# Earthquake Vulnerability Assessment of the Built Environment in Srinagar City, Kashmir Himalaya using GIS

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## ABSTRACT

The study investigates the earthquake vulnerability of buildings in Srinagar, an urban city in the Kashmir Himalaya, India. The city, covering an area of around 246 km$^2$ and divided into 69 municipal wards, is situated in the tectonically active and densely populated mountain ecosystem. Given the haphazard development and high earthquake vulnerability of the city, it is critical to assess the vulnerability of the built environment to inform policy-making for developing effective earthquake risk reduction strategies. Integrating various parameters in Geographic Information System (GIS) using the Analytical Hierarchical Process (AHP) and Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) approaches, the ward-wise vulnerability of the buildings revealed that a total of ~17 km$^2$ area (~7% area; 23 wards) has very high to high vulnerability; Moderate vulnerability affects ~69 km$^2$ of the city area (28% area; 19 wards); ~160 km$^2$ area (~65% area; 27 wards) has vulnerability ranging from very low to low. Overall, the downtown city is most vulnerable to earthquake damage due to the high risk of pounding, high building density, and narrower roads with little or no open spaces. The modern uptown city, on the other hand, has lower earthquake vulnerability due to the relatively wider roads and low building density. To build a safe and resilient city for its 1.5 million citizens, the knowledge generated in this study would inform action plans for developing earthquake risk reduction measures, which should include strict implementation of the building codes, retrofitting of the vulnerable buildings, and creating a disaster consciousness among its citizenry.

Keywords: Earthquake, Earthquake Vulnerability, AHP, GIS, TOPSIS, Kashmir

## 1. Introduction

Among all the natural disasters, earthquakes are unique in the way that they occur without any warning (Langenbach, 2009) and are a major hindrance in the way of achieving sustainable development. Cities are growing fast all over the world as a process of urbanization and more than half of the world's population lives in urban areas (Ritchie and Roser, 2018). Earthquakes cause immense loss of life and damage to properties, livelihoods, economic infrastructures and communities, particularly in major urban centres (Kjekstad and Highland, 2009). Urban earthquake vulnerability has increased over the years due to the increasing complexity of urban built environment (Düzgün et al., 2009; Riedel et al., 2015). The high earthquake susceptibility of urban centres is also due to their situation in hazard-prone locations (Duzgun et al., 2011; Mir et al., 2017), haphazard urbanization (Jena et al., 2020), and growing population (Beck et al., 2012), and that has attracted the attention of emergency planners in estimating the seismic risk associated with future earthquakes (Kontoes et al., 2012). Surveys have shown that collapsing buildings and other physical structures during an earthquake cause huge social, economic, and human losses (Panahi, et al., 2014). The dynamic interaction between different urban components and diverse forms of vulnerability proves that vulnerability is inherently a spatial problem (Hashemi and Alesheikh, 2012). Furthermore, the earthquake vulnerability of a building is an important parameter to consider in the evaluation of the potential earthquake damage in urban fabrics (Amini et al., 2009). Thus, the assessment of earthquake vulnerability of the built environment is crucial for any city located in an earthquake risk zone to better characterise and understand the inherent weakness and vulnerabilities of a city against earthquakes and to help prioritize preparedness and risk mitigation activities.

Structural vulnerabilities to earthquakes have arisen in the Kashmir valley in the recent decades as the traditional construction materials and practises have been abandoned in favour of new ones (Yousuf et al., 2020). The lurking threat of an earthquake in the past had a great influence on the way people traditionally used to build their houses in the Kashmir valley (Langenbach, 2009; Ahmad et al., 2017). The traditional wooden-frame structures were designed to deal with earthquake threat to provide a safe and suitable built environment for people. The buildings constructed with wood substantially reduce the weight of buildings and provide structural flexibility compared to that of the other types of materials used in building construction (Alih and Vafaei, 2019). The traditional building types such as "Taqq" and "Dhajji-Dewari" are earthquake-resistant. In the Taqq type buildings, wooden runners are placed at each floor level that tie the walls with the floor together. Whereas, the Dhajji-

Dewari buildlings consist of a braced timber frame with masonry infill that is placed diagonally in the walls. The timber braced frames offer stable confinement to the infill masonry as long as it rests together (Hicyilmaz et al., 2012). When compared to more contemporary building types, the Dhajji-Dewari constructions are more earthquake-resistant because the seismic energy is dissipated between mortar joints, the frame, and the infill rather than through non-linear deformations. Recently, the traditional ways of constructing houses have been replaced mostly by concrete types, thereby increasing the vulnerability of the structures to earthquakes. The residential buildings in the Kashmir valley are mostly built by local semi-skilled masons who don't have adequate technical expertise in building earthquake resistance infrastructure and therefore these structures lack the basic earthquake risk reduction features including seismic resistance properties as are otherwise prescribed in the building codes. It is therefore of utmost importance to assess the earthquake vulnerability of all the existing buildings in the Kashmir valley, comprising both traditional and modern construction types, since the valley falls in Seismic Zones IV or V (Ali and Ali, 2020). Despite the high vulnerability of the Kashmir valley to earthquakes, no initiative has been taken by the government agencies, non-government agencies and scientific community to develop an earthquake risk assessment strategy for the valley that would inform urban development planning in the region to minimise the damage in the eventuality of an earthquake as has been done in other vulnerable Himalayan areas of the country like Delhi, Dehradun, Kolkata, etc. (Pathak, 2008; Nath, et al., 2015; Rautela et al., 2015; Sinha et al., 2016). This study is therefore the first of its kind aimed at assessing the earthquake vulnerability of the built environment in the capital city of Jammu and Kashmir, i.e., Srinagar.

Many national and international studies have been conducted to estimate the physical vulnerability of the built environment by applying various techniques, viz., MCDM (Multi-Criteria Decision Making), AHP (Analytical Hierarchical Process), and ANN (Artificial Neural Networking) (Jena et al., 2020; Jena and Pradhan, 2020; Lee et al., 2019; Alizadeh et al., 2018). Rashed and Weeks, 2003 studied the physical vulnerability parameters in the Tabriz city of Iran such as, age and height of the buildings, and earthquake intensity, that are major contributors in assessing the vulnerability of buildings. Erden and Karaman, 2012 investigated the impact of systemic vulnerability parameters, such as topography, distance to the epicentre, soil classification, liquefaction, and fault/focal mechanism using the AHP approach for earthquake vulnerability assessment of the Kucukekmece region of Istanbul, Turkey. Pathak, 2008 carried out the earthquake vulnerability assessment of the Guwahati city using Rapid visual screening (RVS) by taking into account demand-capacity computation, structural and non-structural damage grade indexing. Nath et al., 2015 used geotechnical, seismological, and geological data for assessing the seismic risk of the Kolkata city. They used land use/land cover, population density, building typology, age, and height of buildings for earthquake vulnerability assessment. Sinha et al., 2016 used the Spatial Multi-Criteria Analysis and Ranking Tool (SMART) methodology and classified the capital city of India, Delhi, as highly vulnerable to earthquakes using different physical parameters like number of storeys, year-built range, area, occupancy, and construction type. The earthquake vulnerability of Nanital and Mussorie cities in the Uttarakhand state, India was assessed by Rautela et al., 2015 employing the RVS methodology. Ahmad et al., 2012 used the experimental and analytical studies to investigate the vulnerability of the Half-Dressed rubble stone (DS) masonry structures in the Himalayas using the shake table method and fragility analysis of buildings. The study concluded that about 40% of buildings can collapse in the eventuality of a large earthquake. The collapse rate of buildings can go up as high as 80%, if, the epicentre of an earthquake is closer to the settlement. Baruah et al., 2020 have assessed the seismic vulnerability of the mega-city Shillong in India using RVS methodology by including parameters like building typology, local geology, geomorphology, slope angle and population suggesting that 60% of the city is falling under moderate to high vulnerability zones. Jena et al., 2021 carried out an analysis of the earthquake vulnerability of the Indian subcontinent using the LSTM (Long Short-Term Memory) model and multi-criterion analysis (MCA), which suggested that very-high vulnerable areas are situated towards the northern and eastern parts of India. The study, conducted at a coarse scale, classified Jammu and Kashmir, of which the study area is a part, as a highly vulnerable with a moderate to high earthquake vulnerability index.

The present study therefore addresses the knowledge gap through the assessment of earthquake vulnerability of built environment at a spatial high-resolution, i.e., ward level in order to identify the vulnerable areas of Srinagar city, a major rapidly growing and seismically vulnerable urban centre in the Kashmir valley. The location of earthquake epicentre is related to the presence of geological structures (faults) in a particular area (Sana, 2018). The available historical and instrumental records of the earthquake events (Table 1) in the study area indicated a high probability of future earthquakes in the Srinagar city. Dar et al., 2019 have shown that the River Jhelum, running through the Srinagar city itself flows along or parallel to the Jhelum fault at many places in the Kashmir valley. The city is predominantly located on the recent alluvium and Karewas with Panjal traps at some locations (Dar et al., 2015) and has the Seismic Hazard Index (SHI) and Liquefaction Potential Index (LPI) ranging from high to very high (Sana et al., 2016; Sana, 2018; Yousuf and Bukhari, 2020). It is assumed that, due to the past occurance of earthquakes with epicentres in and around Srinagar, and the almost uniform distribution of other geological, geomorphic, and soil parameters in the city, all the city wards would be equally vulnerable in the event of an earthquake. As a result these parameters were kept constant and were not considered in the vulnerability analysis because the primary goal of this study was to assess earthquake vulnerability at the ward level. Based on the literature survey, expert opinion, and analyses of the available data, a set of six important indicators, such as building geometry, density, height, typology, pounding possibility and road network were selected in this study for assessing earthquake vulnerability of the built-up environment in the city. The structural vulnerability asseseement of the Srinagar city, which is located in the high earthquake-prone zone, will inform urban planning and development strategies in order to create a safe and secure built environment with adequate green and open spaces, as well as make the city sustainable, as envisioned under UNDP Sustainable Development Goals (SDGs) 11 for sustainable cities and communities.

