URBAN FLOOD RISK MAPPING FOR BINDAL RAO CATCHMENT OF DEHRADUN

A DISSERTATION

Submitted in partial fulfilment of the

requirements for the award of the degree

of

MASTER OF TECHNOLOGY

in

DISASTER MITIGATION AND MANAGEMENT

By

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CENTRE OF EXCELLENCE IN DISASTER MITIGATION AND MANAGEMENT

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CANDIDATE'S DECLARATION

I hereby declare that the work carried out in this seminar report entitled, **"Urban Flood Risk Mapping for Bindal Rao Catchment of Dehradun"**, is presented on behalf of partial fulfilment of the requirements for the award of degree of **"Master of Technology"** in ***Disaster Mitigation and Management*** submitted to the *Centre of Excellence in Disaster Mitigation and Management (CoEDMM)* of *Indian Institute of Technology, Roorkee,* is a record of my own work carried out during a period from July 2018 up to May 2019 under the supervision of **Dr. D.S. Arya**, Professor in the Centre of Excellence in Disaster Mitigation and Management (CoEDMM) and the Department of Hydrology, Indian Institute of Technology Roorkee, Roorkee, India.

The matter embodied in this dissertation has not been submitted by me for the award of any other degree or diploma.

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CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief.

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ABSTRACT

Urban Flood has been a pressing global concern over the last decade. There have been numerous occurrences of flooding in various towns and cities across India such as that of 2017 and 2005 Mumbai Floods, 2016 Delhi Floods, 2015 Chennai Floods. The country has suffered from huge economic losses, infrastructural damages, human casualties, and even loss of lives during these floods. India, being a developing nation, would witness rapid urbanisation in the coming years further aggravating the issues of urban floods. Thus, it becomes very crucial to map the risks of urban floods for the purpose of efficient mitigation and management.

Dehradun being affected by urban floods in almost every two years, the Bindal Rao catchment of the city has been considered for mapping of risks. The entire area of the Bindal Rao catchment has been categorised into five risk zones according to levels of risks, i.e., negligible, low, moderate, high and very high. To carry out the risk zonation, the flooding and vulnerabilities of the study area have been mapped performed considering the topographical characteristics, urbanisation trends, precipitation trends and Land Use Land Cover characteristics. For the purpose of flood simulation, the United States Environmental Protection Agency - Storm Water Management Model has been used while the mapping activities have been performed using Arc GIS 10. The other software and tools that have been used in the study are ERDAS IMAGINE and Geospatial Storm Water Management Model.

The study area is found to be mostly in low to high vulnerability zones with very small areas under high vulnerability zone in terms of landuse and social factors. Nearly half of the study area is found to be susceptible to urban floods. It is found to be extremely variable in terms of urban flood risks, while approximately one-sixth part of the catchment fall under high to high very high risk zones and about one-fourth of it under low and moderate risk zones. The finding of the study comes under the framework of Sendai Framework of Disaster Risk Reduction for 2015-2030 in understanding disaster risks and strengthening disaster risk governance.

Keywords: *Urbanisation, Precipitation, Topographical Characteristics, Flood Simulation, Vulnerabilities, Risk Mapping, etc.*

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ABBREVIATIONS

ASTER	:	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CN	:	Curve Number
DEM	:	Digital Elevation Model
GIS	:	Geographical Information System
IDF	:	Intensity – Duration - Frequency
IMD	:	India Meteorological Department
IPCC	:	Intergovernmental Panel on Climate Change
LULC	:	Landuse Landcover
MDDA	:	Mussoorie Dehradun Development Authority
MSL	:	Mean Sea Level
NDMA	:	National Disaster Management Authority
PCA	:	Primary Census Abstract
PSP	:	Public and Semi-public
PUF	:	Public Utilities and Facilities
SCS	:	Soil Conservation Services
SFDRR	:	Sendai Framework for Disaster Risk Reduction
SWMM	:	Storm Water Management Model
UNDESA	:	United Nations Department of Economic and Social Affairs
UNSIDR	:	United Nations International Strategy for Disaster Reduction
US - EPA	:	United States – Environmental Protection Agency
USGS	:	United States Geological Survey
WMO	:	World Meteorological Organization

CHAPTER 1
INTRODUCTION

1.1 PREAMBLE

Urban flood, presently, is a primary concern in most of the towns and cities across the globe. The world has witnessed numerous fatal occurrences of urban floods over the last decade such as the 2015 Chennai Floods, 2011 Rio de Janeiro Floods, 2011 Thailand floods, 2005 Mumbai Floods, etc. The rapid and unplanned urbanisation that alters the natural hydrological cycle owing to high population increase and infrastructure development is regarded one of the important reasons. The climate change, which bears on the magnitude and frequency of precipitation and floods in urban arenas, is cited as another important cause.

There has been an increasing trend of urban floods in the Indian towns and cities as well over the last decade. The recent floods in Delhi, Mumbai, Chennai, etc. are shreds of evidence to that. With the increasing number of such instances, India has suffered huge infrastructural damages, destruction of properties, disruption of economic services and activities, human casualties and even loss of lives. Therefore, the issue of urban floods has become a serious concern for town planners and Urban Local Bodies.

1.2 NEED OF THE STUDY

Urbanisation has been at its peak over the last decade. The urban areas across the globe presently cater to a population of approximately 4.1 billion, which is more than half of the total global population (World Bank, 2017), and is further expected to reach 66 percent of the total population by 2050 (UNDESA, 2014). The rate of urbanisation in developing countries is much higher because of the dominant rural-urban migration in comparison to that of the developed ones. India, being a developing nation, has witnessed an increase in urban population by 31.8 percent in the period of 2001 to 2011 (Census of India, 2011). According to the 2011 Census, the urban population constitutes around 31.14 percent of the nation's total population (Census of India, 2011). With this tremendous increase in unplanned urbanisation, the issues related to urban floods would also get aggravated. The high population and presence of several vital infrastructures in the urban areas would further add to their vulnerabilities. Therefore, it is very essential to create urban flood risk and vulnerability maps to address and manage these issues.

1.3 RESEARCH QUESTIONS

The dissertation aims to answer the following research questions:

1. How is unplanned urbanisation affecting the hydrology of the urban areas?
2. What are the vulnerabilities of the towns and cities to urban floods?
3. How the urban flood risks can be assessed?

1.4 OBJECTIVES

To answer the aforementioned research questions, the following objectives have been acted upon in this dissertation:

1. To study the trends of urbanisation and development in the study area.
2. To study the change in rainfall pattern/trends and analysing the changes in Intensity-Duration-Frequency curves.
3. To map the extent of urban floods using a model.
4. To determine and map the potential risks and vulnerabilities of the study area.

1.5 STRUCTURE OF THE DISSERTATION

The structure of the dissertation carried out to attain the aforementioned objectives has been briefly described below:

Chapter 1 provides an overview on the background and need for urban flood risk mapping. This chapter also details out the research questions and the objectives of the study.

Chapter 2 summarises the literature on the basics and process of urban flood, the direct and indirect impacts of urbanization and climate change on urban flood and the process of risk mapping. The methodology developed based on the inferences drawn from the aforementioned literature has also been briefed.

Chapter 3 details out the characteristics of the Dehradun city and the data and model that has been used in this study.

Chapter 4 presents the analysis of urbanisation trend analysis in terms of physical and demographic characteristics and preparation of urban flood risk map for the catchment of Bindal Rao.

Chapter 5 summarises the findings of the study and defines its limitations. This chapter also discusses the relevance of the study within the Sendai Framework and further concludes by briefing about the future scope of the study.

CHAPTER 2
LITERATURE REVIEW

2.1 BASICS OF URBAN FLOOD

2.1.1 Floods

A flood, as defined by Subramanya (2008), is as "an unusually high stage in a river, normally the level at which the river overflows its bank and inundates the joining area". In hydrological sense, "a flood is a relatively high flow, which overflows the natural channel provided for the runoff" (Chow, 1956 as cited in Parker, 2000). In meteorological sense, a flood year is defined as a year when the rainfall is more than a certain amount (mostly 125%) of the normal for that region (WMO, 1975; IMD, 1971 as cited in Parker, 2000).

Floods, as defined by the WMO (2011), is as follows:

i. Rise, usually brief, in the water level in a stream to a peak from which the water level recedes at a slower rate.
ii. Relatively high flow as measured by stage height or discharge.
iii. Rising tide.

2.1.2 Flash Floods

Flash Floods, as defined by WMO, is "a flood of short duration with a relatively high peak discharge"; whereas American Meteorological Society (AMS) defines flash floods as "a flood that rises and falls quite rapidly with little or no advance warning, usually as the result of intense rainfall over a relatively small area" (WMO, 2012). Flash floods are frequently associated with violent convection storms of a short duration falling over a small area. These can take place in virtually any area where there are steep slopes, but is most common in hilly regions.

2.1.3 Urban Floods

The inundation of any urban area, resulted from the confluence of both meteorological and hydrological factors such as rainfall frequency and intensity, storms, temperature, etc. and exacerbated by human actions, is considered as an urban flood (WMO, 2012).

2.1.3.1 Types of Urban Floods

Urban Floods can be classified, based on the root cause, as local floods, riverine floods, flash floods, coastal floods (WMO, 2008; Tingsanchali, 2012). The underlying causes of each one of them in the urban context are stated below:

a) **Local Floods:** Very high rainfall intensity and duration during the rainy season sometimes caused by seasonal storms and depressions and exacerbated by saturated or impervious soil. Built environments like cities generate higher surface run-off that is in excess of local drainage capacity, thereby causing local floods.
b) **Riverine Floods:** River floods occur when the river run-off volume exceeds local flow capacities. Urban areas situated in the low-lying areas in the middle or lower reaches of rivers are particularly exposed to extensive riverine floods. Often, urban growth expands over some of the floodplains, reducing the area in which floods can naturally overflow. Where parts of the city are below flood level and are protected by artificial levees, there is a risk that they may be broken and cause devastating urban flooding.
c) **Flash Floods:** Alterations in the urban area and in storm intensity produce higher flows that exceed capacity of small culverts under roads designed for unurbanised situation. Although adequate when designed, their carrying capacity may turn out to be inadequate and thereby overflow onto the roads, creating new water paths and flood the built up areas.
d) **Coastal Floods:** High tides and storm surges caused by tropical depressions and cyclones can cause coastal floods in urban areas located in estuaries, tidal flats and low-lying land near the sea in general.

2.1.3.2 Urban Flood Process

The natural land cover of the earth's surface and vegetation are being replaced by built-up structures, roads and other impervious surfaces due to urbanisation. This is diminishing the natural storage capacity of the soil. Though artificial drainage channels are being constructed, it alters the existing hydrology and the precipitation often outburst, as the surface runoff increases. *Figure 2-1* illustrates how urbanisation alters the watershed characteristics of any area. In event of urban floods, the flood peaks can increase from 1.8 to 8 times and flood volumes by up to 6 times in comparison to that of rural floods (NDMA, 2010). As a result, urban flooding occurs very quickly due to faster flow times, and sometimes even in a matter of minutes.

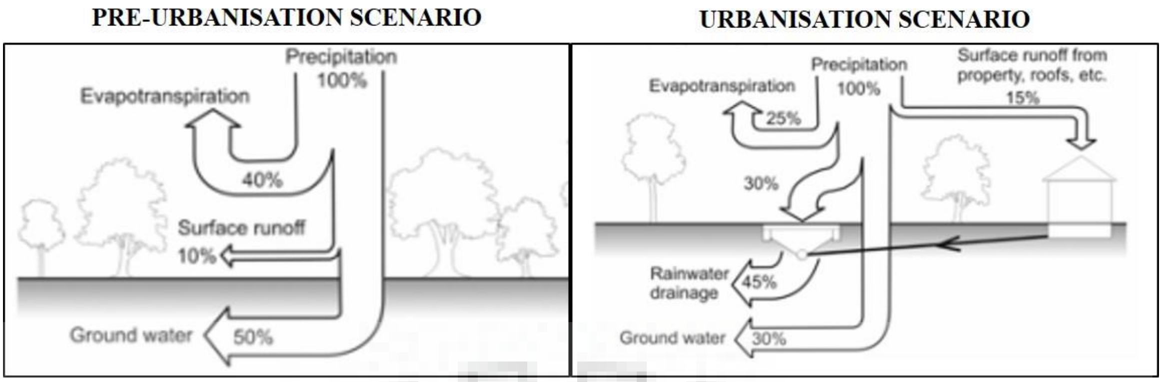


Figure 2-1: Water balance characteristics in an urban watershed
Source: *(Tucci, 2007 as cited in WMO, 2012)*

2.1.3.3 General Causes of Urban Floods

The factors responsible for urban floods have been described below in *Table 2-1*.

Table 2-1: Factors Contributing to Urban Flooding

Meteorological Factors	**Hydrological factors**	**Human factors aggravating natural flood hazards**
• Rainfall • Cyclonic storms • Small-scale storms • Temperature • Snowfall and snowmelt	• Soil moisture level • Groundwater level prior to storm • Natural surface infiltration rate • Presence of impervious cover • Channel cross-sectional shape and roughness • Presence or absence of over bank flow, channel network • Synchronization of runoffs from various parts of watershed • High tide impending Drainage	• Land use changes (e.g. surface sealing due to urbanisation, deforestation) increase runoff and sedimentation • Occupation of the flood plain and thereby obstructing flows • Inefficiency or non-maintenance of infrastructure • Too efficient drainage of upstream areas increases flood peaks • Climate change effects, magnitude and frequency of precipitation and floods • Urban micro-climate may enforce precipitation events

		• Sudden release of water from dams located upstream of cities/towns • Failure to release water from dams resulting in backwater effect • Indiscriminate disposal of solid waste

Source: *(NDMA, 2010)*

2.2 IMPACTS OF URBANISATION ON URBAN FLOODS

Urban areas undergo tremendous modifications such as removal of vegetation, increase in imperviousness, contour modifications, replacement of streams by pipes, etc. (Semadeni-Davies, et al., 2008). These areas, hence, are characterized by reduced rainwater infiltration and increased storm-water runoff resulting in an increase in inundation and decrease in groundwater recharge (Jacobson, 2011; Semadeni-Davies, et al., 2008). Apart from these, several studies have shown that urbanisation also has direct or indirect impacts on the frequency and magnitude of precipitation (Yang, et al., 2013), amount and rate of evapotranspiration (Semadeni-Davies, et al., 2008), water quality (Miller & Hutchins, 2017), flood peak magnitudes (Yang, et al., 2013), subsidence of lands (Semadeni-Davies, et al., 2008) and other environmental issues.

2.2.1 Variability in Precipitation

Several empirical studies around the world, like Mote, et al. (2007); Shepherd (2005); Dixon & Mote (2003), have reported changes in precipitation due to impacts of urbanisation. To investigate the physical mechanisms behind these changes, various modelling studies such as Bornstein & Lin (2007); Lei, et al. (2008); Yang, et al. (2009); Zhang, et al. (2009); Miao, et al. (2010) have been carried out as well. Human activities like transportation, patterns of domestic and commercial water use, etc. affect the urban water cycle (Semadeni-Davies, et al., 2008). It has been reported from in various places such as Korean peninsula and Menomonee River basin that precipitation tends to increase in the area with the increment in population (Kug & Ahn, 2013; Yang, et al., 2013).

The possible reasons stated by various studies for these variabilities are: increase in surface heating due to the Urban Heat Island (UHI) effect and increase in aerosols due to urbanisation (Kug & Ahn, 2013). Several studies such as Bornstein & Lin (2007); Baik & Kim (2000); Rozoff, et al. (2002) has indicated that heat-island effect initiates convective thunderstorms resulting in precipitation in the downwind areas of urban centres. In the summer season especially, the ground heating due to the urbanisation could enhance the precipitation (Kug & Ahn, 2013). Increased levels of aerosols in the atmosphere can suppress as well as enhance the precipitation level. Aerosols, when ingested into shallow and short-lived clouds, would suppress the precipitation, while, they enhance precipitation by delaying the warm-rain's onset leading to eventually deeper and stronger convection (Kug & Ahn, 2013).

2.2.2 Increased Runoff and Flood Peaks

Urban areas result in rapid flow responses and high peak flows following even modest rainfalls (Semadeni-Davies, et al., 2008). The problems of increased runoff develop due to the reduction of perviousness of surfaces in urban regions in comparison to that of non-urban areas (Jacobson, 2011). The increased impervious nature of urban areas reduces rainwater infiltration and hence, increases storm-water runoff. For example, it has been reported that urbanisation, in Mumbai, has contributed to a two or threefold increase in total runoff of the city (Ranger, et al., 2011).

Peak flows in urbanised catchments are 30 percent to more than 100 percent greater (Rose & Peters, 2001). Yang, et al. (2013) reported that the flood peaks in the Menomonee River basin increase with the extent of urbanisation of the drainage area, i.e. more the extent of urbanisation, more would be the flood peaks. In conformity with the Manning’s Equation that indicates the velocity of water flow is indirectly proportional to the roughness of land surfaces, stormwater flow more rapidly across the urban areas because of their smoother nature than across the natural surfaces (Jacobson, 2011).

2.2.3 Increased Inundation

In a modelling study carried out by Huong & Pathirana, 2013 for the city of Can Tho in Vietnam, it has been found that by 2050, the inundation depth would increase by 21 percent, which is around 18 cm, and the extent of inundation area would increase by 18 percent for extreme events (highest rainfall intensity of 45mm/hr). Urbanisation leads to increase in waste-water collection making the drainage systems inefficient during the heavy rains. Furthermore, the problems of urban encroachments and drainage blockades aggravate the inundation. (Ranger, et al., 2011) reported an increase in flood risk of Mumbai due to the rapid urbanisation, especially due to the absence of effective spatial planning and improved drainage systems.

2.2.4 Other Impacts

The impacts of urbanisation are not only limited to the above factors rather disturbs the complete hydrological cycle of the region (Semadeni-Davies, et al., 2008). The local sources of water are heavily affected by urbanisation in terms of both quality and quantity. Urbanisation increase the level of pollutants and other wanted substances resulting in quality deterioration, while the changes in the landuse and landcover have reduced infiltration, ultimately reducing the quantity of local sources like groundwater (Sun & Caldwell, 2015) (Semadeni-Davies, et al., 2008). Issues like subsidence of land might also arise from the extreme reduction in groundwater recharge (Semadeni-Davies, et al., 2008). The urban areas are also often characterized by reduced evapotranspiration rate because of rapid deforestation and removal of natural surfaces (Semadeni-Davies, et al., 2008). The increased speed of water flow in urban areas results in a high increase in stream power, because of the conversion of potential energy into kinetic energy as it flows downhill (Knighton, 1999). The heavily increased stream power can modify the stream channel morphology, i.e. the shape and the flow of channels as well as the surrounding landscape such as riparian vegetation, etc. (Jacobson, 2011)

2.3 IMPACTS OF CLIMATE CHANGE ON URBAN FLOODS

Climate change is an emerging global issue over the recent decades. Many cities and towns across the globe are victims of extreme weather events resulting from climate change and these risks are going to increase further (Ranger, et al., 2011). The major consequence of climate change is global warming, which further results in several other issues (IPCC, 2007). The temperature rise associated with global warming will lead to changes in precipitation patterns (Djordjevic´, et al., 2011). The changes in precipitation patterns are a major cause of urban floods. The unpredictable weather events also put pressure on the existing drainage systems further aggravating the issue of urban floods (Semadeni-Davies, et al., 2008). Climate change is also expected to impact spatial patterns, growth and development of the city in the future (Djordjevic´, et al., 2011). There is a prediction of the sea-level rise in the many parts of the world such as the United Kingdom because of climate change (Hulme, et al., 2002).

2.3.1 Changes in Precipitation Pattern

The intensity and the frequency of the extreme rainfall events are expected to be impacted by climate change (Frei, et al., 1998; IPCC, 2007). Some scientists such as Trenberth (1999); Ntegeka & Williams (2008) have suggested that the frequency of extreme precipitation events may increase due to the effects of climate change, while several studies such as Emori & Brown (2005), have indicated that mean and extreme precipitations will increase over many mid to high-latitude regions (Mailhot & Duchesne, 2010). IPCC (2007) has also stated that the intensity of rainfall would increase in tropical and high-latitude regions (Djordjevic´, et al., 2011).

The major outcome of the global climatic studies, as stated by (Djordjevic´, et al., 2011), is that the global annual average precipitation will increase, though it might vary from region to region. Most of northern Europe, the Arctic, Canada, the north-eastern United States, tropical and eastern Africa, the northern Pacific, Antarctica, northern Asia and the Tibetan Plateau is going to witness an increase in precipitation in the season of winter (Djordjevic´, et al., 2011). The precipitation in the Mediterranean region, northern Africa, northern Sahara, Central America, the American southwest, the southern Andes, and south-western Australia in the winter season though will observe a decline in precipitation (Djordjevic´, et al., 2011). In summer, most parts of the United Kingdom would tend to be drier, when rainfall is expected to decrease up to a level of 50 percent in its southeast regions (Djordjevic´, et al., 2011). In northwestern India, according to IPCC, 2007, no significant trend could be identified, but Alexander, et al. (2006) stated that there are indications of increased contribution from wet days to the total annual rainfall (Djordjevic´, et al., 2011).

2.3.2 Impacts on Drainage Systems

The urban drainage system is considered one of the most important infrastructures for the development of the modern societies. The climate change in recent years, resulting in increased storm-water flows and sewer infiltration, puts heavier loads on the existing systems (Semadeni-Davies, et al., 2008; Niea, et al., 2009). This situation has generated detrimental consequences of flooding and Combined Sewer Outflow (CSO) (Niea, et al., 2009). It has also been indicated by Niea, et al. (2009) that the consequences generated by the increase of precipitation are likely to be less severe in comparison to that defined by flooding and sewer surcharging.

2.4 URBAN FLOOD RISK MAPPING

2.4.1 Urban Flood Risk

Risk is defined as the "likelihood of loss of life, injury or destruction and damage from a disaster in a given period of time", i.e., risk can be recognised as the interaction of hazard that makes people and places exposed and vulnerable (UNISDR, 2015).

Risk = Hazard * Exposure * Vulnerability

Urban Flood Risks can be defined as a function of exposure of the people and the economic activities to it along with the vulnerability of social and economic fabric (WMO, 2008).

2.4.2 Hazard

Hazard is defined as a process, phenomenon or human activity that has the potential to cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation (UNISDR, 2015). For the purpose of risk mapping and assessment, the probable extent of the hazards is determined. For example, in case of urban floods, the probability of occurrence of floods, inundation depth, runoff volume and velocity, etc. are used to determine the extent of the hazard and assess the potential risks.

2.4.3 Exposure

"The people, property, systems, or other elements present in hazard zones that are thereby subject to potential losses" can be termed as exposure to any hazard (UNISDR, 2015). Exposure to urban floods refers to the question of whether or not people or values are in range of flood waters (WMO, 2008). The increasing risks of urban flood are directly proportional to the increase in the number of people and assets that are physically exposed to the floods in the cities (WMO, 2008).

2.4.4 Vulnerability

Vulnerability is defined by UNISDR as "the conditions determined by physical, social, economic and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards" (UNISDR, 2009). The extent of vulnerability determines whether or not exposure to a hazard constitutes a risk that may actually result in a disaster (WMO, 2008). It tends to vary within a population by subgroup because of the several factors like income level, age and health conditions, etc. and may change over time (Birkmann, et al., 2013).

Vulnerability to urban floods, according to the World Meteorological Department (WMO), has been categorised into the following:

- **Physical vulnerability of people and infrastructure:** the vulnerability to flood risks in urban settlements, particularly in developing countries in informal developments can be attributed to the following factors:
  - Risk prone areas are the only areas that the poor migrants are able to afford
  - Failure to perceive flood risks due to lack of knowledge till a flood hits
  - Infrastructure to reduce risk is not economically feasible
  - Flooding (particularly local flooding) occurs so regularly that they become accustomed to living with risks
- **Unfavourable organizational and economic conditions:** Economic vulnerability prevails obviously among those families who lack financial resources and those who cannot afford or are reluctant to purchase flood insurances.
- **Attitudes and motivations:** Reluctance towards flood preparedness and mitigation measures may be the effect of lacking hazard knowledge or of fatalistic attitudes. Moreover, dependence on too much external support can reduce the individual responsibility to deal with problems in a proactive manner.

2.4.5 Risk Assessment

Risk Assessment may be explained as the systematic process of calculating the potential losses that would result in cases of occurrence of a particular disaster of a specific magnitude. The quantification of risks for urban floods starts with the analysis of hydro-meteorological data and the hydraulic simulation of floods. A routine of different scenarios are modelled in order to factor in the effects of likely future changes on urban floods (future development of urbanisation, climate variability and change, land use changes etc.). The outcomes of such models provide information about the expected flood frequencies and magnitudes (extent, depth, duration and flow velocities), thereby marking those areas and subjects, which are exposed to floods. Using the geographical definition of exposed areas, in combination with data about flood frequency and magnitude, the economic risk can be calculated and expressed, e.g. in terms of damage per square meter per year (₹/m²/a) or in damage curves. Similarly, the data about the population residing in the exposed areas can predict the potential risk of human lives as well.

2.4.6 Mapping of Risks

The major tasks involved in the process of mapping the urban flood risks are explained in the *Figure 2-2.*

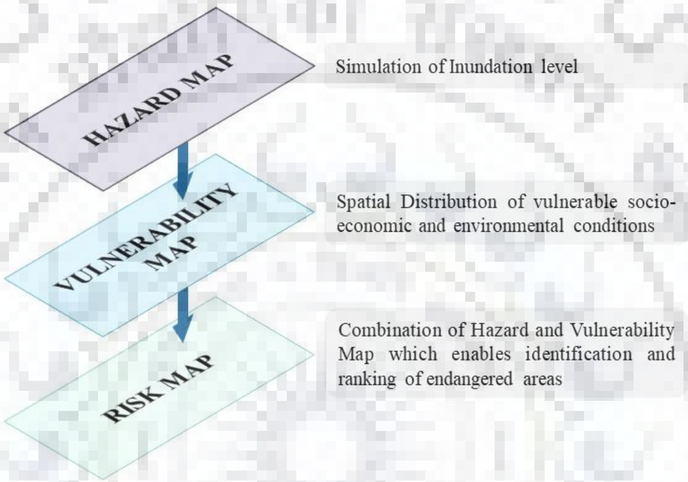


Figure 2-2: Risk Mapping

Source: *(WMO, 2008)*

2.5 INFERENCES

The literature review clearly suggests the problems linked to urban floods is of more concern because of the increased runoff rates and less infiltration of rainwater. The major reason behind this is the change in the surface of the land due to urbanisation. The variability in precipitation due to the increasing pollution has become a major concern. The problems of encroachment and large quantity of wastewater generation is another major indirect impacts further increasing the proneness to floods in urban regions. The potential impacts of climate change should always be taken into consideration. These inferences have been considered to develop the methodology of the study as mentioned in the following section.

