Geospatial analysis of climate change and emerging flood disaster risk in fast urbanizing Himalayan foothill landscape

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Himalaya foothill geo-environment is highly vulnerable for flood disaster due to climate change and dynamic upstream hydrological process which reshaped its downstream foothill geomorphology. Rapid urbanization has caused high rate of land-use change and natural resource degradation, enhancing the vulnerability of flood disaster in the region. The Ramnagar Himalayan Foothill area in Nainital district, Uttarakhand, India, has been selected for the case illustration. The key objective of the study was to investigate spatial dynamics of flood disaster risk due to climate change and rapid urbanization in the region. Development and integration of multiple GIS modules advocate that the extreme flood events have been increasing with the rate of four events/year due to climate change (i.e. increasing temperature and excessive rainfall events by 0.03 °C/year and two events/year, respectively). The fast urbanization and development of new colonies have caused to increase in built-up area (with 1.25% annually) and population density (with 87 persons/km² annually) under different flood hazard zones. Consequently, 29% area of very low flood disaster risk zone has been converted into moderate (6%), high (8%), and very high flood disaster risk zones (15%) at the annual rate of 0.31%, 0.40%, and 0.77%, respectively.

1. Introduction

Natural disaster risk refers to potential losses to society, economy, and environment by different geo-structural (earthquake, volcano, tsunami, slope failure, landslide, etc.), meteorological (cyclones, cloudburst, extreme weather events, etc.), and hydrological hazards (drought, flood, erosion, mass movement, landslide, etc.) (Jain et al. 1994; Shukla et al. 2001; Shukla & Bora 2003; Srivastava et al. 2003; Thakur 2004; Nearing et al. 2005). Occurrence and magnitude of these natural hazards depend on vulnerability (susceptibility to losses) of the landscape to a particular hazard (Alexander 1997; Bajracharya et al. 2007; Birkman 2007; Ebert et al. 2009; Rawat et al. 2011). So the vulnerability of the landscape and magnitude of hazard determine the qualitative and quantitative risk potentials of the respective hazard (Cutter et al. 2003; Goswami & Pant 2007, 2008). Changes in risk potential over a time period denote disaster risk dynamics (Brivio et al. 2002; Apel et al. 2006; Rawat 2013, 2014, Pant & Rawat 2015). Countries in the Himalaya region have a history of devastating earthquakes, floods, landslides, droughts, and cyclones that have caused economic and human losses (Valdiya & Bartarya 1991; Valdiya 2003; Rawat et al. 2012c; Pant & Paul 2007). Although the entire Himalaya is susceptible for natural calamities, but its foothill zone experiences frequent natural
disasters, such as flood, erosion, and landslides during monsoon period mainly due to its complex structural geology, geomorphology, and seasonality in hydro-meteorological conditions (Bull 1964; Dewey & Bird 1970; Hooke & Rohrer 1977; Birkland et al. 2003; Brody et al. 2007; Rawat et al. 2012a, 2012b). Flood and its associated disasters have been accelerated by climate change and increasing excessive rainfall events in the region, causing greater and longer-lasting damage to infrastructure and livelihoods in the region (Millly et al. 2002; Booij 2005; Kay et al. 2006; Graham et al. 2007; Leander & Buish 2007).

Studies pertaining to flood hazard and risk assessment and their triggering factors in the Himalayan region (Hamilton 1987; Haigh et al. 1988; Ives 1989; Valdiya & Bartarya 1989; Jain et al. 1994) have been carried out by various workers. There is no scientific basis to agree with the views expressed by them as there are multiple factors which may contribute to their acceleration during flood. The present study carried out with developing a multidimensional GIS database on geo-ecological informatics of the Himalaya foothills landscape. The present paper discusses geo-ecological GIS database comprising 12 flood-controlling factors and their 60 subfactors pertaining to flood hazard assessment and their mitigation. It may be emphasized that geo-ecological appraisal is a key need to formulate a disaster management plan at local or regional level, because it provides comprehensive scientific guidelines to implement safe developmental activities.

1.1. Study Area

The Ramnagar Himalayan Foothill area (RHFA) in Nainital district, Uttarakhand, India, has been selected for case illustration. Ramnagar Himalayan foothill area represents rich geo-diversity of the Sub-Himalaya mountain and its foothill zone within just about 64.82 km² between 300 and 505 m altitude above mean sea level, and lies between the latitude 29°20’41”–29°25’32”N and longitude 79°05’53”–79°09’48”E in the south-west part of Nainital district of Uttarakhhand state in India (Figure 1). The climate varies throughout the study area from tropical to subtemperate, respectively, between the lowest elevations to the highest elevations. Consequently, the average temperature varies between less than 20 °C within subtemperate zone to more than 24 °C within tropical climatic zone whereas average precipitating varies between below 180 and 220 cm, respectively, from tropical to subtemperate climatic condition. The study area comprises a fast-growing Himalaya foothill Ramnagar Municipal Town and its surrounding urbanized villages fall under Ramnagar Master Plan Town Area. The Ramnagar town is located at the right bank of Kosi River. It is a ninth-order non-glacial river and has a large catchment area (about 738 km²) which covers about 45% area of the Kumaun Himalaya mountain region. Consequently, the Kosi River brings very high volume of water and sediment load especially during monsoon season. A number of perennial and non-perennial streams flowing from Siwalik hills to its foothill plains discharges into Kosi River at different places from north to south, whereas some perennial and non-perennial streams flows towards south-west direction within the study area and discharges into Dhela River, flowing out of the study area. Neotectonically, the Ramnagar Himalaya foothill area is located in the active zones of the Himalaya because Himalayan Frontal Thrust and its associated number of faults and transverse thrusts (Shastri et al. 1971; Mohindra et al. 1992; Singh 1996, 2004; Gupta et al. 2001; Singh & Tandon 2006; Goswami & Pant 2007, 2008) pass across the study area; therefore, the geo-structural and hydrological backgrounds of the area being highly susceptible for natural disasters. The fast-growing urbanization and consequent land-use changes have accelerated this vulnerability, posing a great threat for the socio-economic development of the area.

To avoid the far-reaching environmental and socio-economic consequences of these geocalamities, it is essential to formulate a decision support system to implement optimum sustainable developmental planning considering all geo-environmental factors. Therefore, this reconnaissance study is an attempt to develop multiple GIS modules with their spatial and attribute data; using different geo-techniques; as remote-sensing data and GIS software, global positioning system which has been discussed below.
2. Methodology

The methodological procedure adopted, integrating different GIS modules for flood hazard and emerging disaster risk assessment, is shown in Figure 2.

2.1. Flood hazard assessment

Flood hazard assessment requires a comprehensive geo-ecological appraisal (comprises of geology, geomorphology, land-use pattern, hydrology, and climate) of the area using appropriate data and methods is discussed as follows:

2.1.1. Data collection and geo-referencing

Indian Remote Sensing Satellite (IRS-1C) LISS III (23.50 m spatial resolution) and PAN merged data of 2002 and Google earth data of 2014 have been used to develop geo-ecological informatics of
Ramnagar Himalayan Foothills. The satellite images of the study area were registered in Indigenous GIS software (Arc GIS-9 and Erdas Imagine-8.7) using Survey of India Topographical Sheets (53 O/3) at scale 1:25000 to generate different layers.

2.1.2. GIS modelling
Considering the shape, size, colours, and tones of the objects in the satellite data, an interpretation key generated to delineate required preliminary GIS maps and to develop comprehensive spatial and attribute geo-database of RHFA. Comprehensive field work has been done for detailed geological, geomorphological mapping and mapping natural water springs in the area. The preliminary GIS maps were also validated during fieldwork. These corrections were incorporated during final mapping in the GIS laboratory.

2.1.3. Data integration to assess spatial variability of flood hazard
Multiple spatial and attribute geo-database of Ramnagar Himalayan Foothill integrated and superimposed to identify the vulnerability of existing geo-environmental factors and their sub-factors for the flood hazards following scalogram modelling approach. It combined six GIS modules; these are geo-structural set-up (comprises geology and structural lineaments), relief pattern (comprises slope
and absolute relief), climate (comprises rainfall, temperature), land-use pattern (comprises built and non-built pattern), hydrology (comprises drainage order, drainage pattern, drainage density, and flood run-off), and geomorphology (comprises tectonic geomorphology and fluvial geomorphology). In scalogram modelling approach (Cruz 1992; Rawat et al. 2012a, 2012b, 2012c), an arithmetic operation was combined with the corresponding numerical weights for the main geo-factors and their sub-factors to generate a score that includes attributes.

