

# Landslide Susceptibility Analysis: A Case Study of Nainital Municipal Area

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## Research

**Keywords:** Landslide vulnerability, susceptibility, transmutation, parameters, GIS, factors, mapping

**Posted Date:** November 23rd, 2020

**DOI:** <https://doi.org/10.21203/rs.3.rs-106891/v1>

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# Abstract

Landslides are one of the most recurrent natural phenomena that are of overwhelming significance in the Himalayas. The Himalayan terrain being under severe transmutation by human interference and excess urban penetration has led to triggering of landslides along with causing colossal damage to property and loss of life. Immense risk looms large all along the Himalayas with cumulating conditions that build the potentiality to landslides. The study of landslides has drawn worldwide attention mainly due to the aggravating socio-economic consequences as well as the increasing pressure of urbanization on the mountain environment. In order to reduce the damage and manage vulnerable areas, there is imperative need to formulate comprehensive Landslide Vulnerability and Susceptibility Zonation maps for different areas of the Himalayan region emphasizing the urbanized and burgeoning pockets. The concept of landslide susceptibility and landslide susceptibility assessment have been introduced in the past couple of decades and various methodologies have been developed for evaluating the devastating power of landslides and its associated processes. The ultimate aim is to evolve a method suitable for specific areas through which appropriate management measures can be taken to reduce the risk from potential landslides. Any approach towards LSZ would require identification of the conditions leading to slope failure, their systematic mapping and evaluation of their relative contributions by amalgamation of all factors in the ultimatum.

The aim of this paper is to assess the various landslide vulnerability factors in Nainital Municipality area on raster-based GIS platform and generate landslide vulnerability and susceptibility maps. To achieve the objective, a detailed inventory of maps based on all parameters assessed has been generated of the study area from the satellite imageries and field data. The accuracy of results is being validated by constant observation and prediction accuracies.

## Introduction

The study of landslides has drawn worldwide attention mainly due to increasing awareness of the socio-economic impact of landslides, as well as the increasing pressure of urbanization on the mountain environment (Aleotti and Chowdhury 1999). The mountain environment, which is already a fragile zone due to tectonic activities, slope instability and mass movements of highly crushed and deformed rocks, becomes highly vulnerable to slope failure when anthropogenic factors disturb the stability of the region. In order to reduce the damage caused by landslide initiations and reactivations, a landslide susceptibility map is really needed (Van Den Eeckhaut et al., 2006). Landslide is a recurring disaster often occurring in conjunction with and triggered by other disasters like cloud bursts and further causing disasters like flood in the Himalayas. The concept of landslide susceptibility and landslide susceptibility assessment have been introduced in the past couple of decades and various methodologies have been developed for evaluating the devastating power of landslides and its associated processes. The ultimate aim is to evolve a method through which appropriate management measures can be taken at the right time to reduce the risk from potential landslides. In order to prioritize the area for hazard mitigation efforts, it is beneficial to have a LSZ (Landslide Susceptibility Zonation) map prepared depicting the ranking of the

area based on actual and/or potential threat of slides in future. Any approach towards LSZ would require identification of the conditions leading to slope failure, their systematic mapping and evaluation of their relative contributions.

## **2.0 Study Area**

Nainital town, one of the most favoured tourist destinations is located in the Indian state of Uttarakhand. Study was conducted in this hill station, Nainital,, with elevation ranging between 1400 m. above MSL (approx.) to about 2600 m. above MSL (approx.) and covering an area of 11.73 square km (4.53 sq. mile) and also the headquarter of Nainital district. Latitudinal and longitudinal extensions of the study area are between 29°0' N to 29°36'21" N latitudes and 78°50'53" E to 80°0' E longitudes in the Kumaun foothills of the outer Himalaya. Nainital Municipal Corporation has 12 wards that have been specifically analyzed leaving aside the Army Cantonment Board area (Figure 1).

The area enjoys a sub-tropical to sub-humid climate, with average annual rainfall of 1246 mm. The area is named after the lake (tal) which is the central attraction of tourists flowing here and has experienced burgeoning growth.

## **2.0 Literature Review**

Literature review for the study can be divided into conception development regarding landslide susceptibility studies done so far and an information based appraisal of the study area's demographic growth and tourism growth.

Landslide hazard zonation (LHZ) is the classification of a land surface into homogeneous areas or domains and their ranking according to degrees of actual/potential hazard caused by mass movement (Varnes 1984). Landslide hazard zonation mapping is a significant step of knowledge building which is prerequisite of any comprehensive landslide assessment management, disaster mitigation and further resilience building. The scope of landslide vulnerability assessment study is interdisciplinary and based on spatio-temporal information easily derivable from remote sensing but remains incomplete without being integrated with detailed empirical validation (Pandey et al. 2008). With the help of geospatial techniques, identification and appraisal of landslides in even remote areas of mountain ranges like the Himalayas is rendered possible and delineating landslide vulnerable zones on the basis of major causative factors has been made easy (Anbalagan et al. 2014). The use of geo-informatics or GIS based multi-criteria analysis in the landslide hazard mapping and causation was undertaken by several researchers (Sarkar and Kanungo 2004; Hong et al. 2007; Kouli et al. 2010; Avtar et al. 2011; Othman et al. 2012; Devkota et al. 2013; Paulín et al. 2014; Ahmed 2015; Cárdenas and Mera 2016; Hadmoko et al. 2017; Stanley and Kirschbaum 2017; Mahdadi et al. 2018). The strategy of landslide analyses includes understanding the process, hazard analysis and prediction in order to reduce the impending damages caused. Studies involve generation of landslide inventories, collecting relevant factor information and mapping, exploratory statistical analysis, selection of final factor maps generated by weights and creating criteria tree hierarchy to proceed on to overlay exercise of vulnerability map generation.

Landslide susceptibility studies can be done by various methods, of which four methods are favoured: deterministic, inventory-based probabilistic, heuristic and statistical techniques (Guzzetti et al. 1999). Multi-criteria decision analysis method belongs to heuristic analysis and include the analytic hierarchy process (AHP), the weighted linear combination (WLC), the ordered weighted average (OWA), etc. (Feizizadeh and Blaschke 2013; Ahmed 2015). Heuristic methods allow site-specific and landslide type-specific evaluations of the causal factors along with conjunction of experts' knowledge and experience, and avoid the generalization that is often integral to data-driven ones (Van Westen et al. 2011).

The state of Uttarakhand (India) has got a history full of landslides related events. Memories of major landslides that have caused large-scale human tragedies, material damage and associated environmental and social hazards in Garhwal Himalaya can be traced. The landslides killed about 220 people in the entire rainy season of 2010, where 65 lives were lost, 6 persons went missing, 21 people were injured, 84 livestock died, 534 houses were fully damaged and 2138 houses were partially damaged due to heavy precipitation within 4 days from 18 to 21 September 2010, which virtually brought Uttarakhand to a grinding halt for several days (SEOC report, 2010). Landslides and their secondary hazards such as landslide dams and subsequent flash floods often turn into major disasters as was witnessed in 1970 when a 77 year old landslide dam (Gohana tal) in the Birahi-Ganga river, a tributary of Alakananda, breached and caused major destruction in the downstream areas of Alakananda. There have been numerous studies involving landslide hazard evaluation (Guzzetti et al., 1999). Landslide hazard may be assessed through heuristic (Anbalgan, 1992, Saha et al. 2002), deterministic (Terlien et al., 1995, Gokceoglu and Aksoy 1999, Acharya et al., 2006, Dahal et al., 2008) and statistical approaches (Yin and Yan, 1988; Van Westen, 2000; Lee and Min, 2001; Dai et al., 2001; Van Westen et al., 2003; Suzen and Doyuran, 2004; Saha et al., 2005; Kanungo et al., 2006; Mathew et al., 2007; Dahal et al., 2007 and Chauhan et al., 2010 among others). In the southern margin of Kumaun sub-Himalaya, the frequency of landslides is high due to structural and neotectonic activities along the main boundary thrust (MBT) zone along with superimposition of number of clumsy settlements thriving in the zone.

Physiographically, the Nainital District can be divided into three broad physiographic divisions – the Lesser Himalayan Zone, which is comprised of crystalline metasedimentaries, the Himalayan Foot Hill Zone or the Siwalik formations and the Piedmont Alluvial Tract further subdivided into the Bhabar and Tarai zones hosting a number of “tals” or lakes (Figure 2). Tourism and other factors related to it have led to the steep slopes being highly populated with time, making this area vulnerable to landslides.

### **3.1 Review of Population Growth and Tourism: A Grave Situation in a Fragile Terrain**

The fragile terrain which is naturally highly vulnerable to landslides becomes more susceptible if the built-up area, especially the residential area increases at a fast pace. The situation here is much more aggravated by the escalation of tourism in recent decades. Hence an appraisal of landslide vulnerability entails the need to review population and tourism growth rates of the place.

#### **3.1.1 Population Growth**

The population growth of Nainital Township from 1901 to 2011 has been depicted with the help of a graph. It is seen that the population was much lower during the 1900s but steadily increased thereafter. The total population was just 6903 persons in 1901 but in the next ten years about 3367 persons were added and the total population increased to 10270 in 1911. The following decade saw addition of just 965 people so that the census year 1921 recorded a total population of 11235 people. 1931 was an interesting census year where 5% decrease of total population took place. The total population recorded was 10673, which was almost similar to that of 1911. Since 1941, population steadily grew, first at a slow rate of 9.79%. 1941 census year recorded a total population of 11718 persons. The next decade saw 11.73% growth, making it 13093 persons in 1951. 1971 saw a marked increase of 56.51% growth within 10 years, the total population recorded being 25167 persons after which the rate decreased to 3.68%. In 1981 the total population was 26093 and in 1991 it became 29831. 2001 recorded a total population of 38630 persons and the last census year of 2011 recorded a total population of 41377 persons. Analysis of the growth rate shows a highly fluctuating trend (Figure 3a). But as the total population is increasing, in future Nainital may see an increase in land conversion rate and hence landslides too.

The Exponential growth curve of Nainital Town compares the actual growth of population with the estimated population. It is seen that from 1901 to 1921, the actual population was more than the estimated population. However, the actual population recorded a decrease from 1931 to 1961. This was much lower than the estimated population during this span of time. Since 1971 the actual population has been higher than the estimated population. During the 1991 census year both were seen to be almost same, but thereafter the situation changed. The gap between both rates was highest during 1981 census, when the population was expected to decline to less than 10000, but instead showed an actual increase to 26093. Since 2001 however, the actual population is seen to be higher than estimated (Figure 3b).

The ward-wise population growth rates of Nainital shows that Ward No. 1 i.e. Snow View has experienced the highest growth rate of almost 20.68, followed by Ward No.7 i.e. Sher Ka Danda which is 17.26. Ward no. 6 (Awagarh) and Ward No. 10 (Sukha Tal) has experienced growth rates of 12.56 and 11.17 respectively. Ward Nos. 11, 9, 2, and 3, i.e. Mallital Bazar, Nainital Club, Narayan Nagar and Hari Nagar have population growth rate less than 10. Ward Nos. 4 (Ayarpatta), 5 (Raj Bhawan), 8 (Upper Mall) and 12 (Shri Krishnapur) have growth rate less than 5. The ward with least population growth i.e. 0.3 is No. 13 (Tallital Bazar) (Figure 4a). It is interesting to note that all the wards that have low population growth rate, i.e. at least lower than 10 have low landslide records both with respect to area as well as numbers. Snow View, Sher Ka Danda Awagarh and Sukha Tal are the wards having higher population growth rates and also high records of landslide with respect to area and numbers.

Population projection for these wards show an alarming situation as the population of Snow View ward is projected to be very high in the 2021 Census. While the present population (2011) of the ward is just 5381 persons, the projected value is 382022.877, which means it is more than 6 times the present population. If this truly takes place, not only will the ward be highly susceptible to landslides but the magnitude of disaster will also be high, as a huge amount of people will be affected. The wards Sher Ka Danda and Awagarh also show a high projected population. Whereas the present (2011) population is

3481 and 3597 respectively, both wards show more than three times increase of projected population, i.e.17114.92 and 11740.84 (Figure 4b). These two wards also have high landslide values. All the other wards also show an increase, although not at such a high rate.

Population density shows that highest density is in south-western ward followed by southern and south eastern parts of the town. It is to be also mentioned that although the northern and eastern wards depict lesser density, these areas host mainly the hotels of this burgeoning tourist centre (Figure 4c).

### **3.1.2 Tourism Growth:**

Tourism is the main economic activity of Nainital. Traditionally, Nainital attracts large number of tourist population in the summer even when much is yet to be done to improve and develop its tourist infrastructure. As indicated by the graph, the area is mostly visited by la large number of Indian tourists. The total number of Indian tourists increased from 365941 in 2001 to 898077 in 2012. However, the number fell to 737130 in 2013 due to the Kedarnath Disaster which affected the number of tourist flow to Uttarakhand. According to Nakajo Akihito, previously Indian's tourist population mainly comprised of foreigners and elites. But because of the recent growth of middle income level, the domestic tourism market has expanded. The number of foreign tourists, although minor in proportion to Indian tourists has also been growing at a high rate. Infact the growth rate of foreign Tourists is higher than that of domestic tourists (Figures 5a, b, c). To attract high end tourists including foreign tourists, who have capacity to pay, higher order facilities need to be created for comfortable accommodation, high altitude recreations including adventurous tourism etc. As the tourism sector grows further, more employment opportunities will be created as a result of expansion of the aforesaid activities and enterprises. Not only from India but also from the other countries of the world tourists come here every year. The beauty of the Naintal Lake is the main attraction of the tourist. With its beauty some religious causes are also being attached to its glory. According to the Hindu Puranas, the left eye of the Goddess Sati fell into here. Thus Nainital became one of the famous 51 'Hindu Piths' of India and a large number of tourist and Hindu pilgrims come here which in turn helps the tourism of Nainital but at the same time uncontrolled development and expansion of urbanization shall lead to detrimental consequences, especially in the already landslide susceptible wards of Nainital.

## **4.0 Aim of the Study**

The aim of this paper is to analyze the factors responsible for vulnerability of this area to slope failure with an emphasis on the anthropogenic effect in this terrain through the study of landslide hazard zonation maps of Nainital town region. The main objective is to evaluate preconditioning spatial factors based on image analysis and ground survey integration on a GIS platform to prepare landslide susceptibility maps that can be probabilistically used to predict where landslides may occur in future.

## **Materials And Methods**

The present study is based on geographic information system technology in conjunction with 2 methods, viz. a method based on experts' knowledge and experience, and the analytic hierarchy process (AHP) method. The susceptibility study of Nainital is assessed using the analytical hierarchy process (AHP) via an AHP weighted information content method. Using the AHP method supposedly will make the landslide hazard map of increased validation and acceptance.

To achieve the objective, a detailed landslide inventory map of the study area has been generated from the high resolution satellite imagery and field studies. Apart from this, landslide causal factor parameter maps of the study area has been prepared from various sources viz., satellite imagery, ancillary data, Digital Elevation Model (DEM), published literature / reports and field visits. Finally, landslide susceptibility map of the study area is produced, after which landslide susceptibility assessment is done to identify the areas more prone to such disasters in order to take suitable measures in future (Figure 6).

For the Landslide Vulnerability Mapping based on the inherent nature of the study area, the landslide susceptibility factors and their corresponding landslide susceptibility values are determined, keeping the total 100 and dividing the factor values according to significance (Table 1). The factors may be modified based on availability of data. Slope, relative relief, drainage density, ruggedness, dissection indices, landform are easier to be calculated from topographical sheet and from remote sensing image analysis. For lithological features, geological map analysis and field study sufficed. Following this a map for each factor is prepared and the classes therein are identified. Subclass wise values or weights were then assigned keeping in mind that their sum must be equal to the corresponding LSV (Table 2). The assigning of sub class weights will also depend on significance of the classes on landslide susceptibility of the area concerned.