2.6 METHODOLOGY DEVELOPED

The following methodology has been followed to attain the objectives of the study:

1. Studying the trends of urbanisation and development in the study area in terms of population growth, landuse and landcover changes, physical growth, infrastructure and services, etc.
2. Analysing these trends to determine the impacts of urbanisation on the hydrology of the study area.
3. Studying and analysing the precipitation patterns of last 30 years of the study area for the development of IDF Curves.
4. Simulation of floods of various return periods using SWMM to identify the vulnerable pockets in the study area.
5. Preparation of a composite flood map using the simulation results.
6. Determining the vulnerabilities of the study area based on landuse and social factors.
7. Mapping and categorisation of the potential risks in the study area.

The methodology at a glance is illustrated in *Figure 2-3.*

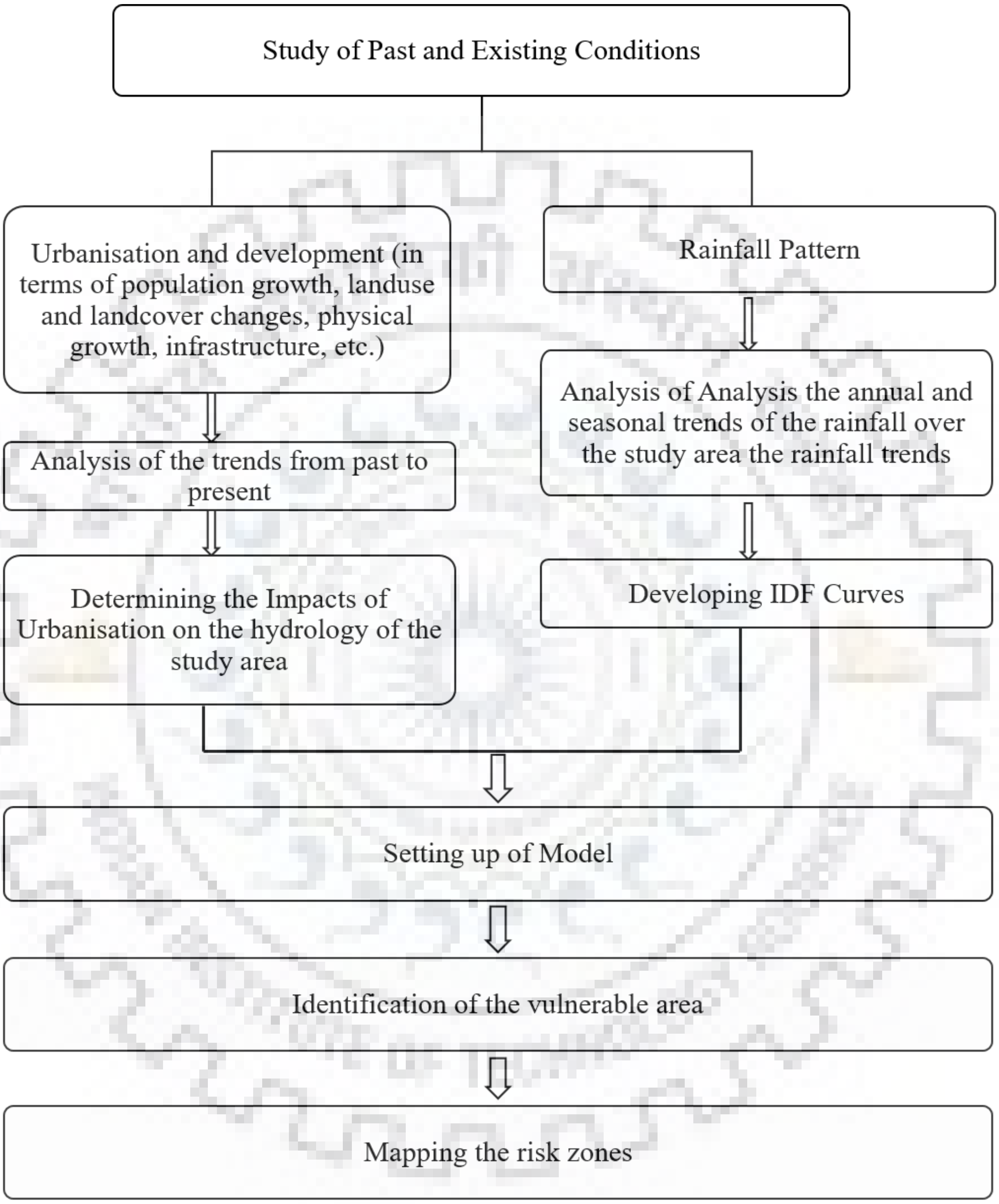


Figure 2-3: Methodology of the Study

CHAPTER 3

STUDY AREA, DATA AND MODEL USED

3.1 DEHRADUN CITY PROFILE

3.1.1 Introduction

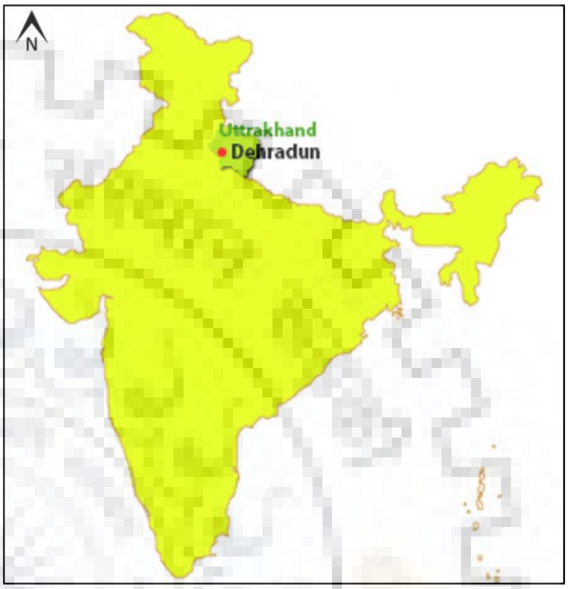


Figure 3-1: Location of Dehradun City in India

Dehradun, the capital city of Uttarakhand, is a major economic centre of the state. The city is situated in the Garhwal region at 30°19’ N and 78° 20’ E (Bansal, et al., 2015). The city is bestowed with a pleasant climate and picturesque natural beauty, earning it a major attractor for the tourists. It is likewise regarded as an important educational centre of the state because of the presence of some of the finest public and convent schools. It is also place to various important institutions like the Indian Military Academy (IMA), Forest Research Institute (FRI), Oil and Natural gas Corporation Ltd. (ONGC).

3.1.2 Linkages and Connectivity

Dehradun is well connected by road to New Delhi and other major towns in northern India. Road distances to some important centres in the region are: Delhi 240 km; Chandigarh 168 km; Shimla 225 km; Roorkee 70 km; Haridwar 54 km; Rishikesh 46 km; Mussoorie 35 km; Nainital 287 km. The city is well linked by daily direct trains coming in from Delhi, Calcutta, Mumbai, Varanasi, Lucknow and other places (GHK International, 2007). The closest airport from Dehradun is the Jolly Grant Airport situated on the fringes of the town, about 25 km away from the city (GHK International, 2007).

3.1.3 Historical background

The city received its name as a compounding of two words "Dehra" which means Camp and "Dun" which means valley. The story of the city goes back to the 17th century, when the Sikh Guru Ram Rai, who belongs to the sect of Udasi Fakirs, took up his abode in the

Dun. Later, Sikhs and Gujjars invaded the city in the 18th century, while, it was under the control of the Gorkhas from 1803-1814. In April 1815, Gorkhas were ousted and was annexed by the British. During 1822 to 1828, new roads were developed and improvements were made to other works of public utility. The growth of the city was further accelerated with the constitutions of two military cantonments in 1872 and 1908. In 1878, training college was set up for forest rangers at national level. In 1884, the Central Government took its possession and named it as "Imperial Forest School".

(GHK International, 2007)

3.1.4 Urban Profile

Being the capital, the city has always attracted a large number of population from the surrounding areas. Dehradun presently has a population of 5.74 lakhs inhabitants (Census of India, 2011). The city spreads across an area of 73.22 Square Kilometres (MDDA, 2008), which is divided into 60 wards (Census of India, 2011). It is mainly provided by the Dehradun Municipal Corporation, while the bodies like Mussoorie Dehradun Development Authority (MDDA), Special Area Development Authority (SADA), Jal Sansthan, and Jal Nigam are also taken in the preparation of specific civic services.

3.1.5 Landuse

According to the Master plan of 2005-2025, the development area of Dehradun constitutes nearly 15 percent of the residential areas while the other built-up areas such as commercial, industrial, etc. comprises approximately 9 percent. The areas reserved for transportation are approximately 4 percent. The open spaces such as recreational areas, agricultural areas, orchards and gardens, etc. constitutes around one-fourth areas of the city. The water bodies constitute 3 percent areas. The chart in the *Figure 3-2* represents the the further detailed distribution of landuse. *Figure 3-3* illustrates the spatial distribution of the 2005-2025 Landuse Plan of Dehradun.

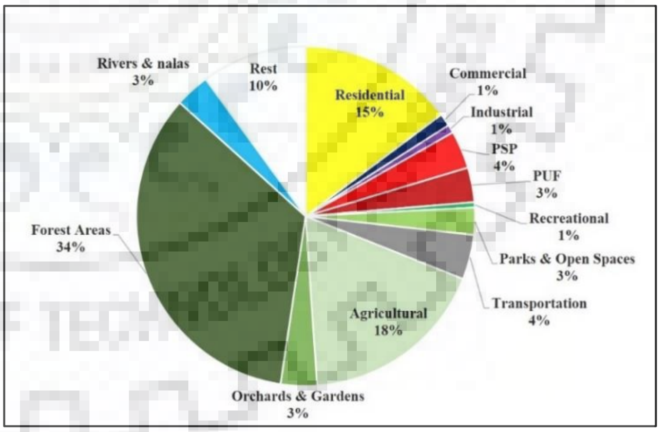


Figure 3-2: 2025 Proposed Landuse Distribution

Source: *(MDDA, 2008)*

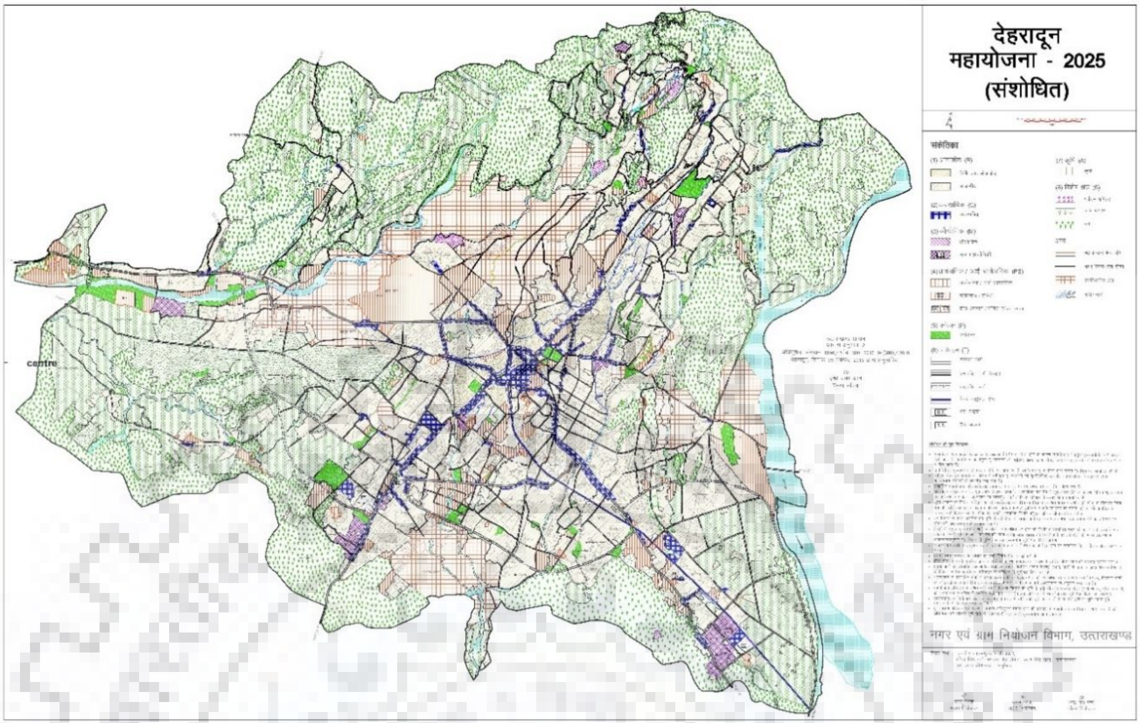


Figure 3-3: 2025 Proposed Landuse Plan of Dehradun

Source: *(MDDA, 2008)*

3.1.6 Climatic Conditions

The climate of the Dehradun is generally temperate (District Administration Dehradun, 2018). During the summer months, the temperature runs between 35.3°C and 13.3° C, while the winter months are colder with the maximum and minimum temperatures touching 26.2°C and 3.6° C respectively (District Administration Dehradun, 2018). Dehradun experiences heavy to moderate showers during late June to mid-August. Most of the annual rainfall of about 2051.4 mm in the district is received during the months from June to September as July and August are the rainiest months (District Administration Dehradun, 2018).

3.1.7 Physical and Geographical Features

Resting in the Doon Valley in the foothills of the Himalayas, the city of Dehradun is surrounded by river Song on the east, river Tons on the West, the Shivalik range on the south while the other ranges of the Himalayas in the North. The surroundings of the city are covered by dense forest cover. It is attributed with a varying height of a minimum of 600 m above MSL at the south and a maximum of 1000 m above MSL at north. The slopes gradually gentle down from the north to the south and south-west (Bansal, et al., 2015).

There a large number of seasonal streams and nallahs present across the city. The rivers Bindal and Rispana borne the natural drainage of the city as illustrated in *Figure 3-4.*

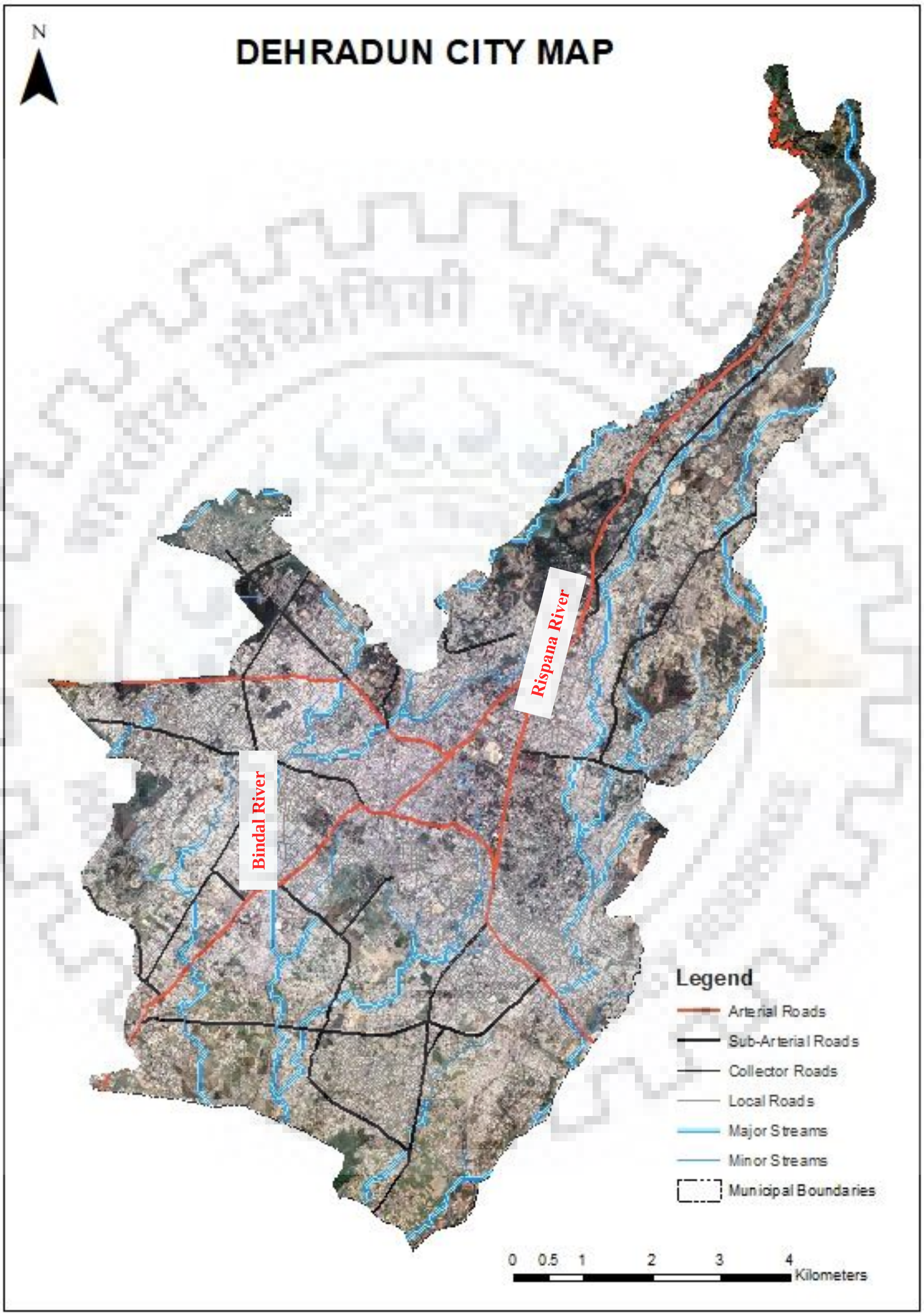


Figure 3-4: Map showing the natural drainage channels of Dehradun

3.1.8 Urban Flood issues

Urban flooding is a serious concern in the city of Dehradun, especially in the denser areas and in the areas adjacent to the river floodplains. The city is usually affected by water logging of streets and seasonal river flooding. The major rivers: Bindal and Rispana, which act as drainage channels, remain out of water throughout the year except for the monsoons when water level reaches the nearby low-lying areas. With the increasing scale of the problem, more number of settlements are getting affected. The localities that are most prone are Guru Tegh Bahadur Road, Balbir Road, Purn Balmiki Basti, Nai Basti, Nimi Road, Mahatma Gandhi Basti, Nai Basti, Rajesh Rawat Colony, Karan Pur, DL Road, Arya Nagar, Bhagat Singh, Shanti Vihar, Indira colony, Chukku Mohalla and Kanwali Road (Bansal, et al., 2015). The situation is going worse year after year and it is becoming worse with the increase in rainfall intensity, which is mainly anticipated due to climate change. The high intensity rainfalls for short durations are primary cause of such flash floods. The studies have demonstrated that the major problems of urban floods are excessive rainfall, encroachment on river catchments, failure of storm water drains, and so on.

3.2 DATA USED

Most of the data used in this study are of secondary data. The data has been primarily collected from several sources like reports such as Primary Census Abstract (PCA), Master Plan of Dehradun, City Development Plan (CDP), etc. and organisations like Indian Meteorological Department (IMD), Urban Local Bodies of Dehradun, etc. The sources of each data has been detailed out in the following sections of this chapter.

3.2.1 Demographic Data

The following demographic data have been analysed for the study:

Decadal Population: The decadal population of the town has been obtained from the Dehradun Master Plan of 2005-2025. *Table 3-1* lists out the relevant data.

Table 3-1: Decadal Population of Dehradun

Year	Population	Increment	Growth rate (in %)
1901	30,995	-	-
1911	42,568	11573	37.34

1921	50,858	8,290	19.47
1931	52,927	2,069	4.07
1941	80,580	27,653	52.25
1951	1,44,216	63,636	78.97
1961	1,56,341	12,125	8.41
1971	2,20,571	64,230	41.08
1981	2,93,010	72,439	32.84
1991	3,67,411	74,401	25.39
2001	5,60,120	1,92,709	52.45
2011	5,74,840	14,720	2.63

Source: *(MDDA, 2008; Census of India, 2011)*

a) **Primary Census Abstract (PCA) 2011:** The PCA 2011 data have been extracted from the Online Census of India Archive to determine the existing scenario of urbanisation of the city in terms of population, socioeconomic scenario, etc. The Census 2011 data provide ward-wise information as well as about the surrounding municipalities and rural areas. The ward-wise distributed data have also been used for the determination of the social vulnerability of the Bindal Rao catchment.

3.2.2 Infrastructure

a) **Educational & Health Facilities:** The list of educational and health facilities have been obtained from the District Census Handbook in 2011 published by Census of India as shown in *Table 3-2, Table 3-3 and Table 3-4.*

Table 3-2: List of Educational Facilities

Type of Facilities	Government Facilities	Private Facilities
Primary Schools	113	87
Middle Schools	46	37
Secondary Schools	8	23
Senior Secondary Schools	16	23
Schools for Disbled	1	4
Degree Colleges	2	32
Medical College	0	1
Engineering College	0	2
Management Instiitute	0	5
Polytechnic College	1	1

Vocational Training	2	21
Non-Formal Education	3	0

Source: *(Census of India, 2011)*

Table 3-3: List of Health Facilities

Types of Facilities	No. of Facilities
Allopathic	3
Aternative Medicine	7
Dispensary Health Centres	5
Family/Welfare Centres	12
Maternity & Child Welfare Centres	7
Maternity Homes	7
Mobile Health Clinics	2
Non-Govt. Charitable Hospitals/Nursing Homes	47
Nursing Homes	47
Others	2
TB Hospital/Clinic	1

Source: *(Census of India, 2011)*

Table 3-4: List of Number of Beds in Health Facilities

Types of Hospitals	No. of Beds
Allopathic	633
Dispensary Health Centres	146
Nursing Homes	1216

Source: (Census of India, 2011)

b) Water Supply & Electricity: The number of households having water supply and electricity has been extracted from Household Series Data reported by Census of India as shown in *Table 3-5* and *Table 3-6.*

Table 3-5: Status of Drinking Water Supply

Sources of Drinking Water	No. of Households
Tap Water	117128
Handpump	5136
Tubewell/Borehole	2255
Other Sources	242

Source: *(Census of India, 2011)*

Table 3-6: Status of Electric Supply

Sources of Electricity	No. of Households
Electricity	122640
Other Sources	2505
No Lighting	251

Source: *(Census of India, 2011)*

3.2.3 Landuse and Landcover

a) **Landuse:** The landuse details from 1982-2005 of Dehradun has been extracted from the Master Plan of 2005-2025 as shown in *Table 3-7*.

Table 3-7: Landuse Data of Dehradun (1982 – 2025)

Landuse	**Area** *(in Hectares)*			
	1982	**2001(Proposed)**	**2003-2004**	**2025 (Proposed)**
Residential	1588.8	3001.77	4071.8	5306.55
Commercial	81	290	341.43	431
Industrial	113.36	350	183.44	281
PSP	267.2	313.52	479.62	1290.9
PUF	802.22	833.21	415.42	1180.01
Transportation	203.3	400.09	821.96	1526.8
Parks & Open Spaces	156	226	2193.17	928.17
Orchards & Gardens	205.65	250.65	709.24	1239.74
Rivers & Nalas	331.5	1295.88	1179.25	1179.25
Rest	55	84.01	25471.87	22503.78
TOTAL	**3802.75**	**7045.13**	**35867.2**	**35867.2**

Source: *(MDDA, 2008; GHK International, 2007)*

b) **Landcover:** The landcover of the study area has been extracted from the LANDSAT 8 (captured during 21st – 27th December 2018) images obtained from the USGS Website through Earth Explorer (https://earthexplorer.usgs.gov). The composite image of area is illustrated in *Figure 3-5*.

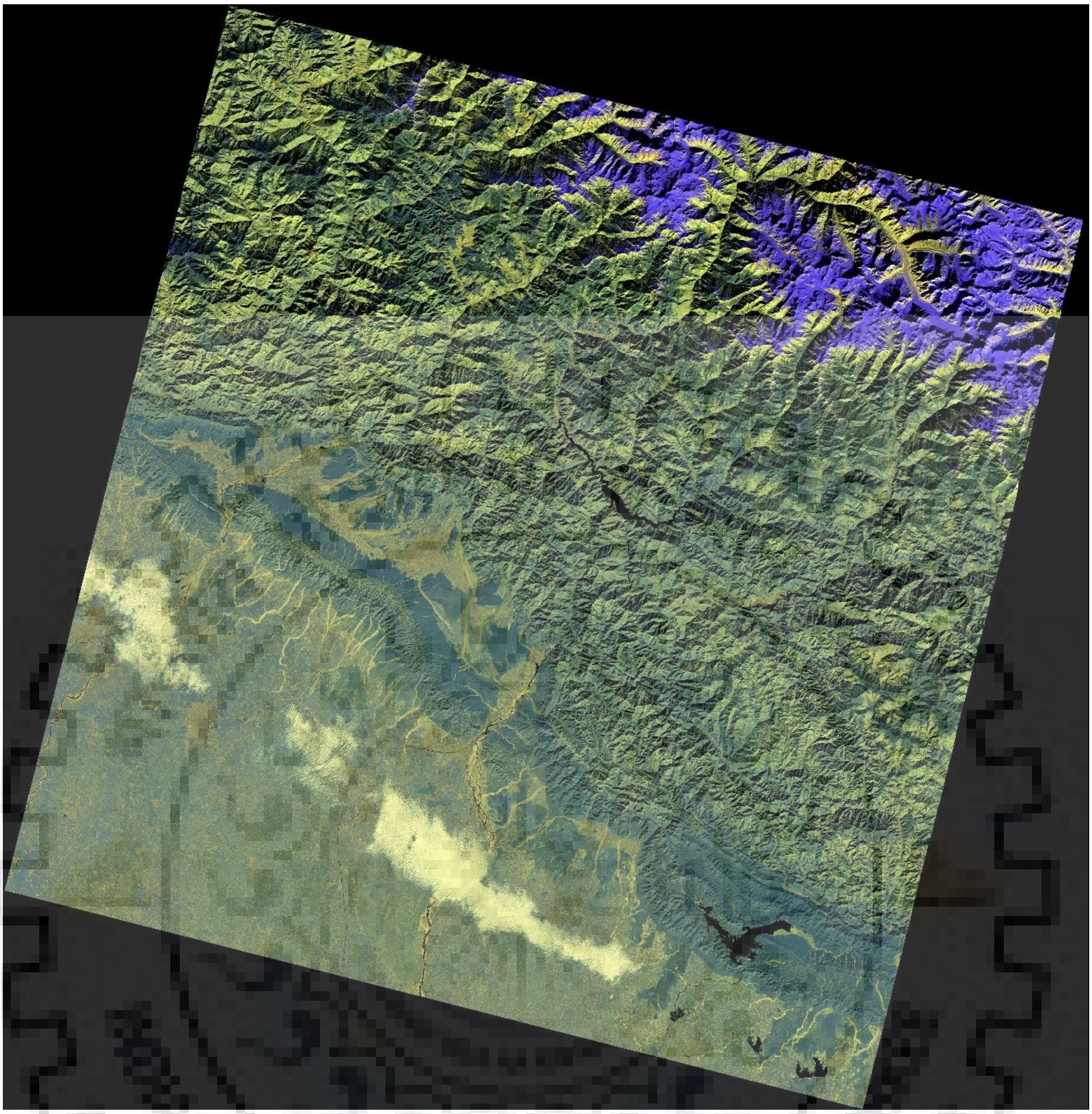


Figure 3-5: Composite LANDSAT 8 Image for the study area

Source: *USGS Website through Earth Explorer*

3.2.4 Climatic Data

The daily precipitation (mm), along with the daily minimum and maximum temperature (in ◦*C)*, as described in *Table 3-8* for the year 1989 to 2018 has been obtained from IMD, Pune for determining the climatic trends of the study area. The precipitation data have also been used for the development of IDF curves in the study area.