## 2. Srinagar city

Srinagar city, spread over an area of 246 $km^2$, lies between 74º 43´ and 74 º 52´ E longitudes and 34º 0´ and 34º 14´ N latitudes and is divided into 69 administrative wards (Fig. 1). The city is situated at an average elevation of 1713 m amsl along the banks of the centrally flowing Jhelum River. The city of Srinagar, home to around 1.5 million people, is an economic hub, a seat of administration, and an important urban centre in the Kashmir Himalaya (Parry et al., 2012). The population of the city is projected to increase to 1.83 million by 2031 (Farooq and Muslim, 2014). The city is susceptible to high seismic hazards due to its peculiar geological setting (Sana, 2018), urban setting (Gupta et al., 2020), demographic profile, and tectonic setting (Chandra et al., 2018). The city is surrounded by Himalayan boundary faults, which are capable of generating destructive earthquakes that are well documented in the historical archives and recent instrumental records as well (Sana, 2018; Gupta et al., 2020). There is a formidable history of earthquakes that have shaken Srinagar in the past millennium and have caused huge loss of human life and property (Table 1) (Rajendran  and Rajendran, 2005; Langenbach, 2007; Bilham et al., 2010; Bilham, 2019; Yousuf et al., 2020). Though Srinagar is an old and historic city, but the city grew organically without following any physical plan or building codes for the construction of its built infrastructure (Yousuf et al., 2020). Post-1947, the city grew very fast, mostly in a haphazard manner with no proper urban planning. The first Master Plan for the city was developed in 1971, followed by Master Plans for 2000-2021 and 2022-2035 periods. However, all the previous plans didn't have effective implementation in the city as per the Master Plan prescriptions because of the problems in the planning and implementation setup, including an inadequate legal framework and institutional structures. Furthermore, there is a distinct cultural and socio-economic inequality within the city, with the lower-middle-income groups residing in the densely populated downtown wards and the upper-middle class and wealthy people residing in the uptown wards of the city. In such a situation, assessing ward-wise earthquake vulnerability of the built environment is very critical for prioritizing risk reduction activities to reduce the earthquake vulnerability of the people and infrastructure in the city (Mouroux et al., 2006; Mili et al., 2018).

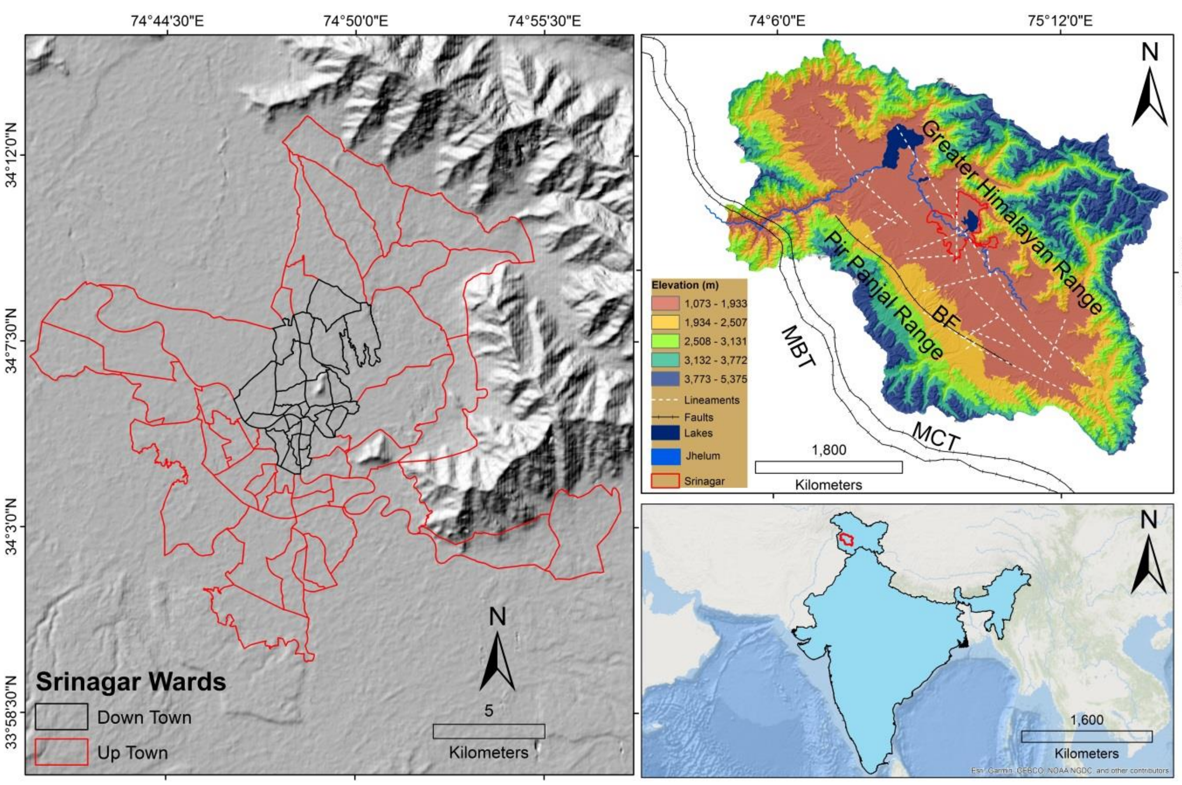


Fig. 1. Location of the study area. Here, the MBT stands for Main Boundary Thrust, MCT for the Main Central Thrust, and BF stands for the Balapur Fault.

| S. No. | Date | Magnitude ($M_w$) | Lat (N) | Long (E) | Location | Damage | References |
|---|---|---|---|---|---|---|---|
| 1 | 844 AD | 6.5 to 7.5 | 34° N | 74.8° E | Srinagar Kashmir | Landslide dammed Jhelum at Khadanyar near Baramulla | Stein, 1982; Stein, 1898; |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | Bilham and Bali, 2014. |
| 2 | 1123 AD | 6.5 to 7.5 | 34° N | 74.8° E | Srinagar Kashmir | Caused damage Sugandhesa Temple | Stein, 1982; Stein, 1898; Bilham and Bali, 2014; Iyengar and Sharma, 1996 ; Iyengar et al., 1999; Iyengar and Sharma, 1999 |
| 3 | 1501 AD | 6.5 to 7 | 34° N | 74.8° E | Srinagar Kashmir | Three months of after shocks | Bilham and Bali, 2014 |
| 4 | 1555 AD | 7.6 to 8 | 34.25° N | 74.8° E | Baramulla, Srinagar and Anantnag | Landslide, Liquefaction and landslides in the Kashmir valley | Bilham and Bali, 2014; Iyengar and Sharma, 1996 ; Iyengar et al., 1999; Iyengar and Sharma, 1999; Ambraseys and Jackson, 2003 |
| 5 | 1669 AD | 6.5 to 7 | 34° N | 74.8° E | Srinagar Kashmir | Mild shaking of buildings with no loss of life | Ahmad et al., 2009; Bilham and Bali, 2014 |
| 6 | 1678 AD | 6.5 to 6.8 | 34° N | 74.8° E | Kashmir | Continuous shaking of buildings | Ahmad et al., 2009; Bilham and Bali, 2014 |
| 7 | 1683 AD | 6.5 to 6.8 | 34° N | 74.8° E | Srinagar Kashmir | Long shocks and destruction of newly constructed houses | Ahmad et al., 2009; Bilham and Bali, 2014 |
| 8 | 1736 AD | 6.5 to 7 | 34° N | 74.8° E | Srinagar Kashmir | Large number of Building in city and adjoin areas collapsed completely | Ahmad et al., 2009 |
| 9 | 1779 AD | 6.5 to 7.5 | 34° N | 74.8° E | Srinagar and villages of Kashmir valley | It destroyed houses in city and villages and caused huge loss to life | Ahmad et al., 2009 |
| 10 | 1784 AD | 6.5 to 7.5 | 34° N | 74.8° E | Srinagar Kashmir | Terrific shocks felt in the area | Bilham, 2019 |
| 11 | 1828 AD | 6.5 to 7.5 | 34° N | 74.8° E | Srinagar Kashmir | About 1200 houses collapsed in this event | Vigne, 1842; Ahmad et al., 2009 |
| 12 | 1885 AD | 7.1 to 7.5 | 34.54° N | 74.68° E | Baramulla Kashmir | Terrific shock felt in the adjoining area | Ahmad et al., 2009; Lawrence, 1895 |
| 13 | 2005 AD | 7.6 | 34.49° N | 73.63° E | Kashmir | Earthquake alone left 86,000 people dead, about 69000 injured in both Indian and Pakistan side and about 25% of buildings were fully damaged in Uri and Poonch areas of J and K | Kumar et al., 2006 |

Table 1: Records of the historical and instrumental earthquake events in the Kashmir valley

## 3. Dataset and Methodology

The availability of high spatial resolution satellite images with a ground pixel size of 1 m, opens up new possibilities for mapping individual features such as buildings (Li et al., 2019). To accomplish this study, ortho-rectified Cartosat-2 data of 2016-17, having a spatial resolution of 1 m, were utilised to extract the spatial information of the built environment in Srinagar city. The very high-resolution Cartosat-2 data has the potential to map individual buildings at a large scale (Sandhu et al., 2021).

### 3.1 Building inventory

Keeping in view the advantages of the manual digitization of features from satellites images over the digital image processing, the visual interpretation method was employed for delineating buildings and associated land use and land cover (Rashid et al., 2017). Various image interpretation elements, viz., tone, texture, pattern, size, shape, etc., supplemented by Google Earth, were used to map the building footprint of the city on high-resolution Cartosat-2 data at a scale of 1:1,000. All the buildings, roads, water bodies, and other associated urban built-up are included in the mapped features. The individual building footprints were accurately mapped, however delineating the complex geometrical shape in unplanned dense and very dense built-up areas proved to be a difficult task (Sandhu et al., 2021). As a result, rather than individual building footprints, building blocks were digitized in the densely populated areas towards the centre of the downtown city where the edges of the buildings become indistinguishable, causing difficulty in extracting individual building footprints. Following the evaluation in the field, these structures were thereafter segregated and corrected. Furthermore, all of the city's major roads were easily identifiable, however, the extraction of minor roads, particularly in the densely built-up downtown wards were difficult to map due to their narrower widths and the metallic rooftop canopy of the adjacent building concealing the narrow alleys. The vector layer with the associated attributes like height, building use, typology, and number of building floors was created by combining the remote sensing data and field data. The high-resolution maps of the building footprint and road network were then utilised to critically assess the ward-wise earthquake vulnerability of buildings in the city.

