous amount of data is required for other features to be taken into consideration. For general building stock, various states of damage probabilities namely no damage, slight damage, moderate damage, extensive damage and complete damage is calculated for complete Dehradun city divided into 60 wards. This damage calculation in terms of number of buildings and percentage gives an idea of vulnerability assessment of buildings across 60 wards. General trend across all building types seen is that the buildings with no damage are higher in number than follows the number with slight damage, after this moderate damage than extensive damage and at last least count of buildings with complete damage.

4) What are the various scenarios to be considered in terms of different magnitudes of earthquake for risk mapping?

Scenarios considered for risk mapping are in terms of earthquake magnitude. These scenarios are generated with three different magnitudes i.e., magnitude 6, magnitude 7 and magnitude 8 considering buildings at risk. Risk map at magnitude 6 have more wards with low risk following some wards with moderate risk and very few wards with high seismic risk. These terms gets reversed while increase in magnitude. The risk map at magnitude 7 has some number of wards with low and high risk while large number of wards fall under moderate risk zone. As magnitude increases, risk zone increases with very few wards under low risk zone. It is in general concluded that the wards towards the outskirts are under high risk than the wards inside the city. Reason behind this trend may be due to increase in value of spectral acceleration and liquefaction susceptibility in the outskirts area.

6.2 Recommendations for future research work

- More accurate data in terms of type of building distribution across total wards can give better results. This will help in generating more accurate damage probability maps.

- Different features data like essential facilities, transportation lifelines, utility lifelines, high potential loss facilities and human life can lead to better processing and can give better results in terms of hazard and risk mapping for future work.

- An historic earthquake data related to this study can prove useful in validation of these kind of results and also HAZUS software for Indian conditions for future research.

References

[1] "Earthquakes with 50,000 or More Deaths." [Online]. Available: http://earthquake.usgs.gov/earthquakes/world/most_destructive.php. [Accessed: 19-Nov-2013].

[2] "Natural Disasters Trends | EM-DAT." [Online]. Available: http://www.emdat.be/natural-disasters-trends. [Accessed: 19-Nov-2013].

[3] C. Van Westen, "Remote Sensing for Natural Disaster Managment," presented at the International Archives of Photogrammetry and Remote Sensing, Amsterdam, vol. XXXIII.

[4] "The Disaster Management Cycle." [Online]. Available: http://www.gdrc.org/uem/disasters/1-dm_cycle.html. [Accessed: 19-Nov-2013].

[5] "Urban Resilience & Disaster Risk Management." [Online]. Available: http://www.worldbank.org/en/topic/urbandevelopment/brief/urban-resilience-disaster-risk-management. [Accessed: 19-Nov-2013].

[6] "List of earthquakes in India," *Wikipedia, the free encyclopedia*. 17-Nov-2013.

[7] "Seismo-Zoning map." [Online]. Available: http://www.imd.gov.in/section/seismo/static/seismo-zone.htm. [Accessed: 19-Nov-2013].

[8] A. S. Arya, "Recent developments toward earthquake risk reduction in India," *Dep. Earthq. Eng. Univ. Roorkee Roorkee*, vol. Seismology 2000, no. Special Section, 2000.

[9] C. Ghosh, "Earthquake Risk Mitigation Strategies in India," in *The 12th International Conference of International Association for Computer Methods and Advances in Geomechanics (IACMAG)*, 2008, pp. 1–6.

[10] "Earthquake Reports." [Online]. Available: http://www.imd.gov.in/section/seismo/dynamic/welcome.htm. [Accessed: 24-Nov-2013].

[11] R. Bilham, "EARTHQUAKES: Himalayan Seismic Hazard," *Science*, vol. 293, no. 5534, pp. 1442–1444, Aug. 2001.

[12] S. Kumar, S. G. Wesnousky, T. K. Rockwell, R. W. Briggs, V. C. Thakur, and R. Jayangondaperumal, "Paleoseismic evidence of great surface rupture earthquakes along the Indian Himalaya," *J. Geophys. Res. Solid Earth*, vol. 111, no. B3, p. n/a–n/a, 2006.

[13] B. Gulati, "Earthquake Risk Assessment of Buildings: Applicability of HAZUS in Dehradun, India," ITC, The Netherlands and Indian Institute of Remote Sensing, Dehradun, 2006.

[14] A. K. Mahajan, S. Slob, R. Ranjan, R. Sporry, P. K. C. Ray, and C. J. van Westen, "Seismic microzonation of Dehradun City using geophysical and geotechnical characteristics in the upper 30 m of soil column," *J. Seismol.*, vol. 11, no. 4, pp. 355–370, Oct. 2007.

[15] G. Dole, P.K.Champati Ray, and B. Shrivastava, "GIS based simulation of seismic hazard in parts of Doon valley," Indian Institute of Remote Sensing, Dehradun, Aug-2001.