In order to prepare the Flood Hazard Index (FHI) of the study area, total 12 major flood hazard triggering geo-ecological factors and their 60 sub-factors were transformed into weight map by assigning weightage to each class of major factors. Each main factor has been divided into five classes or sub-factors which were used to assigned weightage for flood hazard intensity. These sub-factors suggests that 1, 2, 3, 4, and 5 weights which are, respectively, indicative of very low, low, moderate, high, and very high to extreme causative factor for flood hazard. The numerical weights of the sub-factors, respectively, are variable and can be chosen based on field experience and experimental study results of a region. On the basis of these factors and their sub-factors, the following scalogram model was used for flood hazard zone assessment (Cruz 1992; Rawat et al. 2012a, 2012b, 2012c):

\[
FHI(\text{Score}) = \frac{X1(An) + X2(An) + X3(An) + X4(An) + X5(An) + X6(An) + X7(An) + X8(An) + X9(An) + X10(An) + X11(An) + X12(An)}{C138}
\]

where FHI is Flood Hazard Index; X1, X2, X3, X4, X5, X6, X7, X8, X9, X10, X11, and X12 are major factors: geology, structural lineaments, relief, slope, geomorphology, land use, climate, rainfall, drainage order, drainage pattern, drainage density, and flood run-off, respectively.

‘An’ is the total weight score (such as 1 + 2 + 3 + 4 + 5 = 15) of existing sub-factors or classes (respectively, A1, A2, A3, A4, A5) of a particular major factor.

In order that a spatial distribution map of the flood hazard was prepared by integrating the effects of multiple triggering factors by accumulating their assigned weight value calculated by the above equation for each 0.25 km² grid. This integrated weight values ranged from 12 to 60 throughout the study area and have been grouped into five zones: i.e. very low (below 13), low (13–26), moderate (26–39), high (39–52), and very high flood hazard susceptibility zone (above 52).

**Example:** To formulate FHI for a unit of 0.25 km², the following weight values were assigned with respect to existing geo-ecological sub-factors (A1–A5) of different main factors (X1–X12):

\[
FHI = \frac{X1(4) + X2(1) + X3(4) + X4(2) + X5(3) + X6(5) + X7(4) + X8(2) + X9(1) + X10(1) + X11(2) + X12(5)}{C138}
\]

Accumulate weight value = [4 + 1 + 4 + 2 + 3 + 5 + 4 + 2 + 1 + 1 + 2 + 5] = 34

This accumulate weight value of this grid unit subjected to moderate flood hazard as the accumulated weight value between 26 and 39 has been categorized for moderate flood hazard zone.

2.2. **Emerging flood disaster risk assessment**

It is strongly established that the Himalaya foothill landscape is the most vulnerable geo-ecosystem to flood disaster. Subsequently, this region has been experiencing emerging flood disaster risk due to negative geo-hydrological impacts of global climate change and fast urbanization since the last several decades (Millly et al. 2002; Booij 2005; Kay et al. 2006; Graham et al. 2007; Leander & Buishand 2007; Rawat et al. 2011). Keeping this in view, the meteorological data, land-use pattern, and
demographic data of the last three decades have been examined to assess, respectively, the trends of climate change, urbanization, and population growth in the area with the following methods:

2.2.1. Climate change monitoring
The climate change monitoring consists of the spatial distribution of climatic parameters through daily, monthly, and annual weather data (temperature, rainfall, humidity, and evaporation) for a period of 30 years during 1986–2015. Microclimatic variability assessment with elevation and aspect in the mountainous terrain and its foothill landscape mean that a rich density of data sampling sites is needed to capture representative meteorological data than plain areas where the terrain is more uniform. Consequently, the recorded meteorological data were collected from eight representative meteorological stations located within just 200 m height between 300 and 505 m altitude in the study area and its adjoining areas (Figure 1). Four stations (Gosala, Bairaj, Kalagad, Kotabag) run by irrigation department of Uttarakhand state government and two stations (Jalna and Aniya) established and run by the Geology and Geography Departments of Kumaun University were funded by the government of India under its different agencies, including the Department of Environment (during 1985–1990) and the Department of Science and Technology (during 2005–2016). The remaining tow station (Mohan and Sitabani) run by forest department of Uttarakhand state government. Although data from some stations (Mohan, Sitabani, Jalna, Aniya) are discontinuous, it’s compensated by the average data of neighbouring stations for the same years (Table 1 and Figure 1).

2.2.2. Urban growth and land-use change mapping
To monitor urban growth in flood hazard zones, the comprehensive land use/land cover for years 1995 and 2015 has been carried out. For carrying out this important exercise uniformly distributed common ground control points were selected and marked with root mean square (rms) error of one pixel and the images used were re-sampled by the nearest neighbourhood re-sampling method. Both the data-sets were then co-registered for further analysis initially, the LISS and PAN data were co-registered with rms error of 0.3 pixel and the output false colour composite was transformed into intensity, hue and saturation (IHS) colour space images. The reverse transformation from IHS to RBG was performed substituting the original high-resolution image for the intensity component, along with the hue and saturation components from the original RBG images. This merge data product obtained through the fusion of IRS–1C LISS–III and PAN was used for the generation of land-cover/land-use map of the study area. Digital image processing techniques supported by intensive ground truth surveys were used for the interpretation of the remote sensing data. Subsequently, to monitor the dynamics of land utilization pattern in the study area, the land-use maps generated for the years 1995 and 2015 were overlaid using Geographic Information System and land-use changes were detected and mapped. Normalized Difference Vegetation Index (NDVI)-based time series have been used to track extensive vegetation dynamics throughout the area. Principle component analysis (PCA) is a linear transformation of correlated variables into uncorrelated variables which does not change the number of variables (spectral and temporal bands). It’s utilizing the correlation matrix, was applied to NDVI composite images for year 1995 and 2015. The study adopted a stratified random sampling approach to select land use sample sites for assessment of the classification accuracy. Land-use maps for years 1995 and 2015 produced by the highest probability classification were subdivided into individual land-use strata. Sample sites were then arbitrarily disseminated throughout the study area for respective years land-use map using a random number generator in GIS. The x,y coordinates of the sample pixels were then identified in the digital reference data.

2.2.3. Demographic analysis
To monitor population growth in different flood hazard zones, a comparative demographic study of two periods has been carried out because population growth is a key characteristic of the fast
urbanization. It helps to determine the risk potential of disasters. The census data for years 1991 and 2011 studied to carry out the spatial distribution and density of the population in the existing flood hazard zones in the study area. Subsequently, the decadal and annual changes of the population growth and density were carried out.

2.2.4. Data integration to assess flood disaster risk under existing hazard zones
The three key parameters layers comprising flood hazard zones, land use/land cover, and population density maps were overplayed to assess the flood disaster risk under respective hazard zones for years 1995 and 2015. Each map has five classes which were used to assign weightage for flood disaster risk. These classes suggest 1, 2, 3, 4 and 5 weights which are, respectively, indicative of very low, low, moderate, high, and very high to extreme causative factor for flood risk. This integrated weight values ranged from 4 to 20 throughout the area and have been grouped into five zones: i.e. very low (below 4), low (4–8), moderate (8–12), high (12–16), and very-high-risk potential (above 16).

2.2.5. Spatial variability assessment of flood disaster risk
Two-period (1995 and 2015) flood disaster risk zone maps were overplayed to monitor spatial extension of risk under different flood hazard zones. Subsequently, the decadal and annual rates of emerging risk area under different flood hazard zones were carried out using 20-year change between 1995 and 2015.

3. Results
The study developed five broad GIS modules in order to accomplish the key objectives. These modules are geo-ecological informatics, hazard informatics, climate change informatics, land-use change and urban growth informatics, and emerging flood disaster risk informatics.

3.1. Database development on geo-ecological informatics
Spatial and attribute GIS database on existing geo-ecological parameters was developed to integrate all flood-controlling factors in the region. This module comprises the following:

3.1.1. Lineament
Topographic lineaments are linear appearance in the satellite data. Usually these are geophysical (comprises thrust- or fault- subsequent valley, structural fault succession, fold- and fault-aligned geomorphology, etc.) and linear infrastructural parameters (comprises road networks, canals, railway lines, etc.). Lineament orientations are dominantly found in NE to SW and NW to SE directions in the study area (Figure 3(a)).