### 3.2 Building vulnerability indicators

The vulnerability of the built environment determines its earthquake risk. Building collapse causes a major damage during an earthquake. Thus, faulty building structures and the use of unsafe materials are some of the major causes of damage during an earthquake (Lantada et al., 2009). Assessment of the earthquake vulnerability of individual buildings and neighbourhoods is a complex process (Langenbach, 2009; Agrawal and Chourasia, 2007) and involves consideration of numerous parameters, which are described as follows:

**3.2.1 Building height:** Because of its antiquity, tradition, heritage, and significance, the built environment in different wards of Srinagar city shows a remarkable diversity (Meier and Will, 2008). Building height has a substantial impact on earthquake response and the level of structural damage (Kircher et al., 1997; Priestley, 2000). Buildings with a lower height-to-surface area ratio are more earthquake-resistant, and vice-versa (Alizadeh et al., 2018). As a result, high-rise buildings with a smaller surface area are more vulnerable to earthquake damage. When these types of buildings shake and swing during an earthquake, they have a higher probability of pounding. Extensive ward-by-ward field surveys were conducted to generate a comprehensive building height map of the city. During the field surveys, number of floors of the randomly selected buildings from each ward in the city were surveyed and counted. For the building height estimation during the field surveys, three types of buildings were considered: single-story, double-story, and triple- or multiple story buildings. The field data was then combined in a GIS database.

**3.2.2 Masonry building:** The traditional construction practices are considered outmoded, insubstantial, and indicative of poverty in developing countries (Langenbach, 2009). As a result, people are moving away from the traditional types and methods of construction and adopting the modern practices and types of buildings with bricks, cement blocks, and stones. Masonry buildings, as they are known, are extremely vulnerable to earthquakes (Alam and Haque, 2018). The disappearance of traditional construction and buildings in Srinagar and the rise of the contemporary masonry construction practices have made the city more vulnerable to earthquakes. A physical survey of the buildings was conducted to determine the type of buildings for the physical vulnerability assessment of masonry buildings in the city (Rahman et al., 2015). The pattern of buildings along the main and link roads was surveyed during the fieldwork because a majority of the buildings in the city are masonry. The presence of non-masonary building types was recorded using the Trimble Juno 5B handheld GPS having 2-4 meter accuracy, which was then combined with GIS data to estimate the proportion of various masonry building types in the city.

**3.2.3 Pounding Possibility:** One of the most common causes of the structural damage during an earthquake is due to the pounding between neighbouring buildings (Anagnostopoulos, 1988). Pounding occurs when two or more buildings, situated close to each other, collide during an earthquake (Alam and Haque, 2018). Every building has its natural frequency and swings correspondingly during an earthquake (Lu et al., 2017; Jia et al., 2018). If the distance between buildings is insufficient, the buildings cannot swing freely, resulting in local thrashing of the structures (Gioncu and Mazzolani, 2010). Due to the location of the Srinagar city in a seismically active region, its socioeconomic setup, unplanned urbanization and faulty land-use planning (Yousuf et al., 2020), Srinagar faces a significant risk of structural damage from pounding during an earthquake. To determine the potential of pounding in Srinagar, we employed a methodology that requires a minimum separation distance of 4% of the building height between two buildings (FEMA, 1998). The pounding potential was calculated using the following equation:

$$S = 0.04(h_1 + h_2) \qquad (1)$$

Where, 'S' is the minimum separation distance between the buildings, '$h_1$' and '$h_2$' are the heights of two adjacent buildings.

**3.2.4 Building Geometry:** The earthquake damage to a building also depends on its geometry. Compared to regular structures, buildings having geometrical irregularities such as a tall height-to-width ratio, a large length-to-width ratio, or a large offset in plan and elevation, perform poorly and sustain a significant damage during earthquakes (Alih and Vafaei, 2019). We employed high-resolution Cartosat-2 data and validated it against the field data to generate a building geometry map of the city. The remote sensing data was pre-processed and the edge enhancement technique was used for highlighting the edges of buildings (Somvanshi et al., 2018; Huang et al., 2019). The geometry map of the city was then generated using manual digitization of the building edges, which was later validated in the field.

**3.2.5 Road Network:** Urban roadways are a complex network that is extremely vulnerable to disruption in the event of natural disasters such as earthquakes (Golla et al., 2020). Roads play an important role in the post-earthquake response and recovery phase. Roadblocks caused by earthquakes have a negative impact on not just post-earthquake emergency services but also isolate specific areas of cities where basic amenities such as hospitals, shelters, and other critical services are situated (Balijepalli and Oppong, 2014). Thus, the mapping of roads is essential for assessing the earthquake vulnerability of a city. Using the manual digitization technique, all roads in Srinagar were mapped from the high-resolution satellite data at a scale of 1:1,000. Because the buildings in Srinagar are not built in a planned manner, the majority of the roads are small and narrower and are classified into three categories: less than 8 feet, 8 to 16 feet, and more than 16 feet roads (Alam and Haque, 2018). Roads with a width of less than 8 feet are considered particularly vulnerable.

**3.2.6 Building density:** In addition to the aforementioned parameters, the building density of an urban area has a significant impact on its structural vulnerability (Bahadori et al., 2017). The more densely built a place is, the more vulnerable it is to earthquakes (Jena and Pradhan, 2020). For all the wards of Srinagar, the building density was determined as the number of buildings per unit area. For building density mapping, we used 1meter high-resolution Cartosat data, which was then draped onto Google Earth imagery for validation. The building density was also validated during the extensive field surveys.

### 3.3 Field validation

Comprehensive ground-truth surveys were conducted in all the wards of the city to validate the building inventory GIS database. Because there are so many buildings and their area is so large, ward-wise validation of the delineated buildings was done using the stratified random sampling method. It was ensured that the validation sites are well distributed throughout the ward (Han et al., 2020). For field data collection, a proforma was developed to collect data such as latitude, longitude, building use, number of floors, and construction type. The position of individual buildings in every ward was identified on the building inventory map during field surveys through visual observation and using GPS coordinates, and the locations were documented (Ahmad et al., 2009). 8000 field validation points were collected throughout the city (Fig. 2) and the physical attributes of each building were inspected externally to determine various building parameters. Post-field surveys, the building inventory database was updated to match the ground-truth data.

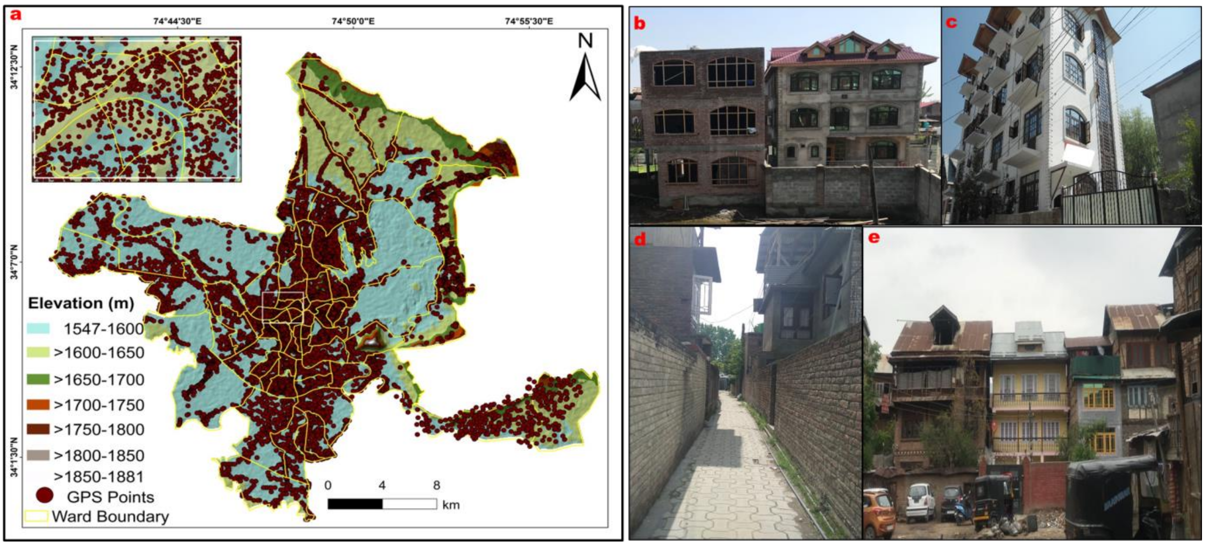


Fig. 2. *a)* Field validation map showing the distribution of ground samples with the inset showing the density of samples. The elevation of study area is based on the ASTER DEM data. *Field photographs; b)* a modern masonry construction practice adopted in a residential area, *c)* a commercial building with large windowpanes, *d)* The narrower roads in the city centre and *e)* the buildings with the insufficient or no separation distance.

### 3.4 Analytical Hierarchical Process (AHP) Approach

Due to its simplicity and rationality (Rezaie and Panahi, 2015; Alam and Mondal, 2019), the AHP is a widely used multi-criteria decision-making method (MCDM) for disaster vulnerability assessment. It considers both qualitative and quantitative parameters to develop a hierarchical solution decision-making among various alternatives and their sub-categories. The Analytical Hierarchical Process (AHP) weights parameters and sub-parameters based on expert opinion, ensuring transparency and consideration of local-specific conditions of a study area that global indices cannot (Füssel, 2010). There are three key assessment steps in AHP. The first step is to create binary comparison matrices on a scale of 1–9 (Saaty, 1980), where 1 indicates that two parameters are equally important, 9 indicates that one parameter is extremely important and 1/9 indicates that the parameter is of the least importance. Table 2 shows the scale of importance. The AHP was used to create indices that measured spatial variations in structural vulnerability ward-by-ward across the Srinagar city.

| Decreasing Relative Intensity of Importance ← | | | | | | | | Equally Important | Increasing Relative Intensity of Importance → | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1/9 | 1/8 | 1/7 | 1/6 | 1/5 | 1/4 | 1/3 | 1/2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |

Table 2: AHP scale used in this study

In the second step, the weights of different factors are determined from row-multiplied value (RMV), in un-normalized and normalized values using equations (2) and (3).

$$\text{Unnormalized value, } mi = \sqrt[n]{RMV} \qquad (2)$$

$$\text{Normalized value} = \frac{mi}{\sum_{i=1}^{n} mi} \qquad (3)$$

Where, *mi* refers to the un-normalized value of the *i-th* parameter and n represents the total influential parameters.