[16] "Earthquake Hazards / Earthquakes / Science Topics / Learning / Home - GNS Science." [Online]. Available: http://www.gns.cri.nz/Home/Learning/Science-Topics/Earthquakes/Earthquake-Hazards. [Accessed: 25-Nov-2013].

[17] "Magnitude / Intensity Comparison." [Online]. Available: http://earthquake.usgs.gov/learn/topics/mag_vs_int.php. [Accessed: 25-Nov-2013].

[18] S. T. G. Raghukanth, "Estimation of Seismicity Parameters for India," *Seismol. Res. Lett.*, vol. 81, no. 2, pp. 207–217, Mar. 2010.

[19] "Terminology - UNISDR." [Online]. Available: http://www.unisdr.org/we/inform/terminology. [Accessed: 25-Nov-2013].

[20] S. Tyagunov, L. Stempniewski, G. Grunthal, R. Wahlstrom, and J. Zschau, "Vulnerability and Risk Assessment for Earthquake prone cities," *13 Th World Conf. Earthq. Eng. BC Can.*, no. Paper No. 868, Aug. 2004.

[21] T. Malladi, "Earthquake Building Vulnerability and Damage Assessment with reference to Sikkim Earthquake, 2011," ITC, The Netherlands and Indian Institute of Remote Sensing, Dehradun, 2011.

[22] B. Aswandono, "Building Replacment cost for Seismic Risk Assessment in Palbapang village, Bantul sub-district, Yogyakarta Indonesia," ITC, University of Twente, The Netherlands, 2011.
[23] C. Sinadinovski, M. Edwards, N. Corby, and M. Milne, "Chapter 5: Earthquake Risk," Geoscience Australia, Canberra.
[24] T. G. Sitharam and P. Anbazhagan, "Seismic Microzonation: Principles, Practices and Experiments," Indian Institute of Remote Sensing, Bangalore.
[25] R. Ranjan, "Seismic Response Analysis of Dehradun City, India," ITC, The Netherlands and Indian Institute of Remote Sensing, Dehradun, 2005.
[26] "Ground Water Brochure, District Dehradun, Uttarakhand." Central Ground Water Board, Ministry of Water Resources, Jun-2011.
[27] D. G. Rossiter, "An introduction to statistical analysis Overheads," 2006.
[28] J. S. R. Prasad, Y. Singh, A. M. Kaynia, and C. Lindholm, "Socioeconomic Clustering in Seismic Risk Assessment of Urban Housing Stock," *Earthquake Spectra*, 31-Jul-2012. [Online]. Available: http://earthquakespectra.org/doi/abs/10.1193/1.3158547. [Accessed: 26-Nov-2013].
[29] FEMA, *HAZUS MH 2.0 User Manual*. Washington, D.C: Department of Homeland Security, 2011.
[30] S. K. Jain, R. P. Singh, V. K. Gupta, and A. Nagar, "Garhwal Earthquake of Oct. 20, 1991," *EERI Spec. Earthq. Rep. EERI Newsl.*, vol. Vol.26, no. No.2, Feb. 1992.
[31] S. K. Jain, C. V. R. Murty, J. N. Arlekar, C. P. Rajendran, K. Rajendran, and R. Sinha, "Chamoli (Himalaya, India) Earthquake of 29 March 1999." EERI Special Earthquake Report, EERI Newsletter, Vol.33, No.7,, Jul-1999.
[32] "Dehardun City Information." [Online]. Available: http://uttaranchalonline.info/Garhwal/Dehradun.html. [Accessed: 26-Nov-2013].
[33] "Information on India Maps." [Online]. Available: http://www.mapsofindia.com/maps/india/. [Accessed: 24-Nov-2013].
[34] ":: Welcome to Mussorrie Dehradun Development Authority ::.." [Online]. Available: http://www.mddaonline.com/master_plan.html. [Accessed: 26-Nov-2013].
[35] U. Sur, "Vulnerability Assessment of Buildings and Population related to earthquake hazard in Dehradun city using remote sensing and GIS," Indian Institute of Remote Sensing, Dehardun, 2005.
[36] R. C. Patel and Y. Kumar, "Geomorphological study of Quaternary Tectonics of the Doon Valley, Garhwal Himalaya, Uttaranchal," *Jour Nepal Geol Soc*, vol. 28, pp. 121–132, 2003.
[37] R. Bilham, "Earthquakes in India and the Himalaya: tectonics, geodesy and history," *Ann. Geophys.*, vol. 47, no. 2–3, Dec. 2004.
[38] "Census 2011 Data of Indian Population 2011 Census." [Online]. Available: http://www.census2011.co.in/. [Accessed: 26-Nov-2013].
[39] FEMA, *HAZUS MH 2.0 Earthquake Technical Manual*. Washington, D.C: Department of Homeland Security, 2011.
[40] B. Mukhopadhyay, "Clusters of Moderate Size Earthquakes along Main Central Thrust (MCT) in Himalaya," *Int. J. Geosci.*, vol. 02, no. 03, pp. 318–325, 2011.
[41] R. Street, E. W. Woolery, Z. Wang, and J. B. Harris, "NEHRP soil classifications for estimating site-dependent seismic coefficients in the Upper Mississippi Embayment," *Eng. Geol.*, vol. 62, no. 1–3, pp. 123–135, Oct. 2001.

