Ministry of Road Transport and Highways

World Bank Technical Assistance Program

Reducing Carbon Footprint and Enhancing Climate Resilience of National Highways in India

Component II: Enhancing Climate Resilience of National Highways

teri

The Energy and Resources Institute

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Abbreviations and Acronyms

AADT	Annual average daily traffic
ADB	Asian Development Bank
BIS	Bureau of Indian Standards
BRO	Border Roads Organisation
DDMA	District Disaster Management Authority
EIA	Environment Impact Assessment
GFDRR	Global Facility for Disaster Reduction and Recovery
HDM-4	Highway Development and Management Version 4
HFL	High Flood Level
HSDMA	Himachal State Disaster Management Authority
FEHRL	Forum of European Highway Research
FHA	Federal Highway Administration
GIS	Geographical Information System
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
IMD	Indian Meteorological Department
INCCA	Indian Network for Climate Change Assessment
IRC	Indian Roads Congress
ISRO	Indian Space Research Organisation
IRI	International Roughness Index
LCLIP	Local Climate Impacts Profile
MDR	Major District Road
MoD	Ministry of Defence
MoEFCC	Ministry of Environment, Forest and Climate Change
MoRTH	Ministry of Road Transport and Highways
NDMA	National Disaster Management Authority
NH	National Highway
NHAI	National Highways Authority of India
NRSC	National Remote Sensing Centre
PCU	Passenger Car Unit
PLCC	Pavement Life Cycle Costing
PSMSL	Permanent Service to Mean Sea Level
PWD	Public Works Department
ROW	Right of Way
SDMA	State Disaster Management Authority
TERI	The Energy and Resources Institute
UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
ULB	Urban Local Body
USAID	United States Agency for International Development
U.S. DOT	The United States Department of Transportation
USGS	United States Geological Survey
VA	vulnerability assessment

Glossary of Terms

Adaptation

"In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate." (IPCC, 2012)

Climate Change

"A change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use." (IPCC, 2012)

Climate Extreme (extreme weather or climate event)

"The occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable. For simplicity, both extreme weather events and extreme climate events are referred to collectively as 'climate extremes." (IPCC, 2012)

Climate Impacts

"Consequences of climate change on natural and human systems. Depending on the consideration of adaptation, one can distinguish between potential impacts and residual impacts.

Potential Impacts—All impacts that may occur given a projected change in climate, without considering adaptation.

Residual Impacts—The impacts of climate change that would occur after adaptation." (IPCC, 2012)

Climate Model

"A numerical representation of the climate system that is based on the physical, chemical, and biological properties of its components, their interactions, and feedback processes, and that accounts for all or some of its known properties. The climate system can be represented by models of varying complexity, that is, for any one component or combination of components a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical, or biological processes are explicitly represented, or the level at which empirical parameterizations are involved." (IPCC, 2012)

Climate Resilient Development

"Climate resilient development is about adding considerations of climate variability and climate change to development decision-making in order to ensure that progress towards development goals includes consideration of climate impacts." (USAID, 2014)

Climate Proofing

"Refers to actions that make infrastructure more resilient and resistant to anticipated scenarios of long-term climate change, as well as the risks associated with geological hazards and climate variability and extremes. It includes internalization of the risks and opportunities that alternative climate change scenarios are likely to imply for the design, operation and maintenance of infrastructure." (UNDP, 2011)

Climate Projection

"A projection of the response of the climate system to emissions or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios, often based upon simulations by climate models. Climate projections are distinguished from climate predictions in order to emphasize that climate projections depend upon the emission/ concentration/ radiative-forcing scenario used, which are based on assumptions concerning, e.g., future socioeconomic and technological developments that may or may not be realized and are therefore subject to substantial uncertainty." (IPCC, 2012)

Climate Scenario

"A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. Climate projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information such as about the observed current climate." (IPCC, 2012)

Critical Infrastructure

"The physical structures, facilities, networks and other assets which provide services that are essential to the social and economic functioning of a community or society." (UNISDR, 2017).