Table 3-8: Climatic Data for the duration of 1989-2018

YEAR	Precipitation *(mm)*	Annual Maximum Temperature *(◦C)*	Annual Minimum Temperature *(◦C)*
1989	693.3	39.73	-1.42
1990	1083.2	39.48	3.55
1991	973.3	39.75	0.65
1992	667.8	39.52	1.29
1993	1292.9	40.04	1.26
1994	1131.7	41.12	2.49
1995	1031.8	42	2.02
1996	1324.7	38.45	2.06
1997	1236.4	37.06	1.36
1998	1461.7	40.25	2.23
1999	686.2	39.22	1.91
2000	761.0	39.28	0.59
2001	1308.4	39.99	1.81
2002	904.3	40.4	1.5
2003	1163.8	40.85	1.81
2004	1186.7	39.32	1.38
2005	1187.4	41.5	2.15
2006	1113.3	37.13	2.93
2007	1488.5	41.82	2.66
2008	1487.8	37.79	1.12
2009	1019.4	40.41	2.71
2010	1859.4	40.97	2.78
2011	1652.1	37.94	0.73
2012	1321.5	40.46	0.97
2013	1997.0	41.14	1.38
2014	1168.0	40.17	0.91
2015	1207.9	38.81	3.21
2016	956.0	38.92	2.43
2017	1228.2	40.35	1.01
2018	1353.1	38.9	1.17

Source: *(IMD, 2018)*

3.2.5 Physiographical Data

The contour, slope and the natural drainage of the study area has been extracted from the 30 metres ASTER-DEM obtained from the USGS Website through Earth Explorer (https://earthexplorer.usgs.gov).

3.2.6 Urban Drainage Data

The details of the urban drainage data has been obtained from the City Development Plan (CDP) of Dehradun and the office of Uttarakhand Pey Jal Nigam, Dehradun. The details has been depicted in *Table 3-9.*

Table 3-9: Major Drains of Bindal Rao catchment

S.N.	Name of the Drains	Length (Km) / Width (m)	Connected Areas
1	From Brijlok to New Cant Road Nala.	4.5 km; width 6m	i) Salawala ii) Chandralok colony iii) Dilaram Bazar iv) New cant. Road v) Rajpur Road
2	Mannu Ganj Nala	4.8 km; 3m to 5m	i) Ghantaghar to Moti Bazar ii) Neshvilla Road iii) Mannu ganj iv) Moti Bazar v) Anand chowk vi) Dandipur vii) Khadri viii) Jilak Road
3	Govind Garh Nala	2.5km; 2.5 to 4.0m	i) Shanti vihar ii) Teacher colony iii) Rajendra nagar iv) Saiyyed Mohalla v) Yamuna Colony
4	Chorkhala Nala	1.0 km; 2m to width	i) Mitralok ii) Deeplok iii) Aakash deep iv) Rajendra bag BBlock
5	Bhandari Bagh Nala	3.5km; 4 to 6m	i) Lakhi Bagh ii) Vishwakarma colony iii) Bhandari bagh. iv) Pathari Bagh v) THDC colony

6	Chandra Nagar to Race course drain	5.5 km; 2 to 5m width	i) Haridwar Road ii) Race course iii) Chander Nagar iv) Police line v) Race cource A,B,C Block vi) Saraswati Vihar.
7	Subhash Road-Police head office	4km; 1.5m	i) Subhash Road ii) Cross Road iii) New Survey Road iv) New Road v) Kachahri Road vi) Chander Nagar
8	Asian School Nala	2.2 km; 3m	i) Ganga Vihar ii) Kalindi Enclave iii) Kanwali village iv) Engineer Enclave v) Om vihar vi) Shastri Nagar
9	Indira Gandhi Marg to Rajeev Juyal Maarg	3.5 km; 1.5 m	i) Uttam Colony ii) Shakti Vihar iii) Niranjanpur iv) Shewala Khurd

Source: *(GHK International, 2007, Uttarakhand Peyjal Jal Nigam, Dehradun.)*

3.2.7 Trend Test

Mann-Kendall Test: The non-parametric Mann-Kendall test is commonly employed to detect monotonic trends in series of environmental data, climate data or hydrological data. The null hypothesis, H_0, is that the data come from a population with independent realizations and are identically distributed. The alternative hypothesis, H_a, is that the data follow a monotonic trend. The Mann-Kendall test statistic is calculated, as described by Gibbons (1994), according to the following:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(X_j - X_k)$$

... (Equation 3-1)

with

$$\operatorname{sgn}(x) = \begin{cases} 1 & \text{if} \quad x > 0 \\ 0 & \text{if} \quad x = 0 \\ -1 & \text{if} \quad x < 0 \end{cases}$$

… (Equation 3-2)

The mean of S is E[S] = 0 and the variance σ^2 is

$$\sigma^2 = \left\{ n\,(n-1)\,(2n+5) - \sum_{j=1}^{p} t_j\,(t_j - 1)\,(2t_j + 5) \right\} / 18$$

… (Equation 3-3)

where p is the number of the tied groups in the data set and t_j is the number of data points in the j^{th} tied group. The statistic S is approximately normal distributed provided that the following Z-transformation is employed:

$$Z = \begin{cases} \frac{S-1}{\sigma} & \text{if} \quad S > 0 \\ 0 & \text{if} \quad S = 0 \\ \frac{S+1}{\sigma} & \text{if} \quad S > 0 \end{cases}$$

… (Equation 3-4)

3.3 MODEL USED

The model used for the simulation of the urban flood scenario in the study area is a United States – Environmental Protection Agency (US-EPA) Storm Water Management Model (SWMM).

3.3.1 Storm Water Management Model (SWMM)

EPA-SWMM is a rainfall runoff model, developed in 1971, used for the simulation of runoff quantity and quality for a single event or long-term duration in urban regions. This model is implemented worldwide for the planning, analysis and design related to stormwater runoff, combined and sanitary sewers, and other drainage systems. It can as well be utilized to evaluate grey infrastructure stormwater control strategies, such as pipes and storm drains, and is a useful tool for producing cost-effective green/grey hybrid stormwater control solutions (USEPA, 2019).

Working of the SWMM: The working of the model depends on tracking the quantity and quality of runoff made within each sub-catchment. The tracking of the flow rate, flow depth, and quality of water in each pipe and channel is another major working principle of this model.

SWMM conceptualizes drainage system as water and material flow between major environmental compartments that include;

- Atmosphere compartment
- Land Surface compartment
- Groundwater compartment
- Transport compartment

The atmosphere compartments make use of rain gauge as an input to the system. The subcatchment objects represent Land Surface compartment, aquifers denotes the Groundwater compartment and a network of channels and pipes etc. denote the transport compartment. One particular model may accept one or more than one compartment as input (USEPA, 2019).

The model captures the following hydrological processes while simulating for an area:

- Time-varying rainfall
- Evaporation of standing surface water
- Snow accumulation and melting
- Rainfall interception from depression storage
- Infiltration of rainfall into unsaturated soil layers
- Percolation of infiltrated water into groundwater layers
- Interflow between groundwater and the drainage system
- Nonlinear reservoir routing of overland flow
- Runoff reduction via LID controls

Applications of the Model:

- Planning and sizing of drainage system components, detention facilities and their appurtenances for flood control and water quality protection.
- Mapping flood plains of natural channel systems.
- Designing control strategies for minimizing combined sewer overflows.
- Evaluating the impact of inflow and infiltration on sanitary sewer overflows.
- Generating non-point source pollutant loadings for waste load allocation studies.
- Controlling site runoff using LID practices.
- Evaluating the effectiveness of management practices for reducing wet weather pollutant loadings.

CHAPTER 4

URBANISATION TREND ANALYSIS AND PREPARATION OF URBAN FLOOD RISK MAP

4.1 URBANISATION TRENDS OF DEHRADUN

The city has seen a tremendous growth in the post-independence period. The establishment of a separate state of Uttarakhand with Dehradun as its capital further aggravated the extent of urbanization in this city. This section of the chapter details out its urbanisation and developmental trends. The major focus has been given on physical growth, demographic growth and dynamics of landuse of the city over the decades.

4.1.1 Physical Growth

4.1.1.1 Urban Morphology

The city has registered an unprecedented urban growth during the post-independence growth. Establishments of large scale industries e.g. Amitabh Textile Mills Ltd in 1960, Miniature Bulb industries of India in 1958, Bengal Immunity in 1969, Doon Valley Combers in 1962, Indian Woollen Textile Mills in 1966, Raj Narain Flour Mills in 1964 and a number of other small scale industries and banks have greatly triggered the growth of the city (GHK International, 2007). The growth rate took a quantum jump from 1991 registering a nearly 40 percent decadal growth during 1991-2001 (GHK International, 2007). *Figure 4-1* shows the growth pattern of the city over the period of 2001-2016. The growth pattern clearly depicts that the northern parts of the city were developed early, and has gradually spread towards the south, i.e., to the direction of the Shivalik Range.

4.1.1.2 Municipal Limits

The total area within municipal limits, according to the 1981-2001 Dehradun Master Plan, was 31.08 Sq.Kms (GHK International, 2007). The municipal limits defined by the Dehradun Master Plan of 2025 extends over an area of 73.22 Sq.Kms (MDDA, 2008), which is more than twice the municipality limits defined by 1981-2001 Dehradun Master Plan. The Municipal Area of the Dehradun has been divided into 60 wards as shown in *Figure 4-2* (Census of India, 2011).

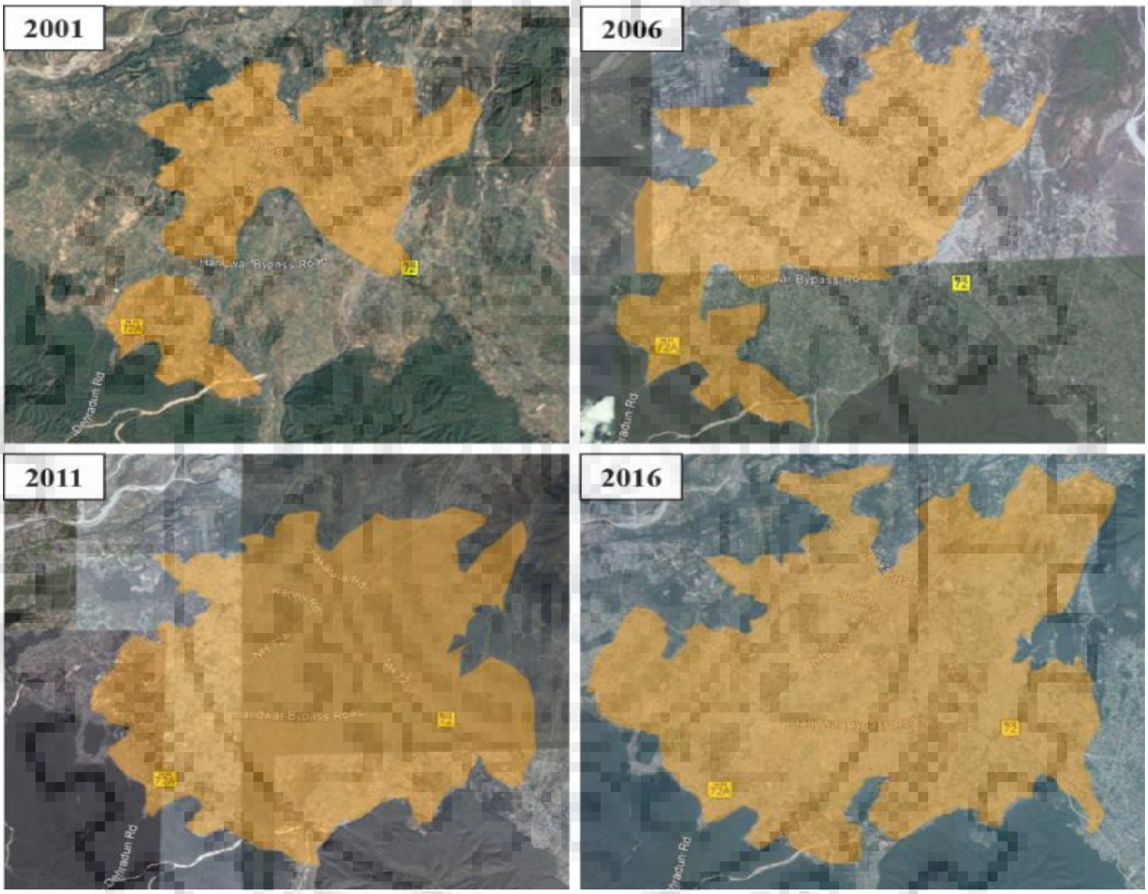


Figure 4-1: Growth Pattern of Dehradun overlaid on Google Earth Image

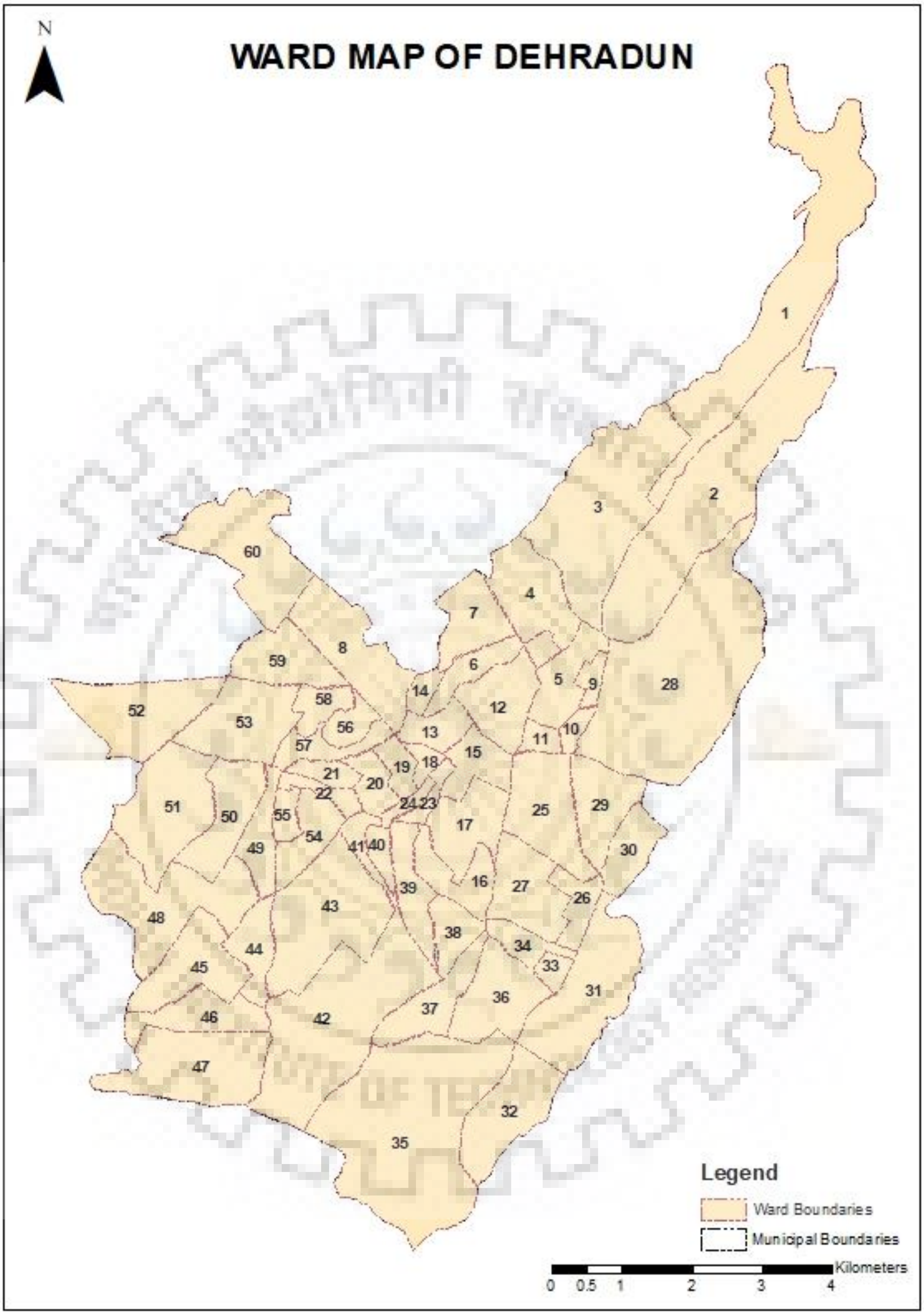


Figure 4-2: Maps showing the ward divisions of the Dehradun Municipal Corporation

Source: *(GHK International, 2007)*

4.1.2 Demographic Profile

4.1.2.1 Decadal Population Growth

The population of the city has increased by more than 18 times from 1991 to 2011. The maximum increase in the population was witnessed in the decade 1941-51, i.e. 78.97 percent, while the minimum was in the decade 2001-2011, i.e. 2.63 percent. The population histogram and changes are shown in *Figure 4-3.* The decadal growth post-independence has been quite high because of the establishment of a large number of industries during this period. In the decade 1991-2001, the high growth of nearly 52.45 percent was because Uttarakhand was made a separate State with Dehradun as its capital.

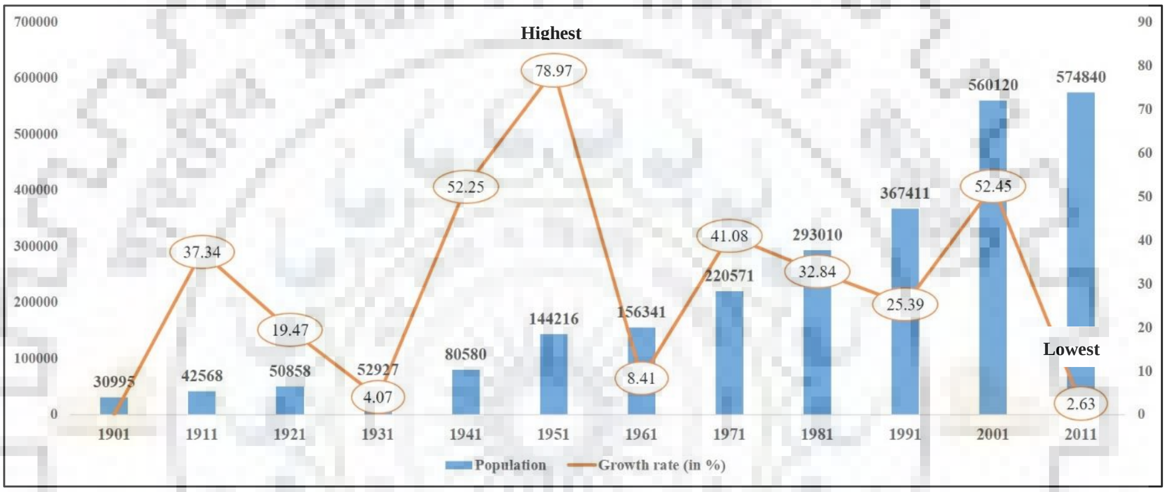


Figure 4-3: Decadal growth of population of Dehradun

Source: *(Census of India, 2011; MDDA, 2008)*

4.1.2.2 Population Density

The overall population density of the Dehradun Municipal Corporation was approximately 79 pph, while the highest is in the Ward No. 24 with a density of nearly 422 pph and the lowest is in the Ward No. 28 with density of nearly 14 pph. The high variation in the population density among the wards is because of the presence of high amount of forest areas, gardens, etc. around the city surroundings. *Figure 4-4* illustrated the detailed ward wise population density in the municipal limits of the city.

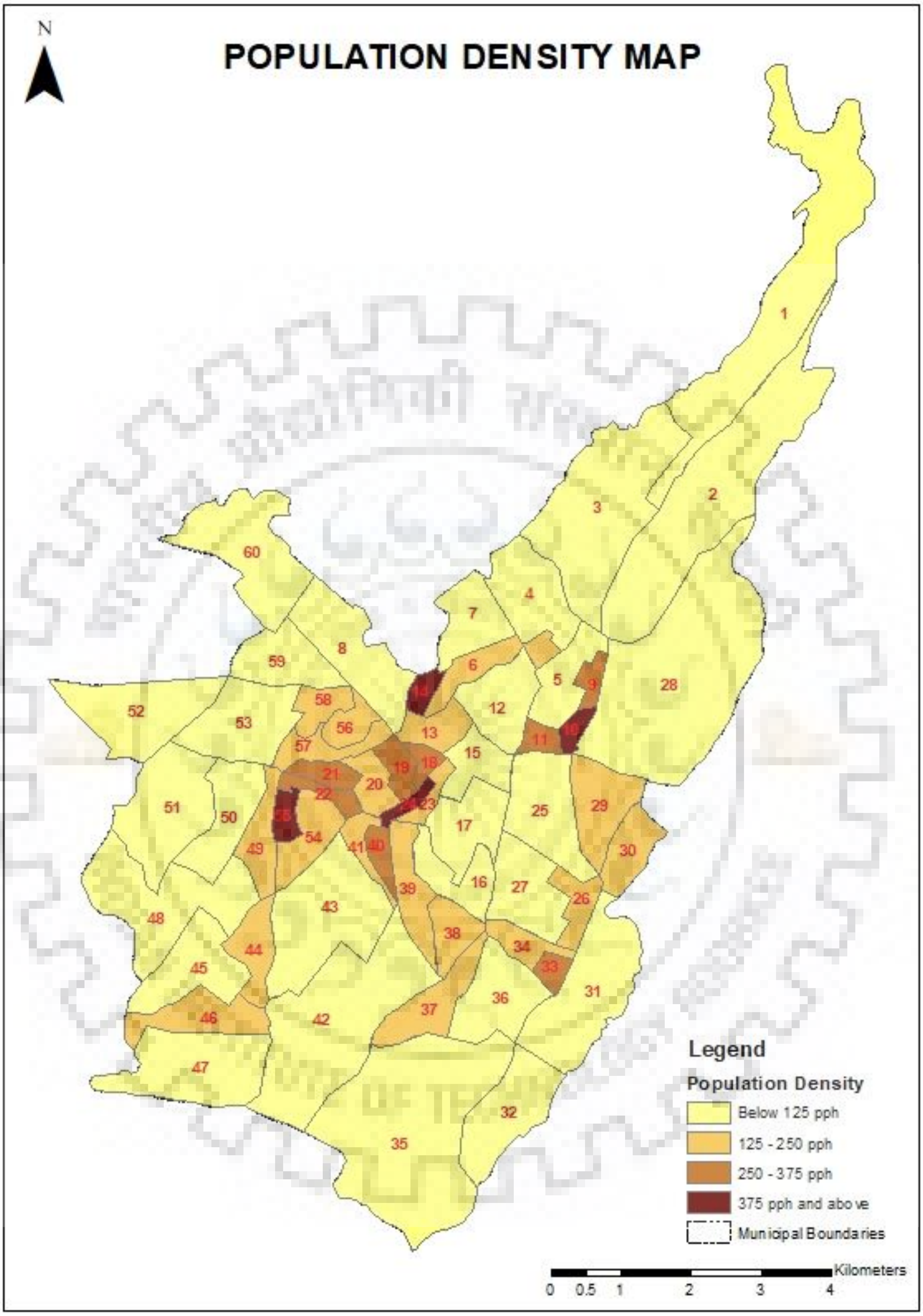


Figure 4-4: Map showing the variation of population density across the wards.

Source: *(Census of India, 2011)*

4.1.2.3 Sex Ratio

The sex ratio of Dehradun according to the Census 2011 is 907, which is higher than that of the district urban average (886) and state urban average (884) but lower than the national urban average (929) (Census of India, 2011). The increase in the sex ratio is negligible over the decade of 2001-2011. *Figure 4-5* shows the sex ratio for the year of 2001 & 2011.

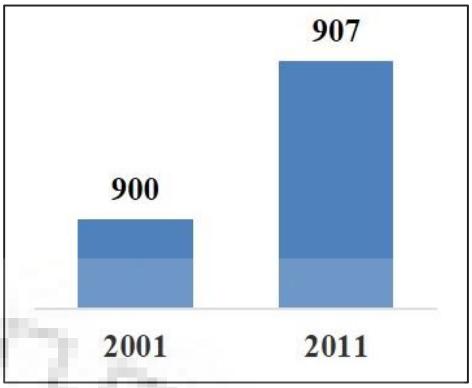


Figure 4-5: Sex Ratio of Dehradun

Source: *(Census of India, 2011)*

4.1.2.4 Literacy Rate

Dehradun has a literacy rate of nearly 79 percent, according to Census 2011, which is nearly equal to that of the state urban average (79.3 percent) and national urban average (79.1 percent) but much lower than the district urban average of 83.9 percent (Census of India, 2011). The literacy rate of the city has witnessed an increase of 3.67 percent over the last decade. *Figure 4-6* illustrates the literacy rate of the city for the year 2001 and 2011.

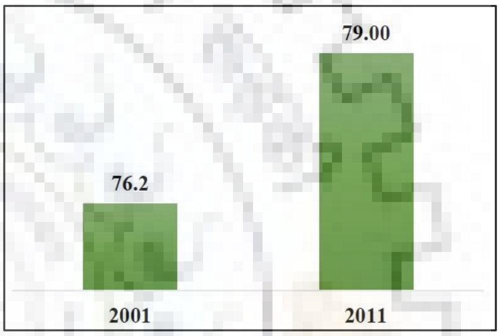


Figure 4-6: Literacy Rate (in %) of Dehradun

Source: *(Census of India, 2011)*

4.1.2.5 Workforce Characteristics

The workforce participation rate of the city has decreased by 7.36 percent over the decade 2001-2011. *Figure 4-7* illustrates the Workforce Participation Rate for the year 2001 and 2011. It can be summarised from *Figure 4-8*: *(left)*, which illustrates the detailed distribution workers across the various industries, that the tertiary industry is majorly predominant in Dehradun. *Figure 4-8*: *(right)* illustrates the male-female ratio in the workforce of the city for the year 2011.

