Seismic Risk Assessment of Built Environment in the Himalayan Foothill City of Dehradun, Uttarakhand

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Abstract: Dehradun is situated in tectonically active Himalayan region and is hence prone to earthquakes. The present study attempts to analyse the seismic vulnerability of single and double storey structures in Dehradun city with respect to seismic micro-zonation. The proposed land use as per Dehradun Masterplan-2041 was also examined with reference to National Earthquake Hazards Reduction Program (NEHRP) for seismic regulating provisions. High resolution remote sensing images of years 2007 and 2022 were classified using object based image analysis (OBIA), for built-up area extraction. OBIA uses geographic objects as basic units for classification and hence reduces the within class variation and salt-and-pepper effects. Using the classified images, ward wise urban growth for the period 2007-2021 was analysed with respect to the seismic micro-zonation map. According to the study's findings, 10% of urban expansion has occurred in spectral acceleration zones that are vulnerable to double-storey buildings, while 38% of urban expansion occurred in spectral acceleration zones that are vulnerable to single-storey buildings. Additionally, the intended land use as per Dehradun Masterplan-2041, is incongruous in areas with higher spectral acceleration zones since it comprises structures with higher occupancy and the amenities required during post-earthquake rehabilitation. On the other hand, the open spaces are more appropriate in these locations, which will lessen susceptibility as the influence of seismic forces can be sufficiently attenuated. The present study, thus highlights the significance of including seismic risk information in urban planning processes in order to ensure resilient cities.

Key words: Geospatial techniques, Urban growth, Spectral acceleration, Seismic micro-zonation, Vulnerability

1. Introduction

Foothill cities in Uttarakhand have grown rapidly in recent decades as they provide better economic prospects and infrastructural services compared to upland urban settlements (Kumar et al. 2019). However, this unregulated growth of cities is characterized by flawed construction practices, lack of adherence to building bylaws, violations of town planning norms and densely populated sub-standard building stock (Joshi et al. 2022). Uttarakhand state falls in Zone IV (High Risk) and Zone V (Very High Risk) of the Bureau of Indian Standards' earthquake zonation map (Indian Standard, 2002), thus making it vulnerable to seismic hazards. The extensive damage to human life and property in Uttarakhand caused by the Uttarkashi and Chamoli earthquakes, underlined the ramifications of failing to incorporate seismic vulnerability in Master Plan formulation (Pandey et al. 2001). Additionally, it is more challenging to reduce seismic vulnerability, in existing urban areas where already concentration of built-up and people has taken place. In these scenarios, to reduce vulnerabilities and ensure sustainable development, policy orientations and programmatic strategies need to be adapted (Jain and Bazaz 2016; Mihalic et al. 2011; McClean 2010; Bull-Kamanga et al. 2003). Integrating these strategies in a city master plan enables optimized land use and infrastructure planning which helps in lowering level of seismic vulnerability (National Disaster Management Plan 2016).

Uttarakhand is experiencing a rapid pace of urban growth, in 2011 the rate of urbanization in the state was 30% compared to the national average of 31% (Census of India 2011). However, this urban growth pattern has a lot of disparity, with the growth being concentrated in the four (04) foot hill districts of Dehradun, Haridwar, Nainital and Udham Singh Nagar while the rest of the nine (09) districts have an urbanization rate of less than 20%. Among the four foothill districts Dehradun has the highest urbanization rate of 56% (Maithani et al. 2019). This has raised concerns regarding the effects of urban expansion on the environment and the susceptibility of cities to various risks. Seismic events are one of these hazards that pose a significant threat to urban areas, causing fatalities, infrastructure damage, and economic losses (Li et al. 2023; Cariolet et al. 2019). Due to the concentration of people and infrastructure in urban areas compared to the rural areas, the damages brought on by hazards are more extensive in urban areas. Developing countries prioritize rehabilitation over the risk mitigation and preparedness due to the lack of resources to devote to planning and building resilience (Hudec et al. 2018).

Dehradun city is located at the Himalayan foothills, in the fertile Doon valley of Uttarakhand state India. Dehradun is the administrative centre and interim capital of Uttarakhand state. The city is nestled between Song river in the east, Tons river in the west, Himalaya range in north and Siwalik range in the south. Dehradun has witnessed an increase of 35% in its population during the decade 2001-2011 (Census of India 2001 and 2011). This rapid unplanned development of Dehradun has led to high concentration of people and associated infrastructure in the city (Maithani 2020).

There are a number of gaps that exists in the planning process and decision, where the risk exposure of any location is completely neglected, and decisions are made based on the political economy (Joshi et al. 2022). The presence of these gaps leads to a preference for rescue and response actions instead of prioritizing preparedness (Leistikow, et al. 2020). Rehman et al. (2023) attempted to assess the seismic preparedness of Dhaka city based on socio-economic datasets. A vulnerability zonation of Tabriz city, Iran using environmental, social, economic and physical indicators was carried out by Alizadeh et al. (2021). Serre and Heinzlef (2018) developed an urban resilience index based on social, economic and technical indicators for city of Avignon, France. The indices were calculated at the census tract level, however the variables and their selection process was not explicitly defined. Cariolet et al. (2019) analysed the issues and problems in mapping of urban resilience to disasters at city level. They concluded that resilience being context dependant, variables and indicators applicable at one city could not be directly translated to other cities, thus making the approach to be analytical in nature. Parizi et al. (2022) carried out an urban seismic vulnerability in Kerman city of Iran using urban physical infrastructure and multi criteria analysis. The authors identified four main elements of physical resilience viz., building density, aspect ratio, robustness of building and street width, out of given set of twenty indicators.