Annexures

Annexure A

Model building types in HAZUS

Sr. No.	Label	Description	Height
1	W1	Wood, Light Frame (W1)	ALL
2	W2	Wood, Commercial and Industrial (W2)	ALL
		Steel Moment Frame (S1)	
3	S1L	Low-Rise	1-3
4	S1M	Mid-Rise	4-7
5	S1H	High-Rise	8+
		Steel Braced Frame (S2)	
6	S2L	Low-Rise	1-3
7	S2M	Mid-Rise	4-7
8	S2H	High-Rise	8+
9	S3	Steel Light Frame (S3)	
		Steel Frame w/ Cast-in-Place Concrete Shear Walls (S4)	
10	S4L	Low-Rise	1-3
11	S4M	Mid-Rise	4-7
12	S4H	High-Rise	8+
		Steel Frame w/ Unreinforced Masonry Infill Walls (S5)	
13	S5L	Low-Rise	1-3
14	S5M	Mid-Rise	4-7
15	S5H	High-Rise	8+
		Reinforced Concrete Moment Resisting Frame (C1)	
16	C1L	Low-Rise	1-3
17	C1M	Mid-Rise	4-7
18	C1H	High-Rise	8+
		Concrete Shear Walls (C2)	
19	C2L	Low-Rise	1-3
20	C2M	Mid-Rise	4-7
21	C2H	High-Rise	8+

Sr. No.	Label	Description	Height
		Concrete Frame Buildings w/ Unreinforced Masonry Infill Walls (C3)	
22	C3L	Low-Rise	1-3
23	C3M	Mid-Rise	4-7
24	C3H	High-Rise	8+
		Precast-Concrete Tilt-Up Walls (PC1)	
25	PC1	Low-Rise	ALL
		Precast Concrete Frames w/ Concrete Shear Walls (PC2)	
26	PC2L	Low-Rise	1-3
27	PC2M	Mid-Rise	4-7
28	PC2H	High-Rise	8+
		Reinforced Masonry Bearing Walls w/ Wood or Metal Deck Diaphragms (RM1)	
29	RM1L	Low-Rise	1-3
30	RM1M	Mid-Rise	4+
		Reinforced Masonry Bearing Walls w/ Precast Concrete Diaphragms (RM2)	
31	RM2L	Low-Rise	1-3
32	RM2M	Mid-Rise	4-7
33	RM2H	High-Rise	8+
		Unreinforced Masonry Bearing Walls (URM)	
34	URML	Low-Rise	1-2
35	URMM	Mid-Rise	3+
36	MH	Manufactured Home	All
37	DFLT	Default Wood	All

Annexure B

Checklist for field work

Location:																
Sr. No.	**Items**	**Characteristics**														
1	Type of Building	RC1L	RC1M	RC2L	RC2M	RC2H	RC3L	RC3M	RC3H	ST1L	ST1H	ST1H	ST2L	ST2M	ST2H	MH
2	Type of Roof	R1	R2	R3	R4	R5	R6									
3	Approximate age of Building	<10 yrs		10-20 yrs		21-30 yrs		31-40 yrs		41-50 yrs		>50 yrs				
4	Utility of Building	Residential		Commercial		Resi + Comm		Hospital		School		Industry		Govt. office		
5	Number of floors	1	2	3	4	5	6	7	8							
6	Building Shape	Symmetrical			Asymmetrical											
7	Roof Type	Flat		Sloping												
8	Plan	Regular		Irregular												
9	Maintenance	Good		Moderate		Poor										
10	Earthquake Resistant	Yes		No												
11	Cracks Seen	Yes		No												
12	Peeling of plaster	Yes		No												