3.1.2. Geology
The study area is located on two physiographic regions: the Siwalik Hills in the north and the piedmont fan in the south. The Siwalik region comprises Upper Siwalik and Middle Siwalik rocks whereas the piedmont comprises Bhabar and Tarai alluvium as demonstrated in Figure 3 (b). The settlements are largely situated on a large Ramnagar fan. The Upper Siwalik constituted of pebbles, cobbles, boulders, conglomerates and clay lenses. Thin lenses of grey to light green colour clays are common. Outcrops of upper Siwaliks are exposed in the northern part of the study area; covered about 12% (7.78 km²) part of the study area. The Middle Siwalik characterized by massive light grey micaceous sandstones. They exhibit sporadic patterns of cementation at different stratigraphic intervals. The Middle Siwalik rocks covered about 14% (9.07 km²) part of the study area. Bhabar alluvium comprised poorly sorted unconsolidated sediments, viz. gravel, pebbles, sand and silt with intervening clay layers. The lithological
constituents are of heterogeneous nature, viz. basic, acidic, and intermediate along with epiclastics and metamorphic lasts. Clay lenses are of limited extent. The belt exhibits NW–SE elongation. Its northern boundary has an abrupt structural with lower Siwalik. Bhabar alluvium covered the maximum part about 4% (2.64 km²) of the study area. Tarai formation consists of sand, clay, silt, sandy clays, and occasionally gravel. The Tarai deposits represent the finer fluvial deposits brought by the streams from the hilly tracts. It forms a small part of the study area.

3.1.3. Relief
It denotes the maximum height in a unit area from the mean sea level. In order to analyse the absolute relief, the study area has been divided into grid of 0.25 km² on the Survey of India Topographical Maps and the maximum heights of all the grids were determined on the map. The spatial distribution of absolute relief in the region has been presented in Figure 4(a). It reveals that the study area has been divided into six zones of absolute relief between less than 330 m and above 450 m from mean sea level. The maximum part of about 37% (23.98 km²) of the study area has low-relief surface below 330 m, whereas the minimum proportion of about 5% (3.24 km²) of the study area falls under moderate high-relief surface (above 420 m from mean sea level).

3.1.4. Slope
Slope is the angle of proclivity of the ground surface on the horizontal plane, i.e. the plane parallel to the earth surface (Zhou & Liu 2014). The analysis of slope and its depiction on the map has been of a special concern for the interpretation of landforms. The slope map also expresses in an implied way the geo-hydrological properties, such as the amount of moisture content. The analysis of slope is highly useful in estimating the amount of water discharge in streams and springs. Besides, the slope has its geological importance as many of the geological features, i.e. faults are easily recognized or explained with the help of slope angle. The spatial variability of slope throughout the study area is demonstrated in Figure 4(b), which indicates the maximum area of about 47% (30.47 km²) having less than 4° slope, whereas about 5% (3.24 km²) of the study area have more than 20° slope (Figure 4(b)).
3.1.5. Climate

According to the meteorological characteristics for the last several decades, the study area may be
categorized into four micro-climatic zones from 305 m altitude of Tarai alluvial plain in the south-
west to 505 m altitude of upper Siwalik hill in the north-east of the study area. The spatial variability
of these micro-climatic zones is demonstrated in Figure 5(a). The spatial variability and weather
characteristics of each climatic zone are being discussed as follows:

3.1.5.1. Tropical climatic zone. The extreme southern part of the study area between altitudes 305
and 325 m from mean sea level has tropical climatic conditions and covers about 19% (12.32 km²)
part of the study area. In this zone, the mean annual rainfall varies from 165 to 180 cm, and the
mean annual temperature varies from 24 to 25 °C (Figure 5(a)).

3.1.5.2. Subtropical climatic zone. The maximum proportion of the study area enjoys subtropical
climatic conditions between altitudes 325 and 410 m from mean sea level and covers about 61%
(39.54 km²) part of the study area. The mean annual rainfall varies from 180 to 200 cm and the mean
annual temperature varies from 22 to 24 °C throughout the subtropical climatic zone (Figure 5(a)).

3.1.5.3. Moist subtropical climatic zone. The north-west part of the study area between altitudes
410 and 450 m from mean sea level has tropical climatic conditions and covers about 12%
(7.78 km²) part of the study area. The mean annual rainfall varies from 200 to 220 cm and the mean
annual temperature varies from 20 to 22 °C throughout the tropical climatic zone (Figure 5(a)).

3.1.5.4. Subtemperate climatic zone. Siwalik hills above moist subtropical climatic zone varies ele-
vation between 405 and 550 m from mean sea level; have subtemperate climatic conditions; and cov-
ers minimum area about 8% (5.19 km²) part of the Ramnagar Himalayan Foothills. The mean
annual rainfall varies from 220 to 235 cm, and the mean annual temperature varies from 19 to
20 °C throughout the tropical climatic zone (Figure 5(a)).

Figure 4. Spatial variability of absolute relief (a) and slope (b) in RHFA.

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20 °C throughout the tropical climatic zone (Figure 5(a)).
3.1.6. Land-use pattern

Land use/land cover is a significant aspect of geo-environmental study (Hamilton 1987; Haigh et al. 1988; Ives 1989; Valdiya & Bartarya 1989, 1991). The land use reflects anthropogenic activities such as residential zones, agricultural fields, industrial zones, grazing, logging, and mining among many others, whereas land cover is distinct by the characteristics of the land surface occupied by natural vegetation, water, desert and ice, the abrupt subsurface, etc. (Rawat et al. 2012d). Land-use/land-cover pattern of the RHFA broadly categorized as built-up area and non-built-up area, which has been discussed below:

3.1.6.1. Built-up area. It poses structured environment of the land surface, comprises existing settlements with road network, bridle paths, canals and river dams, etc. Apart from that the waste land category, emerged by newly developing colonies, throughout the Ramnagar Himalayan foothill area, has been recognized as built-up area which covers about 26% (16.86 km²) part of the study area (Figure 5(b)). A brief description on each category of built-up area is given as follows:

Settlements: Mainly three types of settlements exist in the RHFA: these are domestic (residential houses, farmhouses), official (individual and governmental offices, schools and colleagues), and commercial (shops, workshops, hotels, restaurants, guesthouses) buildings besides necessary road network, canals and river dams, etc. (Figure 5(b)). These all types of settlements simultaneously covered about 19% (12.32 km²) area of the RHFA.

Colonized waste land: Since the last several years, a significant proportion of the rural population of Himalaya Mountain has been migrating to adjoining foothill plain areas for better lifestyle and livelihood. This trend has been accelerated in Uttarakhand state after its separation from UP as a new state of India in year 2000. Consequently, in RHFA, several new colonies are being developed in the agricultural and horticultural land by the colonizers and builders. Unfortunately, out of the total area of each newly developed colony, only 30% area is being acquired by immigrant people to build their houses, whereas 70% area is being acquired by the local brokers for business purpose as they sell out it with big profits in future. Keeping in view the increasing cost of such types of land, the brokers wait for a long period of years to decades for maximum profit. Newly developed colonies have emerged, a new land-use category, throughout the area which has been recognized as waste.
land built-up area because of no use of this land under developing colonies. Waste land built-up area covers about 7% (4.54 km²) of the area (Figure 5(b)).

3.1.6.2. Non-built-up area. It poses natural environment of the land surface, which comprises vegetation, agriculture land, horticulture land, and shrubs land of the study area. Non-built-up land covers about 74% (47.96 km²) of the study area, whereas its spatial distribution under different land categories has been discussed as follows:

Vegetation cover: It comprises forest and shrubs land area. Out of the total area, about 32% (20.74 km²) is under forest land whereas about 9% (5.83 km²) is covered by shrubs land (Figure 5(b)). The species of forest and shrubs throughout the study area varies greatly according to the elevation and climatic conditions from foothill plain to Siwalik Hills. In the foothill plain, the main species of the forest are Sal (Shorea robusta), Sheesam (Dalbergia sissoo), and Sagwaun (Tectona grandis), whereas multiple tropical shrubs species exists under the trees of this forest. The forest in Siwalik hill of the study area comprises 'sain' (Terminadiaichiboca), 'Sandar' (Oytheinia balbiraginrites), 'Aaonla' (Ambica officinalis), 'Chyara' (Madhucabury racca), whereas shrubs species are Dhauila (Woodfordia fruticosis), Hisalu (Rubus), Tungla (Bhespani flora), etc.