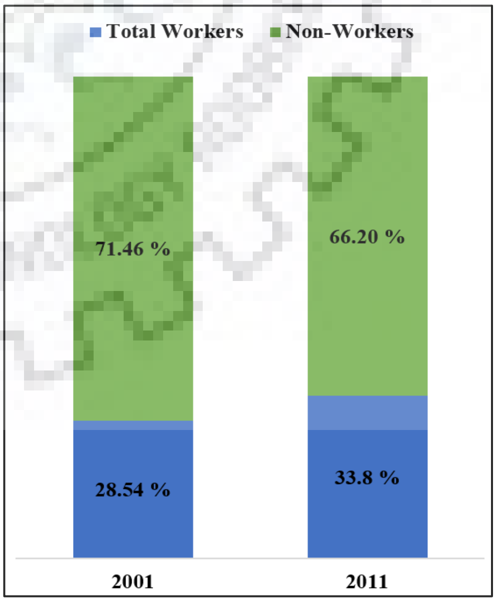


Figure 4-7: Workforce Participation Rate of Dehradun

Source: *(Census of India, 2011)*

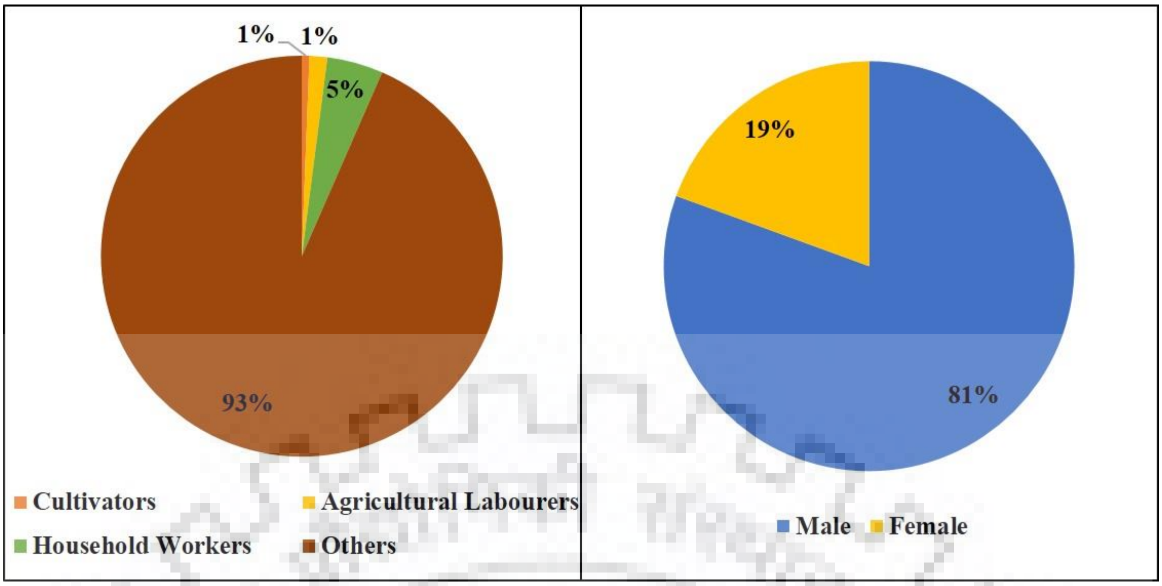


Figure 4-8: Distribution of Workforce across Various Industries (left); Male-Female ratio of Workforce (right)

Source: *(Census of India, 2011)*

4.1.3 Infrastructure

4.1.3.1 Health Facilities

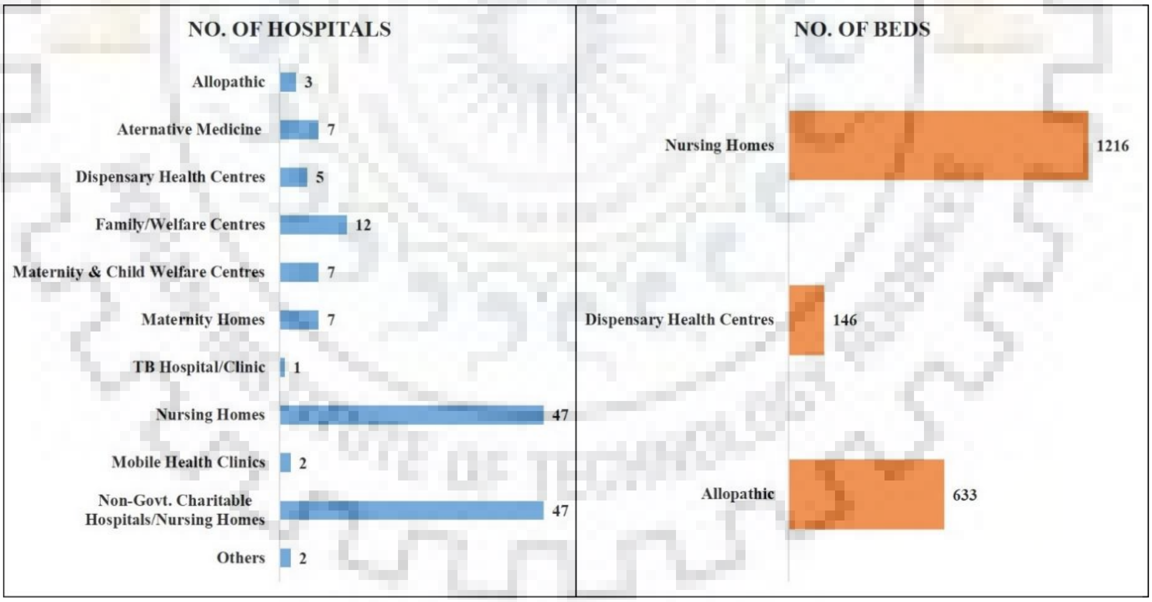


Figure 4-9: List of Medical Facilities in Dehradun

Source: *(Census of India, 2011)*

Figure 4-9 shows the number of various types of healthcare institutions along with the number of bedding facilities in them according to the Census of 2011.

4.1.3.2 *Educational Facilities*

Figure 4-10 shows the number of various types of educational institutions present in the city, according to the Census of 2011. It also shows the classifications of each type of institutions according to their governing body, i.e. Government and Private Institutions.

	Primary Schools	Middle Schools	Secondary Schools	Senior Secondary Schools	Schools for Disbled	Degree Colleges	Medical College	Engineering College	Management Instiitute	Polytechnic College	Vocational Training	Non-Formal Education
Private	87	37	23	23	4	32	1	2	5	1	21	0
Govt.	113	46	8	16	1	2	0	0	0	1	2	3

Figure 4-10: List of Educational Facilities in Dehradun

Source: *(Census of India, 2011)*

4.1.3.3 *Water Supply and Electricity*

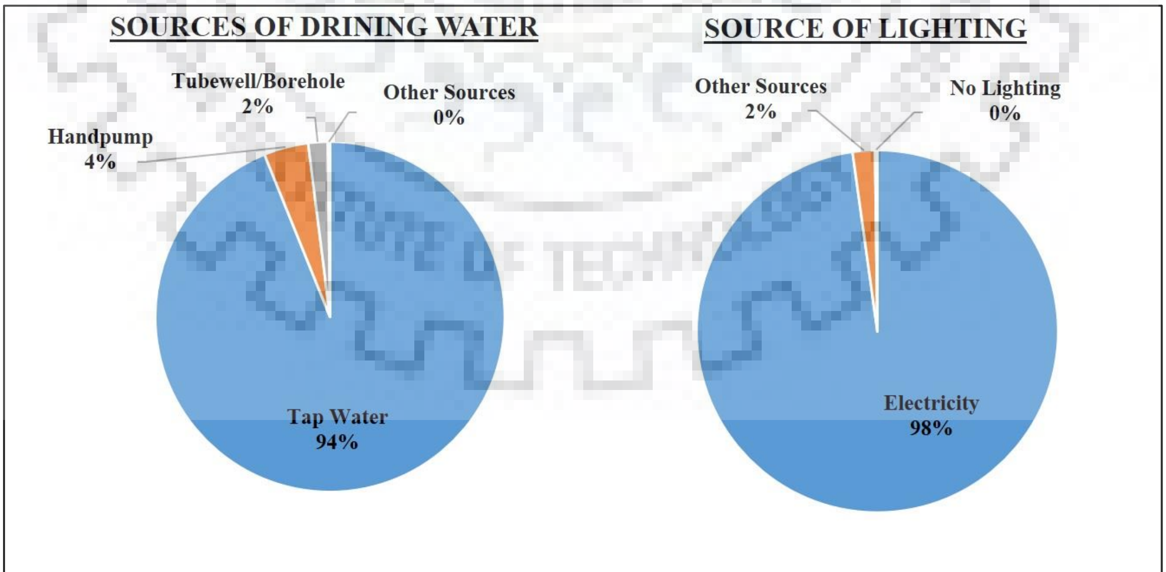


Figure 4-11: Statues of Water Supply and Electrification in Households

Source: *(Census of India, 2011)*

The city of Dehradun has a coverage of municipal tapped water supply in approximately 94 percent of the households, while 98 percent of the households have electrification (Census of India, 2011). *Figure 4-11* illustrates the above statistics.

4.1.4 Landuse

The built-up area of development area of Dehradun, according to the proposed landuse of 2025 by MDDA, is nearly 27.9 percent of the total area, while the existing landuse of 2003-2004 was nearly 17.6 percent (MDDA, 2008). This shows how the urbanisation is influencing the increase in the built-up area of the city. The detailed changes in the landuse of the Dehradun Development Area for each category have been illustrated in *Figure 4-12*.

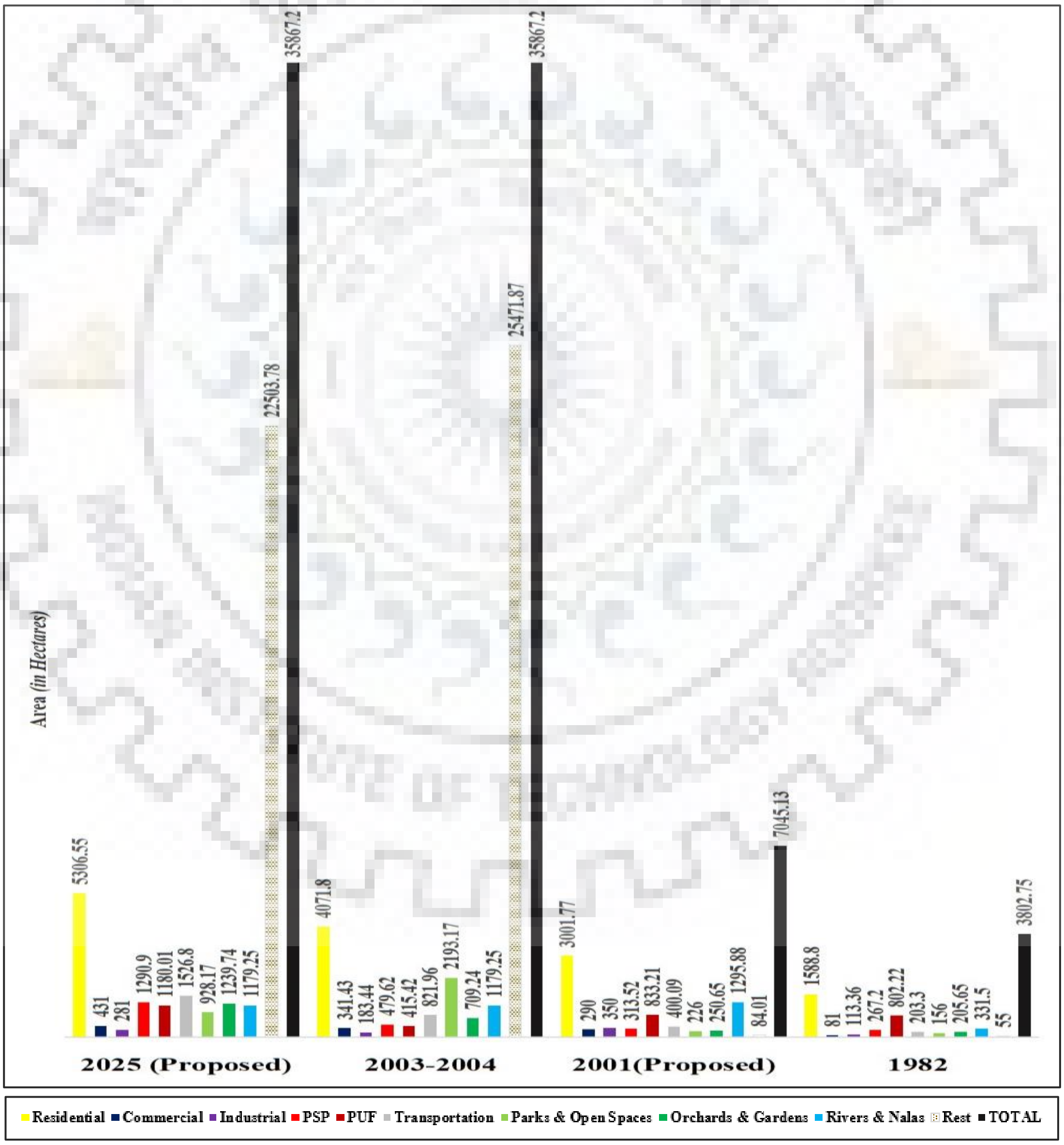


Figure 4-12: Landuse of Dehradun

Source: *(GHK International, 2007; MDDA, 2008)*

4.2 IMPACTS ON URBANISATION ON PRECIPITATION AND TEMPERATURE

4.2.1 Precipitation

The total annual precipitation pattern of Dehradun during the period of 1989-2018 has been presented in *Figure 4-13*. During this period, the city has received an average of nearly 1198.2 mm annual rainfall, the minimum and maximum being 667.8 mm in the year 1992 and 1997.0 mm in the year 2013 respectively. An increasing trend has been observed during the period. Using Mann-Kendall Trend Test *(at 95 percent confidence level)*, an increasing trend has been identified. The Sen's slope indicates an annual average increase of 15.3 mm. The summary of the trend test has been presented in *Table 4-1*. The monthly pattern of the rainfall for the period 1989-2018 has been presented in *Figure 4-14*. The maximum precipitation is observed in the month of August *(average of 347.9 mm)* while the minimum is observed in the month of November *(average of 5.2 mm)*.

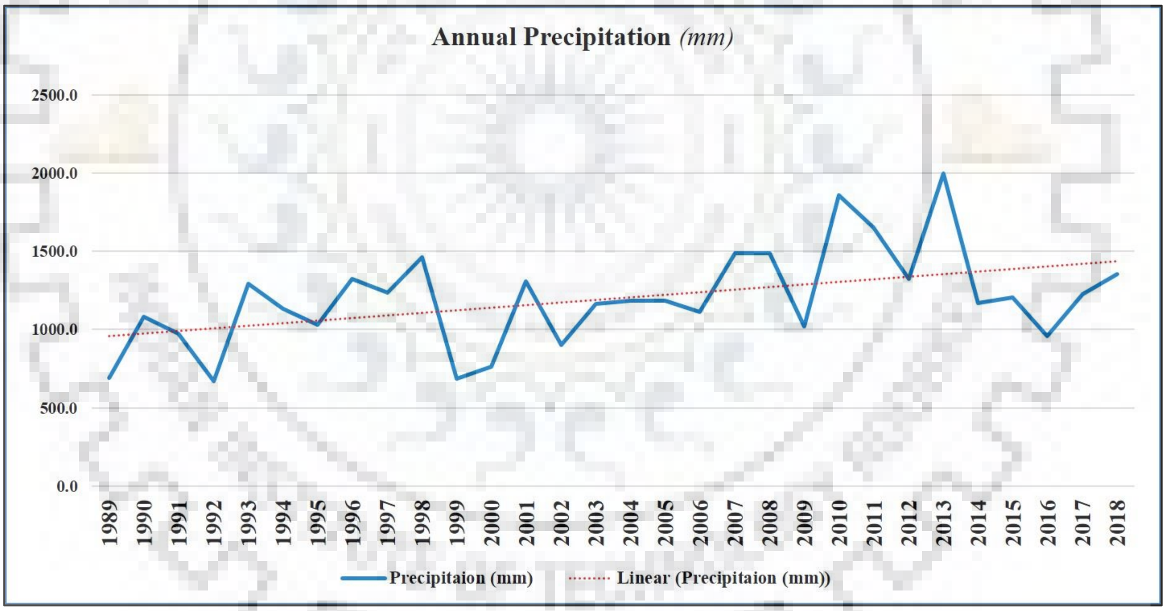


Figure 4-13: Annual Precipitation Pattern of Dehradun

Source: *(IMD, 2018)*

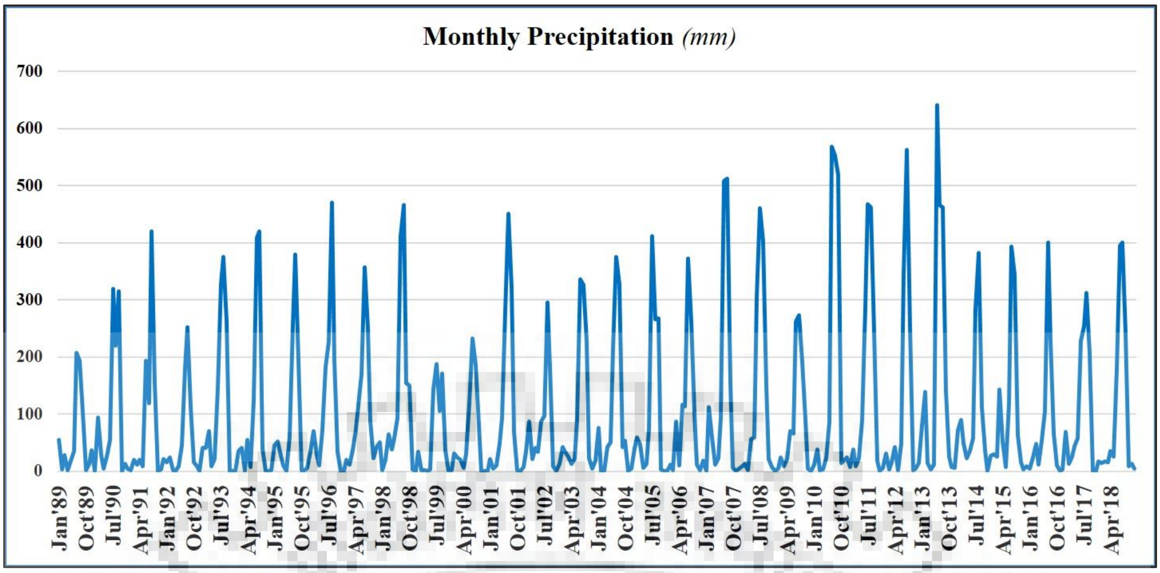


Figure 4-14: Monthly Precipitation Pattern of Dehradun

Source: *(IMD, 2018)*

4.2.2 Temperature

The variations in the annual maximum temperature and the annual minimum temperature for the duration 1989-2018 has been illustrated in the *Figure 4-15.* The lowest annual minimum temperature during this period is -1.4℃ in 1989 while the highest annual maximum temperature is 37.1°C in 2006. The average lowest temperature during this period is nearly 1.7℃, while the average highest temperature being 39.8℃. No significant trends could be identified for both the annual and maximum temperature at 95 percent significance level. The summary of the trend tests has been presented in *Table 4-1*.

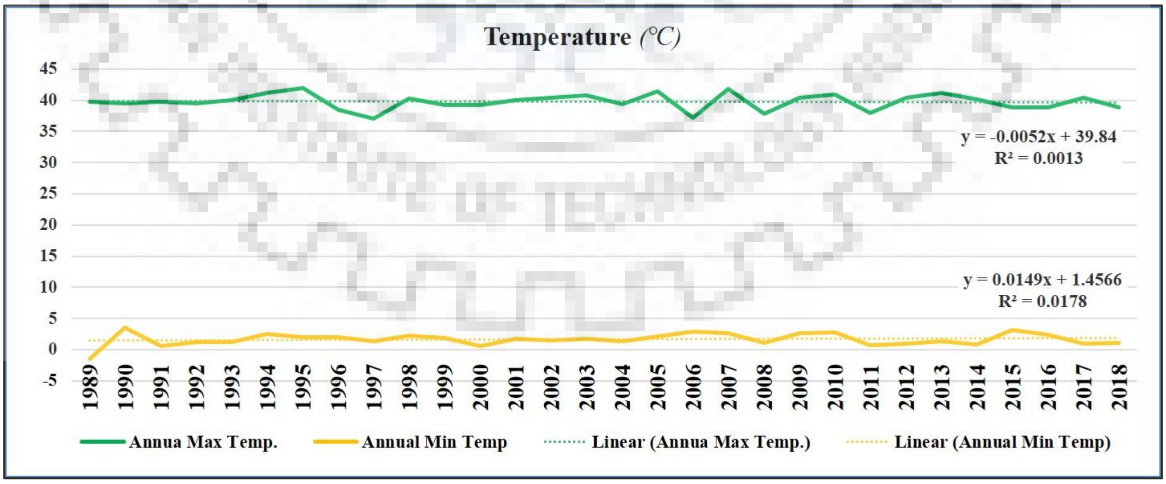


Figure 4-15: Annual Maximum and Minimum Temperature of Dehradun

Source: *(IMD, 2018)*

Table 4-1: Summary of Mann-Kendall's Test

Parameter	Z Value	Sen's Slope	Inferences
Annual Rainfall	2.5	15.291	Increasing Trend
Annual Maximum Temperature	0.14	0.006	No significant Trend
Annual Minimum Temperature	0.29	0.008	No significant Trend

4.3 DEVELOPMENT OF INTENSITY- DURATION-FREQUENCY (IDF) CURVES

The Intensity-Duration-Frequency (IDF) curves has been developed for the study area in order to predict the maximum possible rainfall volume and intensity for different durations at different return periods using the rainfall data of the period of 1989 to 2018. The IDF curves developed, illustrated in *Figure 4-16*. The procedure followed for the development of these IDF Curves has been explained in *Annexure 1*.

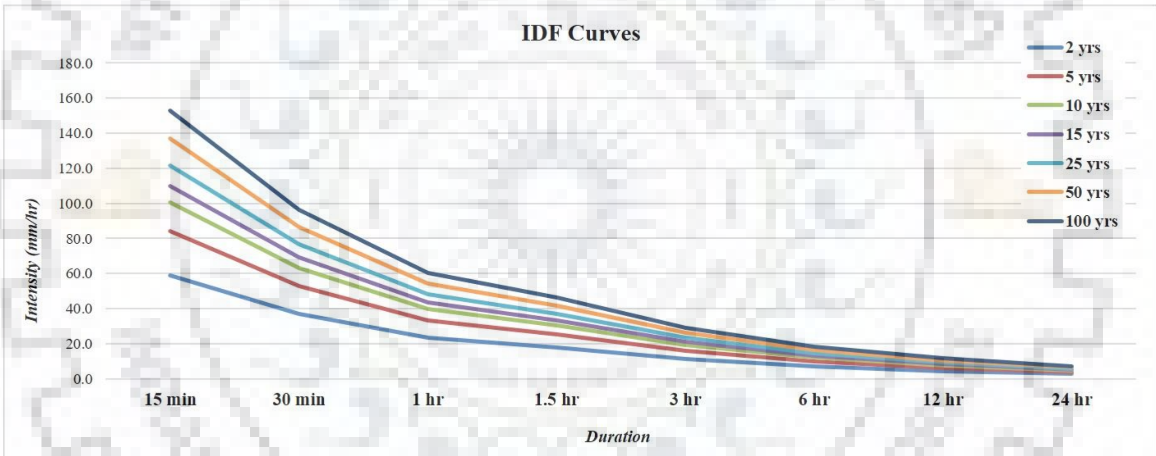


Figure 4-16: IDF Curves for the Study area

4.4 CATCHMENT DELINEATION

The city of Dehradun is spread over the catchments along the two major rivers, Bindal Rao and Rispana, which also acts as the drainage channels of the city. The catchment areas are usually known after their respective rivers as Bindal Rao catchment and Rispana catchment. The delineation of the study area focuses on determining the extent of the Bindal Rao catchment.

4.4.1 Delineation Process

The study area has been delineated using the DEM for the city of Dehradun in ArcGIS platform. The ASTER-DEM of the 30 metre resolution, retrieved from the USGS website, has been used for this purpose. The process of delineation consist of two sub-processes: determining the streamflow pattern and the delineation of the catchment. The tools used in each sub-processes have chronologically listed in the *Figure 4-17*. The catchment of Bindal Rao is found, upon delineation, to be extended over an expanse of 57.95 Sq. Kms. The catchment delineated has been illustrated in *Figure 4-18*.