Additionally, it is more challenging to reduce exposure, particularly in urban areas where already existing concentration of people and developments cannot be reduced (Sharifi, 2019). In these scenarios, policy orientations and programmatic methods can be adapted to reduce the vulnerabilities that could help to accomplish risk reduction and sustainable development (Jain & Bashir Bazaz, 2016).

However most of the studies reported concentrated on the physical infrastructure and socio economic aspects as factors for determining the urban risk/vulnerability. Risk assessment of existing and proposed urban structures/ land uses with reference to seismic microzonation has not been reported to the best of our knowledge. In this context the present study proposes to analyse the seismic vulnerability of the present and future urban areas (as envisaged in the Dehradun Master Plan-2041) with respect to seismic microzonation. The major research questions that will be addressed in present study are (a) What is the present spatial distribution of building vulnerability within the study area (b) What is the extent of seismic vulnerability of future proposed land uses as per the Dehradun Master Plan-2041.

Hence, the present study aims to identify spatial patterns and trends in urban growth with respect to seismic hazards. This will serve as an input for future urban planning processes and making the urban areas more resilient to seismic hazards.

2. Study Area

The present study is carried out in Dehradun municipal area (DMA) which has a longitudinal extent of $30^{0}15$'N to $30^{0}25$'N and a latitudinal extent of $78^{0}00$'E to $78^{0}15$'E. Dehradun city is situated in the large intermontane depression known as Doon valley within the Siwalik foreland basin of the Garhwal Himalaya (Figure 1). It is bounded by the main boundary thrust in the north, Mohand Thrust in the southern margin, east by the Ganga tear fault and west by the Yamuna tear fault. Dehradun city is located in the Zone IV which is the second highest category on the seismic zonation map of India. Doon valley is primarily underlain by the piedmont fan deposits, locally often referred to as Doon gravels, which overlay the Siwalik rocks. Doon gravels consist of gravel beds which becomes coarser with the depth, with occasional clay lenses and layers. In the northern part of Dehradun city, the Doon gravels are absent and the Siwalik rocks are exposed, where as in the south, the gravel thickness increases. The ward map of DMA along with the respective ward numbers is shown in figure 2.

3. Data base and methodology

3.1 *Remote sensing data*:

For analysing the built-up growth pattern in DMA, land cover maps depicting built-up (i.e., land covered by buildings and other impermeable materials) and non-built-up (i.e., bare soil, agricultural, and vacant land) areas in year 2007 and 2022 were generated, by classifying remote sensing images acquired by multispectral sensors on board IKONOS and PlanetScope Dove satellites. Object based image analysis (OBIA) classification approach was used for classifying the images. OBIA uses geographic objects as basic units for classification and hence reduces within class variation and salt-and-pepper effects. It classifies images based on the properties of individual objects within the image instead of each pixel individually. The image is segmented into objects that share similar spectral, spatial, and contextual attributes with minimum heterogeneity. The heterogeneity threshold is defined using a scale parameter which is a heuristic process. In present study the scale factor was kept at 10 as the building were delineated accurately at this scale factor. A lesser scale factor led to fragmentation of the buildings and a larger scale factor resulted in loss of building details due to aggregation (Li et al. 2014). Since the objective of the study was to analyse the built-up growth, the land cover was categorized into the binary classes, depicting built and non-built areas. The binary maps were further used for analysing the expansion of built-up areas over time, thus providing valuable insights into urban development patterns and trends. The accuracy of the classified images of year 2007 and 2022 was assessed using 150 points generated using stratified random sampling. The sample points were visually inspected, and the ground truth information was compared to the corresponding land cover class in the classified images. The kappa coefficient was found to be 0.9 and 0.92 for land cover maps of year 2007 and 2022, respectively. Since in acquired satellite datasets, the northernmost part of ward number 1 was missing (Figure 2), hence built-up growth analysis could not be carried out for the missing area. While the proposed land use as per the master plan were analysed for entire DMA.

3.2 *Seismic micro-zonation of Dehradun city*:

The spectral acceleration map of Dehradun used in present study were referred from the research article 'Seismic micro zonation of Dehradun City using geophysical and geotechnical characteristics in the upper 30 m of soil column' (Mahajan et al., 2007). *Spectral acceleration (S_a)* is a fundamental parameter used in earthquake engineering to quantify the intensity of ground shaking at different frequencies during an earthquake (Figure 3). It measures the acceleration response of a specific structure or site to seismic waves across a range of frequencies, in units of gravity (g). Spectral acceleration represents the maximum acceleration that a ground motion will cause in a linear oscillator with a specified natural period & damping level (Baker and Cornell 2006; Sundararajan and Seshunarayana 2018).

3.3 *Proposed land use map of Dehradun-2041*:
The proposed future land use for the DMA was taken from the Dehradun Master Plan-2041 **(**Town and Country Planning Department 2023) prepared by Town & Country Planning Department**,** Uttarakhand (Figure 3).