Disaster

"A serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability and capacity, leading to one or more of the following: human, material, economic and environmental losses and impacts." (UNISDR, 2017)

Disaster Management

"The organization planning and application of measures preparing for, responding to and recovering from disasters." (UNISDR, 2017)

Disaster Risk

"The potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, vulnerability and capacity."(UNISDR, 2017)

Economic Loss

"Total economic impact that consists of direct economic loss and indirect economic loss. Direct economic loss: the monetary value of total or partial destruction of physical assets existing in the affected area. Direct economic loss is nearly equivalent to physical damage. Indirect economic loss: a decline in economic value added as a consequence of direct economic loss and/or human and environmental impacts." (UNISDR, 2017)

Evacuation

"Moving people and assets temporarily to safer places before, during or after the occurrence of a hazardous event in order to protect them." (UNISDR, 2017)

Exposure

"The situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas." (UNISDR, 2017)

Hazard

A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation ." (UNISDR, 2017)

Landslide

"A mass of material that has moved downhill by gravity, often assisted by water when the material is saturated. The movement of soil, rock, or debris down a slope can occur rapidly, or may involve slow, gradual failure." (IPCC, 2012)

Likelihood

"A probabilistic estimate of the occurrence of a single event or of an outcome, for example, a climate parameter, observed trend, or projected change lying in a given range. Likelihood may be based on statistical or modeling analyses, elicitation of expert views, or other quantitative analyses." (IPCC, 2012)

Mainstreaming

Mainstreaming can be defined as the "integration of climate change related policies and measures into developmental planning process and decision-making." (Eriksen S E H, 2005)

Mitigation

"The lessening or minimizing of the adverse impacts of a hazardous event." (UNISDR, 2017)

Precipitation

"Precipitation whether it is rain or snow is expressed as the depth to which it would cover a horizontal projection of the earth's surface, if there is no loss by evaporation, run–off or infiltration and if any part of the precipitation falling as snow or ice were melted. It is expressed in the units of mm or cm." (Indian Meteorological Department)

Resilience

"The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management," (UNISDR, 2017)

Retrofitting

"Reinforcement or upgrading of existing structures to become more resistant and resilient to the damaging effects of hazards," (UNISDR, 2017)

Severe Cyclonic Storm

"Intense low pressure system represented on a synoptic chart by more than four closed isobars at 2 hPa interval and in which the wind speed on surface level is in between 48 – 63 Kts," (Indian Meteorological Department)

Risk Assessment

"A qualitative or quantitative approach to determine the nature and extent of disaster risk by analysing potential hazards and evaluating existing conditions of exposure and vulnerability that together could harm people, property, services, livelihoods and the environment on which they depend." (UNISDR, 2017)

Storm Surge

"The temporary increase, at a particular locality, in the height of the sea due to extreme meteorological conditions (low atmospheric pressure and/or strong winds). The storm surge is defined as being the excess above the level expected from the tidal variation alone at that time and place." (Indian Meteorological Department).

Super Cyclonic Storm

"Intense low pressure system represented on a synoptic chart by more than four closed isobars at 2 hPa interval and in which the wind speed on surface level is 120 Kts. and above," (Indian Meteorological Department)

Uncertainty

"An expression of the degree to which a value or relationship is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. Uncertainty may originate from many sources, such as quantifiable errors in the data, ambiguously defined concepts or terminology, or uncertain projections of human behaviour. Uncertainty can therefore be represented by quantitative measures, for example, a range of values calculated by various models, or by qualitative statements, for example, reflecting the judgment of a team of experts,"(UNISDR, 2017)

Very Severe Cyclonic Storm

"Intense low pressure system represented on a synoptic chart by more than four closed isobars at 2 hPa interval and in which 7 the wind speed on surface level is in between 64–119 Kts," (Indian Meteorological Department)

Vulnerability

"The conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards." (UNISDR, 2017)

Introduction to the Study

Road transport, especially highways, plays a pivotal role in the development of a country. The development of highways fosters movement of passenger and freight across the country leading to increased national productivity and socio-economic growth. Though constituting only 2% (103,933 km, as on March 31, 2017) of the total road length in the country, National Highways (NHs) form the backbone of the road transport sector, moving almost 40% of the total road traffic (MoRTH, 2015-16).

India has long realized the importance of highways and has been giving the necessary impetus for its development in the country. The Government of India (GoI) has launched various programmes to build new highways and improve and upgrade the existing highways in order to meet the ever-growing transport demand. The government plans to build about 50,000 km of NHs in the next five years (Lok Sabha, 2016). The construction and subsequent use of highways, however, has implications in terms of increased use of energy and generation of CO_2 emissions.