The third and most important step of this approach is to compute the consistency between judgements and weights. The consistency is calculated from the consistency index and consistency ratio employing equations (4) and (5). If the consistency ratio is <0.1, the pairwise comparison matrix is consistent and if it is >0.1, the pairwise comparison between indicators and sub-indicators must be iterated until a good consistency is achieved.

$$\text{Consistency index, } CI = \frac{\mathrm{L}-\mathrm{n}}{n-1} \qquad (4)$$

$$\text{Consistency Ratio, } CR = \frac{\mathrm{CI}}{\mathrm{RI}} \qquad (5)$$

Where, L represents the Eigen-value of the pairwise comparison matrix and RI is the random inconsistency index, which depends on the number of vulnerability assessment parameters (n) used in the assessment. The variation of RI values for a different number of parameters is shown in Table 3.

| N | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RI | 0 | 0 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 | 1.52 | 1.54 |

Table 3: Random inconsistency indices (RI) for n = 1, 2. . . 12. (After Saaty, 1980)

All the four authors were involved in determining the expert judgement process, viz., Prof. Shakil Ahmad Romshoo, Ph.D., Remote Sensing and GIS; Dr. Irfan Rashid, Ph.D., Environmental Sciences; Dr. Rakesh Chandra, Ph.D., Geology; and Midhat Fayaz, M.Sc. (Geoinformatics). Furhtermore, a large body of literature was also consulted that informed the expert judgement process. Based on the multiple judgments, a comparison matrix of six earthquake vulnerability factors was established in this study (Yariyan et al., 2020). The geometric mean of expert opinions were then calculated to compile all of the opinions into a single matrix (Table 4). As a result, the factors are weighted and ranked on a scale of 0 to 1. The Consistency Ratio (CR) of 0.015 was achieved, which indicates consistency in the pairwise comparison of vulnerability factors (Saaty, 1980).

| Parameters | Average Floor Height | Masonry Building (%) | Pounding Possibility (%) | Irregular Building (%) | Average Road Width | Building Density | Sum | Weight |
|---|---|---|---|---|---|---|---|---|
| Average Floor Height (m) | 0.12 | 0.09 | 0.12 | 0.08 | 0.16 | 0.15 | 0.72 | 0.12 |
| Masonry Building (%) | 0.28 | 0.23 | 0.22 | 0.23 | 0.22 | 0.22 | 1.40 | 0.23 |
| Pounding Possibility (%) | 0.28 | 0.32 | 0.31 | 0.31 | 0.27 | 0.31 | 1.80 | 0.30 |
| Irregular Building (%) | 0.12 | 0.08 | 0.08 | 0.08 | 0.05 | 0.08 | 0.48 | 0.08 |
| Road Width (ft) | 0.08 | 0.11 | 0.12 | 0.15 | 0.11 | 0.09 | 0.67 | 0.11 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Building Density (per Ha) | 0.12 | 0.16 | 0.15 | 0.15 | 0.19 | 0.15 | 0.92 | 0.15 |

Table 4: Pair-wise matrix showing weights for each of the factors used in the AHP model

## 3.5 Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) Approach

The TOPSIS is a multi-criteria decision-making analysis (MCDA) method that chooses alternatives based on the distance between positive and negative ideal points (Hwang et al., 1993; Joshi and Kumar, 2014). The TOPSIS model is based on the concept that the chosen alternative should be the closest to the ideal solution while being the farthest from the negative ideal solution. The important steps involved in the TOPSIS approach are listed below.

Step 1: Construction of the normalized decision matrix using equation (6)

$$\text{Normalize score,} r_{ij} = x_{ij}/\left(\sum x_y^2\right) \qquad (6)$$

Where, $x_{ij}$ is the score of option *i* with respect to criterion *j*.

Step 2: Construction of the weighted normalized decision matrix using equation (7)

$$v_{ij} = w_j * r_{ij} \qquad (7)$$

where, $w_j$ is the weight for each criterion.

Step 3: Identifying the positive and negative ideal solutions. The positive ($A^+$) and negative (A') ideal solutions are defined according to the weighted decision matrix using equations (8) and (9) respectively

$$A^+ = \{V_1^+, V_2^+, \dots, V_n^+\}$$

$$\text{Where, } V_j^+ = \left\{\max\left(V_{ij}\right) if j \in J; \min\left(V_{ij}\right) if j \in J'\right\} \qquad (8)$$

$$A' = \{V_1', V_2', \dots, V_n'\}$$

$$\text{Where, } V_j' = \left\{\min\left(V_{ij}\right) if j \in J; \max\left(V_{ij}\right) if j \in J'\right\} \qquad (9)$$

Step 4: Calculating the separation distance of each alternative from the positive and negative ideal solution using equations (10) and (11) respectively after Hwang et al., 1993.

$$S_i^+ = \sqrt{\sum_{j=1} n\left(V_j^+ - V_{ij}\right)^2} \quad (10)$$

$$S_i^- = \sqrt{\sum_{j=1} n\left(V_j^{'} - V_{ij}\right)^2} \quad (11)$$

Where, $S_i^+$ is the distance from the $i^{th}$ alternative from the positive ideal point for the $j^{th}$ feature and $S_i^-$ is the distance between the $i^{th}$ alternative and the negative ideal point for the $j^{th}$ feature and $i = 1, \ldots, m$. The negative and positive ideal point for each seismic vulnerability factor is shown in Table 5.

| Vulnerability Parameters | Positive Ideal Point (V+) | Negative Ideal Point (V-) |
|---|---|---|
| Average Floor Height | 0.0171 | 0.0112 |
| Pounding Possibility | 0.0501 | 0.0083 |
| Irregular Building | 0.0270 | 0.0004 |
| Road Width | 0.0090 | 0.0199 |
| Building Density | 0.0618 | 0.0007 |
| Masonry Building | 0.0283 | 0.0243 |

Table 5: Positive and negative ideal points used in the TOPSIS model

Step 5: Measuring the relative closeness of each parameter to the ideal solution using equation (12).

$$\text{Closeness}, C_i^* = S_i^- / (S_i^- + S_i^+) \quad (12)$$ (After Hwang et al., 1993)

Where, $C_i^*$ is a value between 0 and 1 and the closer the number is to 1, the closer the alternative is to the ideal condition. The positive ideal point in this study is the one with the maximum structural earthquake vulnerability, while the negative ideal point is the one with the lowest vulnerability. Furthermore, the closer an alternative value is to 1, the more vulnerable those limits are, and the closer it is to 0, the less vulnerable they are.

Based on the expert opinions, the AHP model was used to assign weights to all the parameters. Following that, the TOPSIS model was used to rank the wards after evaluating the best alternatives using mathematical calculations. Finally, the weighted and best alternative evaluated structural vulnerability parameters from both the AHP and TOPSIS models are combined in GIS environment to create a ward-by-ward earthquake vulnerability map of the built environment in Srinagar. The integrative use of these two models reduces the uncertainty in the input data and improves accuracy and validity. Furthermore, decision-making based on the integrated use of the AHP and TOPSIS leads to more robust and effective outcomes for addressing the complex problems (Nyimbili et al., 2018). Many studies have recommended the integrated use of TOPSIS with AHP for determining criteria and conducting analyses regarding complex decision-making problems (Behzadian et al., 2012). Additionally, the integrated use of AHP and TOPSIS helps to resolve the weighting problem by incorporating expert opinions and preferences, thereby increasing the consistency of the outputs for arriving at consensus in decision-making in earthquake disaster vulnerability analysis (Nyimbili et al., 2018).

The adopted methodology has a few limitations, much like any other modeling technique. In addition to the inherent flaws in the MCDA, there may be some limitations, such as the fact that certain layers become more dominant than others due to the weighting criteria used, which in turn depends upon the expert perceptions about which of the vulnerability parameters have the greatest impact on modeling outcomes in the vulnerability analysis.

# 4. Results and discussion

## 4.1. Analysis of building parameters:

**4.1.1. Building height:** In the city, around 2.5 lakh buildings were mapped (Fig. 3), with nearly 86.4% of the buildings being residential, 7.1% being commercial, and the remaining ~6.5% having various uses and purposes such as educational, religious, defence, health and medical, industrial, etc. The analysis revealed that the single story buildings account for ~8% of all the buildings, double-story buildings account for ~50% and triple-story buildings account for ~42%. However, only a small number (n=307, 0.12%) of buildings have more than 3 floors. 18 of the 69 wards have an average of two floors, while 51 have an average of three floors.

The building height has a significant impact on the ward's vulnerability to earthquakes. A majority of the residential buildings in Srinagar have an average floor height of three meters, whereas government offices and commercial buildings typically have an average floor height of 3.5 meters. The lowest ward-wise average building height of 6.33 meters was found in municipal ward A (BB Cant), which is primarily a cantonment area used and administered for security and defence purposes. Ward number 50 (Lal Bazar) has the highest ward-wise average building height of 9.68 meters. Figure 4 depicts the spatial distribution of ward-wise average building heights with the average values provided in Table 6.

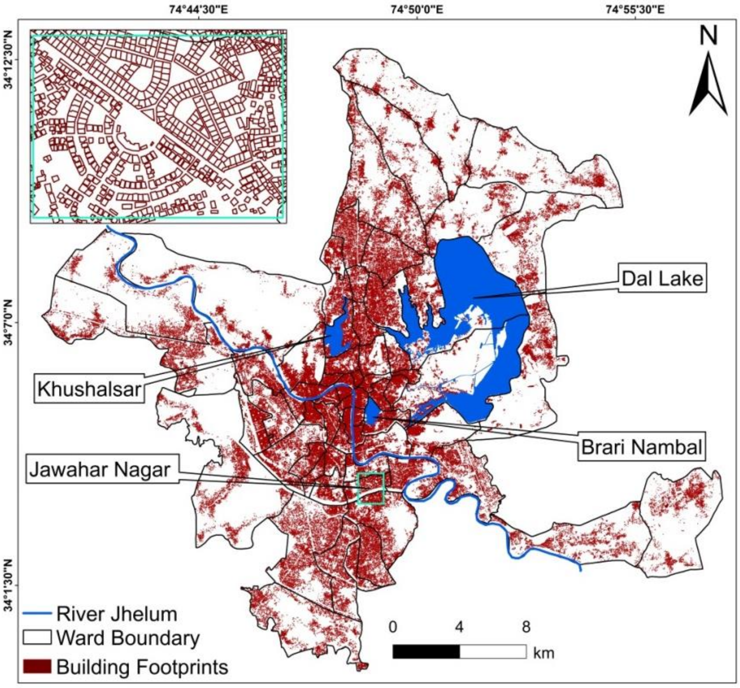


Fig. 3. Building foot print map of Srinagar city.