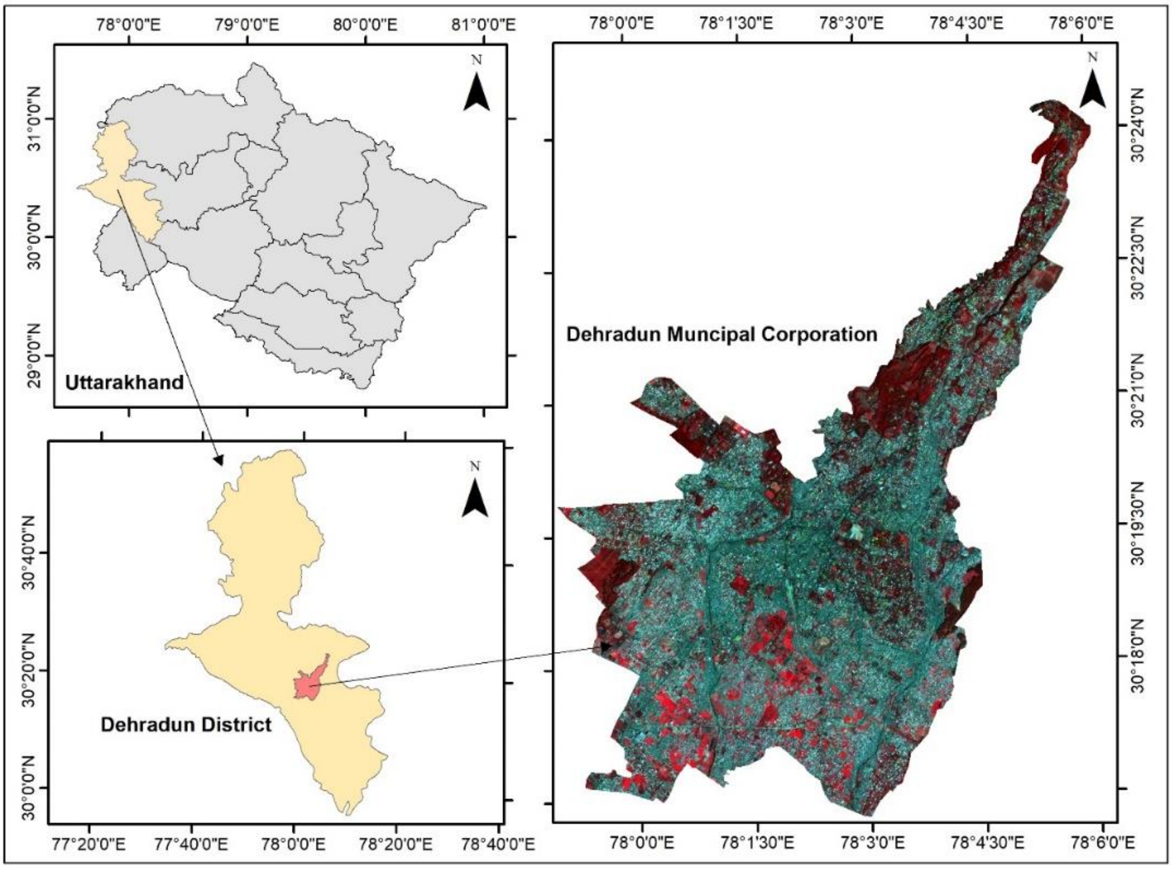

Figure 1. Location map of Dehradun Municipal Area

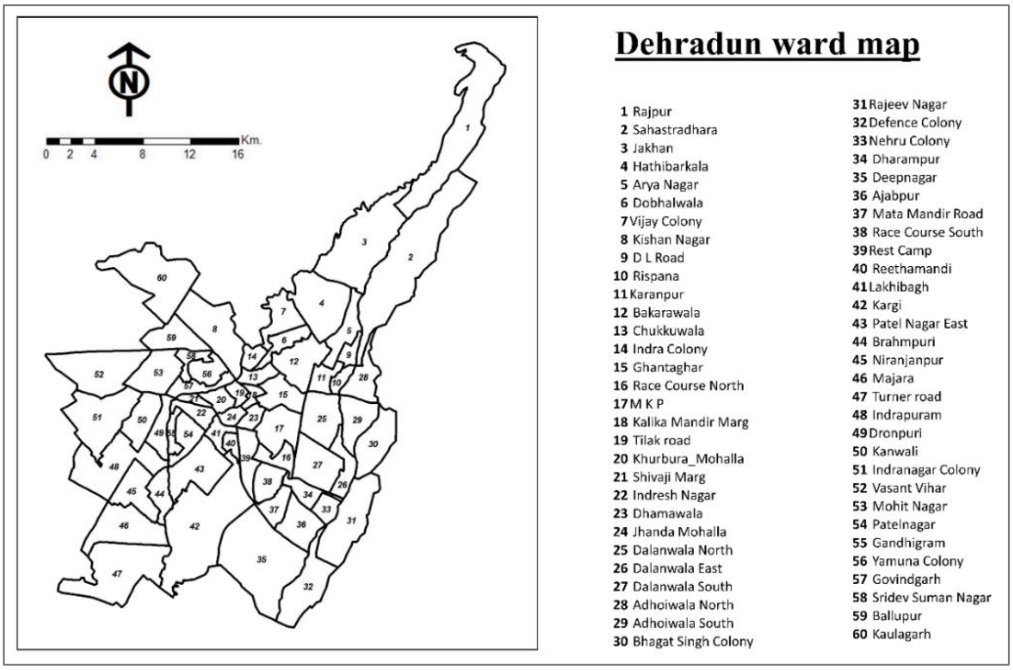

Figure 2. Ward map of Dehradun municipal area along with respective ward numbers

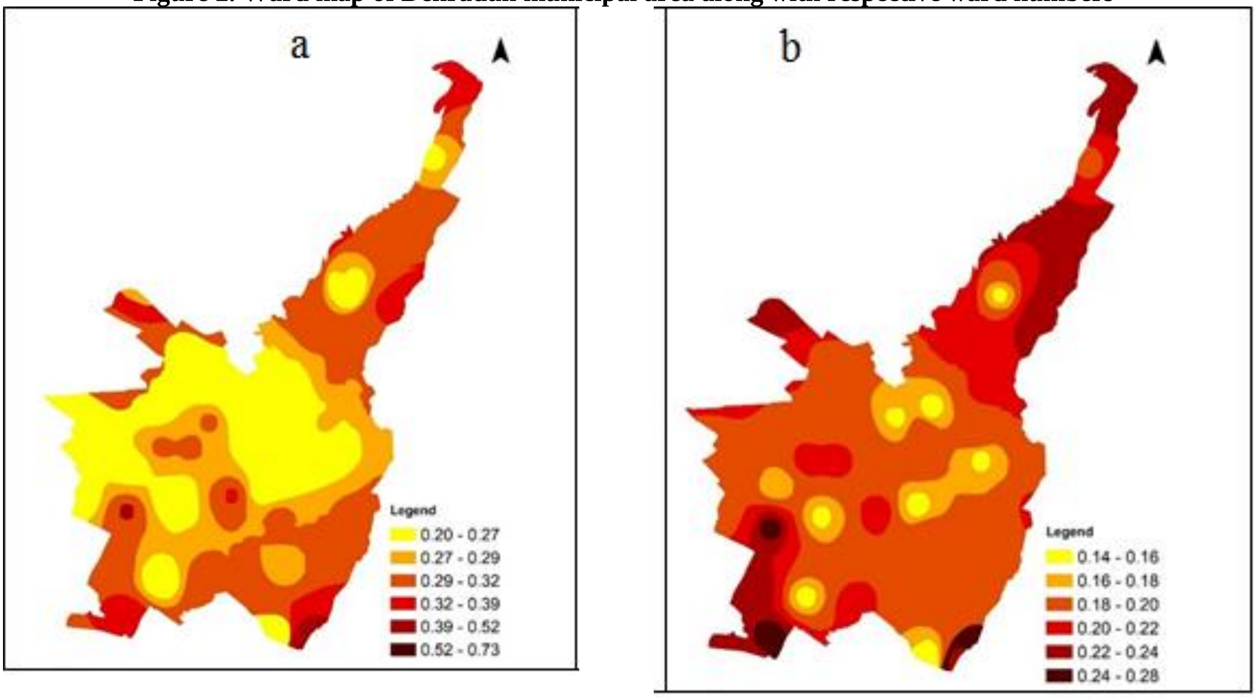

Figure 3. Spectral acceleration in units of "*g*" (a) Two storey (5 Hz) and (b) Single storey (10 Hz) structure

3.4 Methodology

The spatio-temporal analysis of built-up growth in DMA was conducted at an interval of 15 years using remote sensing derived built-up/ non built-up maps of year 2007 and 2022. The methodology followed in present study can broadly be defined as follows,

3.4.1 Ward-wise spatio-temporal analysis of built-up area:

Percentage built-up growth (Equation 1) and density was analysed at ward level for year 2007 and 2022. By analysing ward-wise built-up growth, a comprehensive understanding of urban development patterns and trends

within wards was achieved, shedding light on potential shifts in land use and population dynamics.
Percentage built-up growth = $((T_2 - T_1) / T_1) * 100$. (1)

3.4.2 Seismic vulnerability of ward-wise built-up area:
At the ward level, built-up distribution across various spectral acceleration zones was analysed to identify vulnerable locations. Additionally, the seismic micro-zonation map was analysed in relation to the proposed land use of DMA as per the Dehradun Master Plan 2041, and necessary policy suggestions made in accordance with the National Earthquake Hazards Reduction Program (NEHRP, 2003).

4. Results

4.1 *Ward wise analysis of built-up area*

The amount of urban development in each ward was measured based on built-up area density, which reflects how much of the available land area is taken up by the built environment in each ward. According to figure 4, the DMA's centre portion (wards 9, 10, 14, 18, 21, 23, 24, 57, 58) had the highest built-up density in 2007. In the year 2022, the southern and southeast portions of the DMA (wards 13, 22, 34, and 38) and the central portion of the DMA (wards 9, 10, 14, 18, 21, 23, 24, 57, and 58) experienced substantial increase in population density. In contrast, the wards in DMA's northern part saw far less growth in built-up area. Ward wise percentage built-up growth during the time period 2007-2022 was calculated to provide a measure of the rate of urban expansion.