Agricultural land: It comprises crop land and horticultural land, respectively, which cover about 24% (15.56 km²) and 6% (3.89 km²) parts of the area (Figure 5(b). In the area, seasonal crops are grown. Spatial variability of crop pattern and horticulture practice also varies greatly according to the elevation and climatic conditions from foothill plain to Siwalik Hills.

Riverbed: The streams bring huge amount of sediment load and deposit it in downstream forming huge channel sandbars. Such type of land covers about 3% (1.94 km²) part of the area (Figure 5(b)).

3.1.7. Geomorphology
The geomorphic features of the study are interpreted on satellite data to prepare a preliminary geomorphological map (Figure 6(a)). The interpretation errors have been identified during field mapping (left side) to carry out detailed geomorphological map (right side).
mapping and incorporated to carry out a final geomorphological map after overlaying other required GIS layers (Figure 6(b)). These landforms have been categorized under macro-geomorphology and micro-geomorphology and described as follows.

### 3.1.7.1. Macro-geomorphology

The landforms which have regional extension are categorized as macro-geomorphology. The major regional geomorphic features recognized in the area are tectonic lineaments, gravelled hilly terrain, piedmont zone, river terraces, alluvial plain, drainage divide, and long and gentle-dip slopes.

### 3.1.7.2. Micro-geomorphology

The landforms which have limited extension at different locations throughout the area are categorized as micro-geomorphology (Figure 6). These are comparatively younger landforms and take place on the preliminary regional landforms. The existing regional geomorphic features investigated in the study area are steep and small anti-dip slopes, terrace scarps, younger alluvial fans, debris flow sites, tectonic valleys and subsequent streams, abandoned channels, and triangular facets (Figure 6).

### 3.1.8. Hydrology

The RHFA is a non-glacial hydrological regime. Consequently, the hydrological process completely depends on precipitation pattern. In order that the precipitation is the key source of water flows in the streams within Himalayan foothill area. These streams provide water for household consumption and irrigation to the dense population of the area. Although the hydrology comprises multiple parameters, the present attempt focuses only to explore the existing surface hydrology (drainage pattern, orders, spatial distribution, density, and water discharge to assess surface run-off pattern).

#### 3.1.8.1. Drainage pattern and order

Drainage map of the area shows elongated, triangular, oval, less circular, to circular drainage pattern with a rich network of first-order to ninth-order perennial and non-perennial streams. Perennial streams flow throughout the year whereas non-perennial streams flow during four months of the monsoon period (June to September) and one month after the monsoon period (October). A total of 113 streams were mapped in area out of which 36% (41 streams) are perennial and 64% (72 streams) being non-perennial (Figure 6(a) and Table 1). Perennial streams comprises 18 (16%) first-order streams, 12 (11%) second-order streams, 8 (7%) third-order streams, and 2 (2%) fourth-order streams, whereas non-perennial streams comprises 54 (48%) first-order streams, 16 (14%) second-order streams, and 2 (2%) third-order streams (Figure 7(a) and Table 1).

#### 3.1.8.2. Drainage density

It is expressed as the length of streams in a unit area. The RHFA has been divided into four drainage density classes on the basis of the above analysis (Table 1). About 22.04 km² amounting to 14% of the total area of the Ramnagar Himalaya Foothill lies around the southern area. The index of drainage density in this class stands at less than 1 km/km², around Bhabar and Tarai alluvial plain with small segments of a single first-order stream and a small segment of

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Table 1. Attribute data on spatial variability of drainage density with existing stream orders in Ramnagar Himalayan foothill area.

| Drainage density zones | Drainage density (km/km²) | Number of different order streams in respective zone | Covered area |
|------------------------|----------------------------|----------------------------------------------------|--------------|
|                        | I  | II | III| IV | V  | VI | VII| VIII| IX | km² | %        |
| Very low               | 1  | 0  | 0  | 0  | 0  | 0  | 0  | 0   | 1  | 22.04| 34.00    |
| Low                    | 1–2| 1  | 4  | 2  | 0  | 0  | 0  | 0   | 1  | 25.28| 39.00    |
| Moderate               | 2–3| 5  | 5  | 0  | 0  | 0  | 0  | 0   | 1  | 7.13 | 11.00    |
| High                   | Above 3| 20 | 7  | 0  | 0  | 0  | 0  | 0   | 1  | 10.37| 16.00    |
| Total                  | All above | – | –  | –  | –  | –  | –  | –   | –  | 64.82| 100.00   |
ninth-order stream (Figure 7(b) and Table 1). A large part (25.28 km²) accounting to 39% area of the Ramnagar Himalaya Foothill with low drainage density category of 1–2 km/km² with the total length of 11 first-order, 1 second-order, 2 third-order, 1 fourth-order streams, and a small segment of ninth-order Kosi river (Figure 7(b) and Table 1). Nearly 11% (7.13 km²) falls in moderate drainage density around the western part. The index of moderate drainage density areas varies between 2 and 3 km/km² with the total length of 14 first-order streams, 5 second-order streams, 5 third-order streams, and a small segment of ninth-order Kosi river (Figure 7(b) and Table 1). About 16% of the total area of the Ramnagar Himalaya Foothill in the northern areas falls in high drainage density that accounts 10.37 km² having greater than 3 km/km² with length of 55 first-order streams, 20 second-order streams, 7 third-order streams, and a small segment of ninth-order Kosi river (Figure 7(b) and Table 1). The analysis of drainage density clearly reveals that the RHFA represents the moderate to well-drained landscape with greater run-off and less infiltration which results in flood hazard in rainy season.

3.1.8.3. Flood runoff. It is peak flow of surface run-off during heavy rainfall in the monsoon period. Rawat (2013, 2014) carried out the flood run-off rate of its adjoining Dabka river basin for varied geo-hydrological systems that have been followed in the present study (Figure 8(a)). The natural land surface helps in controlling the floods through a rich cover of trees, plants, shrubs, and different types of grasses, whereas the built-up area covered by settlements, roads, canals, etc. generates high rate of floods due to very poor possibility of groundwater percolation. Consequently, the least stressed land surface under dense forest cover has very low flood run-off rate as it accounts an average of about 58.12 l/s/km² of the study area. The highly stressed land under built-up areas on moderate to high slopes has maximum flood-generating capacity, where the flood magnitude stands an average of about 1180 l/s/km² of the study area. It is being 20 times higher than the flood magnitude of the least stressed dense forest land. On other ecological conditions, the magnitude of maximum flood run-off varies between 430 and 630 l/s/km² on shrubs/waste land and agricultural land (Figure 8(b) and Table 2).
3.2. Hazard informatics

The spatial and attribute database developed under the above geo-environmental GIS module with their 12 key flood-controlling factors (i.e. geology, structural lineaments, relief, slope, geomorphology, land use, climate, rainfall, drainage order, drainage pattern, drainage density, and flood run-off) and 60 sub-factors was transformed into weight map by assigning weightage to each class of major geo-factors following scalogram modelling approach (Cruz 1992; Rawat et al. 2012a, 2012b, 2012c). As discussed in Section 2, an arithmetic operation was combined with the corresponding numerical weights for the main geo-factors and their methodological sub-factors to generate a score that includes attributes (Table 3). Figure 9 illustrates the spatial distribution of these flood hazard susceptibility zone in different locations in the study area and the description is given as follows:

![Figure 8](image)

**Figure 8.** Extreme flood magnitude measured at the mouth of six sample watersheds under varied geo-ecosystem (left) to appraise spatial variability of flood run-off in RHFA (right).
Table 3. Flood hazard geo-informatics (FHGI) include 12 main factors (X) and 60 sub-factors (A) of six GIS modules which have been considered for weightage assignment for very low to very high causative factors of flood hazard.