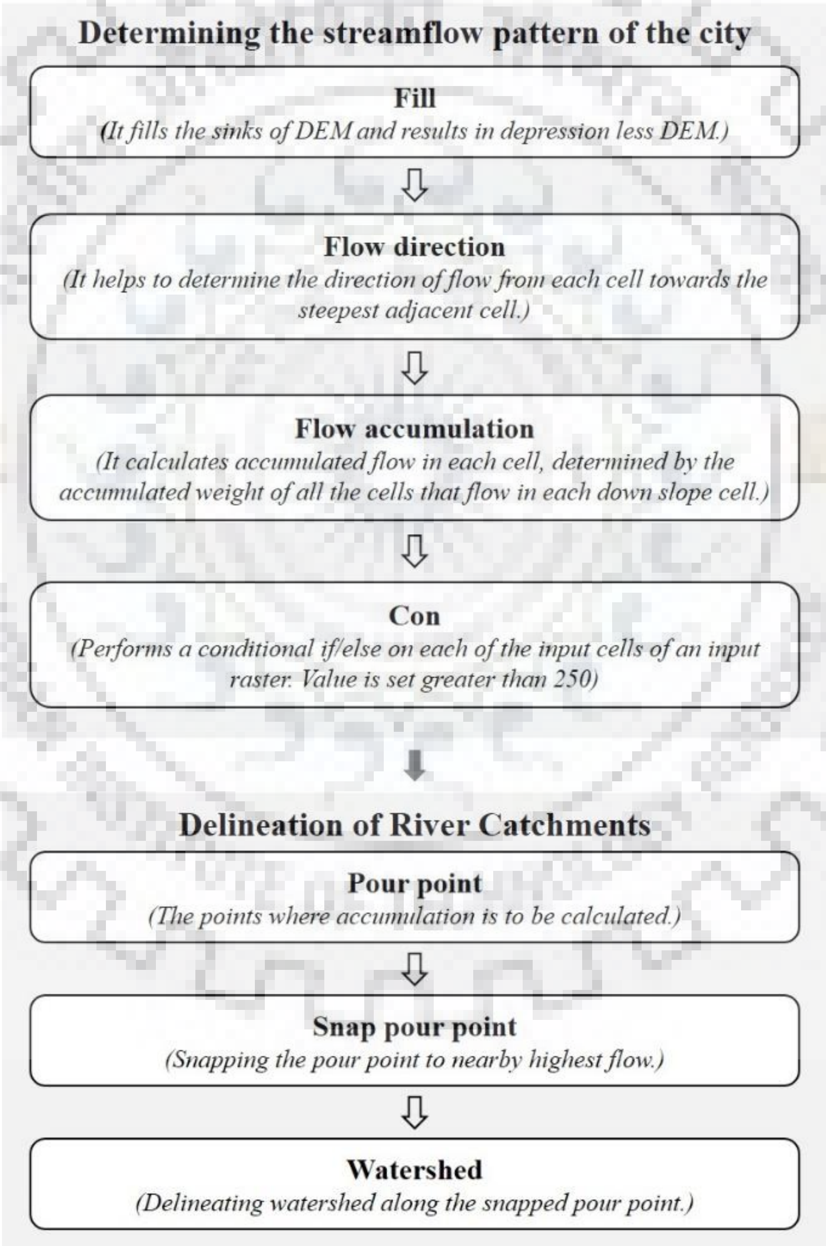


Figure 4-17: Process of delineating river catchment

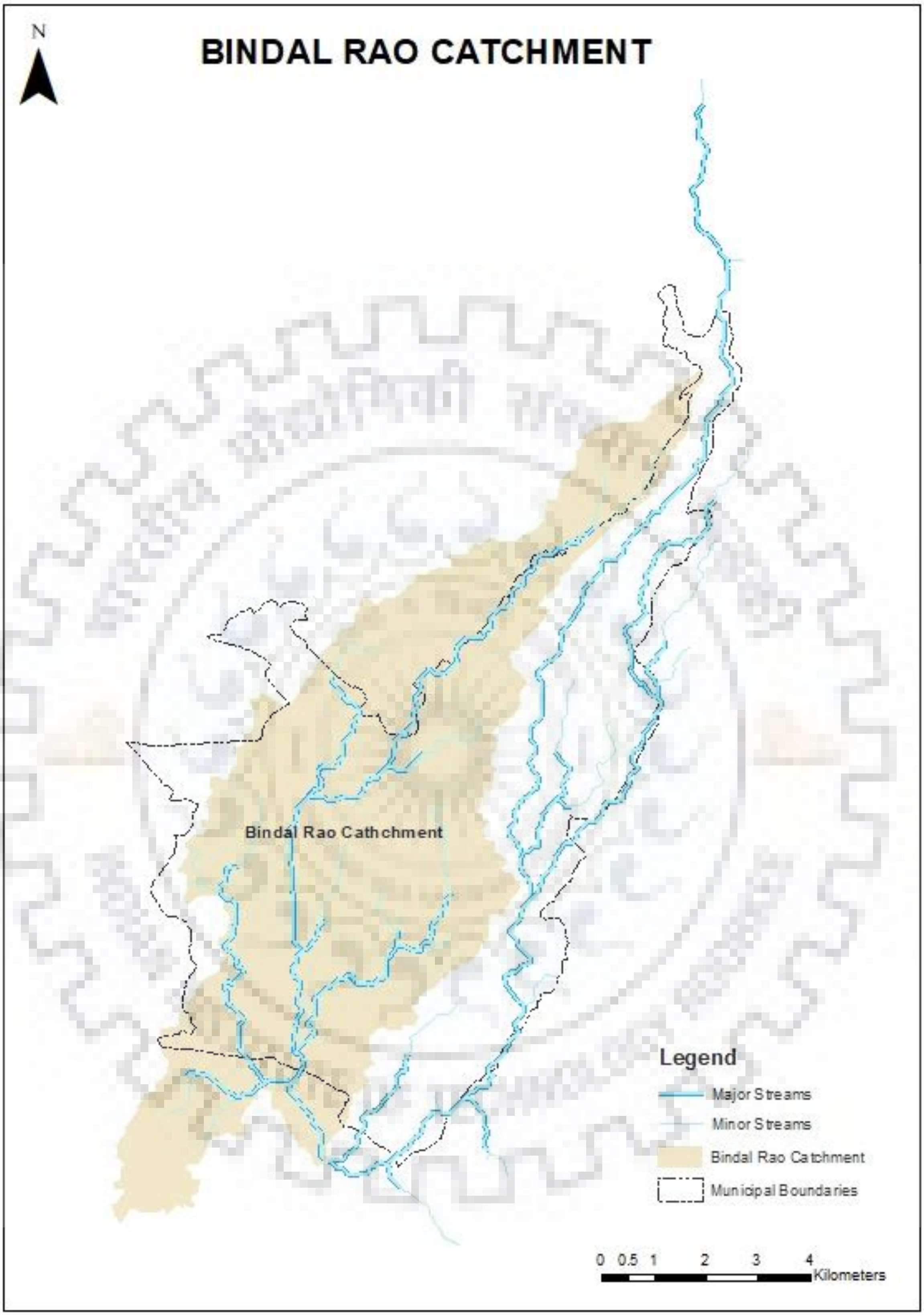


Figure 4-18: Map showing the delineated Bindal Rao catchment

4.4.2 Suitability of Site

The catchment of the Bindal Rao River has a highly varied terrain with elevations ranging from 560 MSL to 1050 MSL. The natural drainage, contour and slope map of the catchment has been illustrated in *Figure 4-19* and *Figure 4-20* respectively. The highly variable terrain of the area increases the issues of water inundation, blockades, etc. during urban floods, making the catchment apt for the dissertation. The catchment of Bindal Rao, further, covers approximately 57.5 Sq. Kms (around 78.6 percent) of the municipal limits of the Dehradun. The data of this catchment are comparatively more accessible because of such high spatial convergence with the municipal limits.

4.5 SUBCATCHMENT ANALYSIS

The study area, i.e., the catchment area of the Bindal Rao River, has been further divided into six sub-catchments as shown in *Figure 4-21*. The subcatchments has been analysed in terms of area, width, slope and LULC as described in the following subsections with a further objective of setting up the SWMM for the Bindal Rao River.

4.5.1 Area and Width

The area of the subcatchments varies in the range of 299.77 hectares to 1920.86 hectares. S1 is the smallest subcatchment while S5 is the largest in terms of area. The width a subcatchments is the cross-section width perpendicular to the overland channel flow path of that particular subcatchment. The width of the subcatchments is in range of 749.33 metres to 4802.5 metres.

4.5.2 Slope

The slope of each subcatchment has been extracted from the ASTER-DEM of the study area. The maximum slope, i.e., 77.01 percent, is found in the subcatchment S2 that the subcatchment has highly variable ground elevations. The slope of the other subcatchments is found to be in the range of 38.72 percent to 48.99 percent. The subcatchment S4 is found to be with the lowest slope indicating that this subcatchment has a comparatively less variable elevation in comparison of others. The slope extraction for the subcatchments has been illustrated in the *Figure 4-22*.

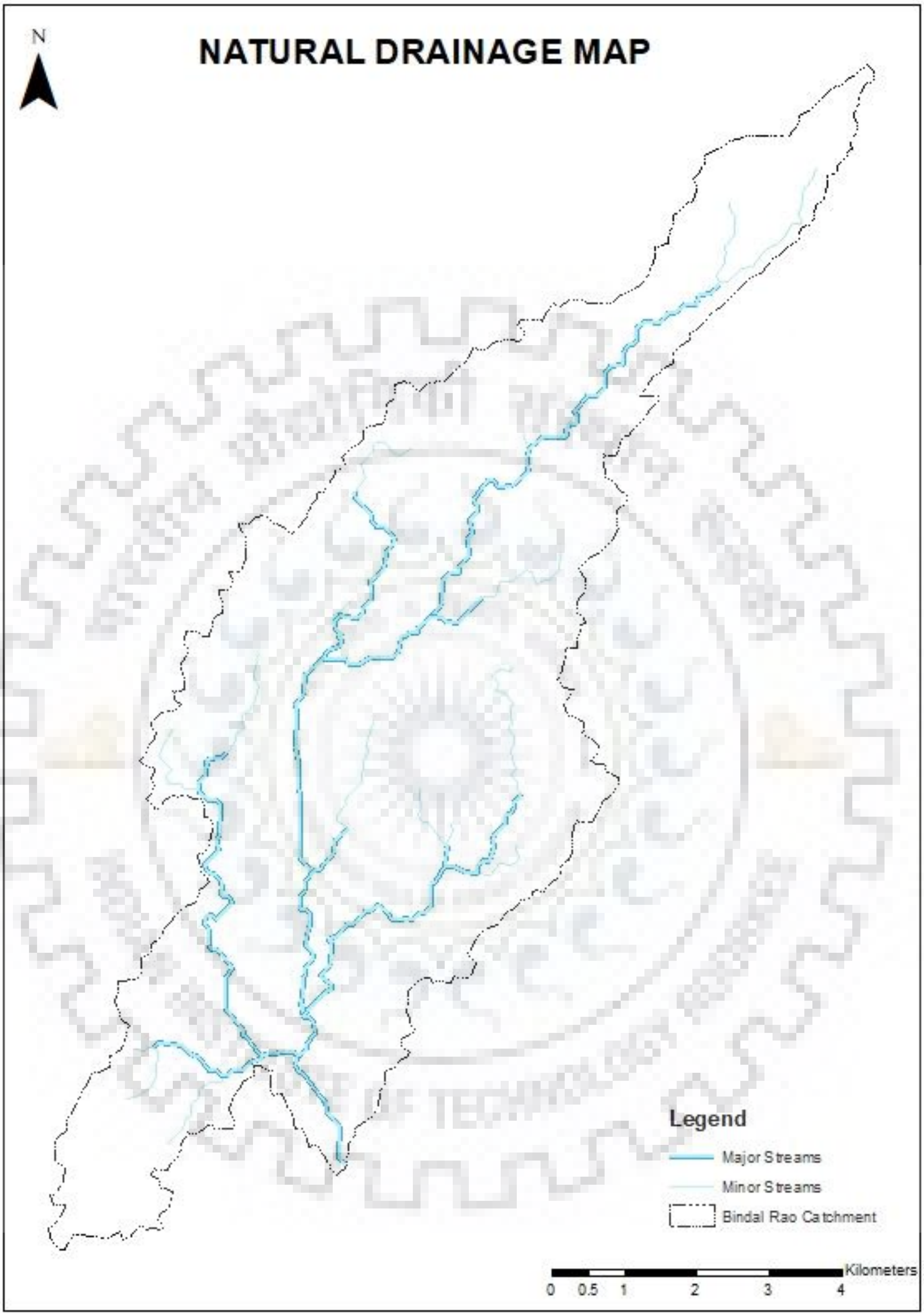


Figure 4-19: Map showing Natural Drainage of the Bindal Rao Catchment

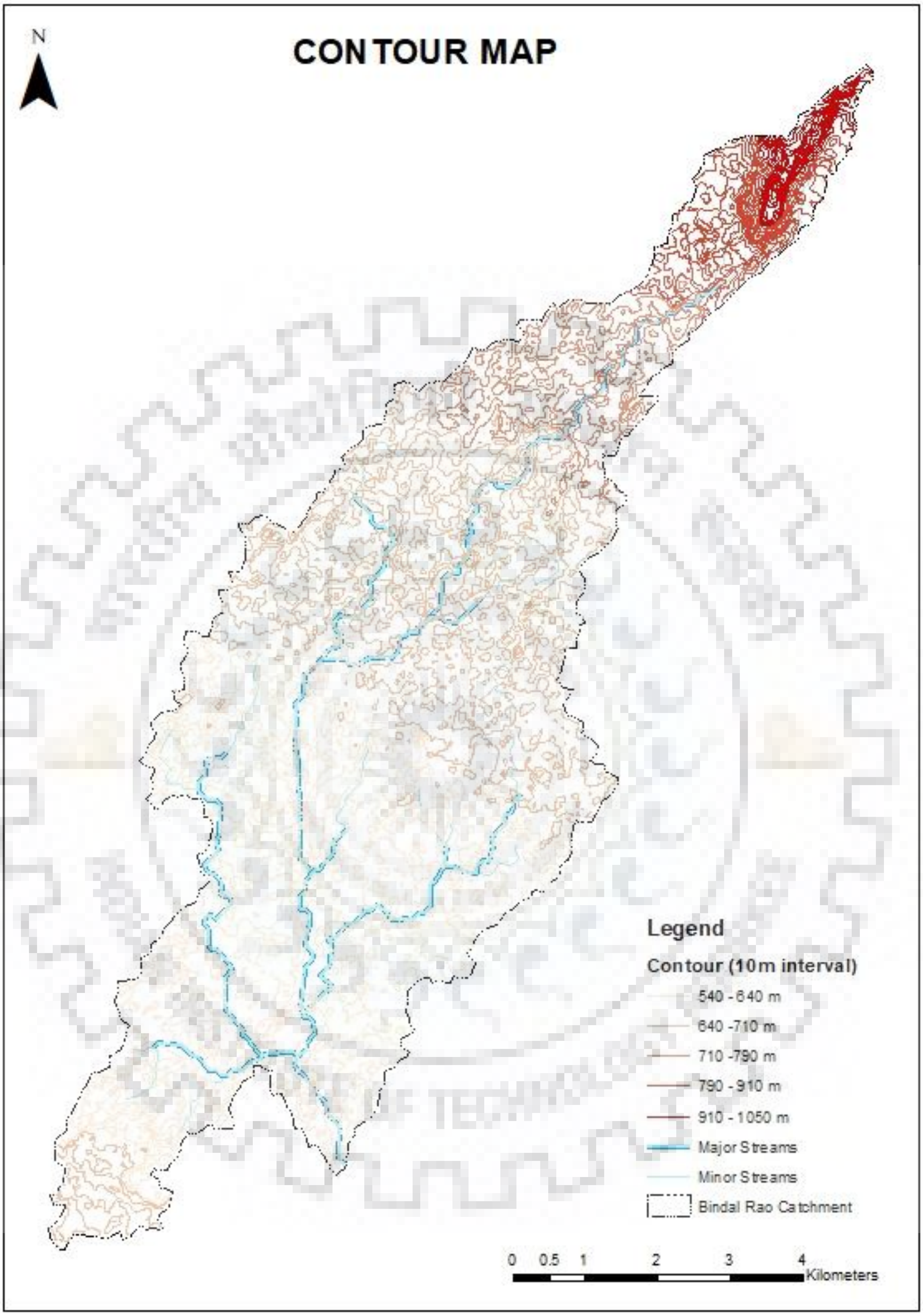


Figure 4-20: Map showing the Contour of the Bindal Rao Catchment

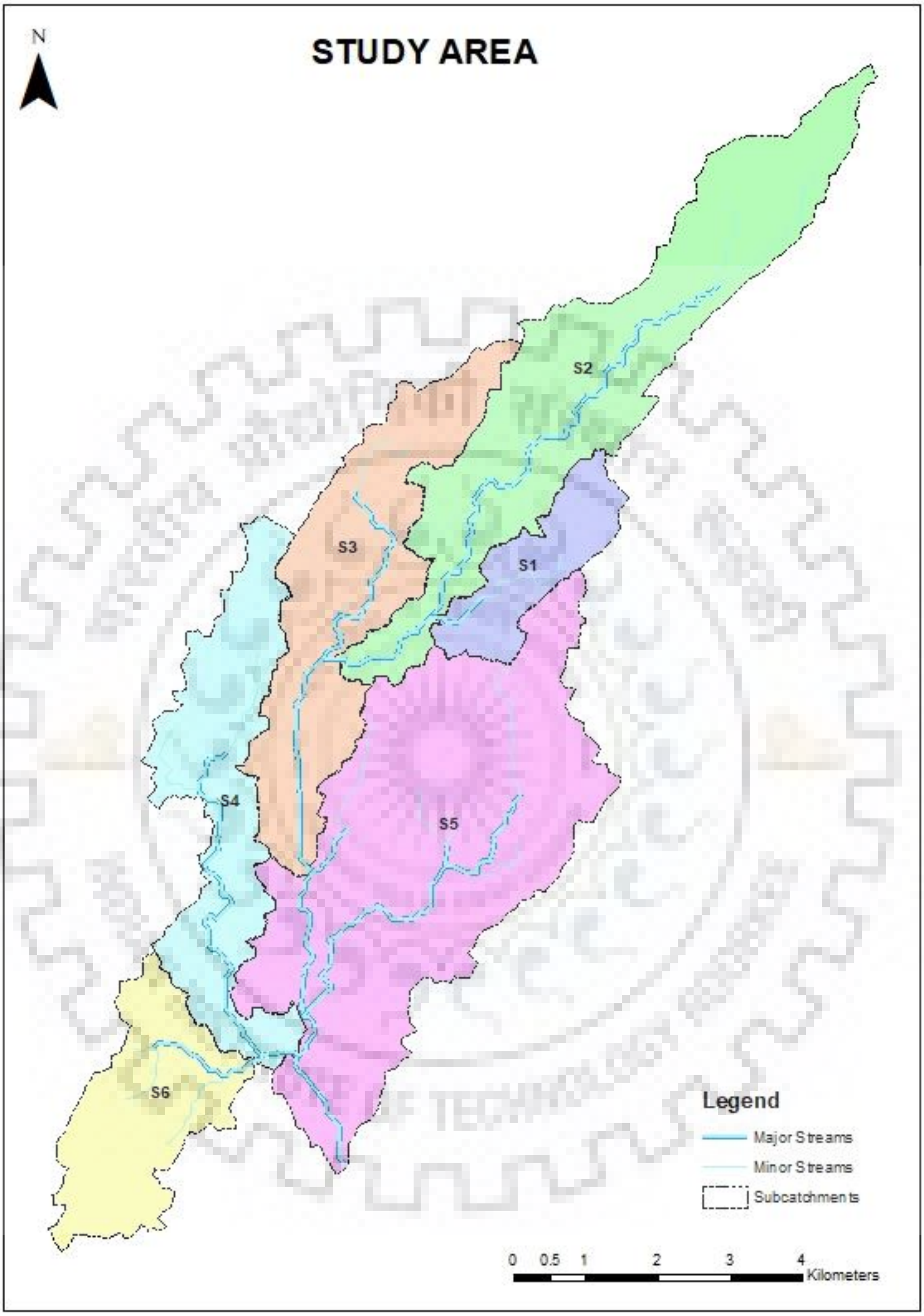


Figure 4-21: Map showing the subcatchments of the Bindal Rao River.

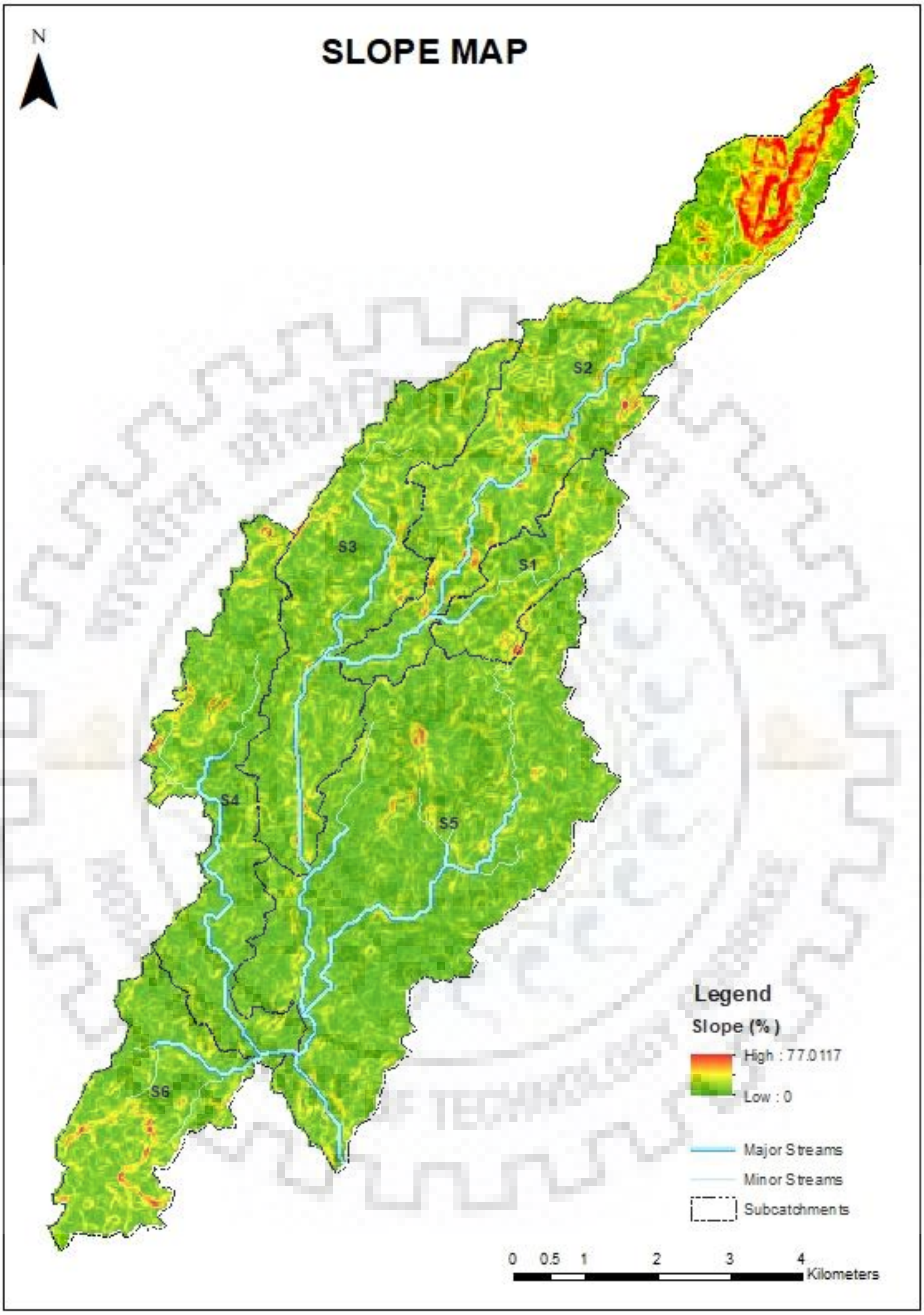


Figure 4-22: Map showing the slope of each subcatchments of the Bindal Rao River

4.5.3 Landuse Landcover (LULC)

The LULC of the subcatchments has been extracted from the LANDSAT 8 images using ERDAS Imagine. The LULC of the subcatchments has been classified into 9 categories excluding water bodies, and mapped in the scale of 1:10,000 with accuracy of 93.15 percent (overall kappa statistics = 0.9252). The detail result of the LULC Mapping has been described in *Annexure 2*, while the map has been illustrated in *Figure 4-23*.

The data extracted from the LULC analysis has been further used to calculate the imperviousness and runoff Curve Number (CN) of each subcatchment. The CN of the subcatchments is calculated considering the runoff CN for different classes of landcover as listed in (Subramanya, 2008). The details of the calculation of the imperviousness and runoff CN have been described in *Annexure 2*.

4.5.4 Summary

The subcatchment analysis has been summarised in *Table 4-2*.

Table 4-2: Characteristics of the subcatchments in the Study Area

Name	Slope (%)	Area (Hectares)	Width (m)	Imperviousness (%)	Weighted CN
S1	48.99	299.77	749.43	76.45	79.46
S2	77.01	1316.20	3290.50	33.59	65.44
S3	40.85	915.15	2287.88	65.70	82.09
S4	38.72	775.18	1937.94	66.79	76.03
S5	42.10	1920.86	4802.15	71.12	77.58
S6	45.46	566.74	1416.85	40.03	79.25

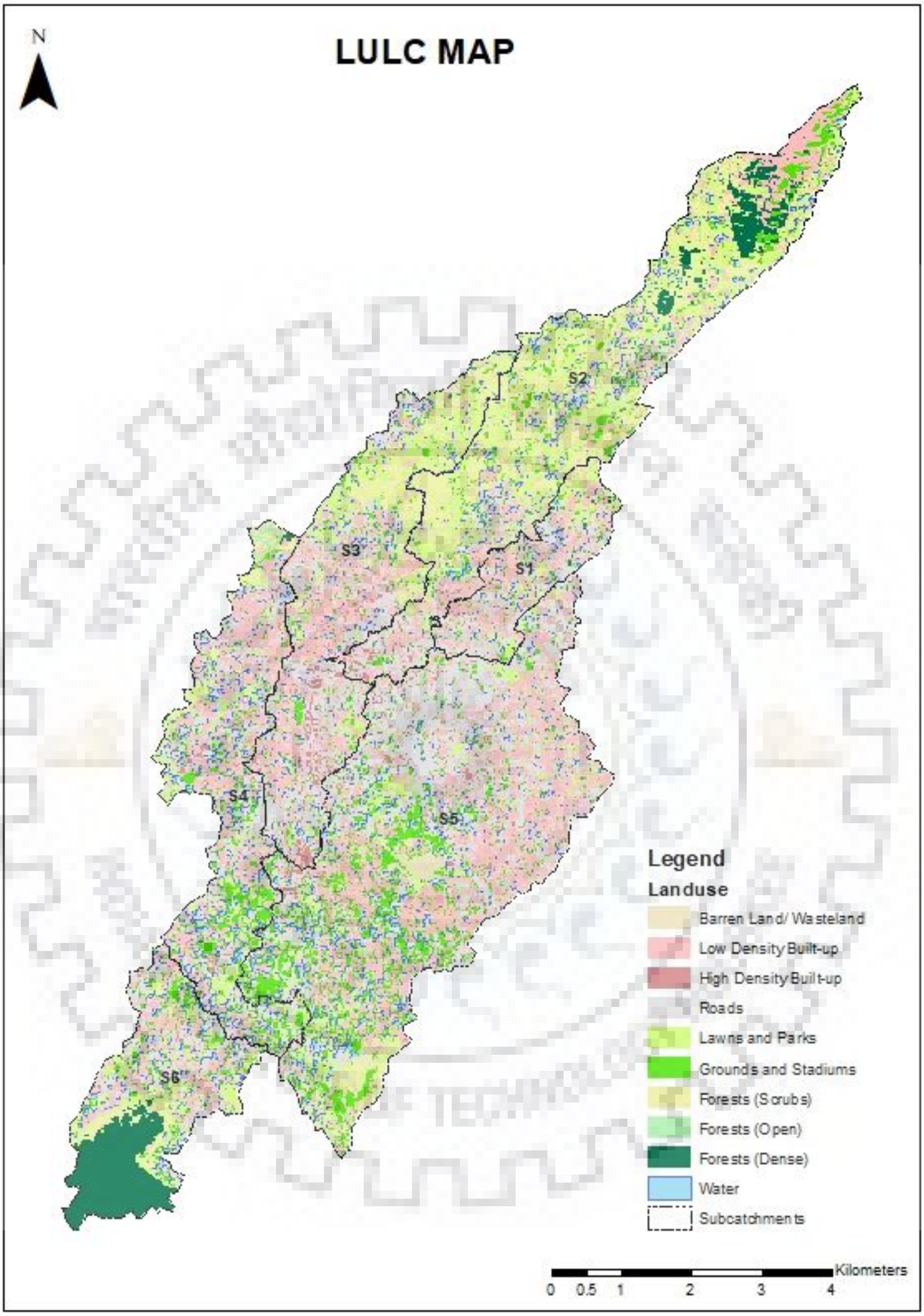


Figure 4-23: Map showing the LULC of the subcatchments of the Bindal Rao River

4.6 FLOOD SIMULATION

The following sub-sections, details about the setting up of the model and discusses about the results of the simulation.