As observed in figure 5, the southern part of the DMA (wards 35, 42, and 47) experienced the highest percentage growth in built-up area. In 2007, the majority of these wards were peri-urban, and a sizable fraction of them were used for agriculture. Built-up areas have, however, encroached upon these contiguous agricultural areas in order to accommodate the DMA's burgeoning population.

4.2 Analysis of built-up area growth with reference to spectral acceleration

Since DMA consist of single and double-storey buildings predominantly, the built-up growth was analyzed with reference to spectral acceleration maps of single and double storey structures.

4.2.1 Analysis of built-up growth during 2007-2022 with reference to Spectral acceleration for double storey structures: For double-storey structures, the spectral acceleration map was overlaid on built-up area. In total, 1.26 km^2 and 0.18 km^2 of built-up area was situated in high spectral acceleration zones of 0.32-0.39 g and 0.39-0.52 g, respectively. Wards 2, 32, 47, and 60 had the largest proportion of built-up areas located in these higher spectral acceleration zones (Figure 6a). Higher spectral acceleration values for the double storey during an earthquake indicate heavier ground shaking at a frequency of 5 Hz.

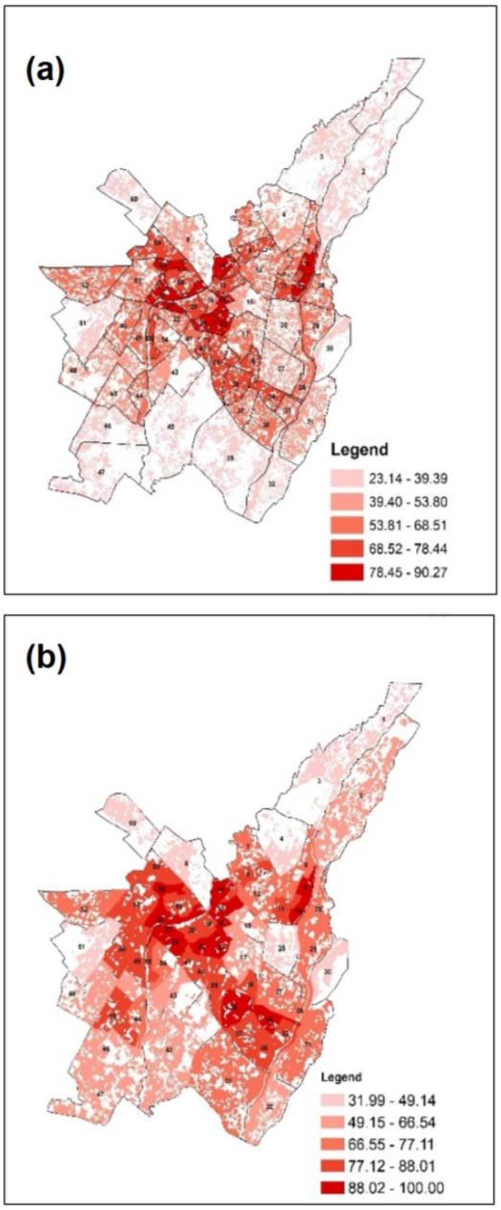

Figure 4. Ward wise built-up area in year (a) 2007 (b) 2022

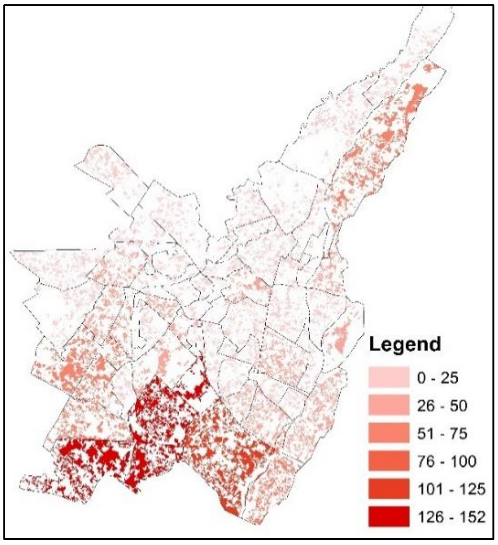

Figure 5. Ward wise percentage built-up growth during the period 2007-2022

***4.2.2 Analysis of built-up growth during 2007-2022 with reference to Spectral acceleration for single storey structures**:* For single-storey structures, overlay analysis of the built-up and spectral acceleration maps showed that 2.35 km^2, 2.72 km^2, and 0.39 km^2 of built-up area falls within the spectral acceleration zones of 0.20 – 0.22 g, 0.22 – 0.22 g and 0.24 – 0.28 g, respectively. Ward no. 2, 3, 42, 45, 36, 47, 48, 60 contain the maximum built-up falling under the three spectral acceleration zones (Figure 6b). The spectral acceleration values indicate stronger ground shaking at a frequency of 10 Hz for the single storey during an earthquake. Hence, any single storey structure that falls within these spectral acceleration range is susceptible to severe ground shaking.