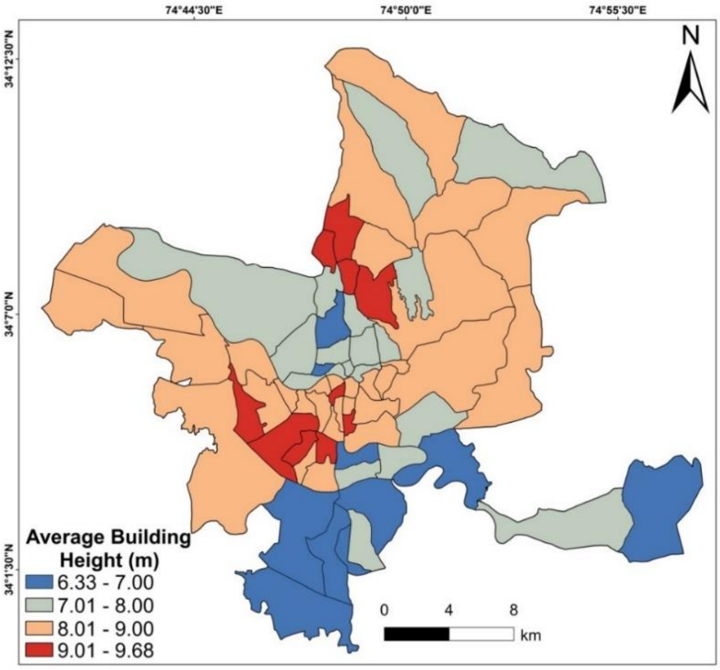


Fig. 4. Ward-wise distribution of average building height in Srinagar city.

| Ward No. | Ward Names | Irregular Buildings (%) | Pounding Possibility (%) | Masonry Buildings (%) | Building Density (per Ha) | Average Height (m) | Average Plinth Area ($m^2$) | Average Road Width (ft) | Road Density (km/k$m^2$) |
|---|---|---|---|---|---|---|---|---|---|
| A | BB Cant | 4.01 | 40.58 | 98.64 | 3.86 | 6.33 | 149.41 | 9.61 | 6.23 |
| 1 | Harwan | 4.81 | 76.71 | 96.57 | 2.82 | 8.86 | 140.19 | 8.78 | 7.55 |
| 2 | Nishat | 3.07 | 56.33 | 98.17 | 2.34 | 8.64 | 124.19 | 8.16 | 6.08 |
| 3 | Dalgate | 2.01 | 36.85 | 85.98 | 3.76 | 7.70 | 128.59 | 9.85 | 7.95 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 4 | Lalchowk | 6.50 | 81.07 | 90.06 | 4.06 | 8.24 | 141.67 | 12.14 | 11.61 |
| 5 | Rajbagh | 3.17 | 46.41 | 97.46 | 7.59 | 7.37 | 130.12 | 8.78 | 15.47 |
| 6 | Jawahar Nagar | 6.08 | 73.48 | 98.41 | 6.92 | 7.39 | 182.51 | 11.20 | 19.77 |
| 7 | Wazir Bagh | 8.76 | 85.58 | 92.29 | 6.05 | 6.64 | 163.73 | 12.02 | 13.93 |
| 8 | Mehjoor Nagar | 0.95 | 60.43 | 99.75 | 7.30 | 6.88 | 115.25 | 8.79 | 12.38 |
| 9 | Natipora | 2.21 | 59.55 | 99.48 | 9.12 | 7.00 | 138.15 | 10.12 | 19.53 |
| 10 | Chanapora | 3.25 | 72.44 | 99.61 | 8.71 | 6.79 | 121.89 | 11.33 | 23.71 |
| 11 | Bagat-I-Barzullah | 3.80 | 46.86 | 99.32 | 4.87 | 6.90 | 152.71 | 10.09 | 13.99 |
| 12 | Rawalpora | 6.03 | 53.65 | 98.66 | 5.37 | 6.92 | 161.29 | 10.88 | 17.20 |
| 13 | Sheikh Dawood Colony | 1.32 | 55.38 | 97.23 | 9.73 | 8.39 | 129.31 | 7.55 | 14.97 |
| 14 | Batamaloo | 2.95 | 84.64 | 96.97 | 11.05 | 9.41 | 158.01 | 7.94 | 19.85 |
| 15 | Aloochi Bagh | 1.88 | 69.81 | 99.36 | 6.72 | 8.15 | 130.03 | 8.78 | 14.53 |
| 16 | Magarmal Bagh | 3.48 | 74.59 | 97.15 | 11.11 | 9.33 | 120.35 | 9.07 | 18.32 |
| 17 | Nund Reshi Colony | 3.24 | 79.26 | 97.47 | 4.99 | 9.05 | 184.49 | 10.08 | 12.21 |
| 18 | Qamarwari | 0.90 | 49.97 | 96.33 | 11.43 | 8.44 | 98.93 | 8.96 | 19.24 |
| 19 | Parimpora | 2.78 | 52.64 | 96.45 | 6.66 | 8.06 | 114.43 | 8.82 | 14.53 |
| 20 | Zainakote | 3.00 | 34.94 | 95.34 | 3.16 | 8.11 | 152.05 | 9.14 | 9.46 |
| 21 | Bemina East | 3.00 | 67.03 | 94.70 | 6.19 | 8.97 | 147.59 | 12.64 | 17.17 |
| 22 | Bemina West | 2.42 | 89.56 | 96.87 | 7.45 | 9.64 | 143.21 | 13.60 | 19.60 |
| 23 | Shaheed Gunj | 3.36 | 85.64 | 97.33 | 11.00 | 8.76 | 95.20 | 12.06 | 24.37 |
| 24 | Karan Nagar | 3.81 | 72.94 | 96.78 | 11.83 | 8.31 | 125.08 | 13.57 | 26.42 |
| 25 | Chattabal | 0.83 | 69.54 | 98.18 | 18.38 | 8.30 | 100.54 | 8.08 | 26.83 |
| 26 | Syed Ali Akbar | 0.61 | 87.41 | 87.41 | 24.53 | 8.50 | 87.57 | 6.12 | 35.38 |
| 27 | Nawab Bazar | 1.12 | 77.45 | 93.01 | 19.90 | 8.19 | 97.25 | 8.60 | 33.67 |
| 28 | Islamyarbal | 0.58 | 82.50 | 96.51 | 25.96 | 9.40 | 73.68 | 7.72 | 34.46 |
| 29 | Aali Kadal | 0.63 | 84.02 | 99.81 | 29.97 | 8.64 | 81.89 | 7.70 | 39.33 |
| 30 | Ganpatyar | 1.04 | 96.27 | 98.66 | 18.58 | 9.45 | 130.66 | 6.42 | 37.36 |
| 31 | Bana Mohalla | 0.54 | 72.28 | 99.76 | 21.75 | 8.79 | 103.71 | 6.14 | 40.22 |
| 32 | Sathoo Barbarshah | 1.46 | 77.23 | 95.05 | 9.21 | 8.05 | 121.44 | 8.69 | 16.15 |
| 33 | Khankai Moulla | 1.05 | 76.08 | 98.61 | 23.95 | 8.18 | 87.06 | 7.10 | 39.79 |
| 34 | S R Gunj | 1.56 | 91.10 | 99.69 | 22.65 | 7.86 | 86.02 | 7.20 | 42.29 |
| 35 | Aqilmir Khanyar | 1.52 | 93.14 | 99.68 | 22.14 | 8.05 | 94.67 | 8.40 | 28.82 |
| 36 | Khawaja Bazar | 1.60 | 97.11 | 99.77 | 24.90 | 7.82 | 73.60 | 9.55 | 27.80 |
| 37 | Safa Kadal | 2.90 | 80.12 | 99.36 | 16.43 | 7.82 | 113.22 | 6.86 | 27.27 |
| 38 | Iddgah | 2.05 | 88.71 | 99.53 | 8.38 | 7.74 | 110.69 | 9.19 | 13.15 |
| 39 | Tarbal | 0.56 | 98.27 | 99.65 | 38.89 | 6.96 | 71.17 | 7.91 | 38.42 |
| 40 | Jogi Lankar | 2.33 | 91.62 | 99.36 | 16.93 | 8.46 | 97.27 | 7.37 | 25.51 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 41 | Zindshah Sahib | 4.37 | 97.94 | 99.07 | 23.73 | 8.40 | 95.92 | 6.17 | 29.72 |
| 42 | Hasanabad | 2.98 | 89.68 | 99.78 | 9.79 | 7.85 | 112.33 | 7.55 | 20.44 |
| 43 | Jamia Masjid | 1.58 | 99.66 | 97.27 | 46.35 | 7.77 | 61.48 | 7.51 | 40.53 |
| 44 | Makhdoom Sahib | 2.06 | 86.04 | 99.04 | 8.60 | 7.78 | 104.74 | 8.73 | 19.49 |
| 45 | Kawdara | 1.16 | 85.52 | 99.23 | 16.67 | 7.02 | 105.54 | 7.74 | 26.03 |
| 46 | Zadibal | 0.87 | 42.34 | 99.69 | 7.20 | 6.96 | 108.13 | 10.11 | 12.63 |
| 47 | Madin Sahib | 2.57 | 70.85 | 99.59 | 13.82 | 7.46 | 103.58 | 11.75 | 22.59 |
| 48 | Nowshera | 3.86 | 65.95 | 99.56 | 8.59 | 9.56 | 145.24 | 8.29 | 20.11 |
| 49 | Zoonimar | 2.28 | 41.22 | 99.66 | 7.56 | 7.52 | 126.14 | 8.40 | 17.12 |
| 50 | Lal Bazar | 5.45 | 93.81 | 99.30 | 9.43 | 9.68 | 147.35 | 10.07 | 16.22 |
| 51 | Umer Colony | 6.65 | 82.78 | 99.77 | 7.86 | 8.54 | 175.91 | 9.32 | 15.49 |
| 52 | Soura | 3.24 | 79.14 | 98.01 | 9.39 | 9.62 | 105.28 | 9.89 | 17.59 |
| 53 | Buchpora | 2.43 | 47.26 | 99.62 | 8.34 | 9.55 | 147.94 | 9.70 | 23.36 |
| 54 | Ahmad Nagar | 5.24 | 79.42 | 99.58 | 4.04 | 8.77 | 167.24 | 8.69 | 9.73 |
| 55 | Zakora | 3.29 | 63.88 | 99.67 | 2.02 | 7.38 | 154.04 | 8.98 | 5.92 |
| 56 | Hazratbal | 6.15 | 83.01 | 96.86 | 4.50 | 8.01 | 158.51 | 11.41 | 11.89 |
| 57 | Tailbal | 1.19 | 53.49 | 99.25 | 2.86 | 8.54 | 106.30 | 8.29 | 7.44 |
| 58 | Bud Dal | 0.73 | 58.98 | 98.74 | 0.49 | 8.86 | 82.14 | 6.14 | 1.35 |
| 59 | Locut Dal | 1.02 | 86.53 | 87.24 | 1.80 | 8.76 | 72.43 | 6.75 | 1.79 |
| 60 | New Theed | 0.86 | 46.17 | 99.08 | 2.03 | 7.84 | 108.99 | 7.89 | 5.63 |
| 61 | Alasteng | 2.42 | 71.43 | 99.25 | 1.74 | 8.02 | 126.34 | 8.17 | 3.93 |
| 62 | Palapora | 0.14 | 28.23 | 99.46 | 1.33 | 7.43 | 83.49 | 8.16 | 2.97 |
| 63 | Maloora | 0.75 | 24.50 | 98.09 | 1.56 | 8.40 | 146.59 | 9.52 | 5.56 |
| 64 | Lawaypora | 1.49 | 39.23 | 99.03 | 1.64 | 8.51 | 143.06 | 9.79 | 4.91 |
| 65 | Khumani Chowk | 1.00 | 90.18 | 99.57 | 1.79 | 8.26 | 112.34 | 7.74 | 4.85 |
| 66 | Humhama | 2.60 | 22.50 | 99.36 | 3.27 | 6.83 | 131.51 | 10.45 | 9.42 |
| 67 | Pantha Chowk | 2.63 | 18.02 | 99.21 | 2.77 | 7.01 | 105.17 | 9.51 | 5.91 |
| 68 | Khonmoh | 1.70 | 16.59 | 99.37 | 2.14 | 6.99 | 89.06 | 9.54 | 5.11 |