A digital elevation model (DEM) of the study area was used based on Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) elevation data (30m resolution) from which a number of landslide responsible factor values were deduced. These factors are elevation, slope, aspect and to some extent drainage. There has been collation done using topographical sheets 530/7 and 530/11 of Survey of India (SOI). These maps with scale 1:50,000 were georeferenced using WGS 84 datum, Universal Transverse Mercator (UTM) zone 45 N projection in ArcGIS desktop 10.5. The drainage aspect was deciphered from SOI topographical sheets and validated with the ASTER DEM data. Contour elevation, slope, aspect maps were prepared from ASTER DEM data in spatial analysis tools in ArcGIS platform and validated with topographical sheet collation and validation. Geological features like lithology were derived from Geological Survey of India and lineament was deciphered from Landsat TM data and validated from GSI information. Land use /land cover data was decoded from precision based digitization from Arc Earth image and validation with cadastral maps provided by Nainital Lake Development Authority. Rainfall data was available for only 1 station and this was found unsuited for the purpose and the study area being very small, the indirect effect of rainfall based on the aspect factor was considered as more relevant. Population data was obtained from Census Reports (Figure 6).

The maps prepared on the factors have zones in a grid-wise framework. It is added that in any grid there can be single values or point features or micro zonal variations. Considering micro zonal variations is more specific for the purpose. If a single average value is there for each grid, corresponding subclass LSV is assigned to each grid factor wise. If micro zones are analysed of each grid, the % of area under each subclass in a grid is calculated and then the area percentages with the corresponding subclass LSVs are multiplied. Then the answers are added to find total subclass values of each grid for every factor. The total value is divided with the factor gross LSV.

**Example:** Say in a grid, 20% area is under 305m relative relief, 50% under 305-395m and 30% under 395-485m. Calculation will be  $20 \times 0.4$  (subclass value acc. to table 2) = 8,  $50 \times 0.6 = 30$  and  $30 \times 1.4 = 42$ , adding  $8 + 30 + 42$  we get the total subclass value as 80. This is then divided by LSV of relative relief i.e. 6 to get 13.33 as the final value.

All the factor LSVs or the factor final values are added to find grid wise total LSV. To find LSI (Landslide Susceptibility Index) data on landslide occurrences in the study area is required. Here too 2 methods have been used. One is considering only grid wise number of landslide sites and second is considering area of the landslide scar/ area affected. Then the following formula is applied:

$$\text{LSI} = \text{Landslides \% per sq.km} \times \text{LSV} / 100$$

A. If no. of landslide is 6 in a grid of area 5sq.km and its LSV is 136.568, then

$$\text{LSI} = 6/5 \times 100 \times 136.568/100 = 163.88$$

B. If area of site is taken, and landslide area is 2sq.km in a grid of 5sq.km, LSV 136.568, then

$$\text{LSI} = 2/5 \times 100 \times 136.568/100 = 54.63$$

A landslide vulnerability map is then prepared with classes selected based on total LSV and two landslide susceptibility maps prepared based on two way measurement of LSI.

## Results And Discussion

### 6.1 Slope and Aspect:

Slope is the most basic parameter for stability considerations, especially in mountains, as with increase in slope, shear stress of basal material increases in direct proportion (Lee et al. 2004). It is the first derivative of elevation with each pixel (pixel size 80 m × 80 m) denoting the angle of slope at a particular location.

Study of the slope aspects of the area reveal that most of the area have gentle (less than 15°) to moderately gentle (25° – 35°) slope. Few areas on the northern, north-western and western border of the town have steep slope i.e. 35° – 50°. The slopes immediately adjoining the Naini Lake on both sides and

the southern part have steep slopes too. Escarpment having very steep slope i.e. more than  $50^\circ$  lies in the western part of the town (Figure 7). The slope aspect plays a great role in determining the type and magnitude of landslide in any area. The areas in Nainital town having steep slope and escarpment are likely to be mass wasted easily and are prone to slides and falls. Gentle slope areas on the other hand are more prone to slow creeping movements. They pose no major danger if vegetated. On the other hand the slope and aspect of the area affect the rate of insolation received by the place, type and intensity of precipitation, runoff and distribution of vegetation in and around the town. Many areas like Sher ka Danda, Naini peak, Golf course, Deopatha and Krishnapur also show steep slopes and the Balia Nala flowing roughly in south-easterly direction has carved out a deep valley due to intense shearing in the area.

On the context of this study involving a small area and highly unsuitable to analyze disparity of precipitation due to unavailability of spatial data, aspect is rendered one of the significant parameters in preparing landslide hazard zonation maps. Exposure to solar radiation, rainfall and discontinuities which are related parameters of aspect largely control the occurrence of landslides. Aspect degree is classified according to the aspect classes as flat, north, east, south and west so on and so forth based on directions, i.e. an aspect map generally refers to the direction to which a mountain slope faces. Nainital topography circumscribes the position of the lake in a basin and left slope having north to north east aspect while the right slope have south- south west – west aspects marking windward and leeward locations. The aspect map is a very important parameter to understand microclimatic effects or impact of solar radiation on local climate of the Nainital area and was derived from ASTER DEM.

The Aspect Map reveals that the area around the lake is flat. The steep slopes right to the lake are directed west and south-west, while that on the left of the lake trend north, northeast and east . Majority of the area in the northeast and southwest have south, southwest and west aspect (Figure 8). The rate of insolation, the amount of rainfall and the type of ground cover and tourism based land use depends on the aspect of the place much more than any other factor.

## **6.2 Relief**

Terrain elevation is an important factor to identify other factor impacts of this landslide-prone area. The elevation map of Nainital MC depicts the relief characteristics with the help of contours drawn at interval of 20m. The average elevation is 2084 metres (6837 ft) above sea level. The highest point is the China or Naina Peak with an elevation of 2619 metres (8593 ft). The average elevation steeply increases from the extreme southeastern corner of the town till the extreme northwestern sector. The contours, especially in the northern, northeastern and western part of the town show a close spacing indicating steepness of the terrain. The presence of a ridge in the northern part and escarpment in the western part is clearly seen from the arrangement of contours. However the area adjoining the Lake has uniform relief (Figures 9a, b).

**6.2.1 Relative Relief (RR)** depicts the range of elevation of a particular place. High values of relative relief indicate a rugged terrain, whereas low values of relative relief indicate that the relief is almost featureless.

The average RR is approximately 900 metres. Elevation is low (1935.5) around the Naini Lake but steeply rises towards the north and south west of the town. Naini peak with height of 2611.5 meters above msl is the highest point of the area while Sher ka Danda, Deopatha and Ayarpatha respectively measure 2402, 2435.1 and 2352 meters above msl. The area around the lake has moderately steep slope and steep slope in some places, which indicates that the RR is also high. The map shows that the area around the Naini Lake has a relative relief of 305m to 350m. The values rise to about 600m towards the north and southwestern part of the town. This indicates that the terrain is rugged due to the presence of rocky knobs, outcrops and escarpments (Figure 10).

**6.2.2 Dissection Index (DI)** is an indicator of the relationship between maximum relief and relative relief. It thus gives an idea of the nature and magnitude of degradation of absolute relief or the whole terrain. The value to DI varies from 0 which indicates no dissection and 1, which indicates high dissection. DI values in the town ranges between 0.16 to 0.36 (approx.), indicating low to moderate dissection. The region around the Naini Lake is least dissected. The northern part having high relief and the whole southern part of the town having steep slopes and escarpment is more dissected (Figure 11).

### 6.3 Lithology

Nainital Lake is covered by limestone or dolomitic limestone and north, eastern and south eastern parts are covered by slate and shale. There are a number of fault lines and small thrust lines in and around the city. A fault runs across and along the lake intersecting from N-S the entire city.

The oldest rocks exposed in the study area, thus, belong to the Almora Group. Three distinct lithological suits can easily be identified within the Almora Group. These are as follows:

1. Crystallines and Schists
2. Quartzite
3. Granite and Augen gneisses

The rocks of the Almora group tectonically lie over the Ramgarh group along the SAT (South Almora thrust). Three distinct lithological sites can easily be identified within the Ramgarh Group also. These are:

1. Profoundly mylonitized chlorite quartz porphyry
2. White and purple sericitic medium grained quartzite interbedded with grey, green and silvery sericite schist and chocolate brown, limonitic phyllite
3. Carbonaceous and locally pyretic phyllites and slates altering with blue green banded marmorized limestone.(Figure 12a)

Lineament studies have been integrated with drawing the geological features and are supposed to help reveal generalities on areas of weakness in understanding the cause of landslides. In the Himalayas that landslide phenomena are aggravated and hastened by being close to regional geological lineaments

(Pachauri and Pant 1992; Mathew et al. 2007; Ramli et al. 2010). The lineament density of the study area was analyzed by using the line density analyst extension of ArcView GIS.

The lineaments thus represent weak zones along which mass wastage is likely. It was encouraging to note that some of the lineaments correlate positively with the structural discontinuities even though the two do not exactly overlap each other. It is important to note that the main lineaments are observed to show a trend both parallel and transverse to the alignment of the Naini Lake. Most lineaments show NE-SW to NNE-SSW and NW-SE trend. A significant lineament showing NNW-SSE trend is observed to traverse through Hanumangarhi area while another one trends parallel to Balianala. The lineament pattern of Nainital area shows a relative close collation with that of drainage line and the ridge patterns (Figure 12b). As for the analysis, the result in this study indicates that most of the landslides have been found to occur at 50-100 metres from lineaments especially along the lake and in the town's south and north outskirts.

#### **6.4 Drainage Density and Distance to Drainage**

Drainage is one of the most important factors that control landslides as its densities denote the nature of the ruggedness of the area, its soil, geological properties and even condition of land use/ land cover.

The streams emerging from the hills on the plain below are strikingly divided into numerous branches and channels. The River Debka, Nihal, Kosi, Gola and Bhakra, all of which presents the same character over the foot hill plain. In the hilly region the main water parting may be marked distinctly, which runs from Nainital north-west ward, separating the south-westerly drainage from the north-easterly drainage which is carried by Jokh Nadi, Ghora Gad and Mawani Gadhera etc. The main river of the basin may be easily marked along the line from which the drainage is flowing into the Tal on one hand and also flowing outwards to the southeastern part of the city.

The Drainage Density (DD) map reveals that the DD is highest in the northern part of the town. Here the values range between 5.8 km/sq.km. to 6.9km/sq.km. The whole area in the northern and northeastern part of the town has high DD values ranging from 4.7 to 5.8 km./sq.km. This corresponds to the location of the Naini Lake. The values continuously decrease outward from the lake area towards the area having gentler slopes then again starts increasing towards the southwestern part of the town from the escarpment area downslope (Figure 13a). The drainage buffer map shows areas close to drainage lines (Figure 13b) and this has been collated further with land use map and landslide occurrence sites to reveal further that areas close to drainage are most vulnerable locations.

#### **6.5 Ruggedness Index**

Ruggedness Index (RI) is an indicator of the relationship between relief and drainage. The RI values around the Lake and main settlement area ranges between below 0.7 to 1.4. Like the DI values RI values also increase northwards and southwestwards. With respect to landslide susceptibility values, however, unlike other factors ruggedness values indicate an assigned subclass value of only 0.3 (Figure 14).

## 6.6 Landforms

The Topographic view of Nainital MC and its surroundings reveal that the area near the mall road appears to have a flat structure with slopes surrounding it on all sides. The stream Balia Nala dissects it from a north west to southeast direction. The area to the southwest appears like a table land having dense vegetation. The boundary of the town has a much higher elevation than the central part, which appears like a basin. Landslide scars are visible on the slopes along the town boundary and on the slopes surrounding the Lake (Figure 15).

The Stability Map of Nainital Town depicts that Ridge Crest lies on both sides of the Lake. The immediate right slope of the Lake is dominated by creep as the mass wasting process. Wasted debris are found on the northern part of the Lake. Both slopes of the ridge, especially the right slope is an active landslide zone. Landslide scars are present in the area bordering the Lake especially to the northeast, northwest and south of the Lake. Landslide areas are seen scattered throughout the town, especially the rock escarpment present along the northwestern boundary of the town. Other major landslide areas are present to the south and southeastern boundary and minor areas are found towards the northeastern boundary (Figure 16).

### 6.6.1 Land use and Land cover of Present Nainital

Residential and built-up area surrounds the Naini Lake, although there is absence of houses along the immediate left and right bank of the lake upto a distance of about 0.5 kilometre owing to the steep slopes. Settlements are mainly concentrated to the northern and southern part of the Lake and in the high and middle zone at an elevation varying between 1400 to 2000 meters and in the lower valley stretch at an elevation less than 1200 meters. Settlements are absent in the upper high zones at elevation above 2000meters. The transportation routes provide a good connectivity to the settlements. The network of roadways is concentrated in the settlement zone around the lake and runs towards the southwest and southeastern part of the town. A playground is located towards the north of the lake and other scattered areas near the lake. Shallow and dense vegetation is found on the steep slopes and escarpment area. The northwestern, western and southeastern part of the town have few scattered open spaces. Only a minor portion in the western part is put to agricultural use. The overall map shows distinct landuse zones existing in relation to relief and slope characteristics (Figure 17).

**Land use / Land cover Change:** The history of evolution of Nainital Town since 1841 to 1947 shows that the built up area was scarce till 1900 except a few government buildings present near the southern bank of Naini Lake. Between 1900 and 1947 urban built up area increased but growth occurred in a scattered manner along the northern bank of Naini Lake near Kumaun University, surrounding Sukha Tal. From 1947 to present day there has been growth of settlements mainly for tourism purposes, mainly concentrated along the north-western and south-eastern banks of Naini Lake surrounding the Municipal Office and Market area respectively, as well as along the eastern bank of the lake. There has been a rise of about 15.96% in the areal coverage of built up space from 1990 to 2010. There has been about 15.36 % decrease in vegetation cover from 1990 to 2010, although there has been slight increase in tree-cover

through plantation near the southern banks of Naini Lake. Area under agricultural land use has decreased slightly by about 0.75% (Figures 18a, b, c, d). It can be seen that land use in different slope areas clearly show relation of land use with slope aspect in parts of Nainital. It is evident from the diagram that the intensity of agricultural land use is highest in south western part of Nainital and built up area is highest in north eastern part. This clearly indicates that the southern part of Nainital has comparatively gentler slope. Percentage of forested area is highest in the moderate and steep slope areas, whereas, open area is present in gentle slope areas. Proportion of built up area declines with increase in steepness but a considerable development has taken place on moderate slopes. The same trend is followed by agricultural land use.

### **6.6.2 Vegetation quality:**

Vegetation quality based on Normalised Difference Vegetation Index (NDVI) has been done to show that much of Nainital has lost its original once present dense vegetation cover suited naturally to the terrain. Less than 40% area is presently under dense vegetation (0.32- 0.58) while lesser dense (0.24- 0.32) encircle these areas and are dissected in continuity by scattered trees. Much of the town centre surrounding the lake has lost vegetation and has scattered trees depicted by low NDVI values (0.049 – 0.24) (Figure 19).

### **6.6.2 Distance from Road**

Nainital Town and its surrounding areas like Sukha Tal, Bhimtal, Saat Tal have high level of accessibility. There is good connectivity of the lake area with nearby towns like Haldwani, Kathgodam etc. Accessibility is highest in the whole region surrounding the Lake, even on the steep and moderately steep slopes on the right bank of the Lake. It continues to be moderately high on the northern and southern part of the lake to the southwest and southeast part of the town. But the southern and extreme northern and northeastern part of the town is least accessible. A study of land use type and relief in connection to accessibility reveals that in case of Nainital town both play an important role in case of accessibility. In fact some areas are inaccessible due to the presence of dense forest here. However, the road network concentration on steep slopes and rugged areas indicate greater danger from landslides which may lead to road closures and related problems.

Road density is highest in the area where Kumaun University and High Court is located and in the residential area surrounding Sukha Tal. Density of road is also high along the eastern bank of Naini Lake dotted with hotels and residences. The southern bank of Naini Lake with Market, Bus stand and Government offices also has high road density. The buffer map (Figure 20) shows the areas in proximity to road network and upon collation with landslide occurrences and other factors reveal that areas close to roads are more prone to landslides, for eg. The eastern bank road of Naini Lake.

## **7.0 Major Findings:**

The main aim of this study is to analyse the landslide susceptibility of the Nainital Municipal Corporation area with the help of the Landslide Susceptibility Index and a Landslide Susceptibility Map prepared on the basis of the LSI. All the factors responsible for landslides in any area are studied in details with the help of maps. The assigned subclass values for each of the factors and their subclasses have been analysed and finally the following inferences have been drawn.