4.6.1 Setting up of the Model

To set up the SWMM for the study area, the following inputs have been extracted from the data collected from various sources:

a) **Subcatchments:** Subcatchments are hydrologic units of land whose topography and drainage system elements direct surface runoff to a single discharge point. The necessary details of the subcatchments for the study area have been extracted as described in the *Section 5.4,* whereas the rest of the parameters has been set to default values. The inputs for the 6 subcatchments in the study area has been listed in *Annexure 3, Table 9.*

b) **Junctions:** Junctions are drainage system nodes where links connect. These can physically represent the confluence of natural surface channels, manholes in a sewer system, or pipe connection fittings. External inflows can enter the system at junctions. The principal input parameters for a junction are invert (channel or manhole bottom) elevation and maximum depth (Height to ground surface). The inputs for the 40 junctions in the study area has been listed in *Annexure 3, Table 10.*

c) **Outfalls:** Outfalls are terminal nodes of the drainage system used to define final downstream boundaries. Only a single link can be connected to an outfall node, and the option exists to have the outfall discharge onto a subcatchment surface. The principal input parameters for outfalls is invert elevation. The study area consists of 5 outfalls. There inputs for the 5 outfalls in the study area has been listed in *Annexure 3, Table 11.*

d) **Conduits:** Conduits are pipes or channels that move water from one node to another in the conveyance system. Their cross-sectional shapes can be selected from a variety of standard open and closed geometries. The principal input parameters for conduits are the names of the inlet and outlet nodes; conduit length; manning's roughness and cross-sectional geometry. There inputs for the 40 conduits in the study area has been listed in *Annexure 3, Table 12.*

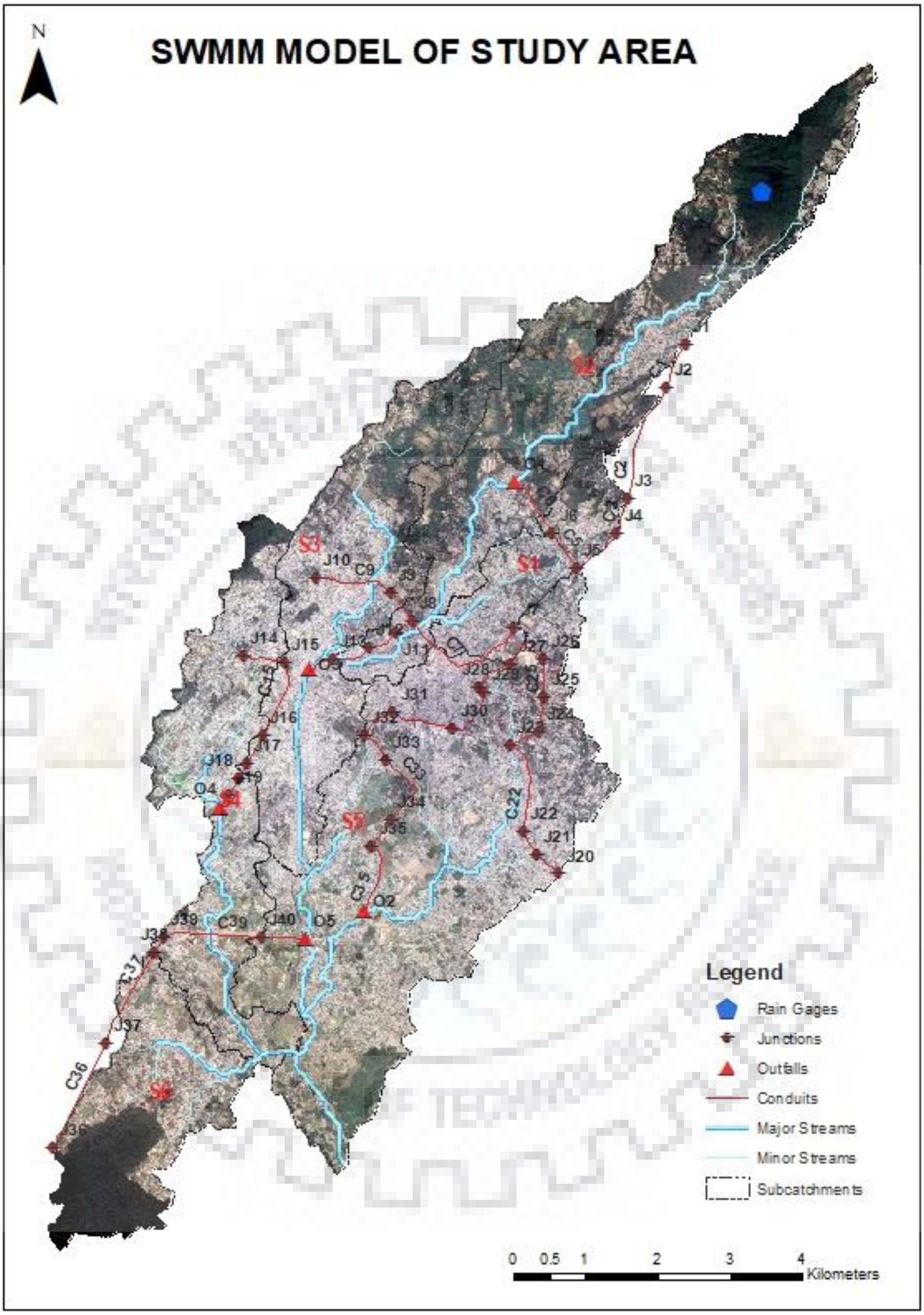


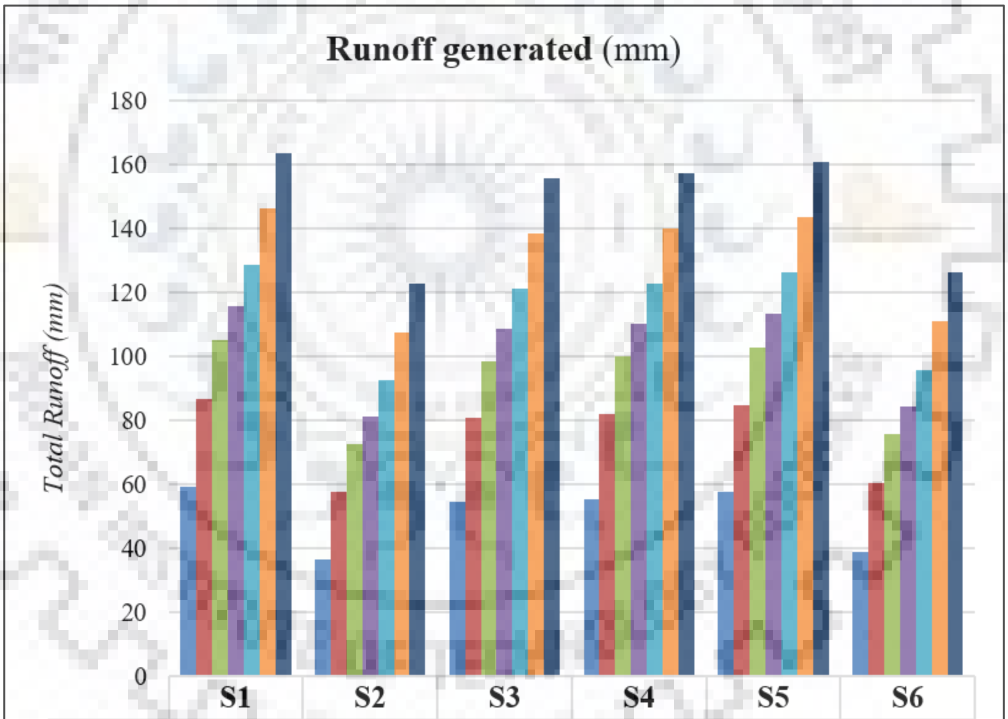
Figure 4-24: Map showing the representation of the SWMM for the Study Area

e) **Rain Gage and Rainfall:** The study area consists of only 1 rain gauge recording the daily rainfall. The 24-hour rainfall values of different return periods are used in this study. The 24-hour values disaggregated into 15 minutes interval using IMD reduction Formula. The time series for each of the return periods used in the study has been listed in *Annexure 3, Table 13 & 14.*

Figure 4-24 illustrates the representation of the SWMM for the study area.

4.6.2 Simulation Results

The subcatchment S5, being the largest in terms of area and the second most impervious after subcatchment S1, observes the highest runoff. The lowest has been observed in the subcatchment of S2 because of the presence of large amounts of pervious surface in the subcatchment. *Figure 4-25* illustrates the above.



	S1	S2	S3	S4	S5	S6
2 yr	59.43	36.71	54.49	55.39	57.59	39.02
5 yr	86.84	57.81	80.77	81.95	84.69	60.54
10 yr	105.33	72.8	98.66	99.99	103.02	75.74
15 yr	115.74	81.45	108.78	110.19	113.36	84.47
25 yr	128.75	92.52	121.48	122.98	126.29	95.64
50 yr	146.23	107.68	138.6	140.2	143.68	110.91
100 yr	163.7	122.98	155.7	157.39	161.04	126.31

Figure 4-25: Runoff Generated at each subcatchments

4.6.3 Validation

The study area has no observed dataof discharge. Therefore, the validation of the simulation has been carried out by indirect runoff method such as calculating the runoff coefficient of the study area using the *Equation 5.1*.

$$Q = C.I.A / 3600 \qquad \ldots(5.1)$$

where, Q is the discharge in m^3/sec; C is the runoff coefficient; I is the rainfall intensity in mm/hr and A is the Area in hectares.

Figure 4-26 shows the discharge generated for the different return periods, and the calculated runoff coefficient is listed in *Table 4-3* showing that all the runoff co-efficient values are within the range valid for the urban area. Hence, the results seem to be correct.

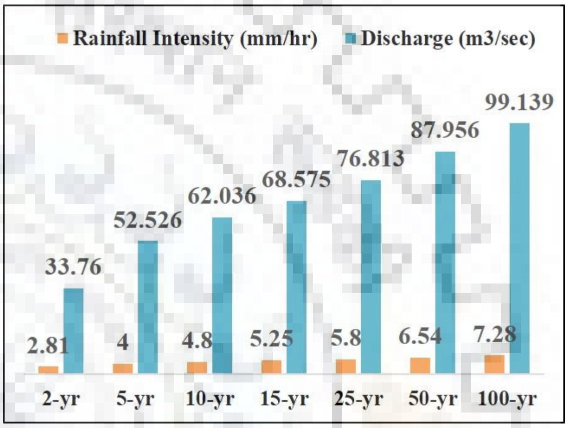


Figure 4-26: Total discharge generated for different return periods

Table 4-3: Calculated Runoff Coefficients

Return Period	Runoff Coefficient
2-yrs	0.746
5-yrs	0.783
10-yrs	0.802
15-yrs	0.811
25-yrs	0.822
50-yrs	0.835
100-yrs	0.845

Secondly, the depth of the total discharge that has been reported while simulation is found to be lesser than the rainfall for every return period that is an indication of acceptable modelling. *Figure 4-27* illustrates the above.

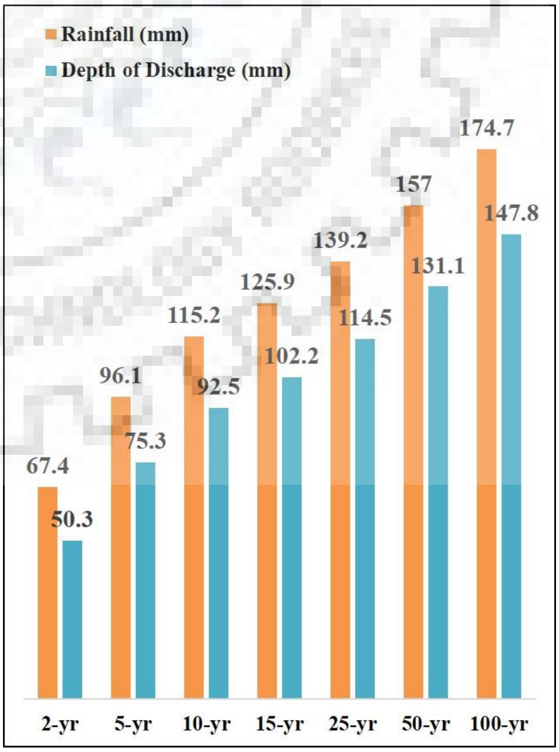


Figure 4-27: Depth of Discharge

4.7 FLOOD MAPPING

The spatial mapping of the inundation has been carried out for the floods of return periods of 2 years, 5 years, 10 years, 15 years, 25 years, 50 years and 100 years as shown in

Figure 4-28. The inundation levels of the study area have been categorized as given below:

i. Low: 0-0.08 m
ii. Moderate: 0.08-0.17 m
iii. High: 0.17-0.30 m
iv. Very High: 0.30-0.62 m

The maximum inundation level observed for floods of different return periods has been listed in *Table 4-4*.

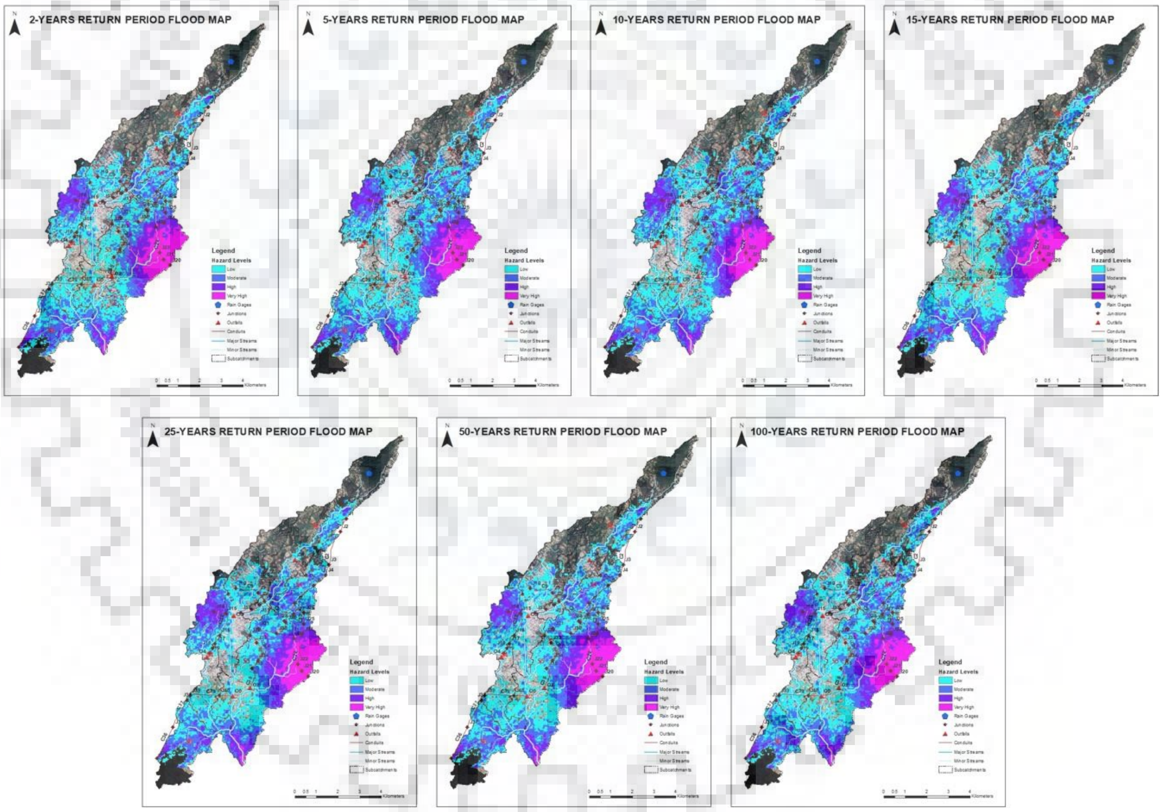


Figure 4-28: Flood Mapping for different Return Periods

Table 4-4: Inundation Levels observed in floods for different return periods

Return Period	Maximum Inundation Level (cm)
2-yrs return period floods	51.97
5-yrs return period floods	54.67
10-yrs return period floods	56.7
15-yrs return period floods	57.37
25-yrs return period floods	58.57
50-yrs return period floods	60.07
100-yrs return period floods	61.67

Using the flood map of different return periods, a composite flood mapping has been developed for the study area by overlaying the flood maps of particular return periods using their respective weightages. The determination of weights for the flood map of a particular return period has been detailed in *Table 4-5*.

Table 4-5: Weights for different return-period floods used for Composite Mapping

Flood of different return periods	Probability of occurrences	Normalized Weights (%)
2 yrs	0.500	53
5 yrs	0.200	21
10 yrs	0.100	11
15 yrs	0.067	7
25 yrs	0.040	4
50 yrs	0.020	2
100 yrs	0.010	2
Total	**0.937**	**100**

For the purpose of overlay, flood map of each return period has been given a weightage as mentioned in *Table 4-5* and the flood levels in each map, i.e., low, moderate, high and very high has been scaled in the range 1 to 4 as depicted in *Table 4-6*. *Figure 4-29* illustrates the composite flood map.

Table 4-6: Scale Values and Weights used for Composite Flood Mapping

<table>
<tr><th rowspan="2">Flood of different return periods</th><th rowspan="2">Weights</th><th colspan="4">Scale Values for Hazard Levels</th></tr>
<tr><th>Low</th><th>Moderate</th><th>High</th><th>Very High</th></tr>
<tr><td>2 yrs</td><td>53</td><td rowspan="6">1</td><td rowspan="6">2</td><td rowspan="6">3</td><td rowspan="6">4</td></tr>
<tr><td>10 yrs</td><td>11</td></tr>
<tr><td>15 yrs</td><td>7</td></tr>
<tr><td>25 yrs</td><td>4</td></tr>
<tr><td>50 yrs</td><td>2</td></tr>
<tr><td>100 yrs</td><td>2</td></tr>
</table>

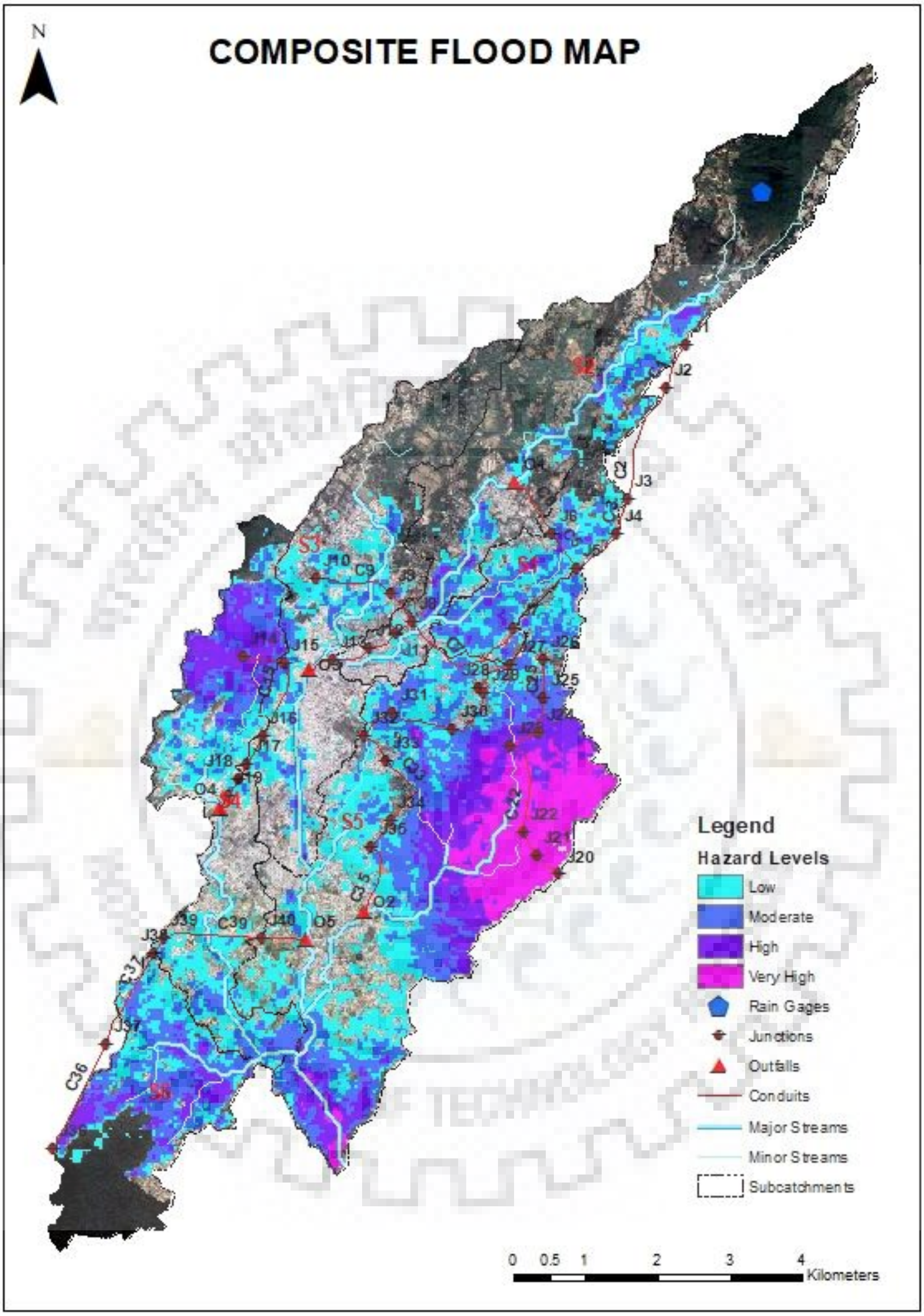


Figure 4-29: Map showing the extent of hazard levels as per the depth of inundation

4.8 VULNERABILITY MAPPING

The vulnerabilities of the study area has been assessed in terms of landuse and social vulnerabilities. The detailed processed of assessing the vulnerabilities has been described in the following subsections.

4.8.1 Landuse Vulnerabilities

The landuse vulnerabilities of the study area has been assessed according to the landuse data extracted from the Development Plan of Dehradun. The landuse categories found in the study area has been classified into 4 levels of vulnerability as described in *Table 4-7*. The classification of landuse categories was done on the basis of the vitality of the infrastructure present in that particular category and the losses and damages associated with that particular category.

Table 4-7: Classification of Landuse categories for Vulnerability Assessment

Landuse	Vulnerability Levels
Emergency Services, Medical Facilities, Transport Facilities, Public Utilities	Very High
Administrative & Commercial	High
Industrial, Residential, Educational & Religious	Moderate
Recreational, Agricultural & Regional Forests	Low

According to the assessment, around 16 percent of the area comes under low vulnerability level, more than 51 percent of the area comes under moderate vulnerability level while 12 percent and 2 percent comes under highly vulnerable and very high vulnerable zones respectively. *Figure 4-30* illustrates the above, while *Figure 4-31* illustrates the landuse vulnerability map of the study area.

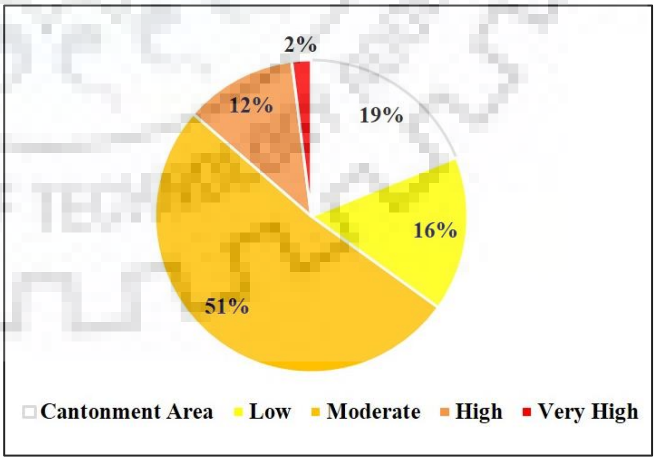


Figure 4-30: Area distribution of Vulnerability Zones according to Landuse

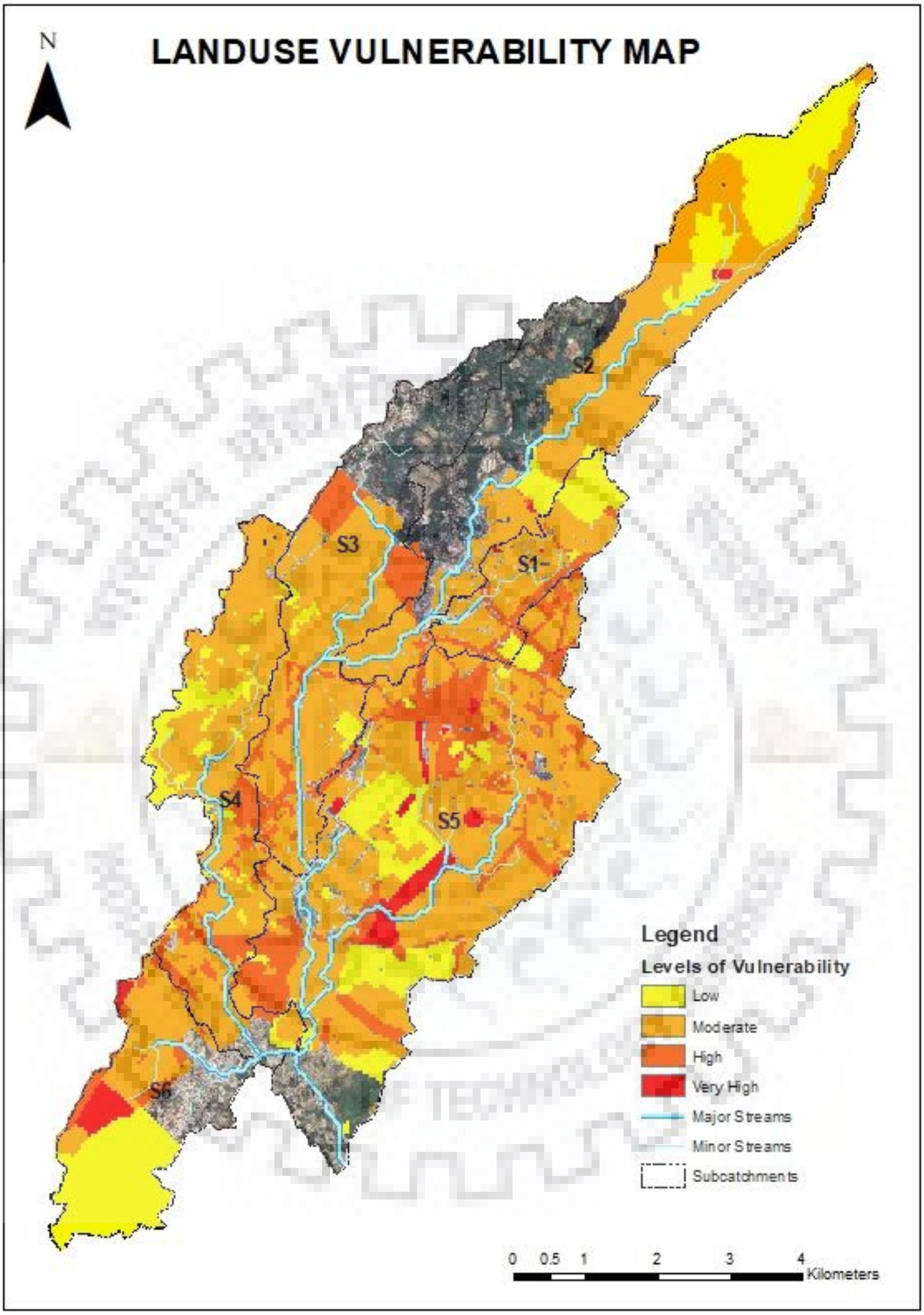


Figure 4-31: Map showing the Landuse Vulnerabilities of the Study Area

4.8.2 Social Vulnerabilities

The assessment of the social vulnerabilities in the study area has been done based on 2011 Census Data. The weights for the social vulnerability parameters has been determined using the Analytical Hierarchy Process (AHP) as described in *Table 4-8.* The detailed calculation of the weights has been detailed in *Annexure 4.*

Table 4-8: Details of the Social Vulnerability Parameters

Social Vulnerability Parameters	Weightage *(%)*
Population Density	48
No. of children per hectares	25
No. of women per hectares	17
No. of unemployed persons per hectares	7
No. of Illiterate persons per hectares	3

Considering the social vulnerabilities, 31 percent of the study area lies within the low vulnerability zone, 49 percent lies in the moderate vulnerability zone, 17 percent lies in the high vulnerability zone and 3 percent lies in the very high vulnerability zone. *Figure 4-32* illustrates the above while *Figure 4-33* illustrates the social vulnerability map of the study area.