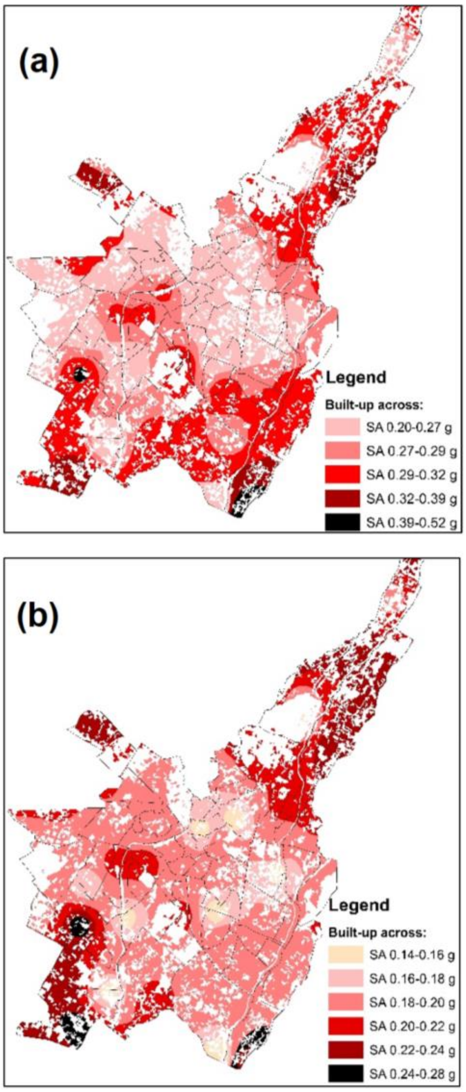

Figure 6. (a) Built-up area distribution across Spectral acceleration for double storey structures (b) Built-up area distribution across Spectral acceleration for single storey structures

4.3 Proposed land uses as per Master Plan with reference to seismic micro-zonation

To ascertain if the Master Plan had appropriately taken into account the potential seismic risks, the spectral acceleration map was superimposed on the proposed land use for DMA as per the Master Plan. The NEHRP (2023) suggested seismic regulations, which classify all buildings into various seismic hazard exposure classes. The seismic hazard exposure group III consists of structures housing vital post-earthquake recovery infrastructure, such as fire, rescue, police, hospital, and medical facilities, emergency preparedness centres, emergency vehicle garages, communication centres, and structures housing sufficient levels of toxic or explosive materials. Buildings that provide a significant public risk due to their usage or occupancy, such as public assembly buildings, schools, colleges, jails, and detention centers, are included in the seismic hazard exposure category II. Buildings that do not fall under categories III or II, such as residential, commercial, etc. are included in Seismic Hazard Exposure Group I (NEHRP, 2023; Fayaz et al., 2023).

4.3.1 *Double storey structures*

a. *Lower spectral acceleration*: The proposed built-up area across lower spectral acceleration for two storey structures is illustrated in figure 7a and 7b. The spectral acceleration for the double storey structures is comparatively less, thus it is feasible to consider the construction of double storey buildings equipped with essential post-earthquake recovery facilities, including fire or rescue, police stations, hospitals, communication centres etc. Additionally, this area may also be suitable for the development of public assembly buildings (double storey) within the socio-cultural and religious zones.

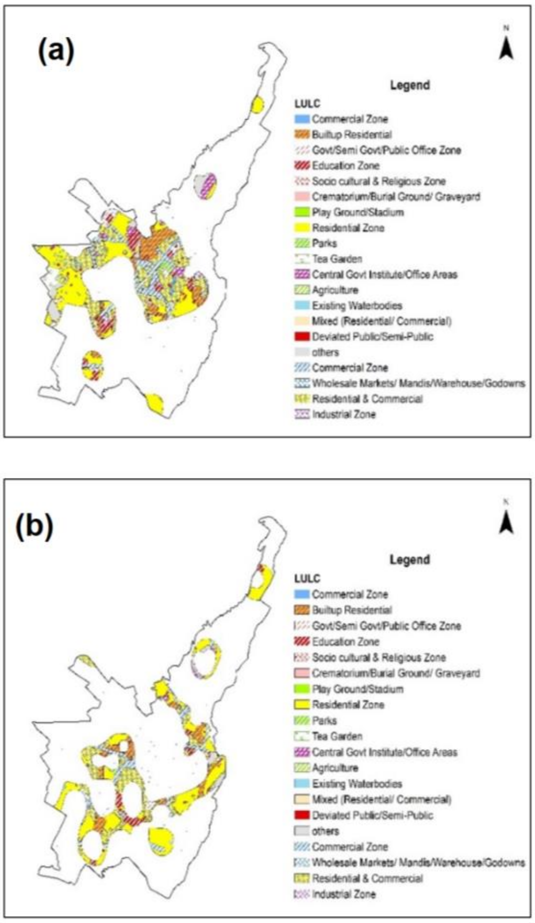

Figure 7. Proposed built-up area across lower spectral acceleration for two storey structures (a) 0.20 -0.27 g (b) 0.27 - 0.29 g

b. *Higher spectral acceleration*: figure 8a and 8b illustrate the proposed built-up area across higher spectral acceleration for two storey structures. The spectral acceleration for the double storey structures is higher within this region, thus it is advisable to implement limitations on the construction of new buildings with occupancies exceeding 300 persons. The designated area is ideally suited for small office and residential use aligning with its limited building capacity.