| Sub-factors: A | Ramnagar environmental geo-informatics (main factors): X | Flood hazard informatics |
|---------------|----------------------------------------------------------|--------------------------|
|               | Geo-structural informatics | Relief informatics | Geomorphic informatics | Land-use informatics | Climate informatics | Hydro-informatics | Flood run-off (l/s/km²) | Assigned weightage as flood causative factor |
|               | Geology with rock types | Structural lineament | Relief (m) | Slope classes | Landforms | Built and non-built patterns | Average rainfall (cm) | Drainage order | Drainage pattern | Drainage density (km/km²) | |
| A1            | Upper Siwalik quartzitic rocks | Fold-aligned hills | Above 450 | Below 4' | Gravelled hilly terrain | Forest land | Tropical | Below 150 | Below II order | Elongated (<0.7) | Below 100 | 1. For very low causative factor |
| A2            | Middle Siwalik massive sandstones | Joint/fractures zones | 420–450 | 4'–8' | High-level fluvial terraces | Scrubs land | Subtropical | 150–175 | II–IV order | Triangular (0.7–0.8) | 100–200 | 2. For low causative factor |
| A3            | Large rock blocks and boulders of Share zone | Shear zone | 390–420 | 8'–12' | Middle-level terraces | Agriculture land | Moist subtropical | 175–200 | IV–VI order | Oval (0.8–0.9) | 2–3 | 3. For moderate causative factor |
| A4            | Bhabar alluvium made up of gravel, pebble, sand, and silt | Fault/thrust-aligned valley | 360–390 | 12'–16' | Low-level terraces, terrace scarps, landslide debris flows areas | Barren land and waste land | Subtemperate | 200–225 | VI–VIII order | Less circular (0.9–0.10) | 400–600 | 4. For high causative factor |
| A5            | Tarai alluvium made up of sand, clay, silt, sand, and clays | Combination of above | Below 360 | Above 16' | Bank cut area, gullying and rills, flood plains, younger alluvial fan | Built-up area of settlement, road and brittle paths, etc. | Temperate | Above 225 | Above VIII order | Circular | Above 600 | 5. For very high causative factor |
3.2.1. Very low flood hazard zone

Upstream areas having very low rate of flood run-off (below 100 l/s/km²) due to least stressed natural geo-environment of dense forest cover on Upper Siwalik sandstone and gravels in the northern areas were identified under very low flood hazard susceptibility (Figure 9). Out of the total area of the Ramnagar Himalaya foothills, about 9% (6.99 km²) area is under very low flood hazard susceptibility zone, around dense reserved forest area of Corbbet National Park, Teda, Bairaj, and Chhoi (Table 4 and Figure 9).

Figure 9. Spatial variability of flood hazard susceptibility in Ramnagar Himalaya foothill area.
3.2.2. Low flood hazard zone
Mid-stream areas having slightly higher rate of flood run-off (100–200 l/s/km²) due to comparatively stressed geo-environmental background of fairly dense and shrubs land on high-level fluvial terraces made up of Middle Siwalik massive sandstones were identified as low susceptibility zone of flood hazard which accounts for 8% (5.15 km²) part of the study area around down slopes of northern areas covered by fairly dense forest (Table 4 and Figure 9).

3.2.3. Moderate flood hazard zone
The areas having moderate rate of flood run-off (200–400 l/s/km²) in middle-level terraces because of fragile geo-environment (comprising large rock blocks and boulders under shear zone covered by shrubs and crops with 200 cm annual rainfall) were identified for moderate susceptibility zone of flood hazard. This zone accounts maximum about 49% (31.70 km²) part of the area (Table 4 and Figure 9).

3.2.4. High flood hazard zone
The land surface of low-level terraces and its adjoining Bhabar alluvial plains receive high rate of flood run-off (400–600 l/s/km²) from upstream areas. Consequently, this zone has high susceptibility of flood hazard which accounts for about 20% (11.59 km²) part of the area (Table 4 and Figure 9).

3.2.5. Very high to extreme flood hazard susceptibility zone
Landforms under river bank cut area, gullies, rills, flood plains, and younger alluvial fans, located along streams and substreams, receive extreme rate of flood run-off (above 600 l/s/km²) from upstream areas, having very high to extreme susceptibility to flood hazard in the area (Table 4 and Figure 9).

3.3. Climate change informatics
Global warming has been affecting the local meteorological characteristics of the study region (IPCC 2007), which has resulted in accelerated flood events as summarized in Table 5 and is discussed as follows:

3.3.1. Variability in average temperature
Figure 10(a) and Table 5 reveal that the decadal average temperature stands about 20.51, 20.69, and 21.19 °C, respectively, for the first decade (1986–1995), second decade (1996–2005), and third decade (2006–2015). It increased by 0.88% (0.18 °C) between the first and second decades, and 2.42% (0.50 °C) between the second and third decades, while the average rate of decadal variability stands about 1.65% (0.34 °C) (Table 5).

The annual statistics accounts that the average temperature increased annually by 0.03% (0.02 °C) between the first decade (1986–1995) and the second decade (1996–2005), and 0.24% (0.05 °C) between the second and third decades (2006–2015), whereas the average rate of annual variability stands about 0.16% (0.03 °C) (Table 5).
The altitudinal trends of climate change reveal the rising rate of decadal and annual temperature in order to mounting elevation (Figure 10(a) and Table 5). It varied from minimum 0.11% (0.03 °C) annual for the elevation below 300 m to maximum 0.24% (0.05 °C) annual for the elevation above 900 m in the area.

3.3.2. Variability in rainfall pattern
To monitor the changes in rainfall pattern, annual rainy days, annual average rainfall, and annual extreme rainfall events during year 1986–2015 have been analysed. Result suggests the following:

Figure 10. Decadal changes in average temperature (a), annual rainy days (b), precipitation (c) and extreme rainfall events (d).
Table 5. Decadal and annual variability in temperature and rainfall pattern (comprises rainy days, average rainfall, and extreme rainfall events) due to climate change impacts in RHFA.

| Climate parameters | Temperature and rainfall pattern (rainy days, average rainfall, extreme rainfall events) at different meteorological stations |
|--------------------|-------------------------------------------------------------------------------------------------|
| Station No.        | Location | Elevation | Gaushala | Bairaj | Kalagad | Sitabani | Kotabag | Jalna | Mohan | Aniya | Average |
| 1                  |          | 257 m     | 22.18    | 21.78  | 21.25   | 20.64    | 20.21   | 19.75 | 19.17 | 19.08 | 20.51   |
| 2                  |          | 360 m     | 22.23    | 21.87  | 21.35   | 20.75    | 20.34   | 20.01 | 19.58 | 19.39 | 20.69   |
| 3                  |          | 431 m     | 22.69    | 23.34  | 21.81   | 21.23    | 20.83   | 20.55 | 20.12 | 19.92 | 21.19   |
| 4                  |          | 512 m     |          |        |         |          |         |       |       |       |         |
| 5                  |          | 610 m     |          |        |         |          |         |       |       |       |         |
| 6                  |          | 760 m     |          |        |         |          |         |       |       |       |         |
| 7                  |          | 845 m     |          |        |         |          |         |       |       |       |         |
| 8                  |          | 937 m     |          |        |         |          |         |       |       |       |         |
| Average            |          | 589 m     |          |        |         |          |         |       |       |       |         |

Temperature (in °C)
- **Annual average temperature**
  - 1986–1995: 22.18
  - 1996–2005: 22.23
  - 2006–2015: 22.69
  - **Decadal variability**
    - I–II decade: 0.05
    - II–III decade: 0.46
    - Average: 0.26
  - **Annual variability**
    - I–II decade: 0.01
    - II–III decade: 0.05
    - Average: 0.03

Rainy days (/days/year)
- **Annual average rainy days**
  - 1986–1995: 94
  - 1996–2005: 93
  - 2006–2015: 90
  - **Decadal variability**
    - I–II decade: -1.00
    - II–III decade: -3.23
    - Average: -2.14
  - **Annual variability**
    - I–II decade: -0.10
    - II–III decade: -0.32
    - Average: -0.20

Rainfall (in mm/year)
- **Annual average rainfall**
  - 1986–1995: 1086.08
  - 1996–2005: 1085.02
  - 2006–2015: 1083.57
  - **Decadal variability**
    - I–II decade: -1.06
    - II–III decade: -0.10
    - Average: -0.06

(continued)
Table 5. (Continued)