- The steep slopes ( $35^{\circ}$  to  $50^{\circ}$ ) and moderately steep slopes ( $25^{\circ}$  to  $35^{\circ}$ ), bordering the Lake have a subclass value to 7 and 5 respectively. Only a small part of escarpment to the southwest part of the town has a subclass value of 10. These areas are more probable to suffer due to landslides. Other areas having moderate and gentle slopes can be assigned subclass values of 2 and 1 respectively. These have a less probability of occurrence of landslides.
- The area surrounding the lake has a sub-class value of 0.6. The north and southwestern part has a sub-class value ranging between 1.4 and 2.2 indicating that they have a greater potential of being affected by landslides.
- Some areas have low DI values, in case of which the assigned sub-class value is 0.2. The values gradually increase in accordance with the changes in relative relief. The northern part has higher DI values of about 0.36. In this case the assigned sub-class value is 1.5 making it a high probability zone for landslides.
- The Nainital town is underlain by shale, siltstones and sandstones, dolomites and limestone and shale which has a subclass value of 4.5 each indicating weak lithology. Moreover the presence of lineaments, thrusts, nappe etc. increases the susceptibility of these areas to landslides.
- The northern part has a high subclass value of 1.5, as the DD here is more than 5.8 km/sq. km. In other parts of northern and northeastern Nainital, the assigned subclass value is 1.2. Thus it is clear that with respect to drainage density the probability of landslides is very high here.
- The built-up area in the high relief part itself is an indication of high probability slope instability. The settlements have been assigned a high sub-class value of 6; open spaces have been assigned a sub-class value of 4. The presence of these indicates the susceptibility of this area to landslides.
- As the road is present around the Lake area which also has steep slope the probability of landslide becomes high as here the assigned subclass value is 5.
- The presence of features like ridge crest, escarpment, landslide scar etc. is an indication of landslide susceptibility, with the assigned sub- class value being 0.4, 2 and 1.5.

## 7.1 Landslide Vulnerability State

The Landslide Vulnerability Index Map of the town (Figure 21) is used to identify the areas most vulnerable to the hazard. Except for small scattered areas in the northeast, east and south the area is moderate to highly vulnerable to slides. The values range between 97 and more than 156. More than 90% area of the town is vulnerable to landslides, of which more than 65% area has vulnerability values above 127. Major areas around the Naini Lake, the western, southwestern and extreme southeastern part of the town is highly vulnerable to landslides with values above 156. A small part of Hari Nagar and Raj

Bhawan, which has least area affected by slides and few occurrences of such hazard, is identified to be least vulnerable. Other parts of Raj Bhawan, Tallital Bazar, Krishna Pur and Upper Mall have moderate vulnerability to landslides. The whole northern part of the town comprising large parts of Narayan Nagar, Sher ka Danda, Sukha Tal, Nainital Club, Ayarpatta, Aawaghar and snow view are highly vulnerable to slope failure. Western part of Sukha Tal, northern part of Naini Lake area, western part of Sher ka Danda, northern part of Upper Mall, eastern part of Mallital Bazar, southern part of Snow View and southern part of Narayan Nagar have the highest vulnerability to slides. This region is connected by transportation routes and settlements are mainly present along these arteries. Slope failures in this area would have disastrous consequences if suitable measures are not taken to check them.

After thorough analysis of the landslide locations and areas covered, the Landslide Susceptibility Zonation Maps prepared with the help of it the following observations can be made:

Landslide Susceptibility Index has been calculated based on the area of landslides in Nainital MC (Figure 22a). The LSI values range between less than 5 to more than 56. The southern part of the Naini Lake i.e. Tallital Bazar, Hari Nagar, Shri Krishna Pur, parts of Upper Mall and Narayan Nagar has very low LSI values and hence low area affected by landslides. The central part of the town comprising the area surrounding the above places has moderate LSI values, between 6 and 22. The northern part of the Lake, comprising parts of Sher Ka Danda, Sukha Tal, Naini Lake and Snow View and the southwestern section of Narayan Nagar, has LSI values ranging between 40 and 56. The extreme northern part comprising Awaghar, Mallital Bazar and Nainital Club has highest LSI values i.e. above 56. Thus it is seen that landslides affect a greater part of the town in the northern and southwestern sectors compared to other areas.

A second map has been prepared with the help of LSI values calculated based on the number of occurrence of landslides (Figure 22b). The value ranges between 201 and 1550. It is seen that with respect to number of slides the LSI value is lowest in the southeastern, central and western part of the town comprising areas under Raj Bhawan, Tallital Bazar, Narayan Nagar, Upper Mall and Hari Nagar. The LSI value is moderate, ranging between 651 and 1000 in parts of Sukha Tal, Ayarpatta, Naini Lake and Sher ka Danda area. The LSI is highest, i.e it ranges between 1101 and more than 1550 in the northern and northeastern part of the town comprising Nainital Club, Aawaghar, Snow View, Mallital Bazar and western part of Sher ka Danda. Thus, it roughly coincides with the region where the total area affected by slides is highest.

## Conclusion

Landslides cause huge loss of human life and property in mountainous areas across the globe every year. There is an inescapable requirement to have landslide susceptibility zonation map so that disaster prone areas can be delineated. The local authorities can make use of this data for disaster preparedness and implement mitigation techniques. Several methodologies have been suggested for landslide hazard/susceptibility zonation. The present research demonstrates the application of statistical based

modeling for landslide susceptibility mapping in part of the Himalaya, which is prone to frequent occurrence of landslides. The potential of remote sensing and GIS has been exploited in database preparation and at integration stages. In this research, a modified method has been used to generate a LSZ map of Nainital Municipal area by taking into account and collating various landslide causal factors (Figure 23). Landslide susceptibility assessment and prediction deals with the spatial component of hazard, and has as a main objective to answer to the following question: Where can future landslides occur? Research on the spatial probability of landslide occurrence is vital to the local administrative authorities and decision makers who are responsible for civil protection, infrastructure planning, environmental management and landslide mitigation strategies. It is hoped that the zonation of landslide susceptible areas may help in effective and efficient management of landslide related hazard.

## **Declarations**

### **Availability of Data and Materials**

The datasets generated and/or analysed during the current study are not publicly available due to it being self-generated data based on on-site primary survey, but are available from the corresponding author on reasonable request. Other base maps are based on satellite images.

### **Competing Interests**

The authors declare that they have no competing interests.

### **Funding**

The work, being our own personal academic research work, has been carried out fully with the personal expenditure of the main and corresponding author Prashasti Bhattacharyya, Asst. Professor, Department of Geography, Sarsuna College.

### **Authors' contributions**

The research paper is a joint endeavour of all the authors each completing their part of work duly assigned by the main and corresponding author.

PB, being the main author, organized and conducted the survey with her team of surveyors. The analysis and interpretation of collected data was also done by her.

SD and SP completed the whole procedure of database management, calculation and mapping.

SDG assisted PB in map analysis, explanations, drawing conclusions and final preparation and writing of the report.

All the authors read and approved the final manuscript.

## Acknowledgements

NA

Authors' information

Added separately

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## Tables

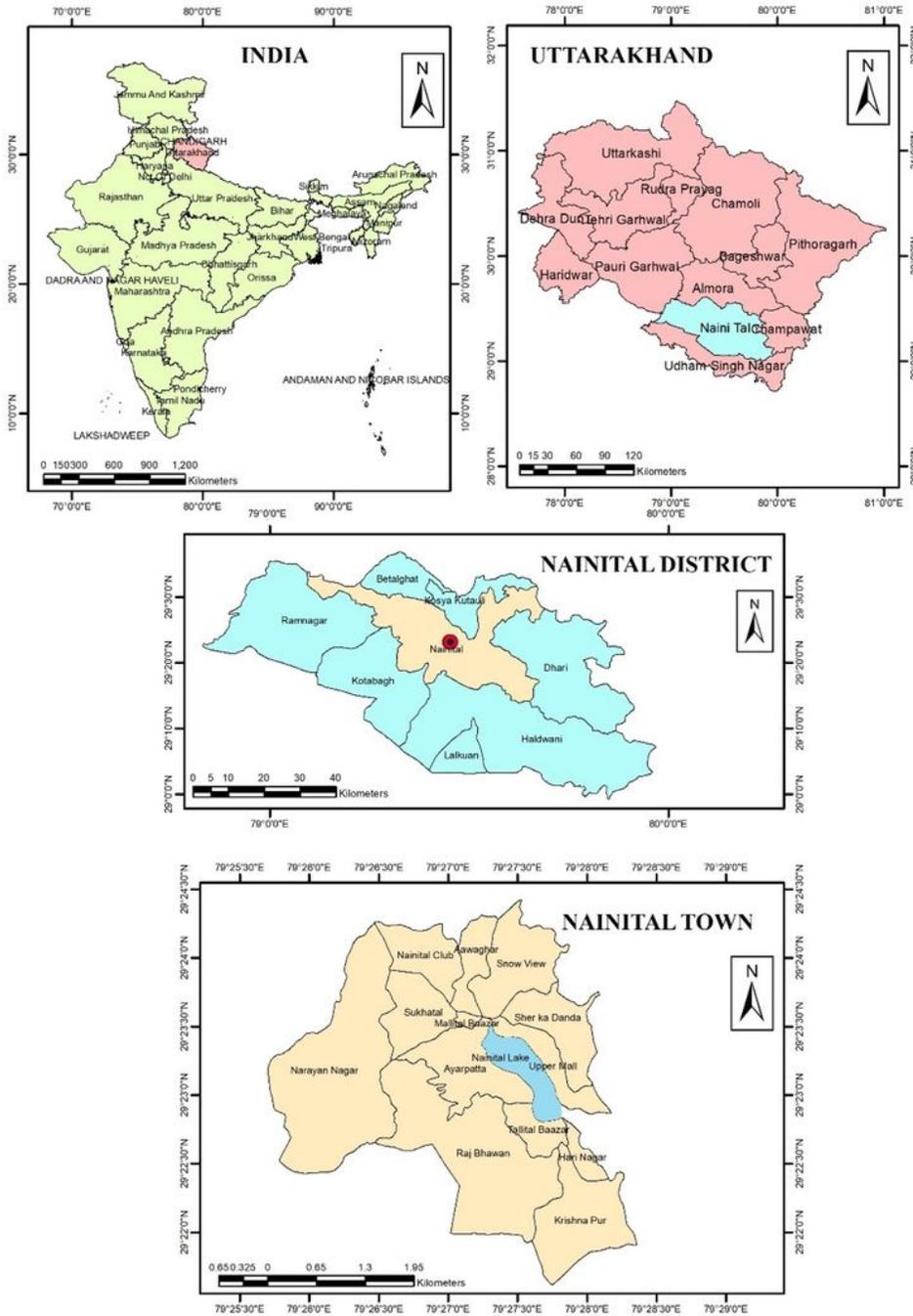
<b>Table 1 Factors And Landslide Susceptibility Values</b>	
<b>FACTOR</b>	<b>LSV</b>
SLOPE	25
LITHOLOGY	20
RELATIVE RELIEF	6
DISSECTION INDEX	5.5
DRAINAGE DENSITY & DISTANCE TO DRAINAGE	10
RUGGEDNESS INDEX	5.5
LANDFORM	3
LANDUSE & LANDCOVER	15
DISTANCE TO ROAD	10
TOTAL	100

<b>Table 2 Subclass wise Breaking of LSVs</b>			
<b>FACTORS</b>	<b>LSV</b>	<b>SUBCLASSES</b>	<b>SUBCLASS VALUES</b>
<b>SLOPE IN DEGREES</b>	25	ABOVE 50	10
		35-50	7
		26-35	5
		15-25	2
		0-15	1
<b>LITHOLOGY</b>	20	Carbonaceous Slate	1
		Shale siltstone with sandstone	4.5
		Dolerite Dyke	0.5
		Shale with Limestone	4.5
		Ferruginous Slate	1
		Dolomite	4.5
		Marlite	4
<b>RELATIVE RELIEF</b>	6	Below 305m	0.4
		305-395m	0.6
		395-485m	1.4
		485-575m	1.4
		Above 575m	2.2
<b>DISSECTION INDEX</b>	5.5	< 0.185	0.2
		0.185- 0.235	0.3
		0.235-0.285	0.8
		0.285-0.335	1.2
		>0.335	1.5
<b>DRAINAGE DENSITY</b>	4	< 2.5	0.2
		2.5-3.6	0.3
		3.6-4.7	0.8
		4.7-5.8	1.2
		>5.8	1.5

<b>DISTANCE FROM DRAINAGE</b>	6	Within 100m	3
		100-200m	2
		above 200m	1
<b>RUGGEDNESS INDEX</b>	5.5	< 0.7	0.2
		0.7-1.4	0.3
		1.4-2.1	0.8
		2.1-2.8	1.2
		>2.8	1.5
<b>LANDFORM</b>	5	Ridge crest and hill top	0.4
		Escarpment & convex slope	2
		lake and flat	0.1
		Landslide scar	1.5
		Concave slope	1
<b>LANDUSE &amp; LANDCOVER</b>	15	Settlement	6
		Shallow Vegetation	2
		Dense Vegetation	1
		Barren land/ rock exposure/open space	4
		Agriculture	2
<b>DISTANCE FROM ROAD</b>	10	Within 100m	5
		100-200m	3
		above 200m	2