Annexure C

Distribution of number of buildings according to discrete damage probability

1) For Building Type – RC1L

Sr. No.	Ward Nos.	Total No. of Buildings	RC1L					
			No. of Buildings	P(N)	P(S)	P(M)	P(E)	P(C)
1	Ward No. 1	1709	1568	683	550	193	111	30
2	Ward No. 2	2345	2152	938	755	265	153	41
3	Ward No. 3	2037	1869	815	656	230	133	36
4	Ward No. 4	1396	1281	558	450	158	91	24
5	Ward No. 5	1275	1170	510	411	144	83	22
6	Ward No. 6	1381	1267	553	445	156	90	24
7	Ward No. 7	1332	1222	533	429	150	87	23
8	Ward No. 8	1559	1430	623	502	176	102	27
9	Ward No. 9	1069	980	427	344	121	70	19
10	Ward No. 10	1075	986	430	346	121	70	19
11	Ward No. 11	1122	1030	449	361	127	73	20
12	Ward No. 12	1139	1045	456	367	129	74	20
13	Ward No. 13	967	887	387	311	109	63	17
14	Ward No. 14	1256	1153	503	405	142	82	22
15	Ward No. 15	886	813	354	285	100	58	15
16	Ward No. 16	1012	929	405	326	114	66	18
17	Ward No. 17	1021	937	408	329	115	67	18
18	Ward No. 18	850	780	340	274	96	55	15
19	Ward No. 19	1376	1262	550	443	155	90	24
20	Ward No. 20	1151	1056	461	371	130	75	20
21	Ward No. 21	1460	1340	584	470	165	95	25
22	Ward No. 22	1236	1134	495	398	140	81	22
23	Ward No. 23	794	728	317	256	90	52	14
24	Ward No. 24	1051	965	421	339	119	68	18
25	Ward No. 25	1354	1242	541	436	153	88	24
26	Ward No. 26	1277	1172	511	411	144	83	22
27	Ward No. 27	1269	1164	507	409	143	83	22
28	Ward No. 28	1209	1109	483	389	136	79	21
29	Ward No. 29	2026	1859	810	652	229	132	35
30	Ward No. 30	1684	1545	673	542	190	110	29
31	Ward No. 31	2584	2371	1034	832	292	168	45
32	Ward No. 32	2166	1987	866	697	244	141	38
33	Ward No. 33	966	886	386	311	109	63	17
34	Ward No. 34	1372	1259	549	442	155	89	24
35	Ward No. 35	2433	2232	973	783	275	158	42
36	Ward No. 36	1856	1703	742	598	209	121	32
37	Ward No. 37	2044	1876	818	658	231	133	36

Sr. No.	Ward Nos.	Total No. of Buildings	RC1L					
			No. of Buildings	P(N)	P(S)	P(M)	P(E)	P(C)
38	Ward No. 38	1149	1054	460	370	130	75	20
39	Ward No. 39	1654	1518	662	533	187	108	29
40	Ward No. 40	965	885	386	311	109	63	17
41	Ward No. 41	829	760	331	267	94	54	14
42	Ward No. 42	2497	2291	999	804	282	163	44
43	Ward No. 43	1285	1179	514	414	145	84	22
44	Ward No. 44	2146	1969	859	691	242	140	37
45	Ward No. 45	1074	985	430	346	121	70	19
46	Ward No. 46	1674	1536	670	539	189	109	29
47	Ward No. 47	1756	1611	702	565	198	114	31
48	Ward No. 48	1654	1517	661	533	187	108	29
49	Ward No. 49	1529	1402	611	492	173	100	27
50	Ward No. 50	1517	1392	607	489	171	99	26
51	Ward No. 51	2234	2050	894	720	252	146	39
52	Ward No. 52	2329	2136	931	750	263	152	41
53	Ward No. 53	1421	1304	568	458	160	93	25
54	Ward No. 54	1594	1463	638	513	180	104	28
55	Ward No. 55	1516	1391	606	488	171	99	26
56	Ward No. 56	1110	1018	444	357	125	72	19
57	Ward No. 57	1577	1447	631	508	178	103	27
58	Ward No. 58	1295	1188	518	417	146	84	23
59	Ward No. 59	1514	1389	605	487	171	99	26
60	Ward No. 60	1536	1409	614	495	173	100	27
	Total	**88592**	**81283**	**35439**	**28530**	**9998**	**5771**	**1544**