Climate parameters Temperature and rainfall pattern (rainy days, average rainfall, extreme rainfall events) at different meteorological stations

| Station No. | Location Elevation | Gaushala | Bairaj | Kalagad | Sitabani | Kotabag | Jalna | Mohan | Aniya | Average |
|-------------|--------------------|----------|--------|---------|----------|---------|-------|-------|-------|---------|
|             |                    | 257 m    | 360 m  | 431 m   | 512 m    | 610 m   | 760 m | 845 m | 937 m | 589 m   |
| II–III decade |                   | −1.45    | −2.79  | −2.67   | −3.04    | −4.05   | −4.56 | −5.54 | −5.22 | −3.67   |
| Average |                   | −1.26    | −1.95  | −1.98   | −2.50    | −3.41   | −3.80 | −4.62 | −4.32 | −2.98   |
| I–II decade |                   | −0.12%   | −0.14% | −0.13%  | −0.14%   | −0.16%  | −0.20%| −0.23%| −0.22%| −0.17%  |
| II–III decade |                   | −0.01%   | −0.01% | −0.01%  | −0.01%   | −0.01%  | −0.02%| −0.02%| −0.02%| −0.01%  |
| Average |                   | −0.01%   | −0.02% | −0.02%  | −0.02%   | −0.02%  | −0.02%| −0.02%| −0.02%| −0.02%  |
| Annual variability |               | −0.13%   | −0.19% | −0.20%  | −0.25%   | −0.34%  | −0.38| −0.46 | −0.43 | −0.30   |
| Excessive rainfall events/year |       | −0.01% | −0.01% | −0.01%  | −0.01%   | −0.02%  | −0.02%| −0.02%| −0.02%| −0.02%  |
| Annual average events |      | 16       | 18     | 20      | 22       | 25      | 27    | 32    | 30    | 24      |
| Decadal variability |            | 1986–1995 | 1996–2005 | 2006–2015 | 6        | 7       | 8     | 11    | 12    | 12      |
| I–II decade |                   | 38%      | 39%    | 40%     | 50%      | 48%     | 44%   | 59%   | 63%   | 38%     |
| II–III decade |                   | 41%      | 36%    | 36%     | 58%      | 59%     | 56%   | 73%   | 65%   | 41%     |
| Average |                   | 39%      | 37%    | 38%     | 54%      | 54%     | 50%   | 66%   | 64%   | 39%     |
| Annual variability |               | 1        | 1      | 1       | 1        | 1       | 1     | 2     | 2     | 1       |
| I–II decade |                   | 4%       | 4%     | 4%      | 5%       | 5%      | 4%    | 6%    | 6%    | 4%      |
| II–III decade |                   | 4%       | 4%     | 4%      | 6%       | 6%      | 6%    | 7%    | 7%    | 4%      |
| Average |                   | 4%       | 4%     | 4%      | 5%       | 5%      | 5%    | 7%    | 6%    | 4%      |
3.3.2.1. Declining rainy days. Figure 10(b) and Table 5 depict about 104, 101, and 96 annual rainy days, respectively, for the first decade (1986–1995), the second decade (1996–2005), and the third decade (2005–2015). The annual rainy days being reduced by 2.88% (three days) between the first and second decades, and 4.95% (five days) between the second and third decades. The decadal average reduction rate of rainy days stands about 3.92% (four days) (Table 5).

Annually, the average rainy days decreased by 0.29% (0.30 days) between the first and second decades and 50% (0.50 days) between the second and third decades. The average reducing rate of annual rainy days stands about 0.39% (0.40 days) (Table 5).

The trends of reducing rainy days follow temperature variability pattern in the study area. In order that lower elevation has low rate of reduction in rainy days, whereas higher elevation has high rate of reduction in rainy days (Figure 10(b) and Table 5). It stands minimum about 0.20% (0.32 days) for lower elevation (257 m) to maximum 0.55% (0.60 days) for higher elevation (927 m) (Table 5).

3.3.2.2. Decreasing average rainfall. As a consequence of declining rainy days, the average annual precipitation has been decreasing (Figure 10(c) and Table 5). Thirty-year average precipitation data reveal that the decadal average precipitation stands about 1740.08, 1737.78, and 1734.12 mm/year, respectively, for the first decade (1986–1995), the second decade (1996–2005), and the third decade (2006–2015). It has decreased by 0.13% (2.29 mm) between the first and second decades, and 0.21% (3.67 mm) between the second and third decades. This advocates that the decadal declining rate of precipitation has been increasing in the next decade and on an average its stands at 0.17% (2.98 mm) (Table 5 and Figure 4(c)).

Annually, the average precipitation has shown a decrease by 0.01% (0.23 mm) between the first and second decades and 0.02% (0.37 mm) between the second and third decades (Table 5). This suggests that the decline rate of precipitation has been increasing annually (Table 1). The three-decade average decrease rate of annual precipitation stands at about 0.02% (0.23 mm).

The meteorological stations located between 257 and 937 m elevation, within the study area and its adjacent areas, reveal a decreasing rate of average precipitation (Figure 10(c) and Table 5). It varies below 0.01% (0.13 mm) annually for the lower elevation (below 300 m) to a maximum of 0.02% (0.46 mm) annually for the higher elevation (above 900 m).

3.3.2.3. Increasing excessive rainfall events. Characteristically, the 30-year rainfall data (1986–2015) reveals that the irritating excessive rainfall events have been increasing whereas the average annual rainfall has been decreasing (Figure 10(d) and Table 5). Annual average excessive rainfall event stands about 24, 36, and 56, respectively, for the first decade (1986–1995), the second decade (1996–2005), and the third decade (2006–2015). It has increased by 38% (12 events) between the first and second decades, and 41% (20 events) between the second and third decades at 4% annual rate. However, on an average, these events have increased by 39% (16 events) over a decade with 4% (1.6 events) annually (Table 5).

Altitudinal variability of excessive rainfall events is increasing with mounting elevation being (Figure 10(d) and Table 5). During the first decade (1986–1995), it varied between 16 events/year for the lowest elevation to 32 events/year for the highest elevation. During the second decade (1995–2005) to third decade (2005–2015), being at the rate of 22 events/year and 31 events/year for the lowest elevation to 51 events/year and 88 events/year for the highest elevation, respectively (Figure 10(d) and Table 5).

3.3.3. Variability in extreme flood events

Increasing excessive rainfall events have caused extreme floods in the study area. Thirty-year (1986–2015) records of flood events at several locations throughout the area overlaid with flood hazard zone map to appraise annual frequency of extreme flood events under different flood hazard zones. Table 6 and Figure 11 depict that during the first decade between 1986 and 1995, the average extreme flood events account for about 80 events/year; comprises maximum 29 events under very
Table 6. Increasing flood events under different flood hazard zones in the study area.

| Flood hazard zones | Average flood events (events/year) | Decadal variability | Annual variability |
|--------------------|-----------------------------------|---------------------|--------------------|
|                    | 1986–1995 1996–2005 2006–2015 | I–II decade II–III decade Average | I–II decade II–III decade Average |
| Very low           | 0 2 3 | 2 1 2 | 0 0 0 |
| Low                | 1 3 5 | 2 2 2 | 0 0 0 |
| Moderate           | 23 29 45 | 6 16 11 | 1 2 1 |
| High               | 27 36 52 | 9 16 13 | 1 2 1 |
| Very high          | 29 42 59 | 13 17 15 | 1 2 2 |
| Total              | 80 112 164 | 32 52 42 | 3 5 4 |

Decadal and annual flood events variability data summarized in Table 6 suggest that on an average about 42 flood events (comprises 15 events under very high flood hazard zone, 13 events under high flood hazard zone, 11 events under flood moderated hazard zone, whereas 4 events under low and very low flood hazard zones) have increased over a decade in the study area at the rate of 4 events/year.