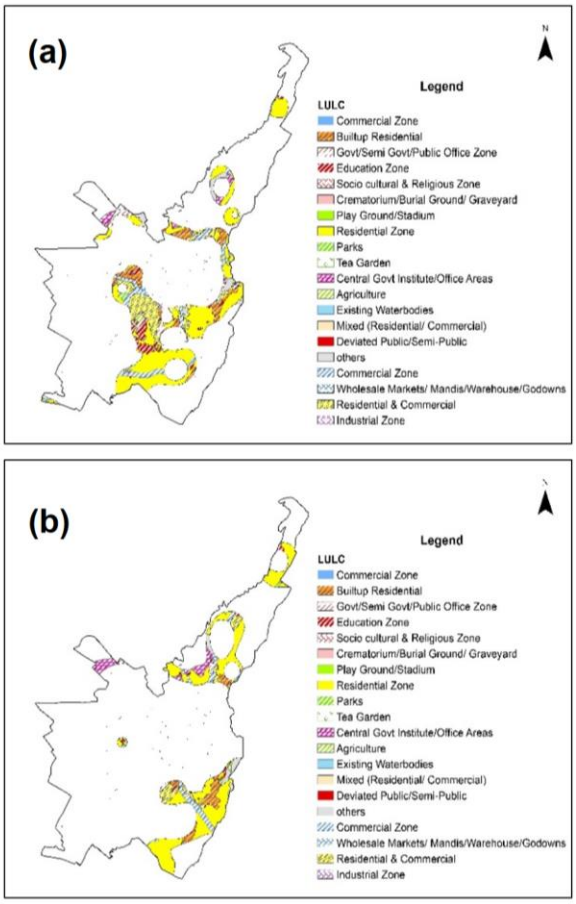

Figure 8. Proposed built-up area across higher spectral acceleration for two storey structures (a) 0.29-0.32g (b) 0.32 – 0.39 g

Incorporating open spaces and green pocket spaces in these regions would be beneficial in reducing seismic damages by providing areas where the impact of seismic forces can be dispersed and absorbed more effectively. By integrating open spaces into the planning and design of these areas, the potential for seismic damages can be minimized. Furthermore, it is advised to restrict the establishment of warehouses that house toxic or explosive substances in order to minimize potential hazards and maintain public safety.

4.3.2 *Single storey structures*

a. *Lower spectral acceleration*: The spectral acceleration for the single-storey structures is lesser in proposed built-up area, hence it becomes conducive to propose single storey buildings equipped with post-earthquake recovery facilities (figure 9a and 9b). Moreover, the strategic location of these areas at the centre of the municipal region, making them easily accessible from all regions in case of emergency. The reduced seismic hazard in the region makes it favourable for accommodating structures with higher capacity and provide essential services.

b. *Higher spectral acceleration*: figure 10a and 10b illustrate proposed built-up area across higher spectral acceleration for single storey structures. Due to the higher spectral acceleration in this region, it is recommended to impose restrictions on buildings with an occupancy exceeding 300 persons (public assembly, schools, and colleges). To further minimize the impact of seismic events, it is advisable to propose the inclusion of more open spaces in this region. The introduction of additional open spaces can contribute to reducing the potential damage caused by seismic hazards. Any building having toxic or explosive substances deemed to be dangerous to the public should be avoided in this area.

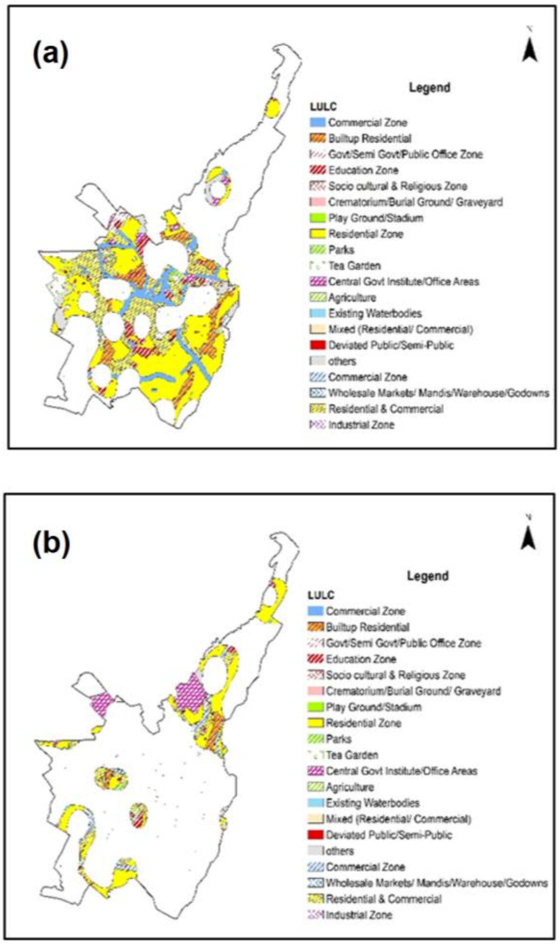

Figure 9. Proposed built-up area across lower spectral acceleration for single storey structures (a) 0.18-0.20g (b) 0.20 – 0.22 g

5. Discussion and Conclusion

Analysis of urban growth with reference to seismic micro-zonation provided valuable insights into the seismic vulnerability of the expanding built-up areas. The analysis of urban growth over a 15-year period revealed growth directions of Dehradun city, particularly in the south, southwest, and north directions. The growth percentage was notably higher for the wards in southern part of DMA compared to other wards. As Dehradun city expanded between the period of 2007 and 2022, it witnessed encroachment upon areas that exhibit a high susceptibility to seismic hazards. Approximately 10% of the urban growth has occurred within a vulnerable spectral acceleration zone for two-storey structures and 38% of the urban growth within a vulnerable spectral acceleration zone for single-storey structures.