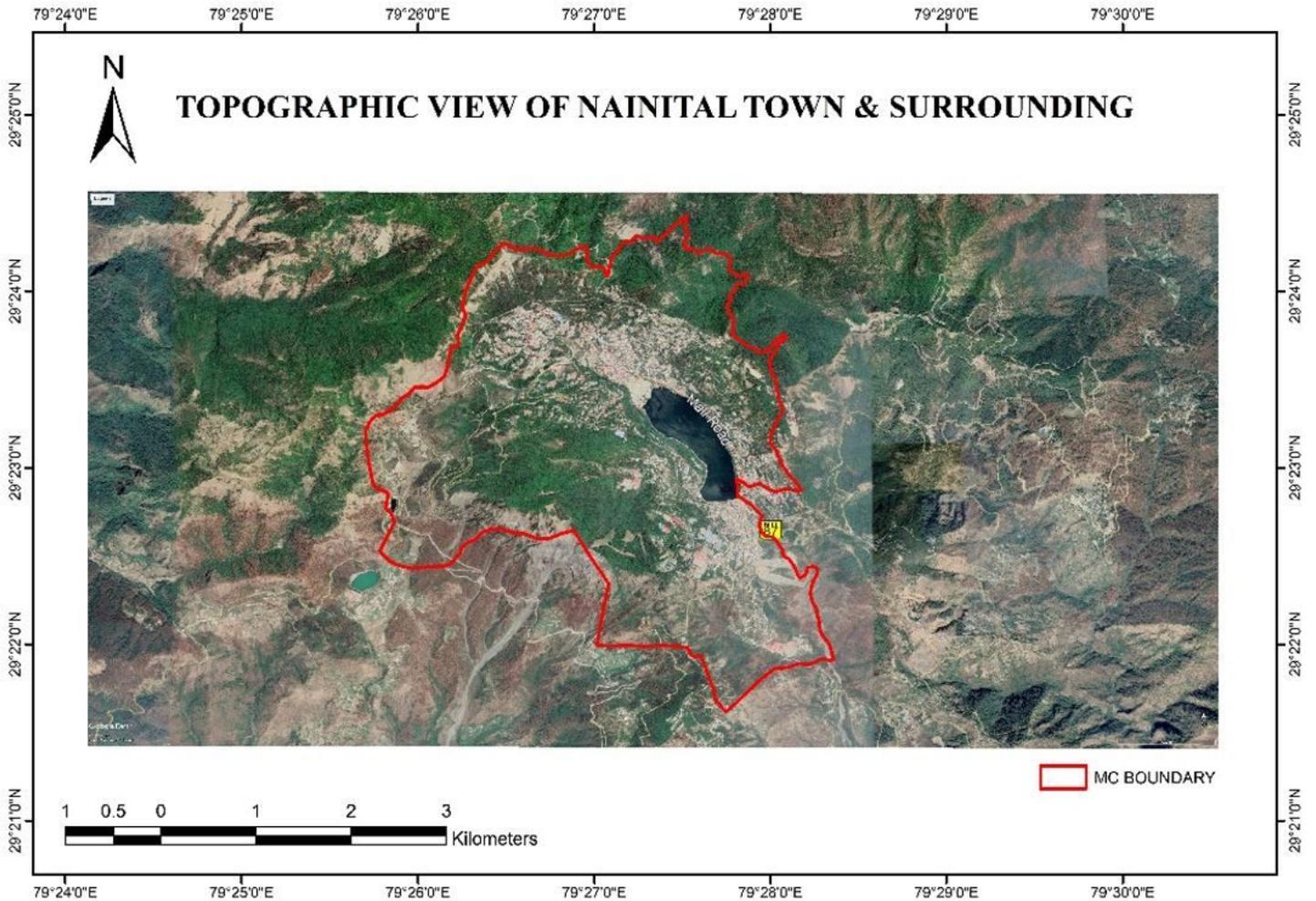
## Figures

## LOCATION OF THE STUDY AREA



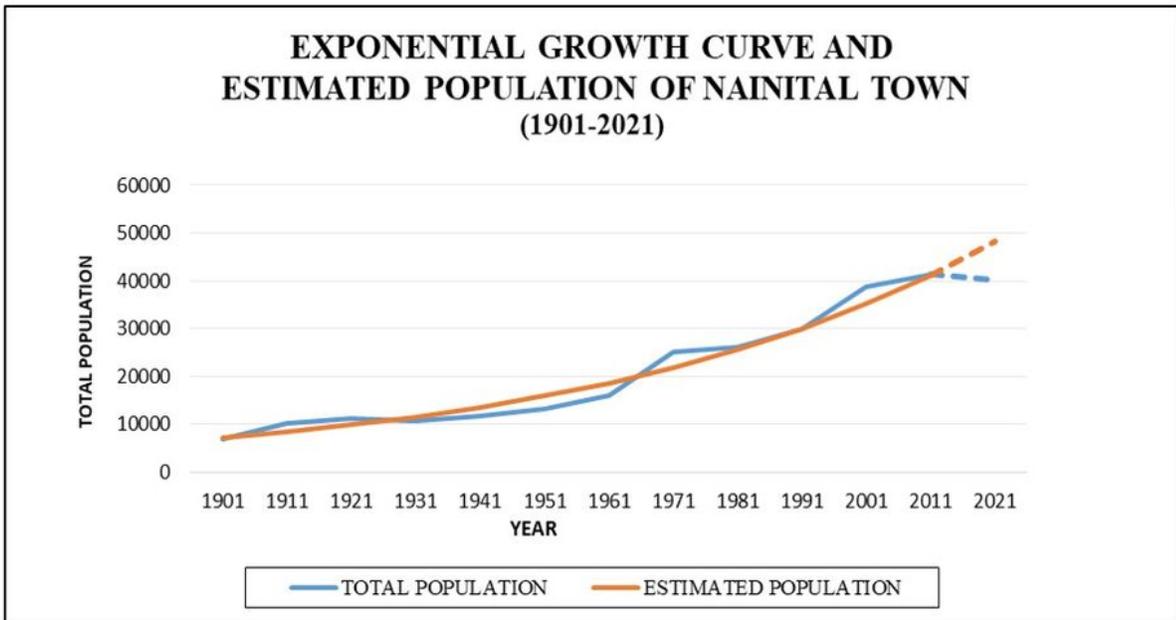
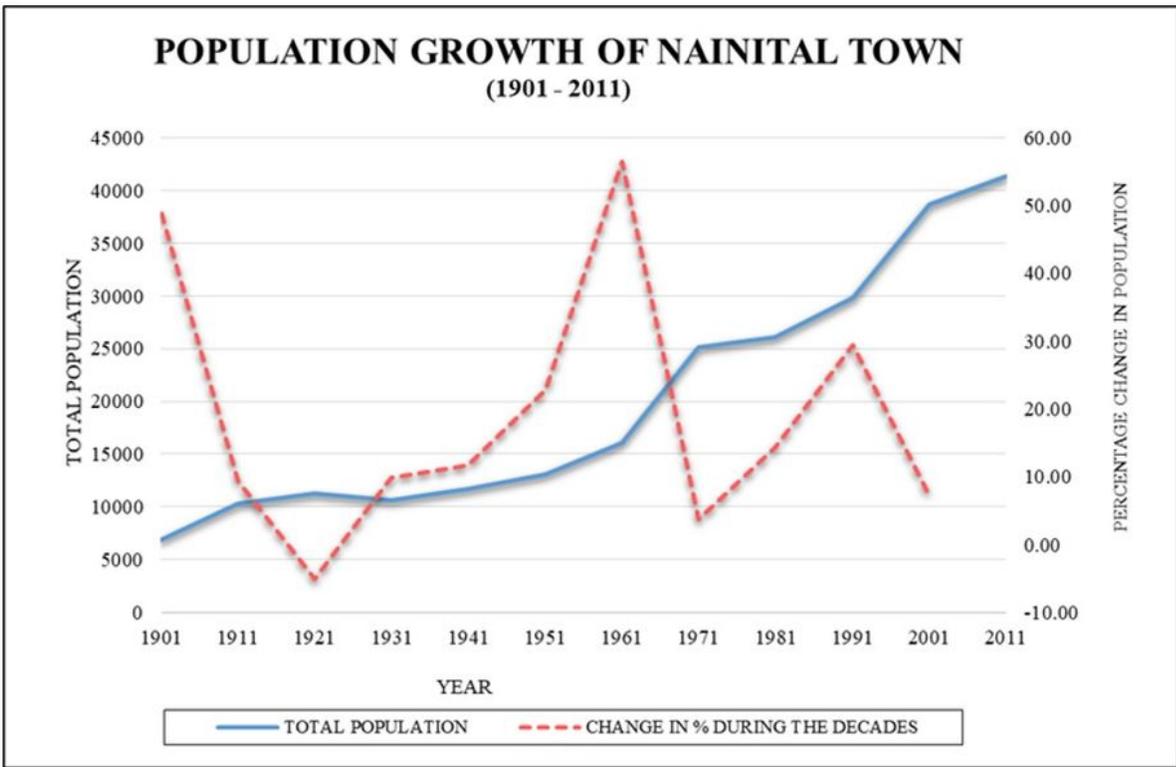
**Figure 1**

Location of Study Area. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



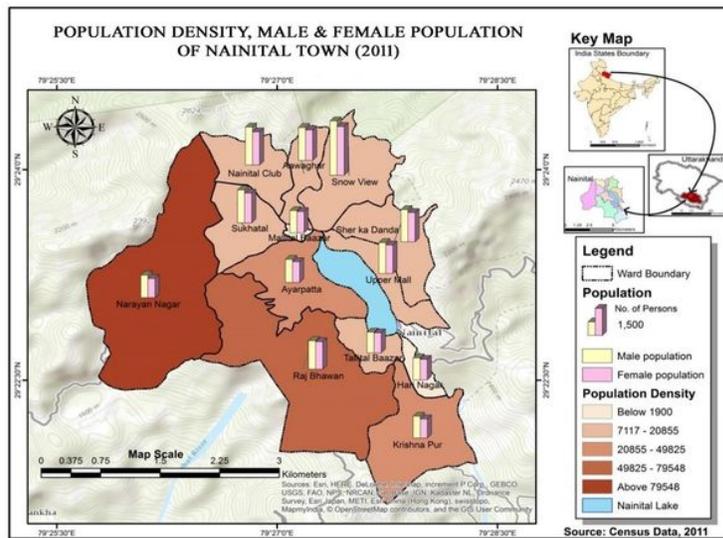
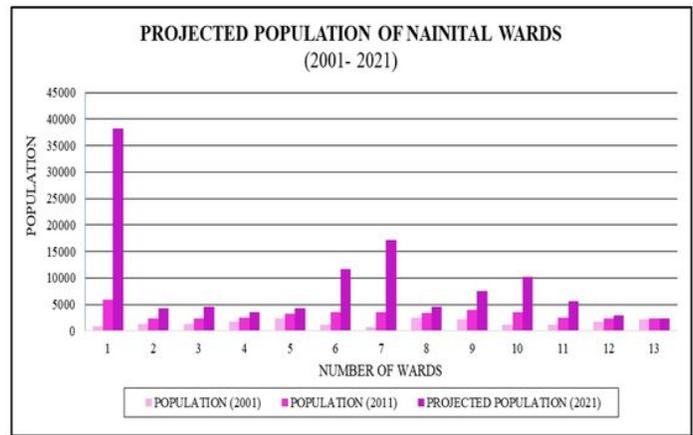
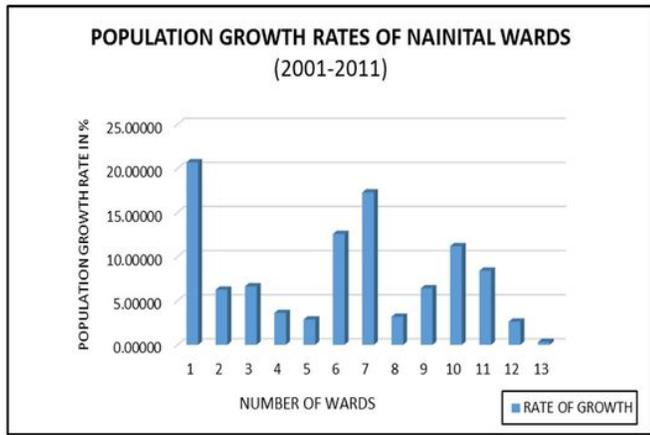
**Figure 2**

Topographic View of Nainital MC and Surrounding. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



**Figure 3**

3a, 3b Population Growth of Nainital Town (1901-2011); Exponential Growth Curve and Estimated Population of Nainital Town (1901-2021)



**Figure 4**

4a, 4b, 4c Population Growth Rates of Nainital Wards (2001-2011); Projected Population of Nainital Wards (2001- 2021); Population Density, Male & Female Population of Nainital Town (2011). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

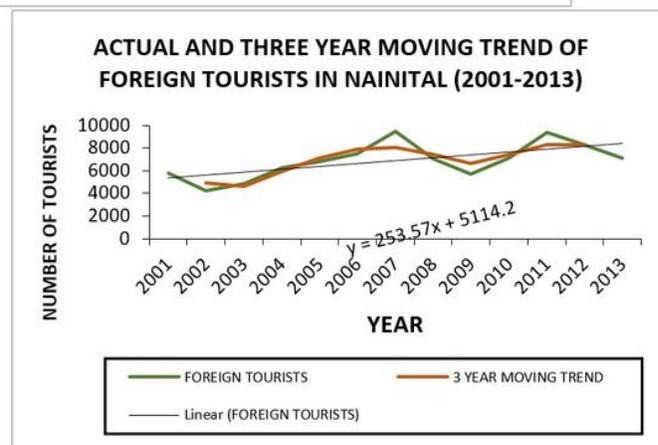
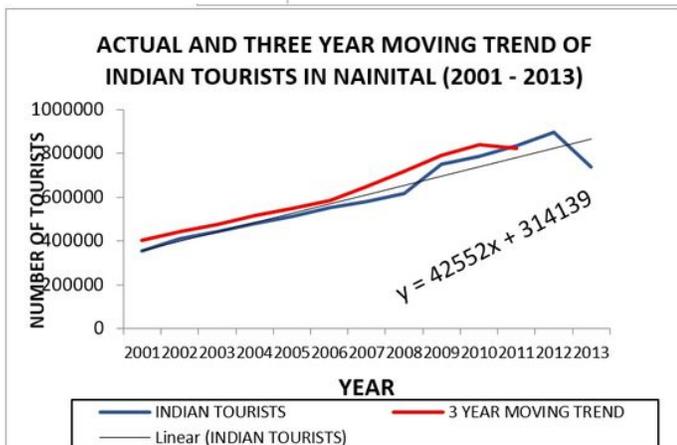
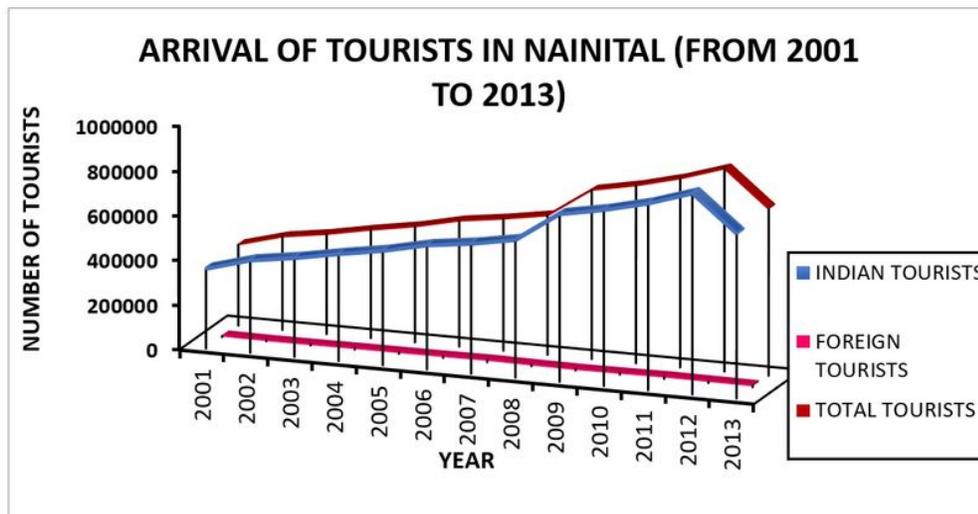


Figure 5

5a, b, c Trend Analysis of Foreign and Domestic Tourist Arrival in Nainital (2001-2013)