3.4. Land-use change and urban growth informatics

This section examines the trends of emerging disaster risk due to rapid urbanization, land-use degradation, and demographic changes in different flood hazard zones over a 20-year period (1995–2015).
3.4.1. Unplanned urban growth and land-use degradation

The GIS integration of the flood hazard zones and land-use mapping suggests that during the last two decades the maximum rate (42%–43%) of urban growth was recorded in the areas under high to very high flood hazard zones, at more than 2% annual rate, whereas the areas under very low to low hazard zones have least (respectively, 7%–11%) urban growth during the last two decades at the rate of less than 1% per year (Figure 12 and Table 7). The land-use pattern of the area is broadly categorized as natural land and built-up land (Table 7). Built-up land represents urban growth with different types of settlements and rich socio-economic infrastructural development (roads, bridle paths, bridges, canals, electronic lines, water supply lines, etc.), whereas natural land comprises forest, shrubs, agriculture, horticulture, and barren land (Figure 12). The land-use change between years 1995 and 2015 suggests that the area is under the process of rapid urbanization and resulted to the following:

Figure 12. Urban growth (a,b) and increased population density (c,d) in different hazard zones during 1995–2015 in RHFA.
3.4.1.1. Increasing built-up environment. Overlay operation of flood hazard and land-use maps reveals that during the last two decades, the maximum rate (42%–43%) of urban growth was recorded in the areas under high to very high flood hazard zones, at more than 2% annual rate (Figure 12 and Table 7). At the same time, the areas under very low to low hazard zones have least rate (respectively, 7%–11%) of urban growth during the last two decades being less than 1% per year (Table 7). On an average, 25% area of the natural landscape that exists under different flood hazard zones has been converted into built-up area during the last two decades (1994–2014), due to high rate (1.5% each year) of urban growth. This being maximum for horticultural land (11%) followed by crop land (9%) and minimum for forest land (1%) and barren land (1%). Shrubs land has been changed by 3%. Consequently, this change transformed into built-up environment as 16% settlement and 9% colonized waste land (Table 7).

3.4.1.2. Increased population. The comparative analysis of two-period (1995 and 2015) demographic characteristics advocates that the rapid urban growth resultant of increased population in different flood hazard zones (Figure 12 and Table 8). The maximum growth of about 48% (52,772 persons) of the total population (110,183 persons) falls in very high flood hazard zone. However, the high flood hazard zone has large population of about 33% (36,509 persons). Moderate, low, and very low flood hazard zones, respectively, have 15% (16,801), 3% (3,650 persons), and 1% (419 persons) population.

Comparatively, 20 years back the maximum people, about 61% (14,645 persons) of the total population (23,849), were living in moderate hazard zone. The high flood hazard zone also had about 28% (6,606 persons) of the total population (23,849 persons). Low, very low, and very high flood hazard zones, respectively, had 3% (762 persons), 1% (98 persons), and 7% (1,737 persons) of the total population (23,849 persons). Population growth statistics revealed that the area under high to very high flood hazard zones have the highest growth rate which account, respectively, 35% and 59%

Table 7. Changing land-use pattern under different flood hazard zones.

| Flood hazard zones | Covered area | Natural land | Built-up land | Total area | Land-use changes in respective zones |
|--------------------|--------------|--------------|----------------|-----------|-------------------------------------|
|                    | Covered area | 1995 | 2015 | 1995 | 2015 | 1995 | 2015 | Natural | Built-up | Natural | Built-up |
| Very low hazard    | 6.99         | 6.99 | 6.49 | 6.00 | 0.5  | 6.99 | 6.99 | 0.5  | 0.00 | 0.5  | 0.00 | 0.5  |
| Low hazard         | 4.41         | 4.41 | 3.85 | 0.74 | 1.3  | 5.15 | 5.15 | 0.74 | 0.50 | 1.3  | 5.15 | 5.15 |
| Moderate hazard    | 30.84        | 30.84 | 24.6 | 0.86 | 7.1  | 31.70 | 31.70 | 0.86 | 0.56 | 7.1  | 31.70 | 31.70 |
| High hazard        | 11.47        | 11.47 | 6.54 | 0.12 | 5.05 | 11.59 | 11.59 | 0.12 | 0.03 | 5.05 | 11.59 | 11.59 |
| Very high hazard   | 9.12         | 9.12 | 5.19 | 0.27 | 4.2  | 9.39 | 9.39 | 0.27 | 0.03 | 4.2  | 9.39 | 9.39 |
| Total              | 62.83        | 62.83 | 46.67 | 1.99 | 18.15 | 64.82 | 64.82 | 1.99 | 0.81 | 18.15 | 64.82 | 64.82 |

Table 8. Changes in spatial distribution of population density under different flood hazard zone in Ramnagar Himalayan Foothill area.

| Flood hazard zones | Covered area | Total population | Population density | Changes in total population and density |
|--------------------|--------------|------------------|--------------------|----------------------------------------|
|                    | km² | % | 1995 | 2015 | 1995 | 2015 | 1995 | 2015 | Natural | Built-up | Natural | Built-up |
| Very low hazard    | 6.99 | 9  | 98 | 1.00 | 419 | 1.00 | 14 | 60  | 322 | 1.00 | 1.00 | 16 | 1.00 |
| Low hazard         | 5.15 | 8  | 762 | 3.00 | 3682 | 3.00 | 148 | 715 | 2920 | 3.00 | 3.00 | 148 | 3.00 |
| Moderate hazard    | 31.70 | 49 | 14,645 | 61 | 16,801 | 15  | 462 | 530 | 2156 | 2.00 | 2.00 | 108 | 2.00 |
| High               | 11.59 | 20 | 6606 | 28 | 36,509 | 33  | 570 | 3150 | 29,902 | 35 | 3.00 | 1495 | 35 |
| Very high          | 9.39 | 14 | 1737 | 7  | 52,772 | 48  | 185 | 5620 | 51,035 | 59 | 5435 | 2552 | 59 |
| Total              | 64.82 | 100 | 23,849 | 100 | 110,183 | 100 | 276 | 2015 | 86,334 | 100 | 1739 | 4317 | 87 |
each year, whereas these annual rates of population growth being 2%, 3%, and 1%, respectively, for moderate, low, and very low flood hazard zones (Table 8). Consequently, since the last two decades, the population density has increased from 185 to 5620 persons/km² in very high flood hazard zone to minimum 14–60 persons/km² in very low flood hazard zone, whereas it varies by 70–3150, 462–530, and 148–715 persons/km², respectively, in high, moderate, and low flood hazard zones. The annual growth rate of population density is the highest, 272 persons/km², in very high flood hazard zone to minimum, 2 persons/km², in very low hazard zone (Figure 12 and Table 8).

3.5. Emerging flood disaster risk informatics

Although climate change is a natural process of planet earth, the rapid urbanization in flood-prone RHFA accelerated it by several anthropogenic factors such as deforestation, land-use degradation, high rate of population growth, infrastructural development, etc. This poses a serious threat of emerging spatial dynamics of flood disaster risk. Keeping this in view, the spatial variability of flood disaster risk carried out for years 1995 and 2015 through integrated weight values of the existing land-use pattern and population demography under different hazard zones (Table 9). The result suggests five levels of flood disaster risk throughout the area: very low, low, moderate, high, and very high-risk zones. Figure 13 demonstrates spatial distributions of these five risk zones analysed between 1995 and 2015. The spatial data of these risk zones are summarized in Table 10 with part ‘A’ for covered area under each risk zone for years 1995 and 2015 and part ‘B’ for spatial changes in respective risk zone during 1995–2015 with annual rates. Spatial dynamics of flood disaster risks revealed that throughout the study region, the area of moderate, high, and very high risk zone has been increasing by 0.31%, 0.40%, and 0.77% annually due to rapid urban growth and associated infrastructural development (Table 10). This dynamic rate varies under different flood hazard zones as a consequent of urbanization:

- Under very low hazard zone, annually about 0.08% area has been converting into very high (0.01%), high (0.01%), moderate (0.02%), and low (0.04%) risk zones.
- Under low hazard zone, annually about 1.05% area has been converting to very high (0.25%), high (0.35%), moderate (0.30%), and low (0.15%) risk zones.
- Under moderate hazard zone, about 1.15% area has been converting to very high (0.25%), high (0.35%), moderate (0.35%), and low (0.20%) risk zones for each year.
- Under high hazard zone, the area of moderate, high, and very high risk has been increasing by 0.25%, 0.75%, and 0.45% annual rates, respectively, whereas the area under low and very low risk has been reducing by 0.60% and 0.85% annual rates, subsequently.
- Under very high hazard zone, the area of moderate, high, and very high risk has been increasing by 0.10%, 0.30%, and 3.70% annually, respectively, while the area under low and very low risk has been reducing by 0.55% and 3.55% annual rates.

| Risk factors       | Land use/cover | Risk assessment | Assigned waitage | Risks potential |
|--------------------|----------------|-----------------|------------------|-----------------|
| Natural landscape  | Built landscape | Population density (person/Km²) |                  |                 |
| Barren             | Brindle paths  | Single          | <500             | 1               | Very low       |
| Shrubs             | Local roads    | Double          | 500–1000         | 2               | Low            |
| Forest             | Communications | Three           | 1000–4000        | 3               | Moderate       |
| Horticulture       | State highway  | Four            | 4000–8000        | 4               | High           |
| Agriculture        | National highway | Above four | >8000            | 5               | Very high      |

Table 9. Flood disaster risk assessment.
4. Discussion

The study advocates that the area has emerging dynamics of flood disaster risk due to rapid urbanization and land-use degradation. Despite that, unfortunately these densely populated areas have been growing since the last three decades with new socio-economic and infrastructural development under high to extreme flood hazard susceptibility zones. Three most vulnerable dense populated built-up areas in the fast urbanizing Ramnagar town are under high to extreme risks of flood disasters and the potential hazard zones identified in the present study are described as follows (Figure 9).