Table 6: Ward-wise built-up parameters used for vulnerability assessment of the Srinagar city.

**4.1.2 Masonry Building:** The type of construction material used in building construction determines the earthquake vulnerability of the built environment (Lang et al., 2018). The masonry buildings have an extremely poor seismic resistence (Alam and Haque, 2018). The strength of the buildings is mostly determined by the material and the type of mortar used for constructing walls (Lang et al., 2018). Table 6 and Fig. 5 show the ward-wise distribution of masonry buildings in Srinagar. The proportion of masonry structures in the city varies between 82% to 99.8%. Masonry buildings account for about 98% of the city's total buildings, making it highly vulnerable to earthquakes. Ward number 29 (Aali Kadal) has the highest number of masonry buildings (99.8%), whereas the wards 3, 26, and 59 (Dalgate, Syed Ali Akbar, and Jawahar Nagar, respectively) have about 15% non-masonry buildings.

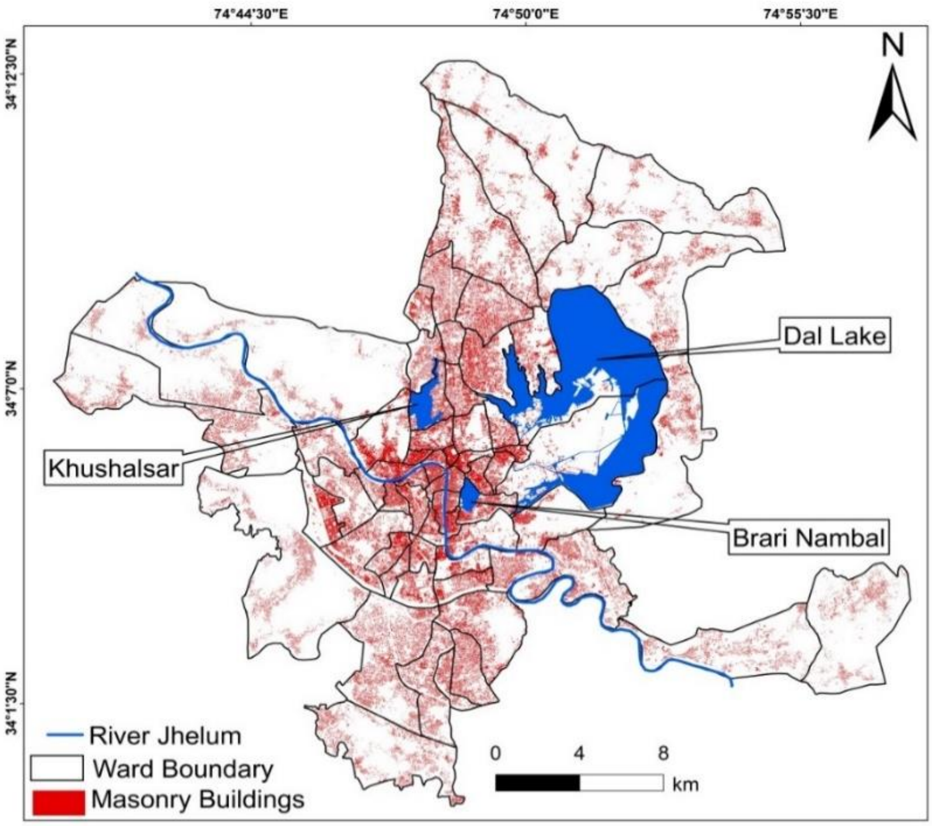


Fig. 5. Ward-wise distribution of Masonry buildings in the city.

**4.1.3 Pounding possibility:** From the analysis of the estimated separation distance and height of the adjacent buildings, it was found that ~ 65% of buildings in the city has a high chance of pounding with neighbouring buildings, at least on one side, because the ideal offset between the buildings has not been maintained due to the haphazard building construction practices, particularly in the downtown wards of the city (Fig. 6). Table 6 provides information about the ward-by-ward pounding probability of the city. It is therefore evident from the analysis that the downtown wards of the city have the highest risk of pounding because the buildings are densely packed in most of the wards. Comparably, the uptown wards show a lower pounding possibility due to the sufficient gaps between the buildings.

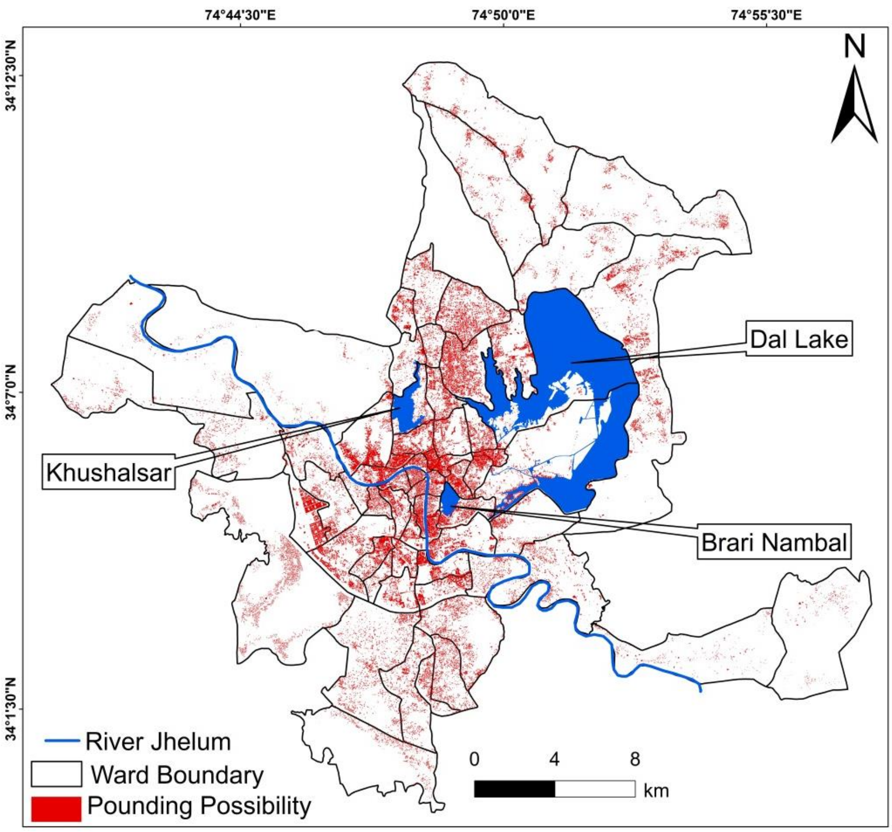


Fig. 6. Ward-wise distribution of building pounding possibility in the city.

**4.1.4 Building Geometry:** Modern buildings in the city are constructed with irregular shapes and frequent offsets for aesthetic building layout and structural design. The building irregularities, either planar or vertical, make structures vulnerable to seismic loading (Mazza, 2014; Ahirwal et al., 2019). As a result, while assessing the earthquake vulnerability of built environment, building irregularity is an important factor to consider. It was found from the analysis of the data provided in Table 6 and Figure 7 that ~3% of the buildings in the city have irregular shapes. A fewer number of irregular buildings are found in the municipal ward number 62 i.e., Palapora (n=8, 0.13%), whereas the largest number of irregular buildings are present in ward number 7 i.e., Wazir Bagh (n=158, 8.76%), increasing the ward's vulnerability in the city. The typical residential buildings usually have a conventional, regular, and rectangular shape with four sides and an average plinth area of 120 $m^2$ (Table 6). Some of the schools, colleges, government offices, hospitals, and commercial complexes have irregular architectural shapes, such as the shape of the letters "O," "L," "U," "T," and "H" making them more vulnerable to earthquakes. Furthermore, most schools, colleges, and hospitals are usually made up of multiple smaller buildings with regular shapes that are close to each other, increasing the risk of pounding and making these building complexes more vulnerable to earthquake damage.