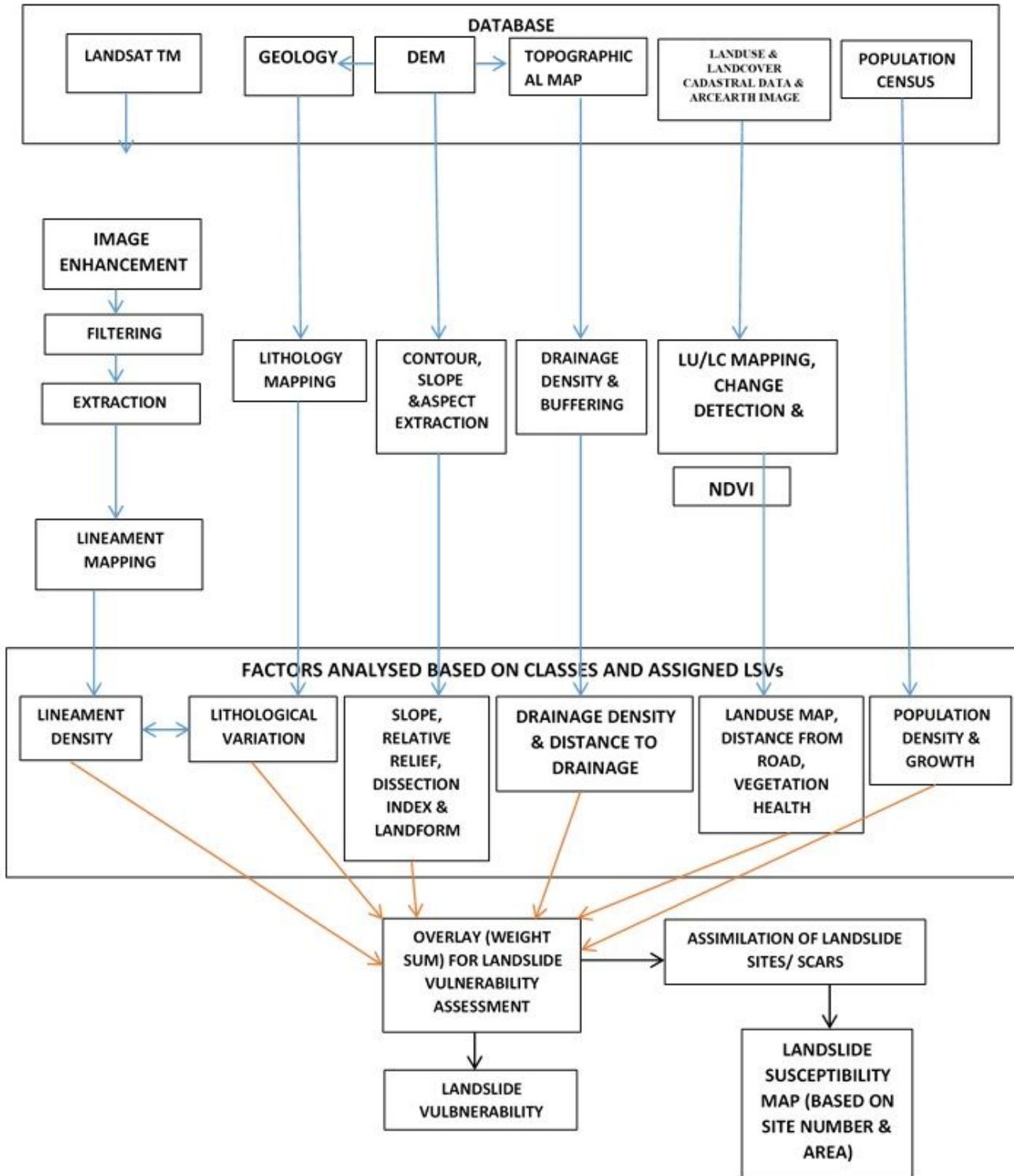
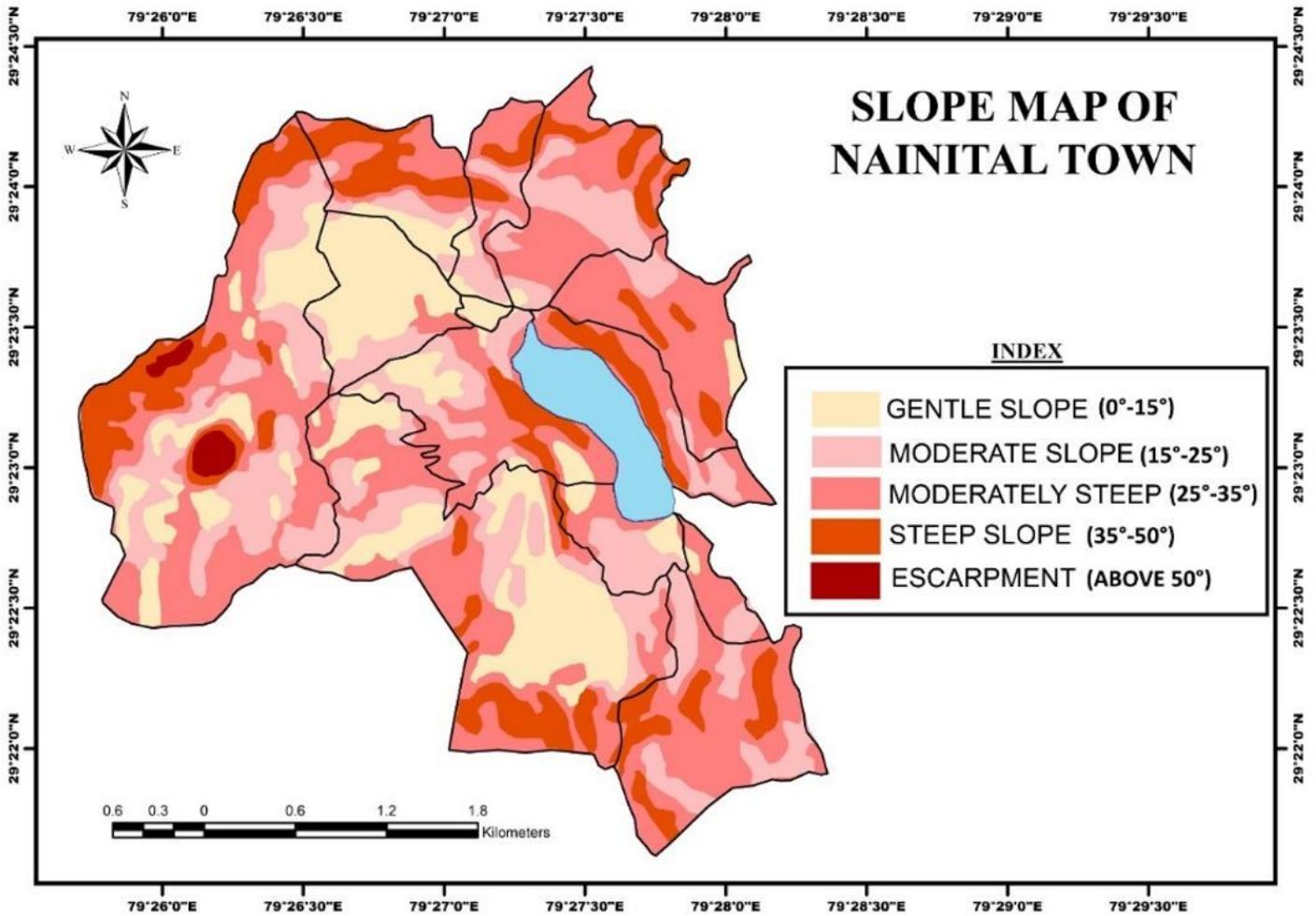


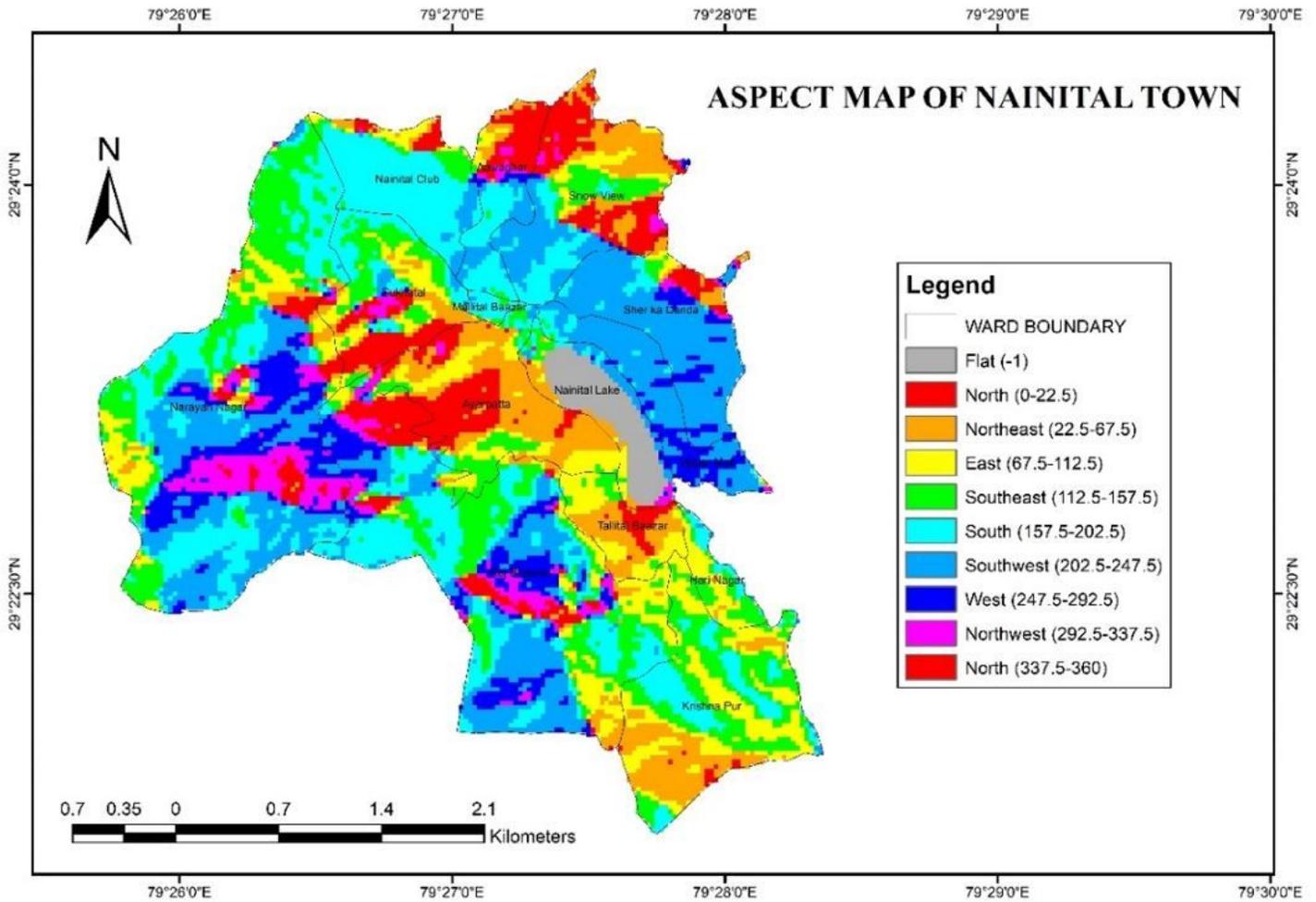
Figure 6

Methodological Process of Landslide Vulnerability and Susceptibility Mapping



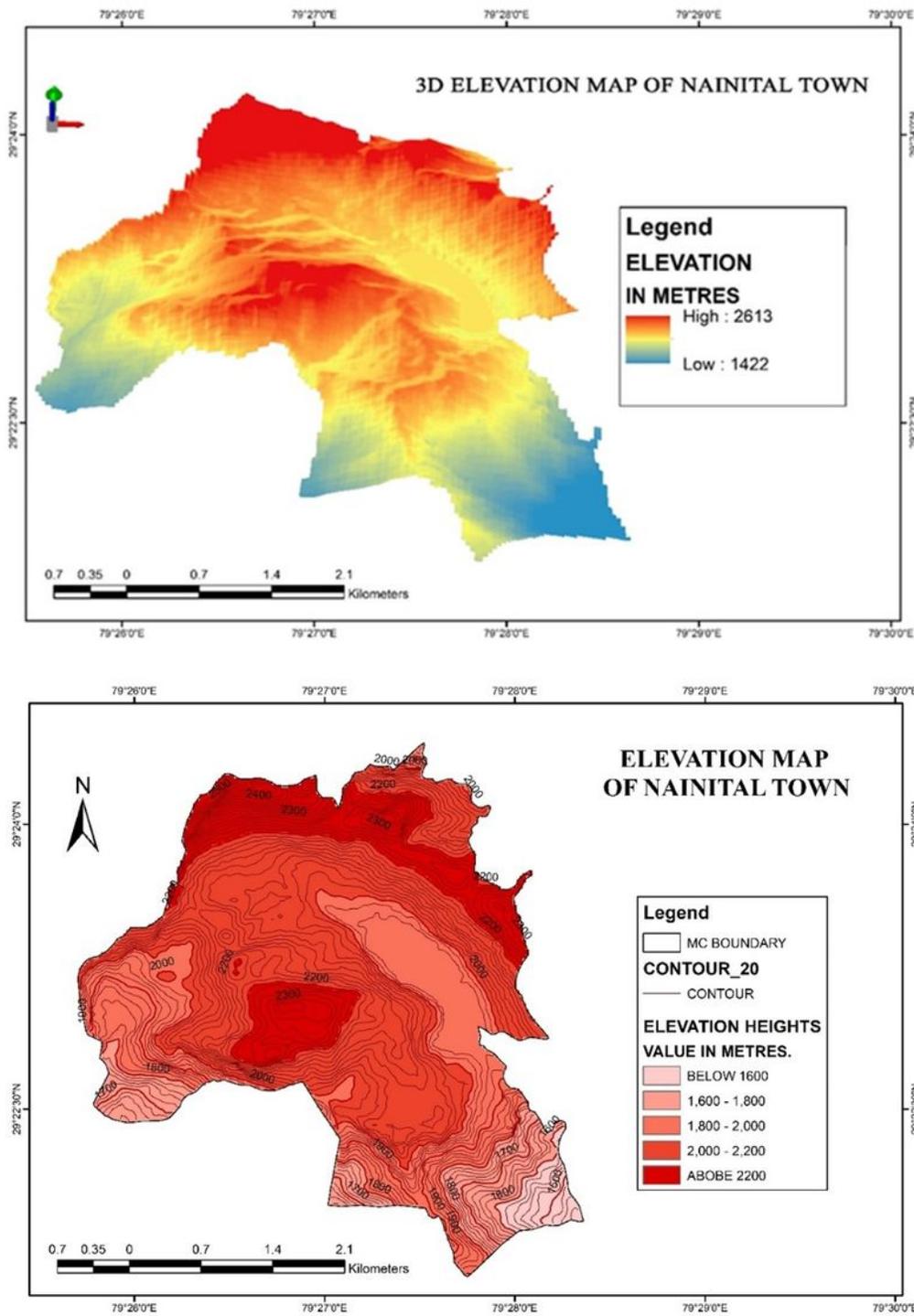
**Figure 7**

Slope Map of Nainital Town. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



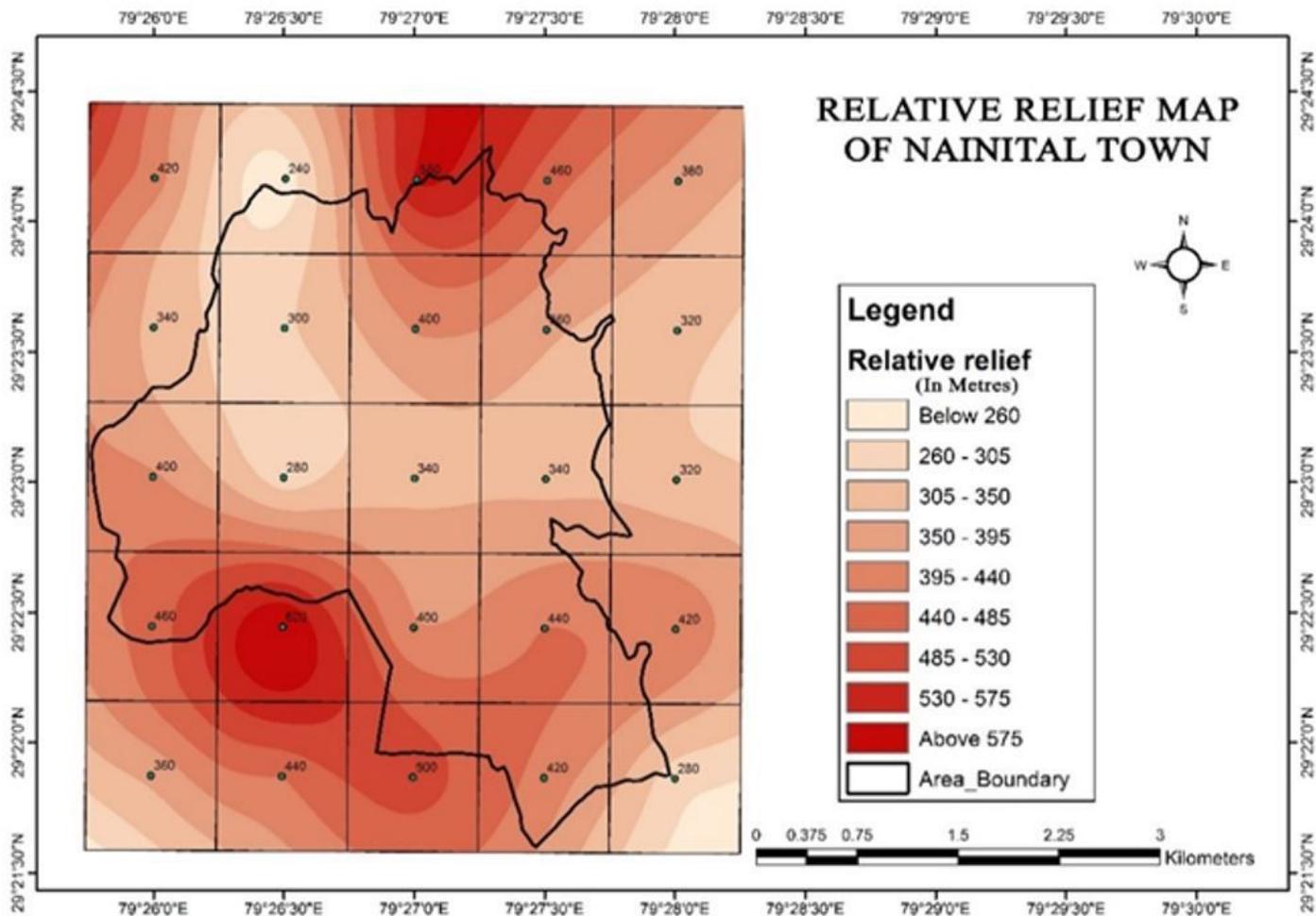
**Figure 8**

Aspect Map of Nainital Town. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