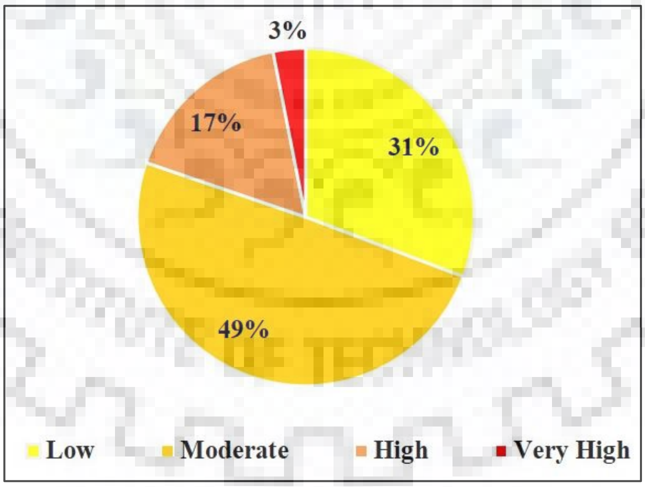


Figure 4-32: Area distribution of Vulnerability Zones according to Social Parameters

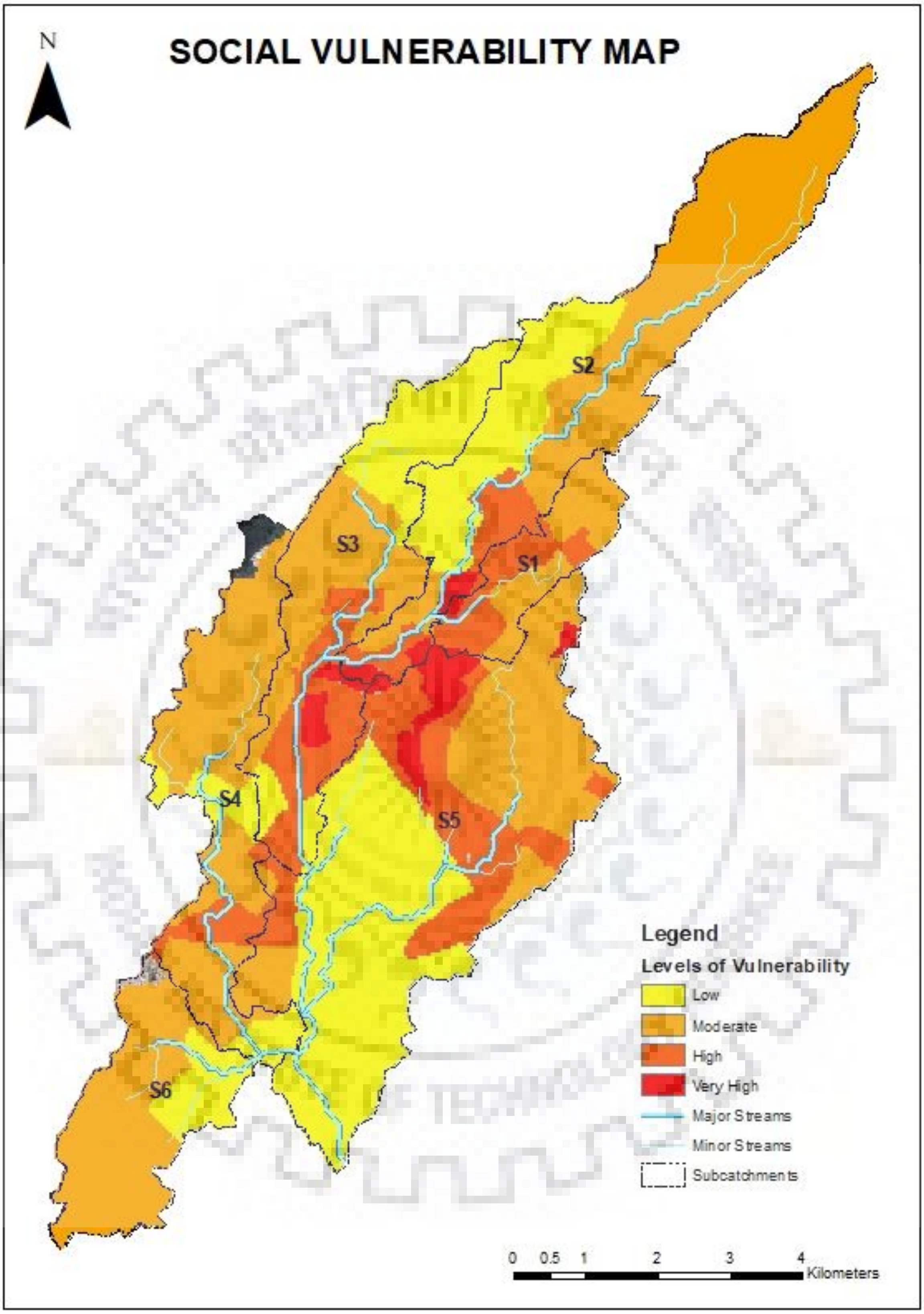


Figure 4-33: Map showing the Social vulnerabilities of the Study Area

4.8.3 Composite Vulnerability Mapping

The composite vulnerability mapping has been carried out by overlaying the landuse and social vulnerabilities with equal weightage (i.e. weightage of 50 out of 100 for each). and the levels of vulnerability in each map, i.e., low, moderate, high and very high has been scaled in the range 1 to 4 as depicted in *Table 4-9*.

Table 4-9: Weights and Scale Values used for Composite Vulnerability Mapping

Vulnerability Map	Weights	Scale Values for Levels of Vulnerability			
		Low	Moderate	High	Very High
Landuse Vulnerability Map	50	1	2	3	4
Social Vulnerability Map	50				
Total	**100**				

Low vulnerability zones consists 4 percent of the study area, moderate vulnerability zones consists 50 percent, high vulnerability zone consists 25 percent and very high zones consists 1 percent of the study area. *Figure 4-34* illustrates the above while *Figure 4-35* illustrates the composite vulnerability map of the study area.

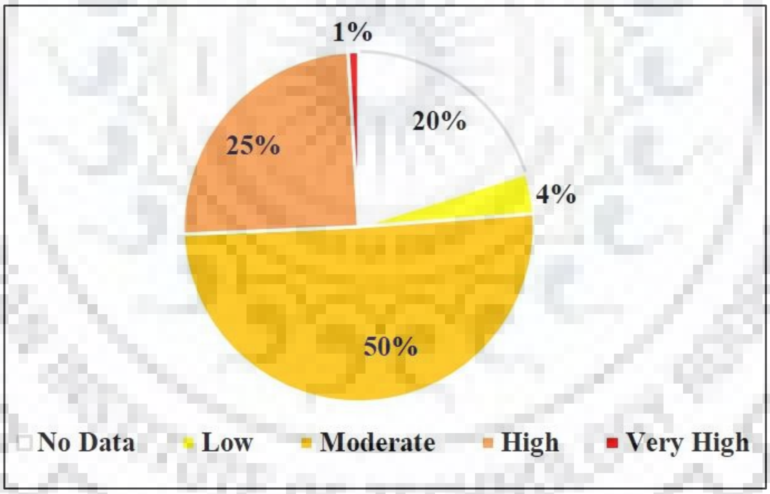


Figure 4-34: Area distribution of Vulnerability zones for Composite Mapping

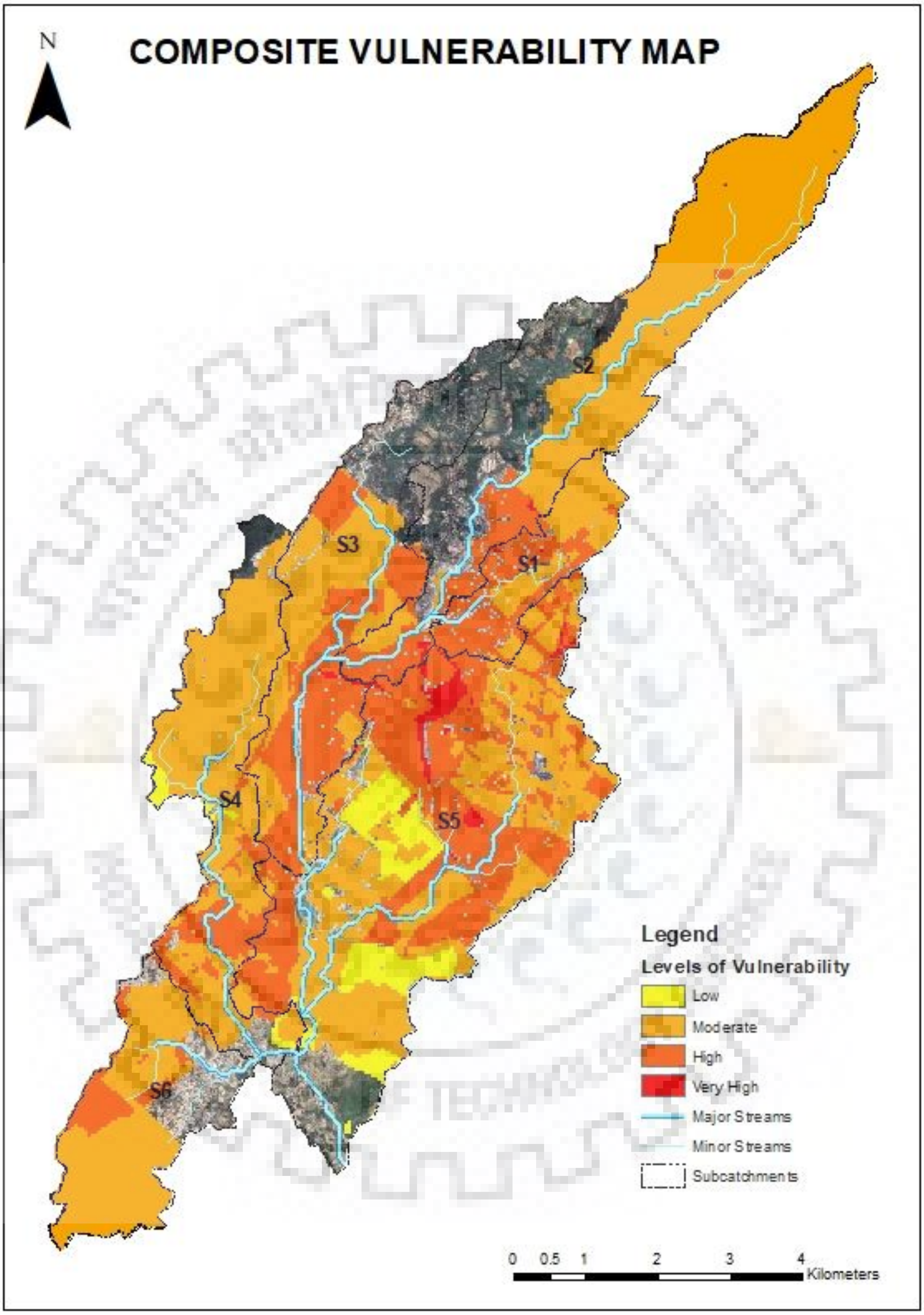


Figure 4-35: Map showing the Composite Vulnerabilities of the Study Area

4.9 RISK MAPPING

The risk mapping of the study area is carried out by overlaying the composite flood map and composite vulnerability map by giving equal weightage (i.e. weightage of 50 out of 100 for each) and the levels of vulnerability and hazard in each map, i.e., low, moderate, high and very high has been scaled in the range 1 to 4 as depicted in *Table 4-10*.

Table 4-10: Weights and Scale Values used for Risk Mapping

Vulnerability Map	Weights	Levels of Hazard/Vulnerability	Scale Values
Composite Flood Map	50	Low Hazard Level	1
		Moderate Hazard Level	2
		High Hazard Level	3
		Very High Hazard Level	4
Composite Vulnerability Map	50	Low Vulnerability Level	1
		Moderate Vulnerability Level	2
		High Vulnerability Level	3
		Very High Vulnerability Level	4
Total	**100**		

Low risk zone consists 1 percent, moderate risk zone consists 25 percent, high risk zone consist 14 percent and very high risk zone consist 3 percent of the study area. *Figure 4-36* illustrates the above, while *Figure 4-37* illustrates the spatial extent of the risk zones of the study area. The localities that are prone to different level of risks has been listed in *Table 4-11*.

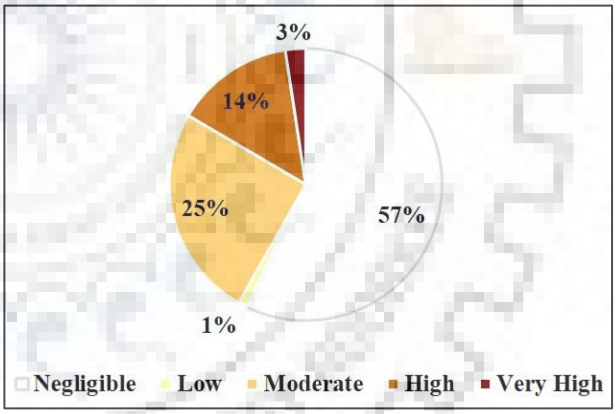


Figure 4-36: Area distribution of Risk Zones

Table 4-11: List of the localities in the different risk zones

Risk Zones	Prone Localities
Very High Risk Zone	Suman Nagar, Anand Vihar, Dharampur Chowk
High Risk Zone	Araghar, Chander Nagar, Guru Nanak Nagar, Jaligaon, Vasant Vihar, Nayapura, Kalindi Enclave, Shanti Vihar,
Medium Risk Zone	Drone Puri, Jakhan, Doon Vihar, Chanderlok Colony, Yamuna Colony, Dhobawala, Ghanta Ghar, Govind Nagar
Low Risk Zone	Parts of Bhagirathipuram, Badrish Vihar, Kargi

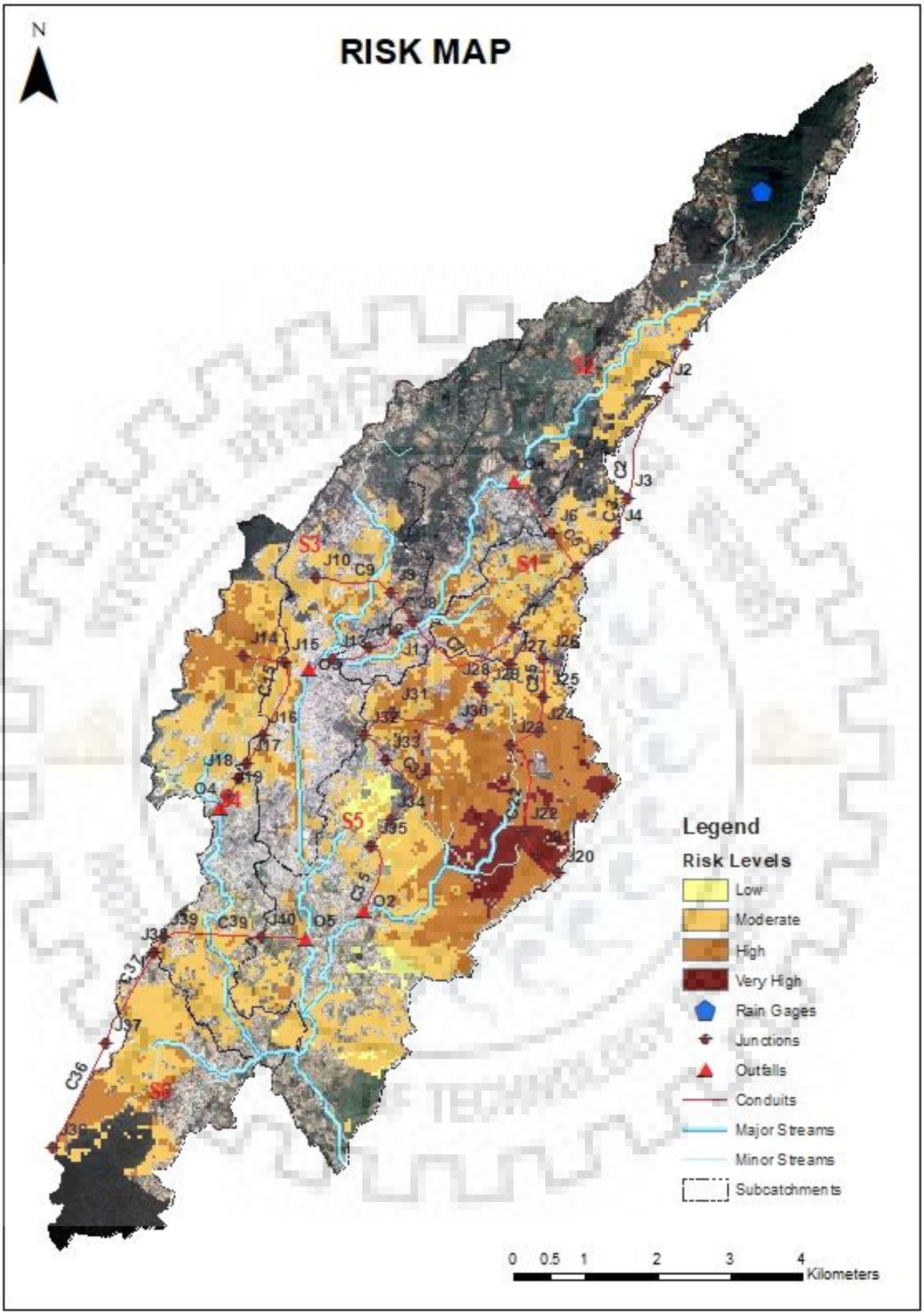


Figure 4-37: Map showing the risk zones of the study area

CHAPTER 5
FINDINGS AND CONCLUSIONS

Urban Flood, a pressing global concern, have recent occurrences of flooding in various towns and cities across India such as that of 2017 and 2005 Mumbai Floods, 2016 Delhi Floods, 2015 Chennai Floods. The country has suffered from economic losses, infrastructural damages, human casualties, and even loss of lives owing to these floods. India, being a developing nation, would witness rapid urbanisation in the coming years further aggravating the issues of urban floods. Thus, a study of Dehradun city was undertaken to study the trends of urbanisation and urban floods. Bindal Rao catchment of the city was considered for mapping vulnerability and risks. The subsequent section highlights of the findings, limitation and future scope of further research.

5.1 FINDINGS

- The city of Dehradun has initially developed in the north and is gradually spreading towards the direction of the south, i.e. in the direction of the Shivalik Ranges. The present growth pattern indicates the city is growing further in the east direction.
- The decadal population growth indicates the city is still in its growing stage, and the population of the Dehradun is expected to increase at an exponential rate until it reaches its maturity.
- The sex ratio and the literacy rate of the city is at par with its counterparts and would tend to increase steadily in the upcoming decade.
- The workforce participation rate has seen a steady increase in the last decade. More than 90 percent of the total workers are employed in the tertiary sector.
- The service such as water supply and electricity has more than 90 percent coverage.
- The proportion of built-up areas is expected to increase with a rate of nearly 58 percent from 2003-2004 to 2025. The pressure of urbanisation is going to increase this proportion in the upcoming decades as well.
- An annual average increase of 15.3 mm rainfall is observed in the last 30 years and this trend is expected to continue in the future as well.
- The temperature of the city is observed to be highly variable. No significant trend is observed.

- The LULC analysis shows that around 55 percent of the study area is impervious in nature, while the urban open spaces and barren land is around 25 percent and the forests constitute around 13 percent of the study area. Water bodies contribute to 7 percent.
- The urban flood simulation carried out for the Bindal Rao catchment shows that 50 percent of the catchment is susceptible to flooding.
- According to the landuse and social vulnerabilities, around 26 percent of the study area is highly to very highly vulnerable; 50 percent is moderately vulnerable.
- The risk mapping for the Bindal Rao catchment shows17 percent of the catchment falls under high to very high risk zones while 25 percent falls under moderate risk zones.

5.2 RELEVANCE TO SENDAI FRAMEWORK FOR DISASTER RISK REDUCTION (SFDRR)

The Sendai Framework is a 15-year; voluntary, non-binding agreement, which recognizes that the State has the primary role to reduce disaster risk but that responsibility should be shared with other stakeholders including local government, the private sector and other stakeholders. The National Disaster Management (NDMA) Plan of India is developed in accordance to this Framework.

The dissertation aligns with the provision of the Sendai Framework of 2015-2030 under the following action areas:

a) **Understanding Disaster Risks**: The study solely focuses on identification, understanding and assessment of the potential risks and vulnerabilities that would be induced from urban floods in the Bindal Rao Basin.

b) **Strengthening disaster risk governance to manage disaster risk:** The outcomes of the study, i.e., the vulnerability and risks maps would aid the local authorities and decision makers in implementing measures for risk reduction.

5.3 LIMITATIONS

The dissertation carried out has certain limitations because of the constraint of data availability. The sub-daily rainfall of the study area and the data related to spatial variation of the rainfall could not be procured. These data would have given much accurate simulations for flood. Further, the model could not also be validated with the actual discharge data, as there is no equipment for the discharge measurement in the study area. The SWMM simulation does not provide with the spatial extent of flooding and hence the Hydraulic Grade Line (HGL) depth for each node is interpolated to find out the water surface elevation layer during flooding. The monetary values of infrastructure & land, economic production, etc. could not be considered for economic vulnerability assessment while the assessment of social vulnerabilities could not cover parameters like family income, the number of aged and ill persons, etc. because of non-availability of data. Ecological Vulnerability could also not be covered for the same reason.

5.4 FURTHER SCOPE

The dissertation carried out can be carried forward for various studies related to such field. The estimation of the potential losses in case of occurrence of a flood of a particular return period can easily be done using the data from this study. This study can also be used for proposing mitigation and management measures for the identified risk zones. Studies related to vulnerability reduction can also be done. This study, further can also be used as a base for developing techniques for using for using and recycling storm-water in the study area. The vulnerability assessment carried out in the study can help in risk assessment of any other hazard in the study area.

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ANNEXURES

ANNEXURE 1: DEVELOPMENT OF IDF CURVES

For the development of the IDF Curves, the following steps have been performed:

- The maximum daily rainfall of each year for the duration of 30 years has been obtained as listed in *Table 1, Column (ix).*
- Since the sub-daily rainfall of the study area could not be obtained, the maximum daily rainfall has been disaggregated for shorter durations using the IMD Reduction Formula (as described in *Equation 1*). The results have been shown in *Table 2.*

  $$\mathbf{P_t = P_{24} (t / 24)^{1/3}} \quad \text{... (Equation 1)}$$

  where, P_t is the rainfall depth in mm at t-hr duration; P_{24} is the daily rainfall in mm and t is the duration of rainfall for which the rainfall depth is required in hour (Rasel & Hossain, 2015).
- The mean and standard deviation for each of shorter durations has been calculated as shown in *Table 1.*
- The IDF curve for this study has been developed using Gumbell's distribution. To fit the Gumbell's Distribution, the *Equation 2* has been used.

  $$\mathbf{X_T = \mu + K_T S} \quad \text{... (Equation 2)}$$

  where, the X_T is the associated with a given return period T; μ is the arithmetic mean of the observations; S is the standard deviations of the observations and K_T is the frequency factor associated with return period T, given by *Equation 3.*

  $$\mathbf{K_T = -\frac{\sqrt{6}}{\pi} [0.5772 + \ln (\ln (T/ (T - 1)))]} \quad \text{... (Equation 3)}$$

  (Subramanya, 2008)

  The K_T calculated for each of return periods has been listed in *Table 2.*

  Using the respective values of K_T of different return periods, maximum rainfall volume for different durations has been calculated using *Equation 2* as shown in *Table 3* and further each of the rainfall volume has been converted to their respective intensities as shown in *Table 4.*

Table 1: Maximum Annual Rainfall Volume for the duration of 1989-2018

(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)
YEAR	**Maximum Annual Rainfall Volume** *(mm)*							
	15 min	**30 min**	**1 hr**	**1.5 hrs**	**3 hrs**	**6 hrs**	**12 hrs**	**24 hrs**
1989	22.67	28.56	35.98	41.19	51.90	65.38	82.38	103.79
1990	29.59	37.28	46.97	53.77	67.75	85.35	107.54	135.49
1991	24.82	31.27	39.40	45.10	56.83	71.60	90.20	113.65
1992	7.76	9.77	12.31	14.10	17.76	22.38	28.19	35.52
1993	20.41	25.72	32.40	37.09	46.73	58.88	74.18	93.46
1994	12.42	15.64	19.71	22.56	28.43	35.81	45.12	56.85
1995	11.95	15.06	18.98	21.72	27.37	34.48	43.45	54.74
1996	13.24	16.68	21.02	24.06	30.32	38.19	48.12	60.63
1997	11.73	14.77	18.61	21.31	26.85	33.82	42.61	53.69
1998	15.60	19.65	24.76	28.34	35.71	44.99	56.68	71.41
1999	9.54	12.01	15.14	17.33	21.83	27.50	34.65	43.66
2000	9.01	11.35	14.30	16.37	20.63	25.99	32.74	41.25
2001	17.85	22.48	28.33	32.43	40.86	51.47	64.85	81.71
2002	7.89	9.95	12.53	14.35	18.08	22.77	28.69	36.15
2003	8.72	10.99	13.84	15.85	19.97	25.15	31.69	39.93
2004	15.48	19.50	24.57	28.12	35.43	44.64	56.24	70.86
2005	12.82	16.15	20.34	23.29	29.34	36.97	46.57	58.68
2006	13.76	17.34	21.84	25.01	31.51	39.69	50.01	63.01
2007	11.98	15.10	19.02	21.77	27.43	34.56	43.54	54.86
2008	13.58	17.11	21.55	24.67	31.09	39.16	49.34	62.17
2009	11.65	14.68	18.49	21.17	26.67	33.60	42.34	53.34
2010	32.65	41.14	51.83	59.33	74.76	94.19	118.67	149.51
2011	18.96	23.89	30.10	34.46	43.42	54.70	68.92	86.83
2012	18.19	22.92	28.87	33.05	41.64	52.46	66.10	83.28
2013	35.88	45.21	56.96	65.20	82.15	103.50	130.40	164.29
2014	17.99	22.66	28.55	32.68	41.18	51.88	65.37	82.36
2015	12.81	16.14	20.33	23.28	29.33	36.95	46.55	58.65
2016	11.64	14.67	18.48	21.15	26.65	33.58	42.30	53.30
2017	12.54	15.81	19.91	22.80	28.72	36.18	45.59	57.44
2018	12.63	15.92	20.05	22.95	28.92	36.44	45.91	57.84
Mean	**15.86**	**19.98**	**25.17**	**28.82**	**36.31**	**45.74**	**57.63**	**72.61**
Std. Dev.	**7.10**	**8.94**	**11.27**	**12.90**	**16.25**	**20.47**	**25.79**	**32.50**

Table 2: Frequency Factor calculated for each of the Return Periods

Return Periods	**2 yrs**	**5 yrs**	**10 yrs**	**15 yrs**	**25 hrs**	**50 yrs**	**100 yrs**
K_T	-0.16	0.72372	1.30913	1.6394	2.04878	2.5975	3.1421721

Table 3: Calculated Maximum Rainfall Volume (mm)

Duration	Return Periods						
	2 yrs	5 yrs	10 yrs	15 yrs	25 yrs	50 yrs	100 yrs
15 min	14.7	21.0	25.1	27.5	30.4	34.3	38.2
30 min	18.5	26.5	31.7	34.6	38.3	43.2	48.1
1.0 hr	23.4	33.3	39.9	43.6	48.3	54.4	60.6
1.5 hrs	26.7	38.1	45.7	50.0	55.2	62.3	69.3
3.0 hrs	33.7	48.1	57.6	62.9	69.6	78.5	87.4
6.0 hrs	42.5	60.6	72.5	79.3	87.7	98.9	110.1
12.0 hrs	53.5	76.3	91.4	99.9	110.5	124.6	138.7
24.0 hrs	67.4	96.1	115.2	125.9	139.2	157.0	174.7

Table 4: Calculated Maximum Rainfall Intensity (mm/hr)

Duration	Return Periods						
	2 yrs	5 yrs	10 yrs	15 yrs	25 yrs	50 yrs	100 yrs
15 min	58.9	84.0	100.6	110.0	121.6	137.2	152.6
30 min	37.1	52.9	63.4	69.3	76.6	86.4	96.2
1.0 hr	23.4	33.3	39.9	43.6	48.3	54.4	60.6
1.5 hrs	17.8	25.4	30.5	33.3	36.8	41.5	46.2
3.0 hrs	11.2	16.0	19.2	21.0	23.2	26.2	29.1
6.0 hrs	7.1	10.1	12.1	13.2	14.6	16.5	18.3
12.0 hrs	4.5	6.4	7.6	8.3	9.2	10.4	11.6
24.0 hrs	1.2	1.7	2.1	2.3	2.5	2.9	3.2

ANNEXURE 2: LULC ANALYSIS, CALCULATION OF IMPERVIOUSNESS AND RUNOFF CN

Table 5: Summary of LULC Classification for each subcatchments

LULC	Area *(in Hectares)*					
	S1	**S2**	**S3**	**S4**	**S5**	**S6**
Low Density Built-up	117.60	264.96	271.45	251.45	635.76	103.53
High Density Built-up	2.87	10.01	36.34	12.72	33.06	3.06
Roads	93.38	136.01	258.64	193.08	582.90	101.71
BarrenLand/Wasteland	3.33	28.72	8.69	9.99	52.08	8.48
Lawns & Parks	31.49	269.77	125.90	66.51	123.19	61.55
Grounds & Stadiums	18.99	120.88	57.85	103.57	283.15	45.08
Forests (Scrubs)	7.25	312.72	93.42	28.58	19.65	30.27
Forests (Open)	0.00	12.58	0.06	16.38	30.30	4.26
Forests (Dense)	4.83	67.86	9.83	2.34	0.00	162.47
Water Bodies	20.03	92.69	52.97	90.58	160.78	46.33
Total Area	**299.77**	**1316.20**	**915.15**	**775.18**	**1920.86**	**566.74**

Calculation of Imperviousness: To calculate the imperviousness of each subcatchment, the proportion of the impervious LULC categories, i.e., built-ups (both low and high density) and roads, with respect to the total area of the subcatchments (excluding the area that comes under water bodies) has been calculated as shown in *Table 6*.