4.1. Pampapur–Durgapuri: very high to extreme flood hazard susceptibility zone

This site is one of the most densely populated flash flood-prone areas of the Ramnagar town, as it lies in extremely vulnerable wider surface of the alluvial fans which are formed by thick younger sediment deposits at the mouth of streams along the right bank of Kosi River flood plain in the north of the Ramnagar town (Figure 9). The site lies between the latitude 29°24′02″–29°24′47″N and longitude 79°07′31″–79°08′30″E which covers an area of about 2.14 km². This extreme flood-prone zone has very high population density of about 9440 persons/km² (Census 2011), whereas 30 years back, it was quite low about 475 persons/km² (Census 1981). High rate of population growth and urbanization has multiplied the vulnerability and socio-economic risks of flood disaster due to very high to extreme flood hazard potentiality of the location.
4.2. Chorpani–Gaujani: very high to extreme flood hazard susceptibility zone

This densely populated flash flood-prone area of Ramnagar town is located on extremely vulnerable alluvial fan (Figure 9). This zone has a covered area of about 2.15 km² and lies between the latitude 29°23’25”–29°23’58”N and longitude 79°05’51”–79°06’47”E. This vulnerable zone has been experiencing rapid urbanization process and new settlements are coming up. Consequently, the population density has increased from 74 to 2610 persons/km² during the last three decades (Census 1981 and 2011), which has increased vulnerability and socio-economic risks due to very high flood hazard potentiality of the location.

4.3. Karanpur: high flood hazard susceptibility zone

It is a river-line flood-prone zone of the Ramnagar town, along the right bank of Fooltal river, which flows from up-slopes of Siwalik Himalaya to Gangetic plain in the north-western part of the town (Figure 9). This river brings very high volume of monsoon flood run-off and sediment from rapidly urbanizing upstream area (Chorpani–Gaujani Himalaya foothill piedmont zone). The river has

Table 10. Spatial distribution (part A) dynamics (part B) of flood disaster risk under different hazard zones in years 1995 and 2015.

| Flood hazard zone | Area (km² and %) | Very low 1995 | Very low 2015 | Low 1995 | Low 2015 | Moderate 1995 | Moderate 2015 | High 1995 | High 2015 | Very high 1995 | Very high 2015 |
|-------------------|-----------------|---------------|---------------|---------|---------|--------------|--------------|---------|---------|---------------|---------------|
| Very low          | 6.99 9%         | 6.71 96%      | 0.21 3%       | 1.05 15%| 0.07 15%| 0.00 0%      | 0.00 0%      | 0.00 0%| 0.00 0%| 0.00 0%       | 0.00 0%       |
| Low               | 5.15 8%         | 4.58 90%      | 0.46 6%       | 0.62 8%| 0.10 12%| 0.00 0%      | 0.00 0%      | 0.00 0%| 0.00 0%| 0.00 0%       | 0.00 0%       |
| Moderate          | 31.70 49%       | 21.87 69%     | 3.17 10%     | 4.44 14%| 3.80 12%| 1.90 6%      | 1.90 6%      | 2.78 12%| 2.78 12%| 2.78 12%      | 2.78 12%      |
| High              | 11.59 14%       | 2.43 9%       | 3.36 14%     | 1.97 6%| 2.20 12%| 2.20 12%     | 2.20 12%     | 2.20 12%| 2.20 12%| 2.20 12%      | 2.20 12%      |
| Very high         | 9.39 14%        | 6.76 8%       | 1.22 2%      | 0.19 1%| 0.66 6%| 0.47 8%      | 0.47 8%      | 0.47 8%| 0.47 8%| 0.47 8%       | 0.47 8%       |
| Total             | 64.82 100%      | 42.36 65%     | 8.43 13%    | 8.26 13%| 6.84 13%| 5.15 8%     | 5.15 8%      | 5.15 8%| 5.15 8%| 5.15 8%       | 5.15 8%       |

Part B: spatial changes in flood disaster risk under respective hazard zone (km² and in %)

| Flood disaster risk zone | Very low 1995–2015 Annual | Low 1995–2015 Annual | Moderate 1995–2015 Annual | High 1995–2015 Annual | Very high 1995–2015 Annual |
|--------------------------|---------------------------|----------------------|---------------------------|-----------------------|---------------------------|
| Very low flood hazard zone | –1.68 –0.08             | 0.84 0.04            | 0.35 0.02                 | 0.28 0.01             | 0.21 0.01                 |
| Low flood hazard zone     | –1.08 –0.05              | 0.15 0.01            | 0.31 0.02                 | 0.36 0.02             | 0.26 0.01                 |
| Moderate flood hazard zone| –7.29 –0.36              | 1.27 0.06            | 2.22 0.11                 | 2.22 0.11             | 1.59 0.08                 |
| High flood hazard zone    | –1.97 –0.10              | –1.39 –0.07          | 0.58 0.03                 | 1.74 0.09             | 1.04 0.05                 |
| Very high flood hazard zone| –6.67 –0.33             | –1.03 –0.05          | 0.09 0.01                 | 0.56 0.03             | 7.04 0.35                 |
| Total                    | –18.69 –0.93             | –0.16 –0.04          | 3.64 0.18                 | 5.16 0.26             | 10.14 0.50                |
|                          | –29.14 –1.44             | –1.06 –0.06          | 6.03 0.31                 | 8.04 0.40             | 15.07 0.77                |
caused tremendous amounts of erosion along the banks washing away crops and productive land, sometimes depositing unsorted sediments over agricultural fields and settlements. The zone covers an area about 2.54 km² lying between the latitude 29°22′20″–29°23′02″N and longitude 79°05′15″–79°05′44″E. Karanpur is a newly affected flood-prone area caused due to over flow of the Fooltal river (Figure 9). There are two key causes for such events:

1. Rising river bed due to high rate of sedimentation which comes with surface run-off of rapidly urbanizing (constructions and developing colonies, roads and settlements, etc.) upstream area (Chaorpani–Gaujani Himalaya foothill piedmont zone).
2. Farmers occupied the flood plain of the river banks from both sides to enlarge their agricultural land and leaving very narrow tract for stream flow.

Figure 9 demonstrates the site from where the monsoon peak flood flows off the Foolthal river; diverts towards Karanpur area as the flood run-off following natural river course and adequate depth and width of the river bed. At peak of discharge during floods, the Karanpur inhabitants have great threat for socio-economic risks during monsoon

5. Conclusions

The study demonstrates that the RHFA is under high flood hazard zone as it generates average flood run-off 492 l/s/km² during the monsoon season. Spatial variability of flood hazard suggests that the areas of extreme flood comprises densely populated settlement areas with rich socio-economic and infrastructural development and fertile agricultural land having approximately 10 times high rate of flood run-off (864 l/s/km²) than the areas which are under natural geo-ecosystem (86 l/s/km²). The study demonstrates that maximum area, about 83% part of the terrain, has extreme to moderate flood hazard susceptibility comprising densely populated settlement areas with rich socio-economic, infrastructural development, and fertile agricultural land. The remaining 17% area is under low to very low flood hazard susceptibility, mainly comprising dense to fairly dense forested areas in hilly terrain. Result concluded that the global climate change impacts (i.e. increasing temperature and excessive rainfall events by 0.03 °C/year and 2 events/year, respectively) accelerated extreme flood events with the rate of 4 events/year, whereas the fast urbanization and development of new colonies have caused to increase in built-up area (with 1.25% annually) and population density (with 87 persons/km² annually) under different flood hazard zones. Consequently, 29% area of very low flood disaster risk zone being converted into moderate (6%), high (8%), and very high flood disaster risk zones (15%) with 0.31%, 0.40%, and 0.77% annual rates, respectively.

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