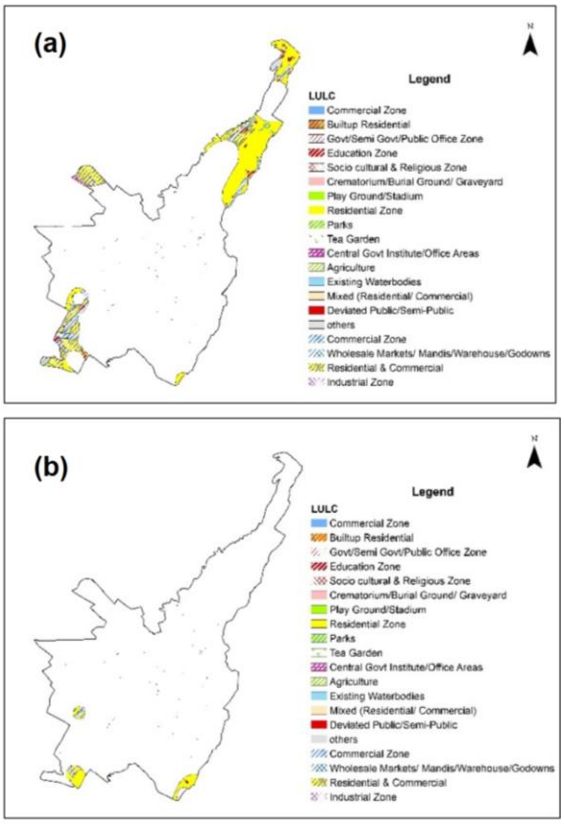

Figure 10. Proposed built-up area across higher spectral acceleration for single storey structures (a) 0.22-0.24 g (b) 0.24 – 0.28 g.

The overlay analysis shows that the ward numbers 2,32,47 and 60 consists of major built up area within the higher spectral acceleration zone that is high-risk for two-storey structures. Similarly ward numbers 1,2,3,4,5.42,45,46 and 47 consists of major built up area within the higher spectral acceleration zone that is high risk for the single storey structures. Public assembly buildings or buildings having higher capacity like schools, colleges etc. are most suitable across the lower spectral acceleration zones. Any proposed land use that consist of higher capacity buildings and public assembly uses across higher spectral acceleration zones should have some regulations to be followed. To reduce the impact of seismic events, it is advisable to propose more open spaces within higher spectral acceleration zones. The study underscores the importance of seismic hazard considerations into land use planning processes by suggesting necessary policy recommendations to enforce strict building regulations.

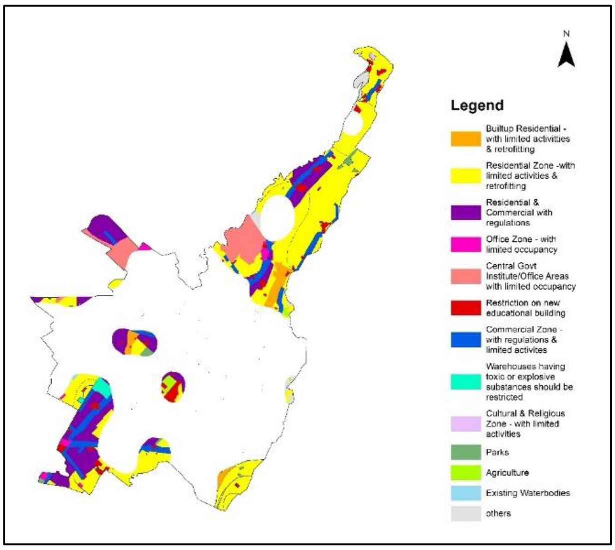

Figure 11. Policy recommendations for proposed land use

5.1 Policy recommendation

Some of the policy recommendations to address the higher spectral acceleration and potential seismic hazard impact in the proposed land use area include (Figure 11),

- Zoning regulations to prevent the construction of Seismic hazard exposure Group III buildings (those having essential facilities that are required for post-earthquake)
- Mandate seismic assessments for existing buildings to determine their structural vulnerabilities and establish retrofitting requirements to meet the recommended seismic standards.
- Provide financial assistance, tax incentives, or low-interest loans to support building owners in the retrofitting process.

Integrating risk information in a master plan enables optimized land use and infrastructure planning through incorporating strategies, projects and actions that can lower the risk in development planning. This helps in mitigating the impact of disasters when they occur by implementing necessary regulations to avoid the construction of critical facilities or essential infrastructure in high-risk zones and helps in determining suitable locations for housing, schools, hospitals and other vital services.

5.2 Limitation of study and future research

The present study used a micro-zonation map based on fifty (50) test sites and only the single and double storey buildings were analysed. Dehradun city which is one of the fastest growing city of Uttarakhand has however sprawled on to the contiguous agricultural areas. Hence, there is a need to add more test sites and generate a microzonation map covering the DMA and surrounding peri urban areas. Additionally, seismic acceleration map for multi-storey buildings also need to be generated for further analysis, as this will provide a better understanding of the seismic hazard in DMA and its surroundings.

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