Table 6: Calculation of Imperviousness *(in %)* for each subcatchments

Name	Impervious Area *(Hectares)*	Total Area excluding water bodies *(Hectares)*	Imperviousness *(%)*
S1	213.85	279.74	76.45
S2	410.98	1223.51	33.59
S3	566.43	862.18	65.70
S4	457.24	684.60	66.79
S5	1251.72	1760.08	71.12
S6	208.31	520.41	40.03

Calculation of Weighted CN: To calculate the weighted CN of each subcatchment, the SCS-CN values have been referred from the CN_{II} (i.e., average Antecedent Moisture Condition) Values as listed in (Subramanya, 2008). The hydrologic soil group (as classified by SCS of United States) that has been considered for the study area is Group B. The details of the particular value considered has been listed in *Table 7*.

Table 7: CN_{II} Values considered for each LULC categories

LULC Categories *(defined for the Study)*	**Cover and Treatment** *(defined by SCS)*	**CN_{II} Values**
Low-density Built-up	Residential, average 65% impervious	85
High-density Built-up	Commercial and business areas (85% impervious)	92
Roads	Street and roads (Gravel)	85
Barren Land	Wasteland	80
Lawns & Parks	Open spaces, lawns, parks, etc. Good condition; grass cover on 75% or more of the area	61
Grounds & Stadiums	Open spaces, lawns, parks, etc. Fair condition; grass cover on 50-75% of the area	69
Forests (Scrubs)	Forests (Scrubs)	47
Forests (Open)	Forests (Open)	44
Forests (Dense)	Forests (Dense)	40

Source: (Subramanya, 2008)

The weighted CN for each individual subcatchments has been calculated using Equation

$$\textbf{Weighted CN} = \sum (A_{LULC\ category} * CN_{LULC\ category}) / A_{sb} \quad \ldots \text{(Equation 4)}$$

where, $A_{LULC\ category}$ is the area under each LULC category; $CN_{LULC\ category}$ is the considered CN_{II} values for that LULC category; A_{sb} is the total area of the subcatchment (excluding water bodies). *Table 8* lists out the calculated weighted CN for each subcatchments.

Table 8: Weighted CN for each subcatchments

Name of The Subcatchments	**Weighted CN**
S1	79.46
S2	65.44
S3	76.03
S4	77.58
S5	79.60
S6	64.14

ANNEXURE 3: DETAILS OF SWMM INPUTS

Table 9: Details of inputs for Subcatchments

Name	Rain Gage	Outlet	Area	Width	Slope (%)	Impervious (%)	Curve Number	Drying Time
S1	R1	J1	299.77	749.4	48.99	76.45	79.46	3
S2	R1	J7	1316.2	3290.5	77.01	33.59	65.44	3
S3	R1	J34	915.15	2287.9	40.85	65.7	82.09	3
S4	R1	J39	775.18	1937.9	38.72	66.79	76.03	3
S5	R1	J17	1920.86	4802.2	42.1	71.12	77.58	3
S6	R1	J36	566.74	1416.9	45.46	40.03	79.25	3

Table 10: Details of inputs for Junctions

Name	Invert Elevation	Maximum Depth	Name	Invert Elevation	Maximum Depth
J1	786.7	1.3	J21	683.7	1.3
J2	778.7	1.3	J22	683.7	1.3
J3	730.7	1.3	J23	683.7	1.3
J4	717.7	1.3	J24	683.7	1.3
J5	710.7	1.3	J25	683.7	1.3
J6	701.7	1.3	J26	683.7	1.3
J7	687.7	1.3	J27	679.7	1.3
J8	659.7	1.3	J28	675.7	1.3
J9	664.7	1.3	J29	671.7	1.3
J10	667.7	1.3	J30	661.7	1.3
J11	651.7	1.3	J31	658.7	1.3
J12	642.7	1.3	J32	641.7	1.3
J13	633.7	1.3	J33	634.7	1.3
J14	664.2	1.3	J34	631.7	1.3
J15	663.7	1.3	J35	618.7	1.3
J16	632.7	1.3	J36	663.7	1.3
J17	625.7	1.3	J37	607.7	1.3
J18	625.7	1.3	J38	605.7	1.3
J19	619.7	1.3	J39	601.7	1.3
J20	683.7	1.3	J40	599.7	1.3

Table 11: Details of inputs for Outfalls

Name	O1	O2	O3	O4	O5
Inert Elevation	686.35	604.2	622	608	592.5

Table 12: Details of inputs for Conduits

Name	Inlet Node	Outlet Node	Shape	Maximum Depth	Bottom Width	Length	Roughness
C1	J1	J2	RECT_CLOSED	3	6	665.6474	0.013
C2	J2	J3	RECT_CLOSED	3	6	1680.836	0.013
C3	J3	J4	RECT_CLOSED	3	6	494.0018	0.013
C4	J4	J5	RECT_CLOSED	3	6	753.6575	0.013
C5	J5	J6	RECT_CLOSED	3	6	598.3227	0.013
C6	J6	O1	RECT_CLOSED	3	6	948.35	0.013
C7	J7	J8	RECT_CLOSED	2.5	5	1969.986	0.013
C8	J9	J8	RECT_CLOSED	1	2	492.3954	0.013
C9	J10	J9	RECT_OPEN	1	2	1102.977	0.013
C10	J8	J11	RECT_CLOSED	2	4	278.8019	0.013
C11	J11	J12	RECT_CLOSED	2	4	450.5218	0.013
C12	J12	J13	RECT_CLOSED	2	4	558.5107	0.013
C13	J13	O3	RECT_CLOSED	2	4	364.7376	0.013
C14	J14	J15	RECT_CLOSED	1.5	3	589.0398	0.013
C15	J15	J16	RECT_CLOSED	1.5	3	1086.38	0.013
C16	J16	J17	RECT_CLOSED	1.5	3	453.5796	0.013
C17	J17	J18	RECT_OPEN	1.5	3	239.4551	0.013
C18	J18	J19	RECT_OPEN	1.5	3	264.7436	0.013
C19	J19	O4	RECT_CLOSED	1.5	3	214.581	0.013
C20	J20	J21	RECT_CLOSED	2.5	5	407.7447	0.013
C21	J21	J22	RECT_CLOSED	2.5	5	366.7135	0.013
C22	J22	J23	RECT_CLOSED	2.5	5	1300.245	0.013
C23	J23	J24	RECT_CLOSED	2	4	428.3457	0.013
C24	J24	J25	RECT_CLOSED	1.5	3	470.9346	0.013
C25	J25	J26	RECT_CLOSED	1.5	3	529.4943	0.013
C26	J26	J27	RECT_CLOSED	0.75	1.5	681.991	0.013
C27	J27	J28	RECT_CLOSED	0.75	1.5	587.5031	0.013
C28	J28	J29	RECT_CLOSED	0.75	1.5	107.6829	0.013
C29	J29	J30	RECT_CLOSED	0.75	1.5	757.4184	0.013
C30	J30	J31	RECT_CLOSED	2.5	5	871.302	0.013
C31	J31	J32	RECT_CLOSED	3	6	544.9072	0.013
C32	J32	J33	RECT_CLOSED	2	4	485.5289	0.013
C33	J33	J34	RECT_CLOSED	2	4	1149.343	0.013
C34	J34	J35	RECT_OPEN	2.5	5	446.9025	0.013
C35	J35	O2	RECT_CLOSED	3	6	991.915	0.013
C36	J36	J37	RECT_CLOSED	1.2	2.4	1608.245	0.013
C37	J37	J38	RECT_CLOSED	1.2	2.4	1442.112	0.013
C38	J38	J39	RECT_CLOSED	1.2	2.4	252.5932	0.013
C39	J39	J40	RECT_OPEN	1.2	2.4	1369.041	0.013
C40	J40	O5	RECT_OPEN	1.2	2.4	621.441	0.013

Table 13: Rainfall Series for Return Periods of 2 yrs, 5 yrs, 10 yrs and 15 yrs

Return Periods							
2 yrs		5 yrs		10 yrs		15 yrs	
Time	Cumulative Rainfal (mm)	Time	Cumulative Rainfall (mm)	Time	Cumulative Rainfall (mm)	Time	Cumulative Rainfall (mm)
08:45	14.7	08:45	21	08:45	25.1	08:45	27.5
09:00	18.5	09:00	26.5	09:00	31.7	09:00	34.6
09:15	21.2	09:15	30.3	09:15	36.3	09:15	39.7
09:30	23.4	09:30	33.3	09:30	39.9	09:30	43.6
09:45	25.2	09:45	35.9	09:45	43	09:45	47
10:00	26.7	10:00	38.1	10:00	45.7	10:00	50
10:15	28.2	10:15	40.2	10:15	48.1	10:15	52.6
10:30	29.4	10:30	42	10:30	50.3	10:30	55
10:45	30.6	10:45	43.7	10:45	52.3	10:45	57.2
11:00	31.7	11:00	45.2	11:00	54.2	11:00	59.2
11:15	32.7	11:15	46.7	11:15	55.9	11:15	61.1
11:30	33.7	11:30	48.1	11:30	57.6	11:30	62.9
11:45	34.6	11:45	49.4	11:45	59.1	11:45	64.6
12:00	35.5	12:00	50.6	12:00	60.6	12:00	66.3
12:15	36.3	12:15	51.8	12:15	62	12:15	67.8
12:30	37.1	12:30	52.9	12:30	63.4	12:30	69.3
12:45	37.8	12:45	54	12:45	64.7	12:45	70.7
13:00	38.6	13:00	55	13:00	65.9	13:00	72.1
13:15	39.3	13:15	56	13:15	67.1	13:15	73.4
13:30	40	13:30	57	13:30	68.3	13:30	74.6
13:45	40.6	13:45	57.9	13:45	69.4	13:45	75.9
14:00	41.2	14:00	58.8	14:00	70.5	14:00	77
14:15	41.9	14:15	59.7	14:15	71.5	14:15	78.2
14:30	42.5	14:30	60.6	14:30	72.5	14:30	79.3
14:45	43	14:45	61.4	14:45	73.5	14:45	80.4
15:00	43.6	15:00	62.2	15:00	74.5	15:00	81.4
15:15	44.2	15:15	63	15:15	75.4	15:15	82.5
15:30	44.7	15:30	63.8	15:30	76.4	15:30	83.5
15:45	45.2	15:45	64.5	15:45	77.3	15:45	84.5
16:00	45.7	16:00	65.2	16:00	78.1	16:00	85.4
16:15	46.2	16:15	66	16:15	79	16:15	86.4
16:30	46.7	16:30	66.7	16:30	79.8	16:30	87.3
16:45	47.2	16:45	67.3	16:45	80.7	16:45	88.2
17:00	47.7	17:00	68	17:00	81.5	17:00	89.1
17:15	48.1	17:15	68.7	17:15	82.3	17:15	89.9
17:30	48.6	17:30	69.3	17:30	83	17:30	90.8
17:45	49	17:45	70	17:45	83.8	17:45	91.6
18:00	49.5	18:00	70.6	18:00	84.5	18:00	92.4

18:15	49.9	18:15	71.2	18:15	85.3	18:15	93.2
18:30	50.3	18:30	71.8	18:30	86	18:30	94
18:45	50.8	18:45	72.4	18:45	86.7	18:45	94.8
19:00	51.2	19:00	73	19:00	87.4	19:00	95.6
19:15	51.6	19:15	73.6	19:15	88.1	19:15	96.3
19:30	52	19:30	74.1	19:30	88.8	19:30	97.1
19:45	52.4	19:45	74.7	19:45	89.5	19:45	97.8
20:00	52.7	20:00	75.2	20:00	90.1	20:00	98.5
20:15	53.1	20:15	75.8	20:15	90.8	20:15	99.2
20:30	53.5	20:30	76.3	20:30	91.4	20:30	99.9
20:45	53.9	20:45	76.8	20:45	92	20:45	100.6
21:00	54.2	21:00	77.3	21:00	92.6	21:00	101.3
21:15	54.6	21:15	77.9	21:15	93.3	21:15	102
21:30	54.9	21:30	78.4	21:30	93.9	21:30	102.6
21:45	55.3	21:45	78.9	21:45	94.5	21:45	103.3
22:00	55.6	22:00	79.4	22:00	95.1	22:00	103.9
22:15	56	22:15	79.8	22:15	95.6	22:15	104.6
22:30	56.3	22:30	80.3	22:30	96.2	22:30	105.2
22:45	56.6	22:45	80.8	22:45	96.8	22:45	105.8
23:00	57	23:00	81.3	23:00	97.3	23:00	106.4
23:15	57.3	23:15	81.7	23:15	97.9	23:15	107
23:30	57.6	23:30	82.2	23:30	98.5	23:30	107.6
23:45	57.9	23:45	82.6	23:45	99	23:45	108.2
00:00	58.3	00:00	83.1	00:00	99.5	00:00	108.8
00:15	58.6	00:15	83.5	00:15	100.1	00:15	109.4
00:30	58.9	00:30	84	00:30	100.6	00:30	110
00:45	59.2	00:45	84.4	00:45	101.1	00:45	110.5
01:00	59.5	01:00	84.8	01:00	101.6	01:00	111.1
01:15	59.8	01:15	85.3	01:15	102.1	01:15	111.7
01:30	60.1	01:30	85.7	01:30	102.6	01:30	112.2
01:45	60.4	01:45	86.1	01:45	103.1	01:45	112.8
02:00	60.7	02:00	86.5	02:00	103.6	02:00	113.3
02:15	60.9	02:15	86.9	02:15	104.1	02:15	113.8
02:30	61.2	02:30	87.3	02:30	104.6	02:30	114.4
02:45	61.5	02:45	87.7	02:45	105.1	02:45	114.9
03:00	61.8	03:00	88.1	03:00	105.6	03:00	115.4
03:15	62.1	03:15	88.5	03:15	106.1	03:15	115.9
03:30	62.3	03:30	88.9	03:30	106.5	03:30	116.5
03:45	62.6	03:45	89.3	03:45	107	03:45	117
04:00	62.9	04:00	89.7	04:00	107.5	04:00	117.5
04:15	63.2	04:15	90.1	04:15	107.9	04:15	118
04:30	63.4	04:30	90.5	04:30	108.4	04:30	118.5
04:45	63.7	04:45	90.8	04:45	108.8	04:45	119
05:00	63.9	05:00	91.2	05:00	109.3	05:00	119.4

05:15	64.2	05:15	91.6	05:15	109.7	05:15	119.9
05:30	64.5	05:30	91.9	05:30	110.1	05:30	120.4
05:45	64.7	05:45	92.3	05:45	110.6	05:45	120.9
06:00	65	06:00	92.7	06:00	111	06:00	121.4
06:15	65.2	06:15	93	06:15	111.4	06:15	121.8
06:30	65.5	06:30	93.4	06:30	111.9	06:30	122.3
06:45	65.7	06:45	93.7	06:45	112.3	06:45	122.7
07:00	66	07:00	94.1	07:00	112.7	07:00	123.2
07:15	66.2	07:15	94.4	07:15	113.1	07:15	123.7
07:30	66.4	07:30	94.8	07:30	113.5	07:30	124.1
07:45	66.7	07:45	95.1	07:45	113.9	07:45	124.6
08:00	66.9	08:00	95.5	08:00	114.3	08:00	125
08:15	67.2	08:15	95.8	08:15	114.8	08:15	125.4
08:30	67.4	08:30	96.1	08:30	115.2	08:30	125.9

Table 14: Rainfall Series for Return Periods of 25 yrs, 50 yrs and 100 yrs

Return Periods					
25 yrs		50 yrs		100 yrs	
Time	Cumulative Rainfal (mm)	Time	Cumulative Rainfall (mm)	Time	Cumulative Rainfall (mm)
08:45	30.4	08:45	34.3	08:45	38.2
09:00	38.3	09:00	43.2	09:00	48.1
09:15	43.8	09:15	49.5	09:15	55
09:30	48.3	09:30	54.4	09:30	60.6
09:45	52	09:45	58.6	09:45	65.2
10:00	55.2	10:00	62.3	10:00	69.3
10:15	58.1	10:15	65.6	10:15	73
10:30	60.8	10:30	68.6	10:30	76.3
10:45	63.2	10:45	71.3	10:45	79.4
11:00	65.5	11:00	73.9	11:00	82.2
11:15	67.6	11:15	76.3	11:15	84.9
11:30	69.6	11:30	78.5	11:30	87.4
11:45	71.5	11:45	80.6	11:45	89.7
12:00	73.3	12:00	82.6	12:00	92
12:15	75	12:15	84.6	12:15	94.1
12:30	76.6	12:30	86.4	12:30	96.2
12:45	78.2	12:45	88.2	12:45	98.1
13:00	79.7	13:00	89.9	13:00	100
13:15	81.1	13:15	91.5	13:15	101.8
13:30	82.5	13:30	93.1	13:30	103.6
13:45	83.9	13:45	94.6	13:45	105.3
14:00	85.2	14:00	96.1	14:00	106.9

14:15	86.4	14:15	97.5	14:15	108.5
14:30	87.7	14:30	98.9	14:30	110.1
14:45	88.9	14:45	100.3	14:45	111.6
15:00	90.1	15:00	101.6	15:00	113
15:15	91.2	15:15	102.9	15:15	114.5
15:30	92.3	15:30	104.1	15:30	115.9
15:45	93.4	15:45	105.4	15:45	117.2
16:00	94.5	16:00	106.6	16:00	118.6
16:15	95.5	16:15	107.7	16:15	119.9
16:30	96.5	16:30	108.9	16:30	121.1
16:45	97.5	16:45	110	16:45	122.4
17:00	98.5	17:00	111.1	17:00	123.6
17:15	99.4	17:15	112.2	17:15	124.8
17:30	100.4	17:30	113.2	17:30	126
17:45	101.3	17:45	114.3	17:45	127.2
18:00	102.2	18:00	115.3	18:00	128.3
18:15	103.1	18:15	116.3	18:15	129.4
18:30	104	18:30	117.3	18:30	130.5
18:45	104.8	18:45	118.2	18:45	131.6
19:00	105.7	19:00	119.2	19:00	132.6
19:15	106.5	19:15	120.1	19:15	133.7
19:30	107.3	19:30	121.1	19:30	134.7
19:45	108.1	19:45	122	19:45	135.7
20:00	108.9	20:00	122.9	20:00	136.7
20:15	109.7	20:15	123.8	20:15	137.7
20:30	110.5	20:30	124.6	20:30	138.7
20:45	111.2	20:45	125.5	20:45	139.6
21:00	112	21:00	126.3	21:00	140.6
21:15	112.7	21:15	127.2	21:15	141.5
21:30	113.5	21:30	128	21:30	142.4
21:45	114.2	21:45	128.8	21:45	143.3
22:00	114.9	22:00	129.6	22:00	144.2
22:15	115.6	22:15	130.4	22:15	145.1
22:30	116.3	22:30	131.2	22:30	146
22:45	117	22:45	132	22:45	146.9
23:00	117.7	23:00	132.7	23:00	147.7
23:15	118.3	23:15	133.5	23:15	148.5
23:30	119	23:30	134.3	23:30	149.4
23:45	119.7	23:45	135	23:45	150.2
00:00	120.3	00:00	135.7	00:00	151
00:15	121	00:15	136.5	00:15	151.8
00:30	121.6	00:30	137.2	00:30	152.6
00:45	122.2	00:45	137.9	00:45	153.4
01:00	122.8	01:00	138.6	01:00	154.2

01:15	123.5	01:15	139.3	01:15	155
01:30	124.1	01:30	140	01:30	155.7
01:45	124.7	01:45	140.7	01:45	156.5
02:00	125.3	02:00	141.3	02:00	157.3
02:15	125.9	02:15	142	02:15	158
02:30	126.5	02:30	142.7	02:30	158.7
02:45	127	02:45	143.3	02:45	159.5
03:00	127.6	03:00	144	03:00	160.2
03:15	128.2	03:15	144.6	03:15	160.9
03:30	128.8	03:30	145.3	03:30	161.6
03:45	129.3	03:45	145.9	03:45	162.3
04:00	129.9	04:00	146.5	04:00	163
04:15	130.4	04:15	147.1	04:15	163.7
04:30	131	04:30	147.8	04:30	164.4
04:45	131.5	04:45	148.4	04:45	165.1
05:00	132.1	05:00	149	05:00	165.8
05:15	132.6	05:15	149.6	05:15	166.4
05:30	133.1	05:30	150.2	05:30	167.1
05:45	133.7	05:45	150.8	05:45	167.8
06:00	134.2	06:00	151.4	06:00	168.4
06:15	134.7	06:15	152	06:15	169.1
06:30	135.2	06:30	152.5	06:30	169.7
06:45	135.7	06:45	153.1	06:45	170.4
07:00	136.2	07:00	153.7	07:00	171
07:15	136.7	07:15	154.2	07:15	171.6
07:30	137.2	07:30	154.8	07:30	172.3
07:45	137.7	07:45	155.4	07:45	172.9
08:00	138.2	08:00	155.9	08:00	173.5
08:15	138.7	08:15	156.5	08:15	174.1
08:30	139.2	08:30	157	08:30	174.7

ANNEXURE 4: CALCULATION OF WEIGHTS FOR SOCIAL VULNERABILITY PARAMETERS

Analytical Hierarchy Process (AHP): AHP is a technique introduced by Thomas Saty for dealing with complex decision making. The AHP considers a set of evaluation criteria, and a set of alternative options among which the best decision is to taken in. The AHP generates a weight for each evaluation criterion according to the decision maker's pairwise comparisons of the criteria. The higher the weight, the more important the corresponding criterion. For a fixed criterion, the AHP assigns a score to each option according to the decision maker's pairwise comparisons of the options based on that criterion. The higher the score, the better the performance of the option with respect to the considered criterion. Finally, the AHP combines the criteria weights and the option scores, so setting a global score for each option, and a consequent ranking. The global score for a given option is a weighted sum of the scores it obtained with respect to all the criteria.

(Brunelli, 2015)

The pairwise comparisons use a scale that ranges from equally preferred to extremely preferred (*Reciprocal relationships are also possible –the reciprocal of an integer n is equal to 1/n.)* as given in *Table 15*.

Table 15: Scale of Pairwise Comparisons

Judgement of Preferences	Numerical Rating
Extremely preferred	9
Very strongly to extremely	8
Very strongly preferred	7
Strongly to very strongly	6
Strongly preferred	5
Moderately to strongly	4
Moderately preferred	3
Equally to moderately	2
Equally preferred	1

The detailed computation of weight for the parameters of social vulnerabilities has been described in *Table 16*.

Table 16: Detailed Calculation of Weights of Social Vulnerabilities Parameters

	Population Density	No. of Children per hectares	No. of Women per hectares	No. of unemployed persons per hectares	No. of Illiterate persons per hectares	n^{th} Root of Product	Priority Vector *100
Population Density	1	3	4	6	8	3.565	48
No. of children per hectares	0.333	1	2	5	7	1.878	25
No. of Women per hectares	0.250	0.5	1	4	6	1.246	17
No. of Unemployed persons per hectares	0.167	0.2	0.250	1	3	0.478	7
No. of Illiterate persons per hectares	0.125	0.143	0.167	0.333	1	0.251	3
Total					**25**	**7.417**	**100**

Calculating the Consistency Ratio (CR)

λ_{max} = 5.271

CI = (λ_{max} – n)/ (n-1) = 0.068

CR = CI/ Random Index = 0.060

CR being <0.1, indicates that the pairwise comparisons have been consistent.

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