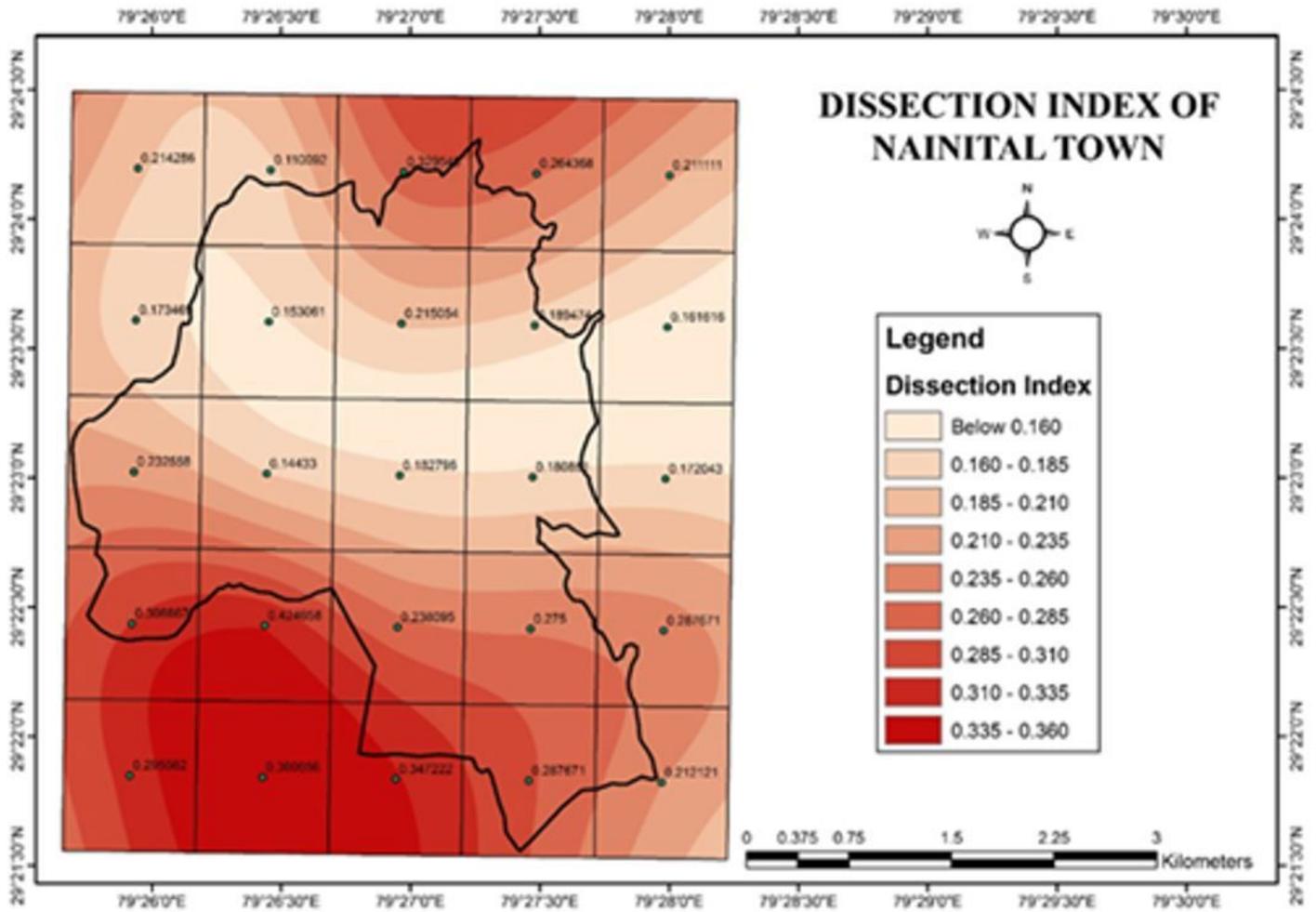
**Figure 9**

9a, b 3D Elevation Map of Nainital Town; Elevation Maps of Nainital Town. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



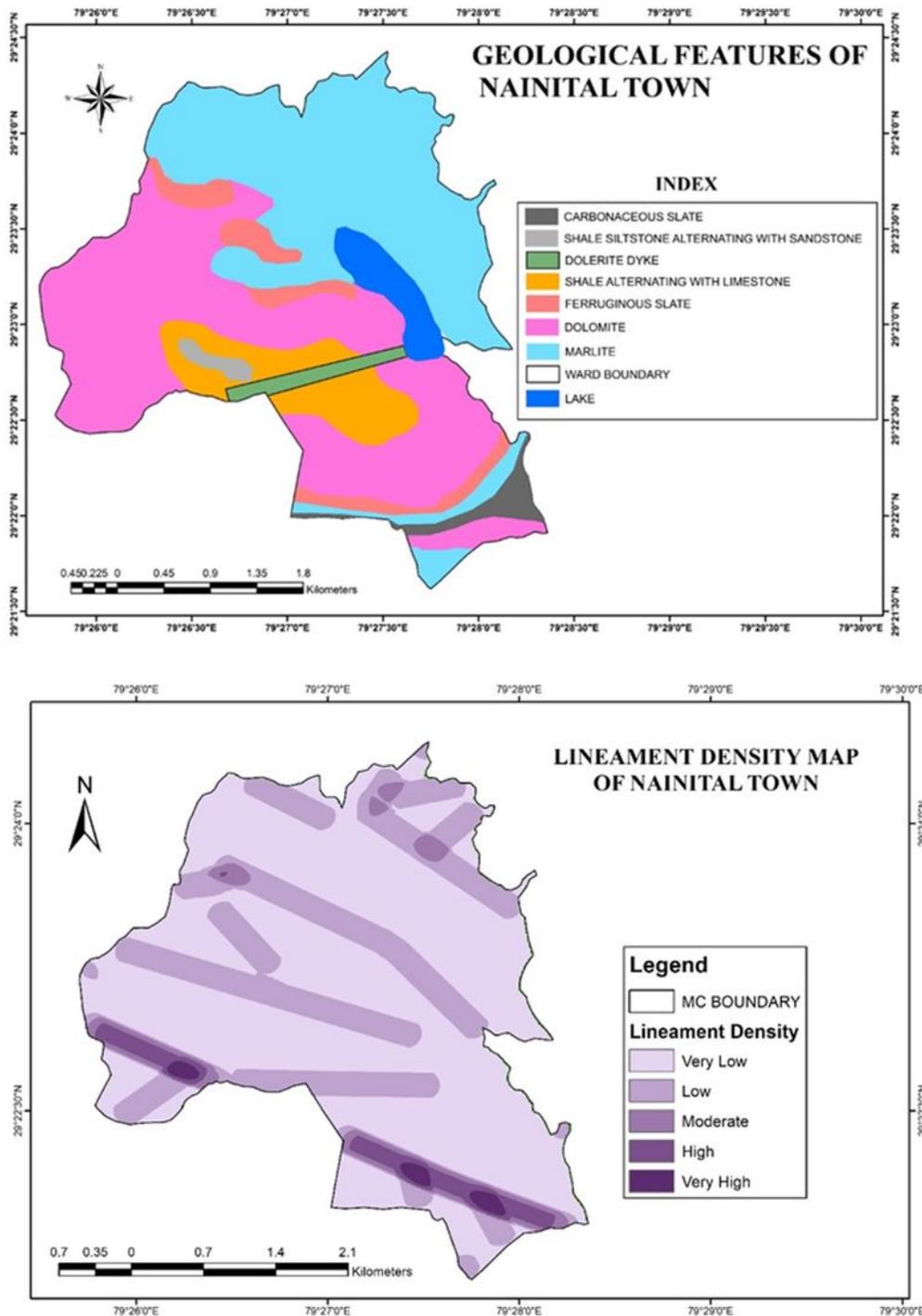
**Figure 10**

Relative Relief Map of Nainital Town. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



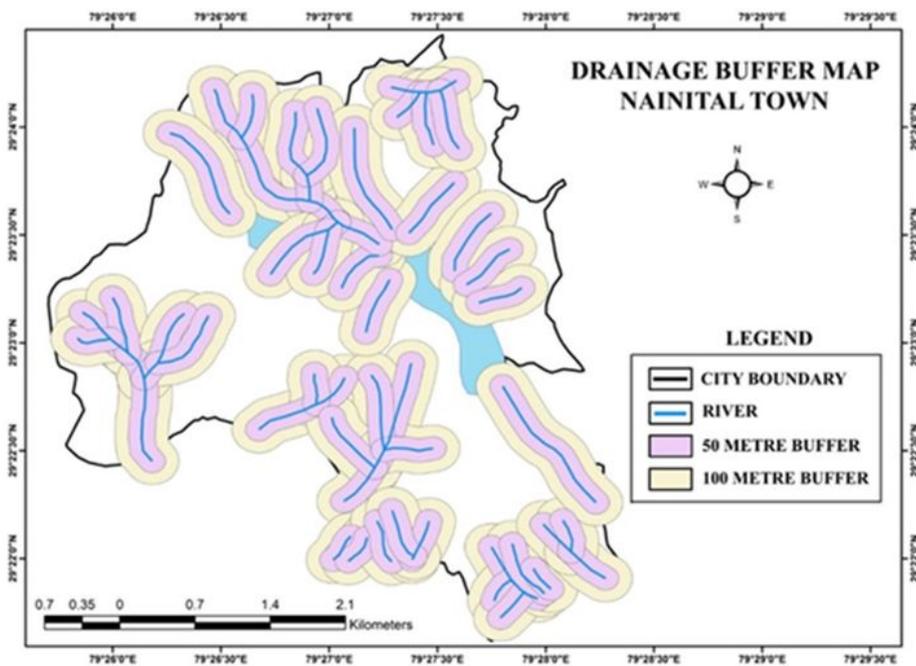
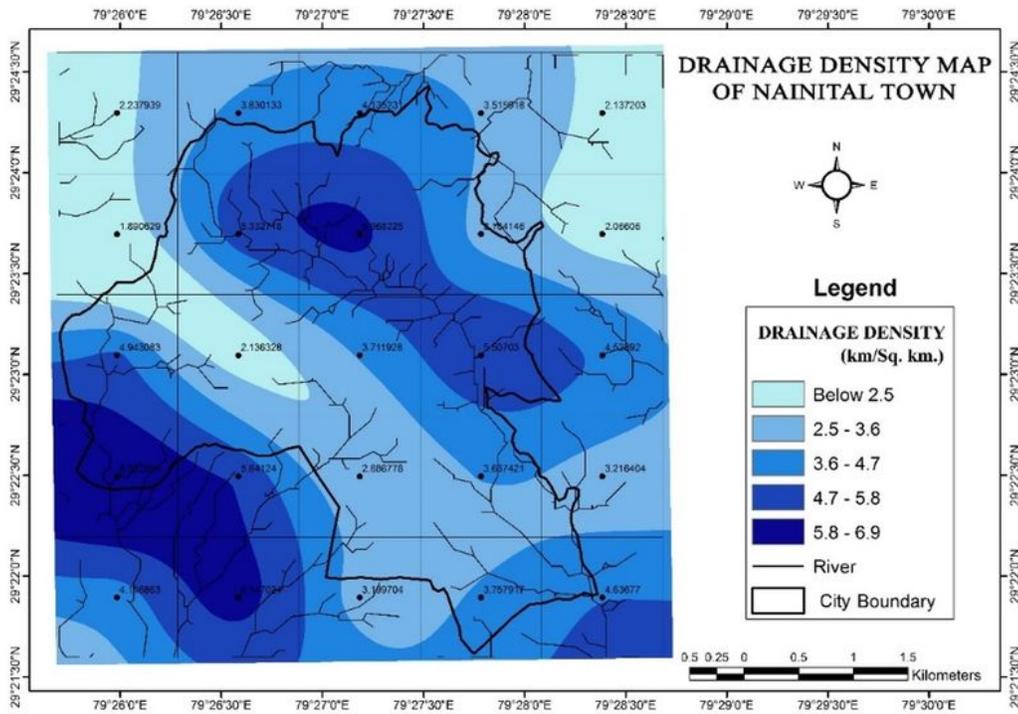
**Figure 11**

Dissection Index Map of Nainital Town. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



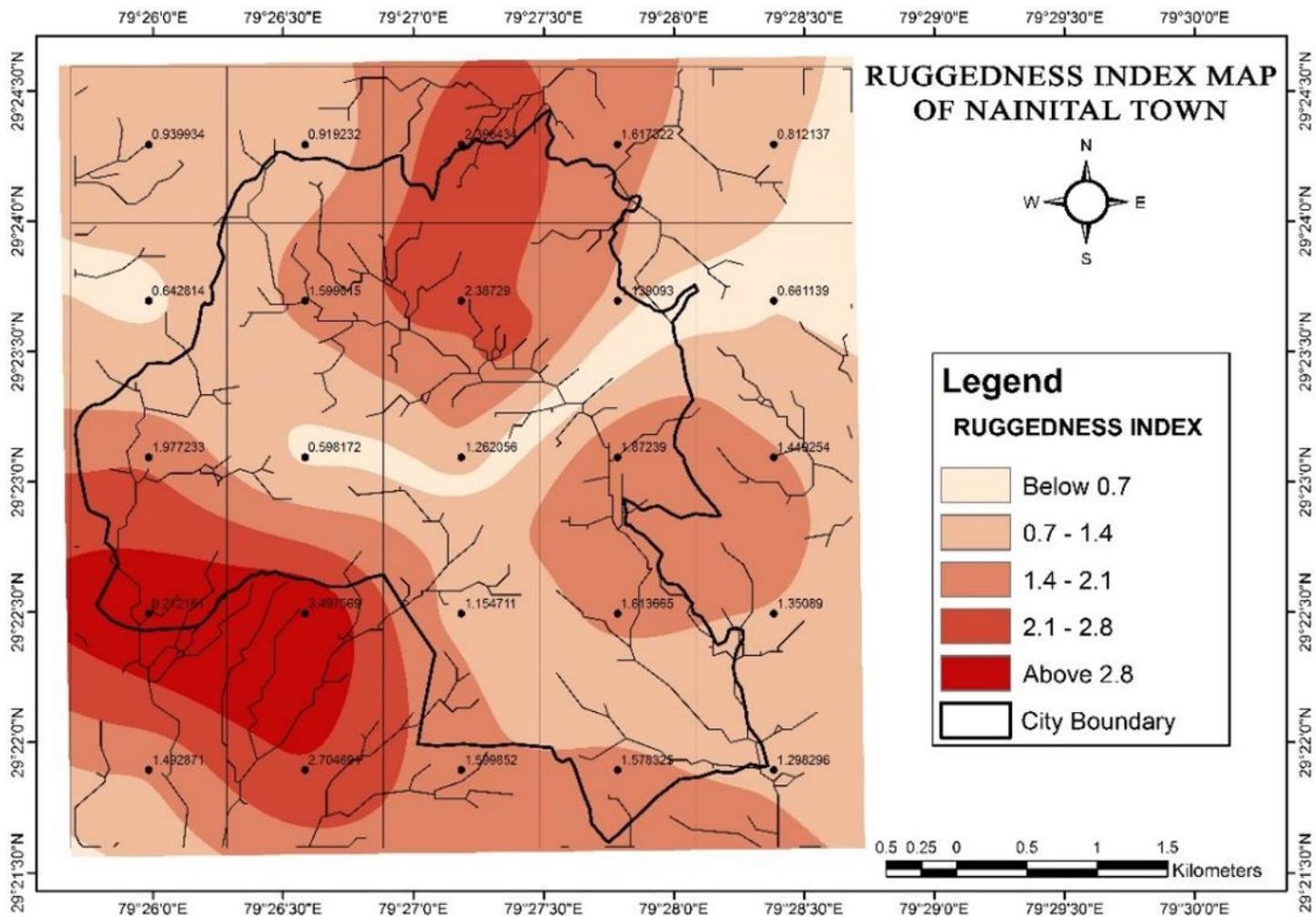
**Figure 12**

a, b Geological Features of Nainital Town; Lineament Density of Nainital Town 6.4 Drainage Density and Distance to Drainage. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