2) For Building Type – RC1M

Sr. No.	Ward Nos.	Total No. of Buildings	RC1M					
			No. of Buildings	P(N)	P(S)	P(M)	P(E)	P(C)
1	Ward No. 1	1709	13	6	4	2	0	0
2	Ward No. 2	2345	18	9	2	3	2	2
3	Ward No. 3	2037	15	7	2	2	1	2
4	Ward No. 4	1396	10	5	1	2	1	1
5	Ward No. 5	1275	10	5	1	1	1	1
6	Ward No. 6	1381	10	5	1	2	1	1
7	Ward No. 7	1332	10	5	1	1	1	1
8	Ward No. 8	1559	12	6	2	2	1	2
9	Ward No. 9	1069	8	4	1	1	1	1
10	Ward No. 10	1075	8	4	1	1	1	1
11	Ward No. 11	1122	8	4	1	1	1	1
12	Ward No. 12	1139	9	4	1	1	1	1
13	Ward No. 13	967	7	4	1	1	1	1
14	Ward No. 14	1256	9	5	1	1	1	1
15	Ward No. 15	886	7	3	1	1	1	1
16	Ward No. 16	1012	8	4	1	1	1	1
17	Ward No. 17	1021	8	4	1	1	1	1
18	Ward No. 18	850	6	3	1	1	1	1
19	Ward No. 19	1376	10	5	1	2	1	1
20	Ward No. 20	1151	9	4	1	1	1	1
21	Ward No. 21	1460	11	5	2	2	1	2
22	Ward No. 22	1236	9	4	1	1	1	1
23	Ward No. 23	794	6	3	1	1	1	1
24	Ward No. 24	1051	8	4	1	1	1	1
25	Ward No. 25	1354	10	5	1	2	1	1
26	Ward No. 26	1277	10	5	1	1	1	1
27	Ward No. 27	1269	10	5	1	1	1	1
28	Ward No. 28	1209	9	4	1	1	1	1
29	Ward No. 29	2026	15	7	2	2	1	2
30	Ward No. 30	1684	13	6	2	2	1	2
31	Ward No. 31	2584	19	9	3	3	2	3
32	Ward No. 32	2166	16	8	2	2	1	2
33	Ward No. 33	966	7	4	1	1	1	1
34	Ward No. 34	1372	10	5	1	2	1	1
35	Ward No. 35	2433	18	9	3	3	2	3
36	Ward No. 36	1856	14	7	2	2	1	2
37	Ward No. 37	2044	15	7	2	2	1	2
38	Ward No. 38	1149	9	4	1	1	1	1
39	Ward No. 39	1654	12	6	2	2	1	2
40	Ward No. 40	965	7	4	1	1	1	1

Sr. No.	Ward Nos.	Total No. of Buildings	RC1M					
			No. of Buildings	P(N)	P(S)	P(M)	P(E)	P(C)
41	Ward No. 41	829	6	3	1	1	1	1
42	Ward No. 42	2497	19	9	3	3	2	3
43	Ward No. 43	1285	10	5	1	1	1	1
44	Ward No. 44	2146	16	8	2	2	1	2
45	Ward No. 45	1074	8	4	1	1	1	1
46	Ward No. 46	1674	13	6	2	2	1	2
47	Ward No. 47	1756	13	6	2	2	1	2
48	Ward No. 48	1654	12	6	2	2	1	2
49	Ward No. 49	1529	11	6	2	2	1	2
50	Ward No. 50	1517	11	6	2	2	1	2
51	Ward No. 51	2234	17	8	2	2	2	2
52	Ward No. 52	2329	17	8	2	3	2	2
53	Ward No. 53	1421	11	5	1	2	1	1
54	Ward No. 54	1594	12	6	2	2	1	2
55	Ward No. 55	1516	11	6	2	2	1	2
56	Ward No. 56	1110	8	4	1	1	1	1
57	Ward No. 57	1577	12	6	2	2	1	2
58	Ward No. 58	1295	10	5	1	1	1	1
59	Ward No. 59	1514	11	5	2	2	1	2
60	Ward No. 60	1536	12	6	2	2	1	2
	Total	**88592**	**664**	**322**	**91**	**99**	**60**	**93**

3) For Building Type – RC2L

Sr. No.	Ward No.	Total No. of Buildings	RC2L					
			No. of Buildings	P(N)	P(S)	P(M)	P(E)	P(C)
1	Ward No. 1	1709	26	11	8	5	1	0
2	Ward No. 2	2345	35	16	11	6	2	1
3	Ward No. 3	2037	31	14	10	5	2	1
4	Ward No. 4	1396	21	9	7	4	1	0
5	Ward No. 5	1275	19	9	6	3	1	0
6	Ward No. 6	1381	21	9	6	4	1	0
7	Ward No. 7	1332	20	9	6	4	1	0
8	Ward No. 8	1559	23	10	7	4	1	0
9	Ward No. 9	1069	16	7	5	3	1	0
10	Ward No. 10	1075	16	7	5	3	1	0
11	Ward No. 11	1122	17	8	5	3	1	0
12	Ward No. 12	1139	17	8	5	3	1	0
13	Ward No. 13	967	15	6	5	3	1	0
14	Ward No. 14	1256	19	8	6	3	1	0
15	Ward No. 15	886	13	6	4	2	1	0
16	Ward No. 16	1012	15	7	5	3	1	0
17	Ward No. 17	1021	15	7	5	3	1	0
18	Ward No. 18	850	13	6	4	2	1	0
19	Ward No. 19	1376	21	9	6	4	1	0
20	Ward No. 20	1151	17	8	5	3	1	0
21	Ward No. 21	1460	22	10	7	4	1	0
22	Ward No. 22	1236	19	8	6	3	1	0
23	Ward No. 23	794	12	5	4	2	1	0
24	Ward No. 24	1051	16	7	5	3	1	0
25	Ward No. 25	1354	20	9	6	4	1	0
26	Ward No. 26	1277	19	9	6	3	1	0
27	Ward No. 27	1269	19	9	6	3	1	0
28	Ward No. 28	1209	18	8	6	3	1	0
29	Ward No. 29	2026	30	14	10	5	2	1
30	Ward No. 30	1684	25	11	8	4	1	0
31	Ward No. 31	2584	39	17	12	7	2	1
32	Ward No. 32	2166	32	15	10	6	2	1
33	Ward No. 33	966	14	6	5	3	1	0
34	Ward No. 34	1372	21	9	6	4	1	0
35	Ward No. 35	2433	36	16	11	6	2	1
36	Ward No. 36	1856	28	12	9	5	1	1
37	Ward No. 37	2044	31	14	10	5	2	1
38	Ward No. 38	1149	17	8	5	3	1	0
39	Ward No. 39	1654	25	11	8	4	1	0
40	Ward No. 40	965	14	6	5	3	1	0