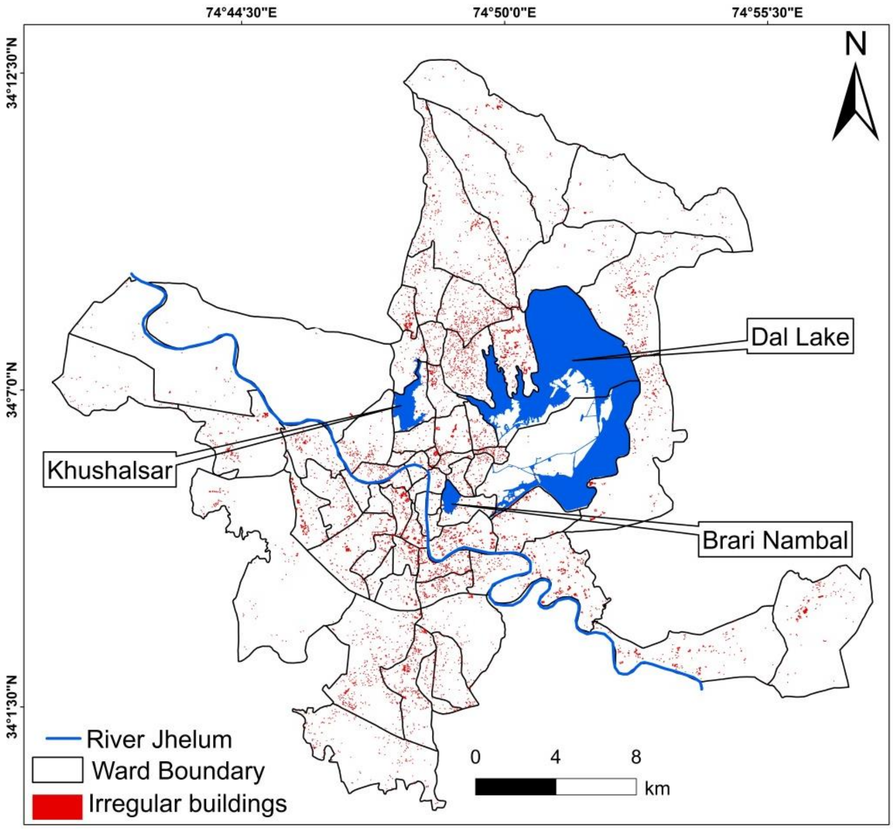


Fig. 7. Ward-wise distribution of irregular shaped buildings in the city.

**4.1.5 Building Density:** The average building density of Srinagar is ten buildings per hectare (including residential and commercial buildings). However, the building density in 17 wards of the downtown city is more than 15 buildings per hectare (Table 6; Fig. 8). The highest building density of 46 buildings per hectare was observed in municipal ward number 43 (Jamia Masjid), followed by ward 39 (Tarabal) and ward 29 (Aali Kadal), which have a building density of 39 and 30, respectively. Ward number 58 (Bud Dal) has the lowest building density, with only one building per hectare. Srinagar is one of the largest urban centres in the Himalayan region and is experiencing considerably high rates of population growth and built-up area expansion, leading to the extension of urban areas and the merging of the citys' fringe areas into the main city (Bhat et al., 2012). The outer peripheral wards have mostly low building density, and these are the developing areas proposed under the Srinagar Master Plan 2035. Knowledge about the building packing within the urban city centre is crucial information for the earthquake vulnerability assessment. The current practise of constructing buildings with insufficient space between them increases the congestion and building density of cities (Bahadori et al., 2017). The areas with high building density (Table 6) are more vulnerable to earthquake damage than those with the low building density (Shadmaan and Islam, 2021). The high building density also leads to a small separation distance between buildings and a reduction in the open space area. This reduces the amount of useful space available for evacuation and shelters during post-earthquake rescue operations. In order to decrease the loss and damage to human life and infrastructure caused by earthquakes, it is important to regulate building density and ensure the reinforcement of old structures (Jena et al., 2020). Good planning, a lower building density, and evenly spaced buildings reduces seismic vulnerability of a city (Aghataher et al., 2018).

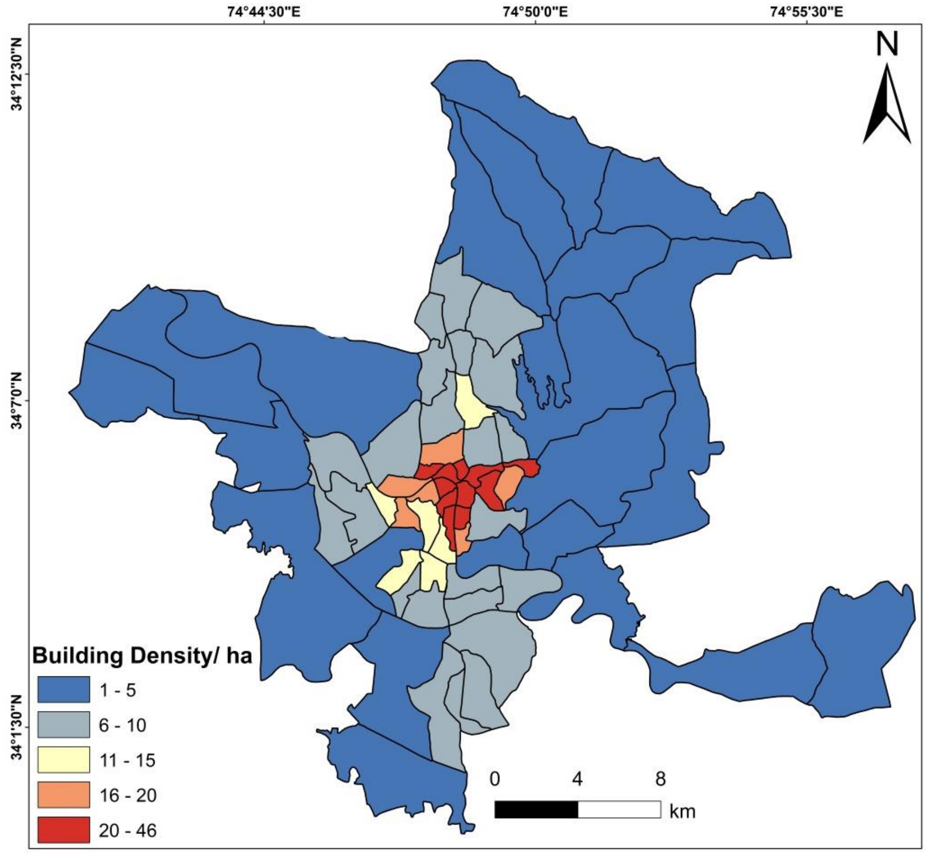


Fig. 8. Ward-wise distribution of building density in the city**.**

**4.1.6 Road Network:** Despite the high population and building density in the city, the road network connectivity in the city is good, with a total road length of 2246 kilometers. In the eventuality of an earthquake, the effectiveness of a urban road network decreases significantly due to road damage caused by collapsed buildings and blockages (Bono and Gutiérrez, 2011; Zanini et al., 2017). On the basis of their width, the roads in the city were classified into three categories: <8 ft, 8 to 16 ft, and > 16 ft (Fig. 9). The roads or streets with a width of less than 8 feet are considered possible blockade sites. From the analysis of the data provided in Table 6, it is evident that wards 26 (Syed Ali Akbar), 31 (Bana Mohalla), 58 (Bud Dal), 41 (Zind Shah Sahib), 30 (Ganpatyar), and 37 (Safa Kadal) have the smallest average road width of less than 7 ft., despite having high road densities except for ward 58 (Bud Dal), which has a road density of 1.35 km $km^{-2}$ due to the fact that most of the ward is covered by waters (Dal Lake). Ward 31 has a road density of 40.22 km $km^{-2}$, ward 26 has a road density of 35.38 km $km^{-2}$, ward 30 has a road density of 37.36 km $km^{-2}$, ward 41 has a road density of 29.72 km $km^{-2}$, and ward 37 has a road density of 27.27 km $km^{-2}$. Wards 24 (KaranNagar) and 22 (Bemina West) have the largest average road width of 13.58 ft and a road density of 26.42 and 19.60 km $km^{-2}$, respectively (Table 6). It is worth noting that the road network in the city is relatively denser in the downtown city and as a result, the roads being narrower there make these places in the city more vulnerable to earthquake damage and would possibly impede the post-earthquake evacuation and rehabilitation operations. The road network in the uptown wards towards the periphery of the city, on the other hand, is less dense. The roads being relatively wider in the outer wards make them more suitable for evacuation and would facilitate easy movement of traffic and relief during an earthquake compared to the inner city wards.

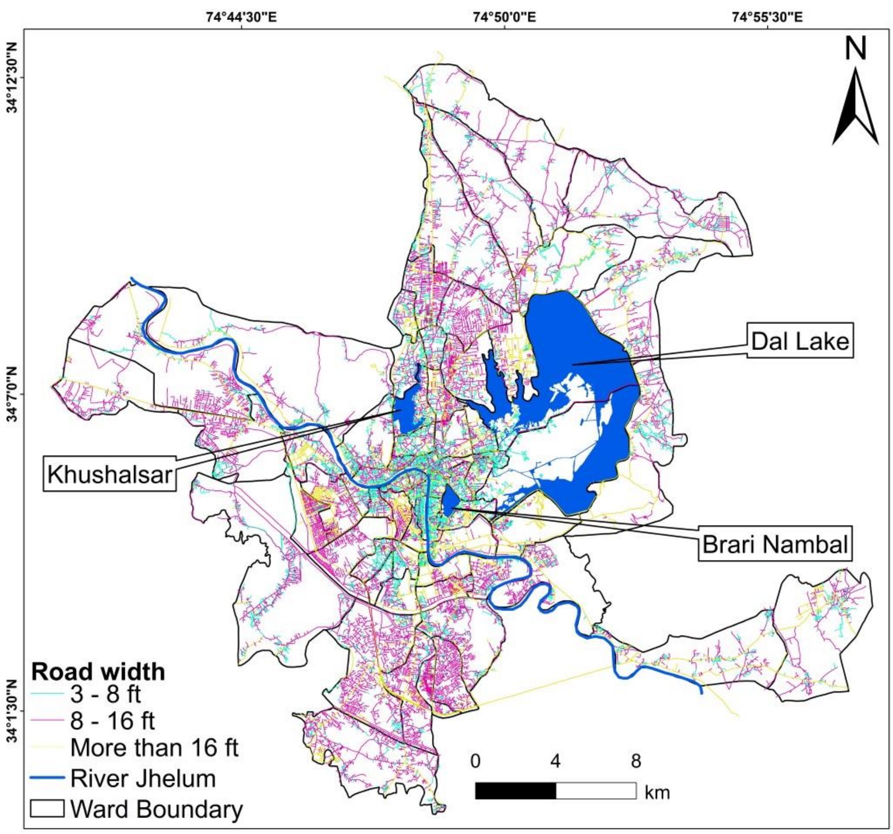


Fig. 9. Ward-wise road network in the city.