**Figure 13**

13a, b Drainage Density Map of Nainital Town; Drainage Buffer Map of Nainital Town. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



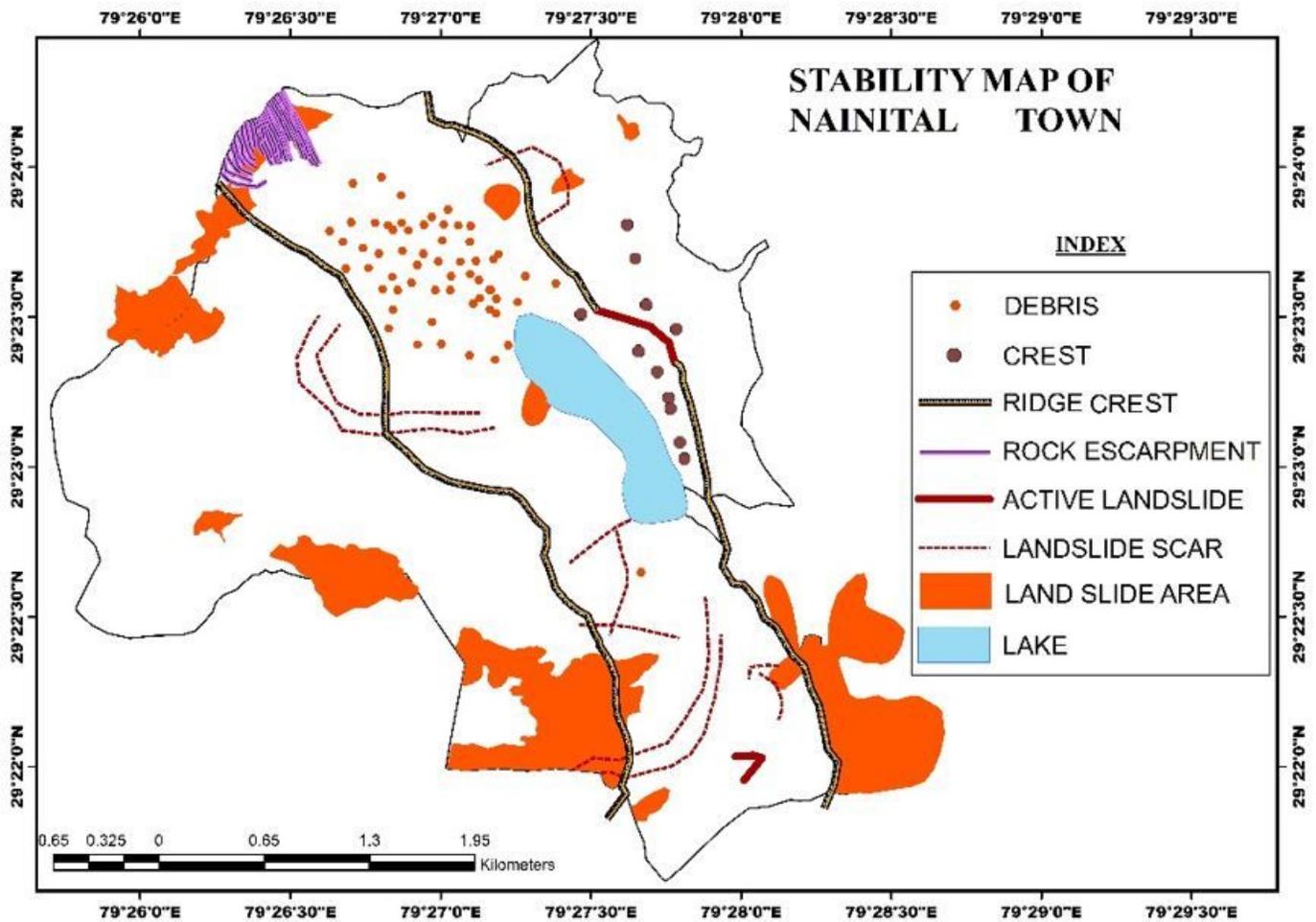
**Figure 14**

Ruggedness Index Map of Nainital Town. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



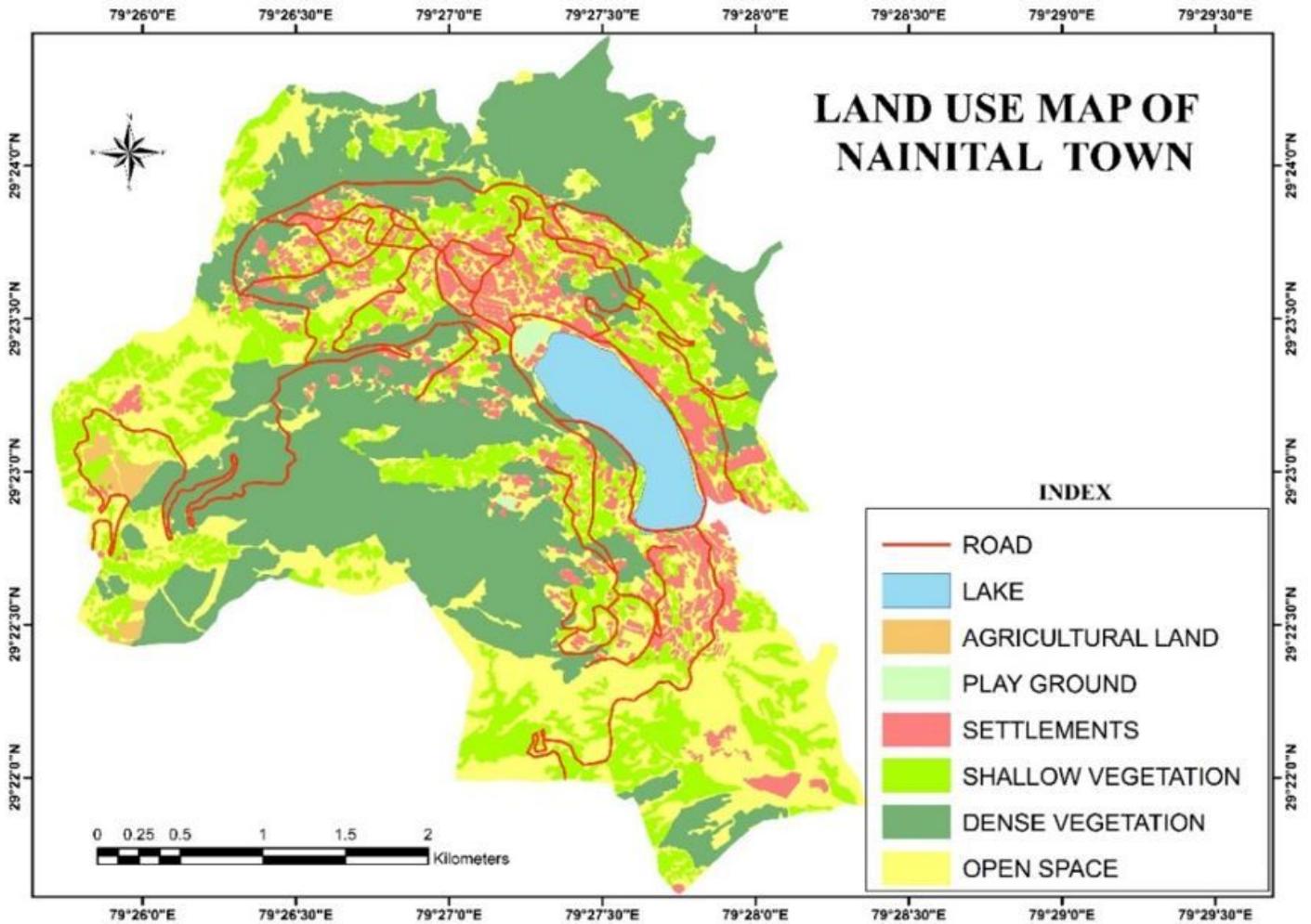
**Figure 15**

3D Topographic View of Nainital Town and Surrounding. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



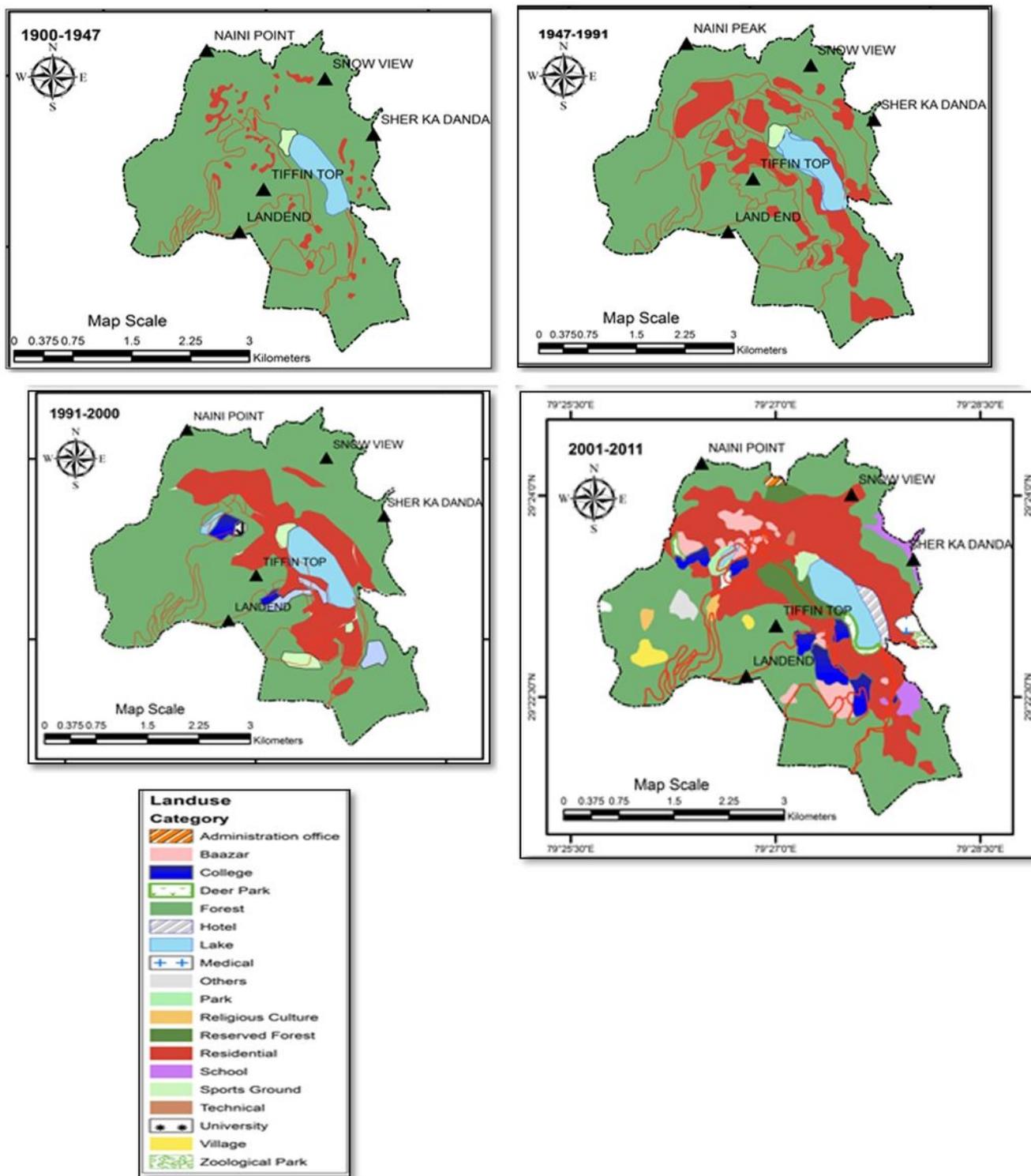
**Figure 16**

Stability Map of Nainital Town. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



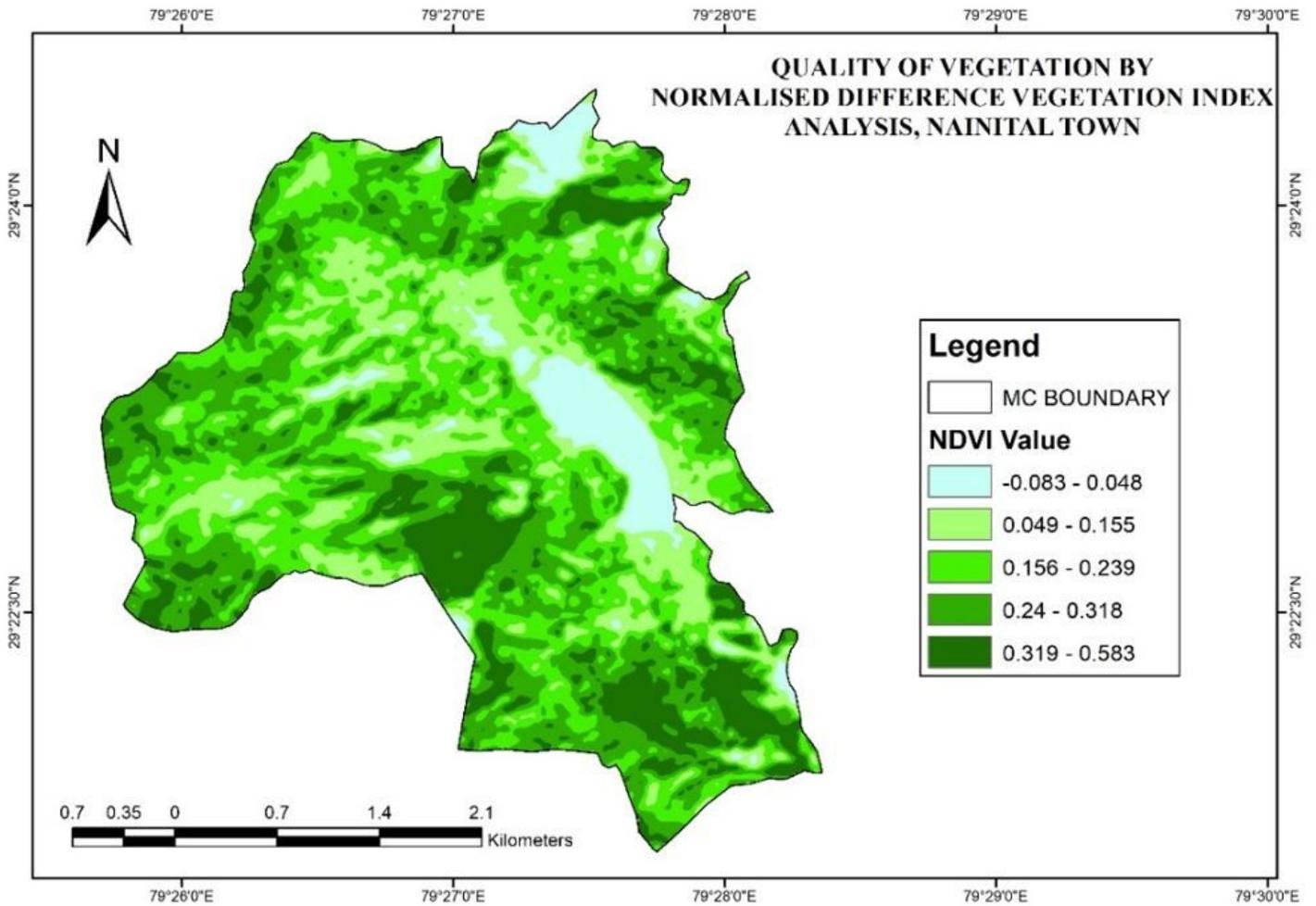
**Figure 17**

Land use Map of Nainital Town. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