Sr. No.	Ward No.	Total No. of Buildings	RC2L					
			No. of Buildings	P(N)	P(S)	P(M)	P(E)	P(C)
41	Ward No. 41	829	12	6	4	2	1	0
42	Ward No. 42	2497	37	17	12	7	2	1
43	Ward No. 43	1285	19	9	6	3	1	0
44	Ward No. 44	2146	32	14	10	6	2	1
45	Ward No. 45	1074	16	7	5	3	1	0
46	Ward No. 46	1674	25	11	8	4	1	0
47	Ward No. 47	1756	26	12	8	5	1	1
48	Ward No. 48	1654	25	11	8	4	1	0
49	Ward No. 49	1529	23	10	7	4	1	0
50	Ward No. 50	1517	23	10	7	4	1	0
51	Ward No. 51	2234	34	15	10	6	2	1
52	Ward No. 52	2329	35	16	11	6	2	1
53	Ward No. 53	1421	21	10	7	4	1	0
54	Ward No. 54	1594	24	11	7	4	1	0
55	Ward No. 55	1516	23	10	7	4	1	0
56	Ward No. 56	1110	17	7	5	3	1	0
57	Ward No. 57	1577	24	11	7	4	1	0
58	Ward No. 58	1295	19	9	6	3	1	0
59	Ward No. 59	1514	23	10	7	4	1	0
60	Ward No. 60	1536	23	10	7	4	1	0
	Total	**88592**	**1329**	**595**	**416**	**234**	**70**	**25**

4) For Building Type – RC2M

Sr. No.	Ward No.	Total No. of Buildings	RC2M					
			No. of Buildings	P(N)	P(S)	P(M)	P(E)	P(C)
1	Ward No. 1	1709	56	29	18	8	0	0
2	Ward No. 2	2345	76	40	24	11	1	0
3	Ward No. 3	2037	66	35	21	9	1	0
4	Ward No. 4	1396	45	24	14	6	0	0
5	Ward No. 5	1275	41	22	13	6	0	0
6	Ward No. 6	1381	45	24	14	6	0	0
7	Ward No. 7	1332	43	23	14	6	0	0
8	Ward No. 8	1559	51	27	16	7	0	0
9	Ward No. 9	1069	35	18	11	5	0	0
10	Ward No. 10	1075	35	18	11	5	0	0
11	Ward No. 11	1122	36	19	12	5	0	0
12	Ward No. 12	1139	37	20	12	5	0	0
13	Ward No. 13	967	31	17	10	4	0	0
14	Ward No. 14	1256	41	22	13	6	0	0
15	Ward No. 15	886	29	15	9	4	0	0
16	Ward No. 16	1012	33	17	10	5	0	0
17	Ward No. 17	1021	33	18	11	5	0	0
18	Ward No. 18	850	28	15	9	4	0	0
19	Ward No. 19	1376	45	24	14	6	0	0
20	Ward No. 20	1151	37	20	12	5	0	0
21	Ward No. 21	1460	47	25	15	7	0	0
22	Ward No. 22	1236	40	21	13	6	0	0
23	Ward No. 23	794	26	14	8	4	0	0
24	Ward No. 24	1051	34	18	11	5	0	0
25	Ward No. 25	1354	44	23	14	6	0	0
26	Ward No. 26	1277	42	22	13	6	0	0
27	Ward No. 27	1269	41	22	13	6	0	0
28	Ward No. 28	1209	39	21	12	6	0	0
29	Ward No. 29	2026	66	35	21	9	1	0
30	Ward No. 30	1684	55	29	17	8	0	0
31	Ward No. 31	2584	84	44	27	12	1	0
32	Ward No. 32	2166	70	37	22	10	1	0
33	Ward No. 33	966	31	17	10	4	0	0
34	Ward No. 34	1372	45	24	14	6	0	0
35	Ward No. 35	2433	79	42	25	11	1	0
36	Ward No. 36	1856	60	32	19	9	1	0
37	Ward No. 37	2044	66	35	21	9	1	0
38	Ward No. 38	1149	37	20	12	5	0	0
39	Ward No. 39	1654	54	28	17	8	0	0
40	Ward No. 40	965	31	17	10	4	0	0