## 4.2 Earthquake vulnerability Analysis:

Earthquake events are usually characterised by high exposure to social and economic consequences that can be severe (Oliveira, 2003) and therefore, earthquake vulnerability assessment aids pre-earthquake planning and post-earthquake emergency operations by providing vital information that informs earthquake risk reduction measures (Saputra et al., 2017). The GIS-based analysis of the earthquake vulnerability of the built environment in Srinagar, using the coupled model of AHP and TOPSIS was carried out to highlight the ward-wise vulnerability in the event of an earthquake. Because all of the structural vulnerability parameters have different importance and impacts, the structural vulnerability of the city cannot be achieved by relying on a single parameter (Panahi et al., 2014). Therefore, six important parameters were considered in this study to produce a robust earthquake vulnerability assessment of the city. This study classified 69 municipal wards of the city into five earthquake vulnerable classes: very high, high, moderate, low, and very low earthquake vulnerability. The results showed that 9 municipal wards in the city are very highly vulnerable, 14 wards are highly vulnerable, 19 wards are moderately vulnerable, 17 wards are low vulnerable, and 10 wards fall in the very low vulnerable category (Fig. 10). The vulnerability map reveals that wards categorised under the same vulnerability class are contagious to one another, indicating a clear pattern of earthquake vulnerability in Srinagar. The city centre, which also happens to be the site of ancient urban settlements including several heritage buildings and shrines, has a very high level of structural vulnerability, and as we move towards the outer peripheral wards, the vulnerability changes from moderate to low. The probability of masonry buildings collapsing in the event of an earthquake is higher (Bhosale et al., 2018), and the city has a large percentage of such buildings, making it more vulnerable to earthquakes. Buildings with regular geometry, uniform mass distribution and rigidity in plan and elevation are more resistant to earthquakes than buildings with irregular geometry and hence variable mass distribution (Stein, 1982). As the findings of this study show, a good number of buildings in a few wards of the city have irregular geometry, making them more vulnerable to earthquakes. The high building density, maximal pounding potential and narrower road network near the city centre make these wards particularly vulnerable when compared to the other wards located in the periphery of the city.

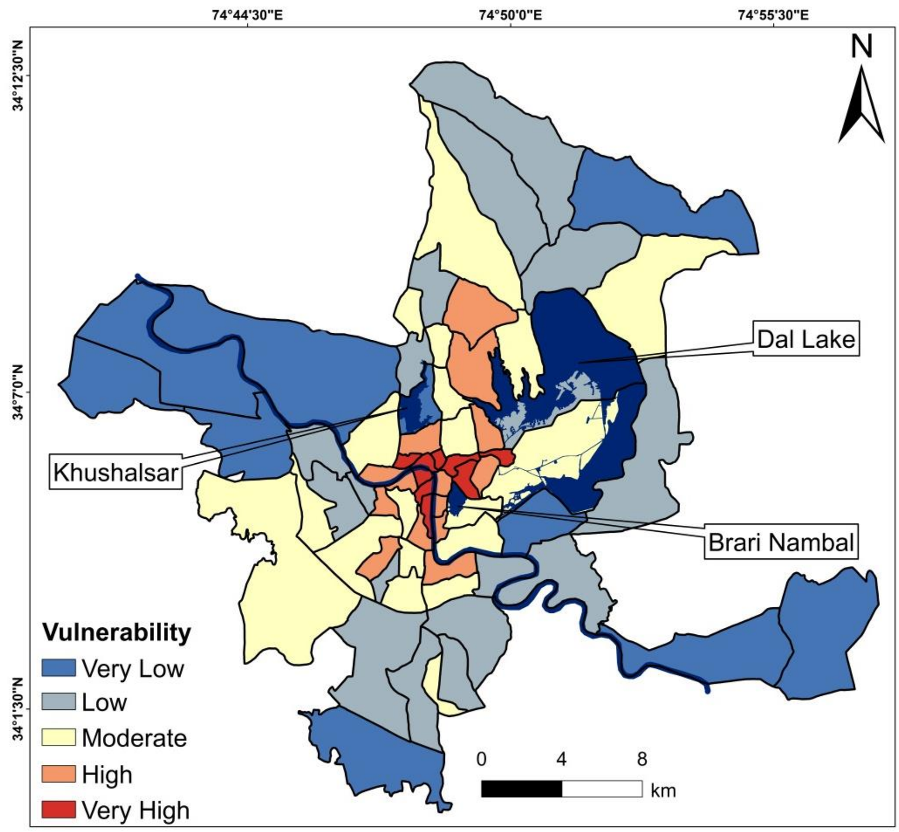


Fig. 10. Structural vulnerability of Srinagar city.

Since majority of the built-up in the city is non-engineered, highly dense, irregular and masonry based, the results indicate that infrastructure development of any type in the very high and high vulnerable zones of the city must adhere to the prescribed building codes and bylaws to achieve the desired resilience to earthquakes. It is pertinent to mention here that wetlands and marshlands were masked in this study and hence not used in the analysis. However, the continued construction of both government and residential buildings in the wetlands and marshy areas of Srinagar city, particularly towards the south of the city, is worrisome because it makes these wards in the city more vulnerable to earthquake damage.

The socio-economic conditions of an area play an important role in determining the vulnerability of an area to earthquake hazards. Srinagar has witnessed a population explosion, with the population increasing from 0.25 million in 1961 to 1.5 million in 2011. The city also has a high proportion of female and child residents (59%) and a population density of 4000 people per square kilometer. Migration from the rural areas and population growth are the primary drivers of this enhanced population expansion in the city (Nengroo et al., 2018). The city has been under pressure to expand its built-up area in order to cater to the population boom, which has also led to excessive resource depletion, widening wealth and poverty gaps, and deteriorated the environmental and socioeconomic conditions (Mitsovaa et al., 2010; Kamat and Mahasur, 1997). With the mounting demand for new housing in the city, the quality and condition of houses have received negligible attention. These concerns about accelerated population progression, along with high urbanization, have increased the socio-economic vulnerability of the built environment in Srinagar to earthquakes. Furthermore, in the event of a major earthquake, the lack of critical amenities such as trauma hospitals, shelters, etc., as well as poor road conditions in several wards of Srinagar city, could result in significant loss of life and property.

Earthquake vulnerability assessment of the built-up environment in Srinagar, if followed by retrofitting, restoration, and rehabilitation initiatives in the most vulnerable wards of the city, will help to reduce the damage during earthquakes. This study can guide city planners in choosing safe, and low-density areas for housing and infrastructure development and even help them to evaluate the suitability of the new infrastructural development as envisaged under the 2035 Master Plan. The study has identified densely populated areas that are particularly vulnerable to earthquakes and where no further infrastructural development should be permitted other than the development of open and green spaces. In Very High and High earthquake vulnerable zones, provision for emergency services such as firefighters, shelters, specialized medical facilities and so on must be made to minimize the loss of life and property in the event of an earthquake. Pre- and post-earthquake disaster mitigation and capacity-building initiatives are critical for transforming Srinagar into a safe, sustainable, and earthquake-resistant city. The challenges surrounding the earthquake threat to Srinagar and the city's preparedness thereof necessitate the adoption of new scientific and innovative urban development planning and inexpensive measures aimed at inculcating a culture of earthquake consciousness among its citizenry. The establishment of a culture of earthquake-resistant and safe construction will undoubtedly make the city safer and reduce the adverse consequences of earthquakes.

## 5. Conclusions

Understanding the structural vulnerability of a city situated in a high earthquake-prone zone at a ward scale is critical for deciding the appropriate urban planning and development strategies to build and promote a safe, inclusive, sustainable, and earthquake-resilient living environment as contemplated under SDG 11. The current study, which is the first of its kind for Srinagar, reveals the micro-level structural vulnerability of the built-up environment in the city. The vulnerability zonation map generated for the city reveals that around 32% of the city has very low vulnerability, which covers 10 municipality wards. The low earthquake vulnerability zone encompasses around 33% of the city comprising of 17 wards; the moderate vulnerability zone covers around 28% of the city comprising of 19 wards; the high vulnerability zone covers 5.7 % of the city and 14 wards; and the very high vulnerability zone covers 1.28 % of the city and 9 municipality wards. Overall, about 7% of the city, covering 1/3$^{rd}$ of the city municipal wards (n=23) are falling into either high or very high earthquake vulnerability zones. The downtown wards in the city's central area are the most vulnerable to earthquakes due to the high population density, high pounding potential, high building density, and narrower streets with little or no open and green areas. Reducing infrastructure development in these neighbourhoods by relocating residents and services to the less congested areas is an intervention that must be undertaken. Since green and open spaces are used as evacuation places, it is strongly advised that new construction in these areas, as well as the development of these spaces, must be avoided. The study underlines the importance of developing emergency action plans that outline how to prevent causalities by allowing for the rapid, selective and effective utilisation of resources as well as retrofitting schemes and capacity-building programs to safeguard human life and the economy in the city. The current study is in accordance with the 2030 Agenda for SDGs, which recognises and reiterates the urgent need to lower the risk of disasters. The study will help to reduce the exposure and vulnerability of people to disasters and build resilient infrastructure. The findings of this study will support sensible urban planning, which calls for the construction of resilient infrastructure to reduce vulnerability to natural disasters, as well as sustainable development in line with SDG 11 and SDG 9, which demand manageable population and building densities, user-friendly public spaces, and mixed-use urban development. These findings are consistent with the posteriori knowledge of the study area’s vulnerability and will help the urban planners and policymakers in developing future land use planning and strategies. The socio-economic vulnerability of the city was not analysed in this study, but it would be included in future research to produce a more accurate and holistic assessment of the earthquake vulnerability to better inform policymaking for developing earthquake risk reduction strategies in the city.

**Author contributions:**

**Shakil Ahmad Romshoo:** Conceptualization, Methodology, Supervision. Manuscript preparation with inputs from co-authors**, Midhat Fayaz:** Data generation, Methodology, Formal analysis, Field surveys, Investigation, Manuscript editing **Irfan Rashid:** Review and Editing, **Rakesh Chandra**: Investigation, Review and Editing.

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