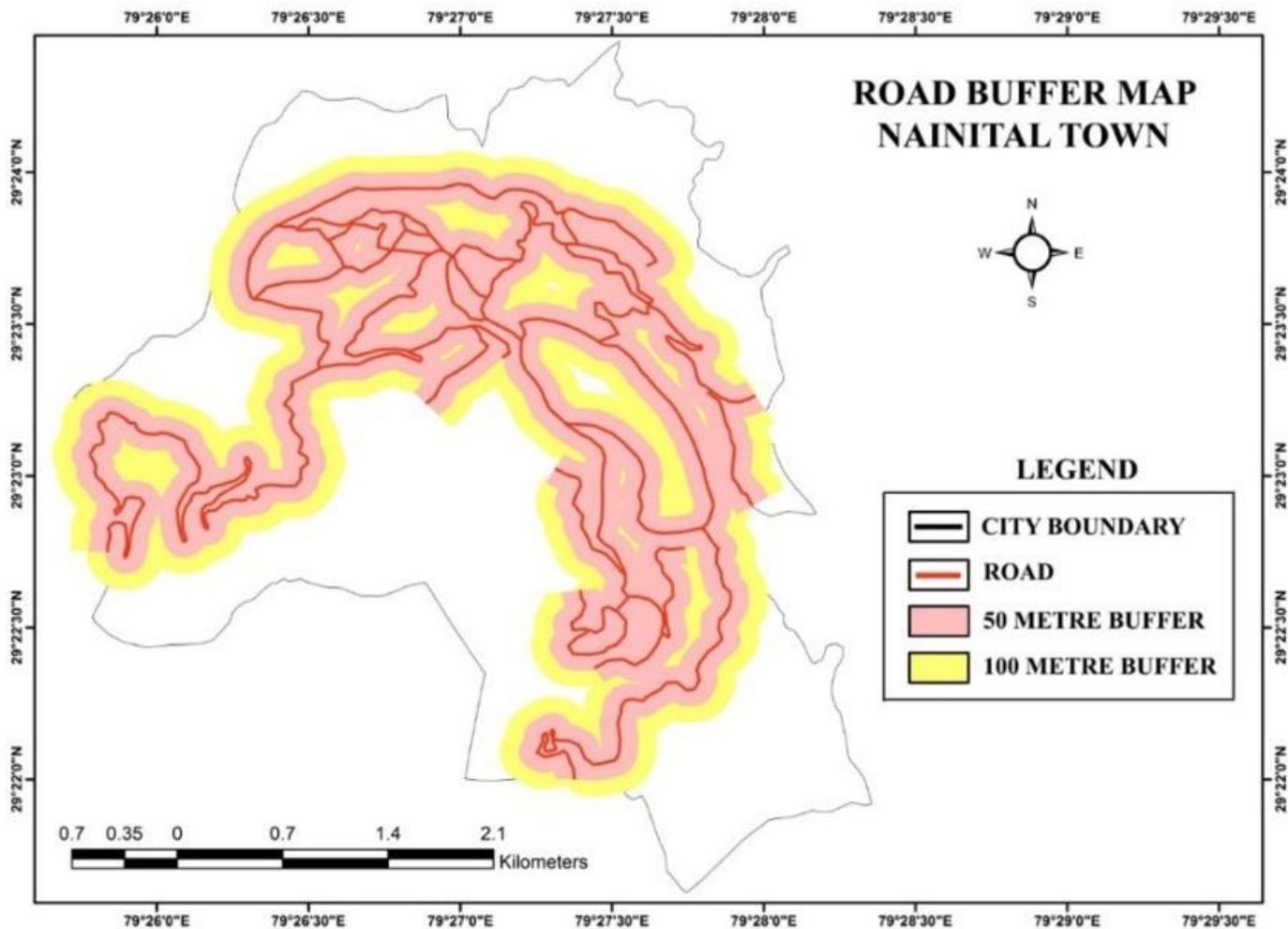
**Figure 18**

18a, b, c, d Evolution of Nainital Town Land use (1900 – 2011). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



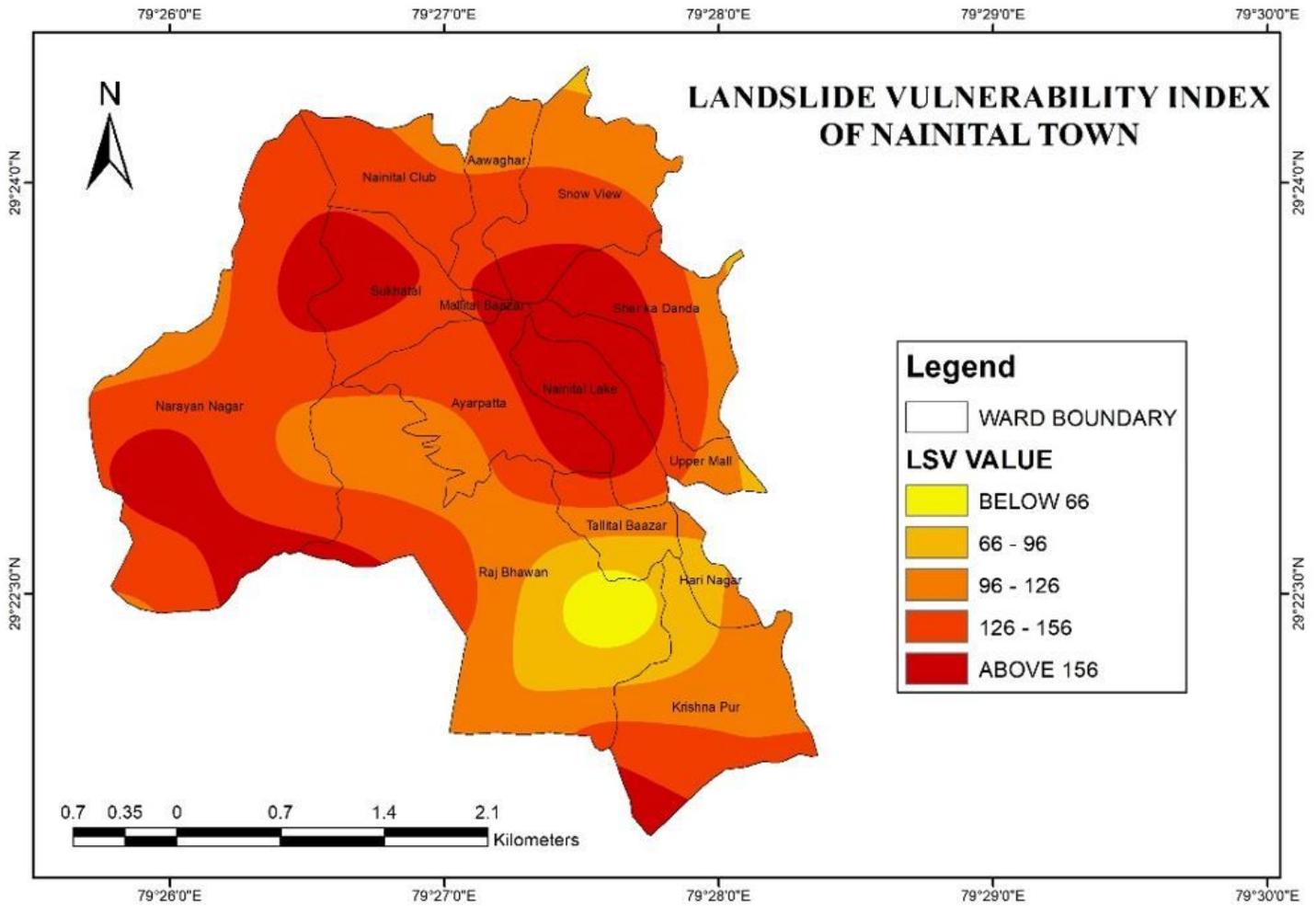
**Figure 19**

Quality of Vegetation by Normalised Difference Vegetation Index Analysis of Nainital Town. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



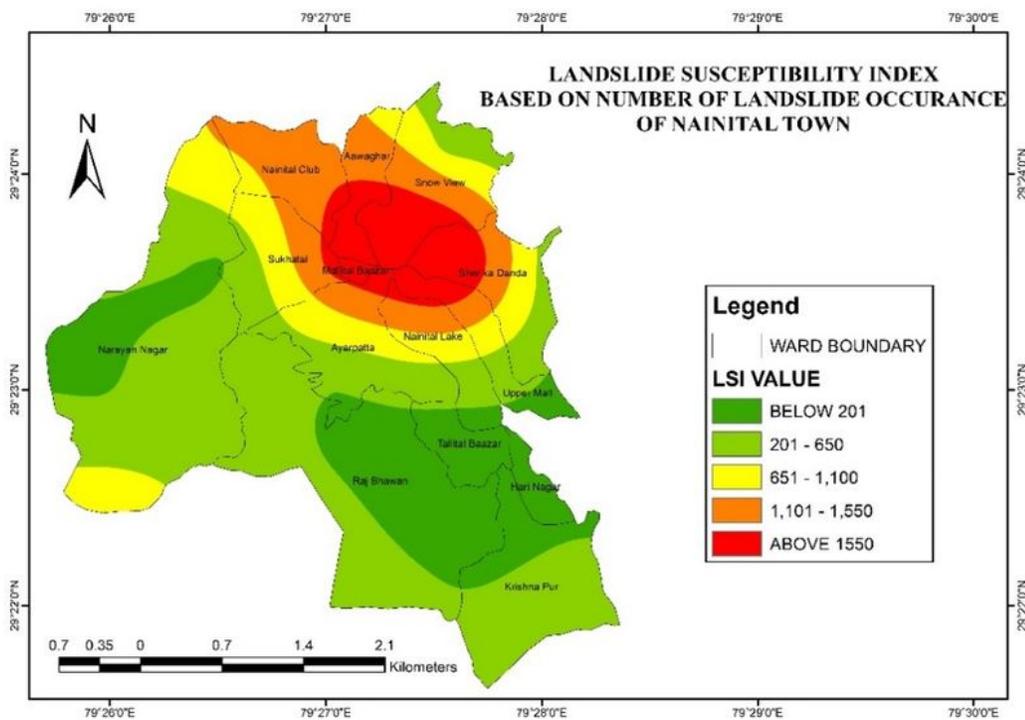
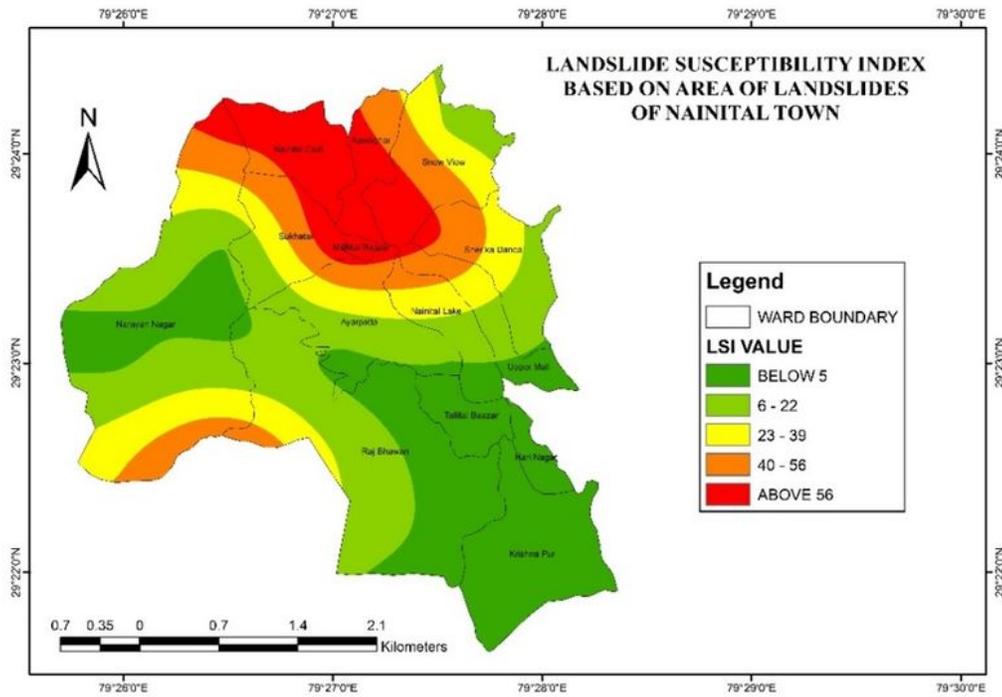
**Figure 20**

Road Buffer Map of Nainital Town. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



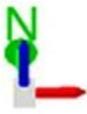
**Figure 21**

Landslide Vulnerability Index of Nainital Town. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

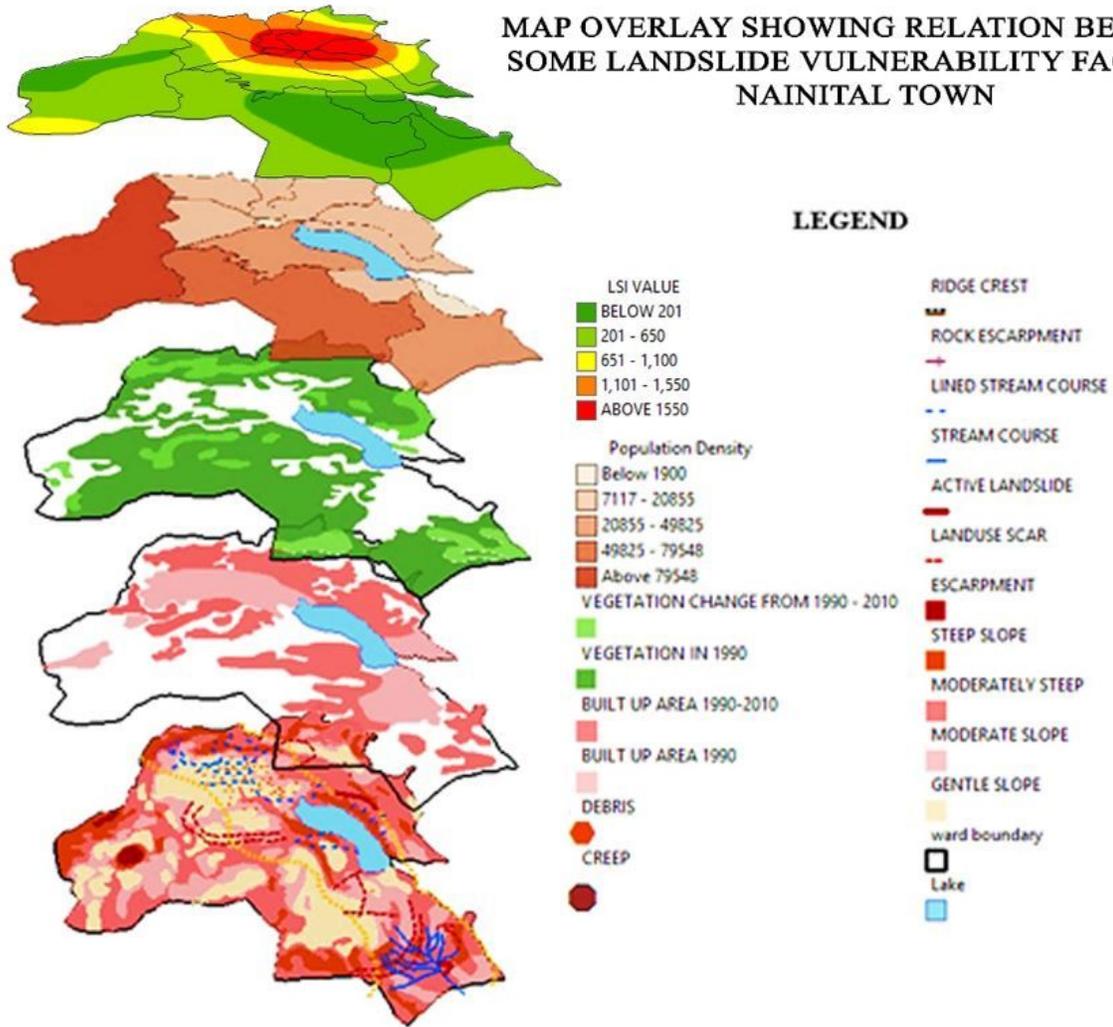


**Figure 22**

22a, b Landslide Susceptibility Index Maps of Nainital Town. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



### MAP OVERLAY SHOWING RELATION BETWEEN SOME LANDSLIDE VULNERABILITY FACTORS, NAINITAL TOWN



**Figure 23**

Map Overlay Showing Relation Between Some Landslide Vulnerability Factors, Nainital Town. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.