Sr. No.	Ward No.	Total No. of Buildings	RC2M					
			No. of Buildings	P(N)	P(S)	P(M)	P(E)	P(C)
41	Ward No. 41	829	27	14	9	4	0	0
42	Ward No. 42	2497	81	43	26	11	1	0
43	Ward No. 43	1285	42	22	13	6	0	0
44	Ward No. 44	2146	70	37	22	10	1	0
45	Ward No. 45	1074	35	18	11	5	0	0
46	Ward No. 46	1674	54	29	17	8	0	0
47	Ward No. 47	1756	57	30	18	8	1	0
48	Ward No. 48	1654	54	28	17	8	0	0
49	Ward No. 49	1529	50	26	16	7	0	0
50	Ward No. 50	1517	49	26	16	7	0	0
51	Ward No. 51	2234	73	38	23	10	1	0
52	Ward No. 52	2329	76	40	24	11	1	0
53	Ward No. 53	1421	46	24	15	7	0	0
54	Ward No. 54	1594	52	27	16	7	0	0
55	Ward No. 55	1516	49	26	16	7	0	0
56	Ward No. 56	1110	36	19	11	5	0	0
57	Ward No. 57	1577	51	27	16	7	0	0
58	Ward No. 58	1295	42	22	13	6	0	0
59	Ward No. 59	1514	49	26	16	7	0	0
60	Ward No. 60	1536	50	26	16	7	0	0
	Total	**88592**	**2879**	**1520**	**916**	**406**	**26**	**12**

5) For Building Type – MH

Sr. No.	Ward No.	Total No. of Buildings	MH					
			No. of Buildings	P(N)	P(S)	P(M)	P(E)	P(C)
1	Ward No. 1	1709	47	19	14	11	2	1
2	Ward No. 2	2345	64	27	19	15	3	1
3	Ward No. 3	2037	56	23	17	13	3	1
4	Ward No. 4	1396	38	16	12	9	2	0
5	Ward No. 5	1275	35	14	11	8	2	0
6	Ward No. 6	1381	38	16	11	9	2	0
7	Ward No. 7	1332	37	15	11	8	2	0
8	Ward No. 8	1559	43	18	13	10	2	1
9	Ward No. 9	1069	29	12	9	7	1	0
10	Ward No. 10	1075	30	12	9	7	1	0
11	Ward No. 11	1122	31	13	9	7	1	0
12	Ward No. 12	1139	31	13	9	7	1	0
13	Ward No. 13	967	27	11	8	6	1	0
14	Ward No. 14	1256	35	14	10	8	2	0
15	Ward No. 15	886	24	10	7	6	1	0
16	Ward No. 16	1012	28	11	8	6	1	0
17	Ward No. 17	1021	28	12	8	6	1	0
18	Ward No. 18	850	23	10	7	5	1	0
19	Ward No. 19	1376	38	16	11	9	2	0
20	Ward No. 20	1151	32	13	9	7	1	0
21	Ward No. 21	1460	40	17	12	9	2	0
22	Ward No. 22	1236	34	14	10	8	2	0
23	Ward No. 23	794	22	9	7	5	1	0
24	Ward No. 24	1051	29	12	9	7	1	0
25	Ward No. 25	1354	37	15	11	9	2	0
26	Ward No. 26	1277	35	14	11	8	2	0
27	Ward No. 27	1269	35	14	10	8	2	0
28	Ward No. 28	1209	33	14	10	8	2	0
29	Ward No. 29	2026	56	23	17	13	3	1
30	Ward No. 30	1684	46	19	14	11	2	1
31	Ward No. 31	2584	71	29	21	16	3	1
32	Ward No. 32	2166	60	24	18	14	3	1
33	Ward No. 33	966	27	11	8	6	1	0
34	Ward No. 34	1372	38	16	11	9	2	0
35	Ward No. 35	2433	67	27	20	15	3	1
36	Ward No. 36	1856	51	21	15	12	2	1
37	Ward No. 37	2044	56	23	17	13	3	1
38	Ward No. 38	1149	32	13	9	7	1	0
39	Ward No. 39	1654	45	19	14	11	2	1
40	Ward No. 40	965	27	11	8	6	1	0
41	Ward No. 41	829	23	9	7	5	1	0

Sr. No.	Ward No.	Total No. of Buildings	MH					
			No. of Buildings	P(N)	P(S)	P(M)	P(E)	P(C)
42	Ward No. 42	2497	69	28	21	16	3	1
43	Ward No. 43	1285	35	15	11	8	2	0
44	Ward No. 44	2146	59	24	18	14	3	1
45	Ward No. 45	1074	30	12	9	7	1	0
46	Ward No. 46	1674	46	19	14	11	2	1
47	Ward No. 47	1756	48	20	14	11	2	1
48	Ward No. 48	1654	45	19	14	11	2	1
49	Ward No. 49	1529	42	17	13	10	2	1
50	Ward No. 50	1517	42	17	13	10	2	1
51	Ward No. 51	2234	61	25	18	14	3	1
52	Ward No. 52	2329	64	26	19	15	3	1
53	Ward No. 53	1421	39	16	12	9	2	0
54	Ward No. 54	1594	44	18	13	10	2	1
55	Ward No. 55	1516	42	17	13	10	2	1
56	Ward No. 56	1110	31	13	9	7	1	0
57	Ward No. 57	1577	43	18	13	10	2	1
58	Ward No. 58	1295	36	15	11	8	2	0
59	Ward No. 59	1514	42	17	12	10	2	0
60	Ward No. 60	1536	42	17	13	10	2	1
	Total	**88592**	**2436**	**1001**	**731**	**563**	**115**	**29**

Annexure D

Ward wise total no. of buildings distribution according to final damage probability

Sr. No.	Ward No.	Total No. of Buildings	P(N)	P(S)	P(M)	P(E)	P(C)
1	Ward No. 1	1709	750	594	218	116	31
2	Ward No. 2	2345	1029	812	299	160	45
3	Ward No. 3	2037	894	706	260	139	39
4	Ward No. 4	1396	613	484	178	95	27
5	Ward No. 5	1275	560	442	163	87	25
6	Ward No. 6	1381	606	478	176	94	27
7	Ward No. 7	1332	585	461	170	91	26
8	Ward No. 8	1559	684	540	199	106	30
9	Ward No. 9	1069	469	370	136	73	21
10	Ward No. 10	1075	472	372	137	73	21
11	Ward No. 11	1122	492	389	143	77	22
12	Ward No. 12	1139	500	395	145	78	22
13	Ward No. 13	967	424	335	123	66	19
14	Ward No. 14	1256	551	435	160	86	24
15	Ward No. 15	886	389	307	113	60	17
16	Ward No. 16	1012	444	351	129	69	19
17	Ward No. 17	1021	448	354	130	70	20
18	Ward No. 18	850	373	294	108	58	16
19	Ward No. 19	1376	604	476	175	94	26
20	Ward No. 20	1151	505	399	147	79	22
21	Ward No. 21	1460	641	506	186	100	28
22	Ward No. 22	1236	543	428	158	84	24
23	Ward No. 23	794	348	275	101	54	15
24	Ward No. 24	1051	461	364	134	72	20
25	Ward No. 25	1354	594	469	173	92	26
26	Ward No. 26	1277	560	442	163	87	25
27	Ward No. 27	1269	557	439	162	87	24
28	Ward No. 28	1209	530	419	154	82	23
29	Ward No. 29	2026	889	702	258	138	39
30	Ward No. 30	1684	739	583	215	115	32
31	Ward No. 31	2584	1134	895	330	176	50
32	Ward No. 32	2166	950	750	276	148	42
33	Ward No. 33	966	424	335	123	66	19
34	Ward No. 34	1372	602	475	175	94	26
35	Ward No. 35	2433	1068	843	310	166	47
36	Ward No. 36	1856	814	643	237	127	36
37	Ward No. 37	2044	897	708	261	139	39
38	Ward No. 38	1149	504	398	147	78	22
39	Ward No. 39	1654	726	573	211	113	32

Sr. No.	Ward No.	Total No. of Buildings	P(N)	P(S)	P(M)	P(E)	P(C)
40	Ward No. 40	965	423	334	123	66	19
41	Ward No. 41	829	364	287	106	57	16
42	Ward No. 42	2497	1096	865	318	170	48
43	Ward No. 43	1285	564	445	164	88	25
44	Ward No. 44	2146	942	743	274	146	41
45	Ward No. 45	1074	471	372	137	73	21
46	Ward No. 46	1674	735	580	214	114	32
47	Ward No. 47	1756	770	608	224	120	34
48	Ward No. 48	1654	726	573	211	113	32
49	Ward No. 49	1529	671	529	195	104	29
50	Ward No. 50	1517	666	525	193	103	29
51	Ward No. 51	2234	981	774	285	152	43
52	Ward No. 52	2329	1022	807	297	159	45
53	Ward No. 53	1421	623	492	181	97	27
54	Ward No. 54	1594	700	552	203	109	31
55	Ward No. 55	1516	665	525	193	103	29
56	Ward No. 56	1110	487	384	142	76	21
57	Ward No. 57	1577	692	546	201	108	30
58	Ward No. 58	1295	568	449	165	88	25
59	Ward No. 59	1514	664	524	193	103	29
60	Ward No. 60	1536	674	532	196	105	30
	Total	**88592**	**38878**	**30684**	**11299**	**6041**	**1703**