Amidst growing concerns of energy security and climate change, there is a realization that the transport sector, especially the road sector, should lower its dependence on fossil energy and reduce its carbon footprint. Overall, India's transport sector contributed about 14% of total energy-related CO_2 emissions in 2010, of which, road transport is estimated to contribute about 88% (BUR, 2015).

Given the increasing length/capacity of the highway network, and the increasing volumes of traffic on highways, CO_2 emissions from highways (on account of construction, maintenance, and operation activities) are expected to continue increasing in a business-as-usual scenario, if interventions are not made to mitigate the same. With India's Nationally Determined Contributions (NDCs) commitment to reduce carbon emissions, it has become imperative that the country's highway sector be made low carbon.

Additionally, the sector is also required to build resilience to climate change impacts in order to reduce risks and protect the highway infrastructure from impacts of climate change, such as sea-level rise, extreme precipitation, rising temperature, and climate-induced extreme events. This requires an understanding of carbon emissions emitted from the highway sector in India and an assessment of vulnerability of NHs to extreme weather events induced by climate change.

Both the components—(a) carbon footprint exercise for the National Highway network of India and recommended interventions to reduce the same and (b) developing vulnerability assessment methodology and recommended interventions for enhancing the climate resilience of the NH network—are interlinked, as carbon emissions, in general from all anthropogenic activities have been cited as a key reason for climate change and the associated extreme events (IPCC, 2012, 2014).

While studies have been undertaken to understand project-level carbon footprint of specific NH stretches, there are no studies to our knowledge that have been undertaken to estimate the carbon footprint of the entire NH sector in India. Also, there are no known studies that have aimed at understanding the climate vulnerability of the NHs in the country.

The Ministry of Road Transport and Highways (MoRTH), Government of India, supported by the World Bank, therefore, has commissioned this particular study to The Energy and Resources Institute (TERI), New Delhi, to estimate the carbon emissions from NHs sector (emissions from construction, operation, and maintenance activities) and to suggest methodologies and interventions to assess and reduce the vulnerability of the highway sector to climate change-induced extreme weather events. The study is divided into the following two components:

- Component I of the study focusses on estimating and suggesting measures to reduce the carbon footprint of the NH sector
- Component II of the study focusses on suggesting a methodology for assessing and enhancing climate resilience of the NH sector

The report is divided into two parts and states the work carried out under the two components separately.

COMPONENT II

Enhancing Climate Resilience of National Highways in India

1 Introduction

1

Introduction

Climate change affects us in numerous ways, economically, socially, and environmentally. It is important to note that climate risks are embedded in our developmental goals and this includes planning and maintenance of highways. A detailed discussion on the impacts of climate change and the need to build resilience of highways has been incorporated in Chapter 2 'Impact of Climate Change on Highways'. Taking into account the changing climate and the associated extreme events, there is need for a comprehensive policy that foresees the long-term challenges of the increasing intensity of climate risks and provides a direction for building resilience of existing and new highways in the country. The current study is aligned to assist the Ministry of Road Transport and Highways, Government of India, in this direction and aims to guide policymakers and practitioners on enhancing the climate resilience of National Highways (NHs) sector in India. The study will provide recommendations on the development approach and interventions needed to incorporate climate resilience in the NH network and mainstream climate resilience in the framework of highway infrastructure management in India. The main objectives of the study are to:

- Establish the need to enhance climate resilience for the NHs in India.
- Understand and document the impacts of climate change on the NHs in India.
- Develop and demonstrate a methodology for vulnerability assessment of the highway network.
- Identify engineering and non-engineering interventions for building climate resilient NHs in India with specific recommendations.

Figure 1 illustrates the methodology adopted for this study, indicating the objectives and associated tasks and the approaches followed for the same. The study looks exclusively at the vulnerability of the NHs to climate change impacts (both gradual as well as climate-induced extreme events). The scope of the study however, does not include the vulnerability of highways to other natural hazards.

1.1 Background and Need

Climate change and the need for building climate resilience

Identified as an emerging global challenge, climate change, today, manifests itself through weather anomalies and extreme weather events. The impacts of climate change, such as rising temperatures, sea level rise, increase in heavy precipitation events, and increase in frequency and intensity of cyclones, all pose direct physical risks to people, assets, and infrastructure. Countries across the globe are experiencing the growing intensity and frequency of floods, extreme weather events, and rise in extreme heat events that are often associated with catastrophic impacts on transport infrastructure, such as roads, railways, and airports. The impacts of climate change go way beyond these direct physical risks. Increased incidences

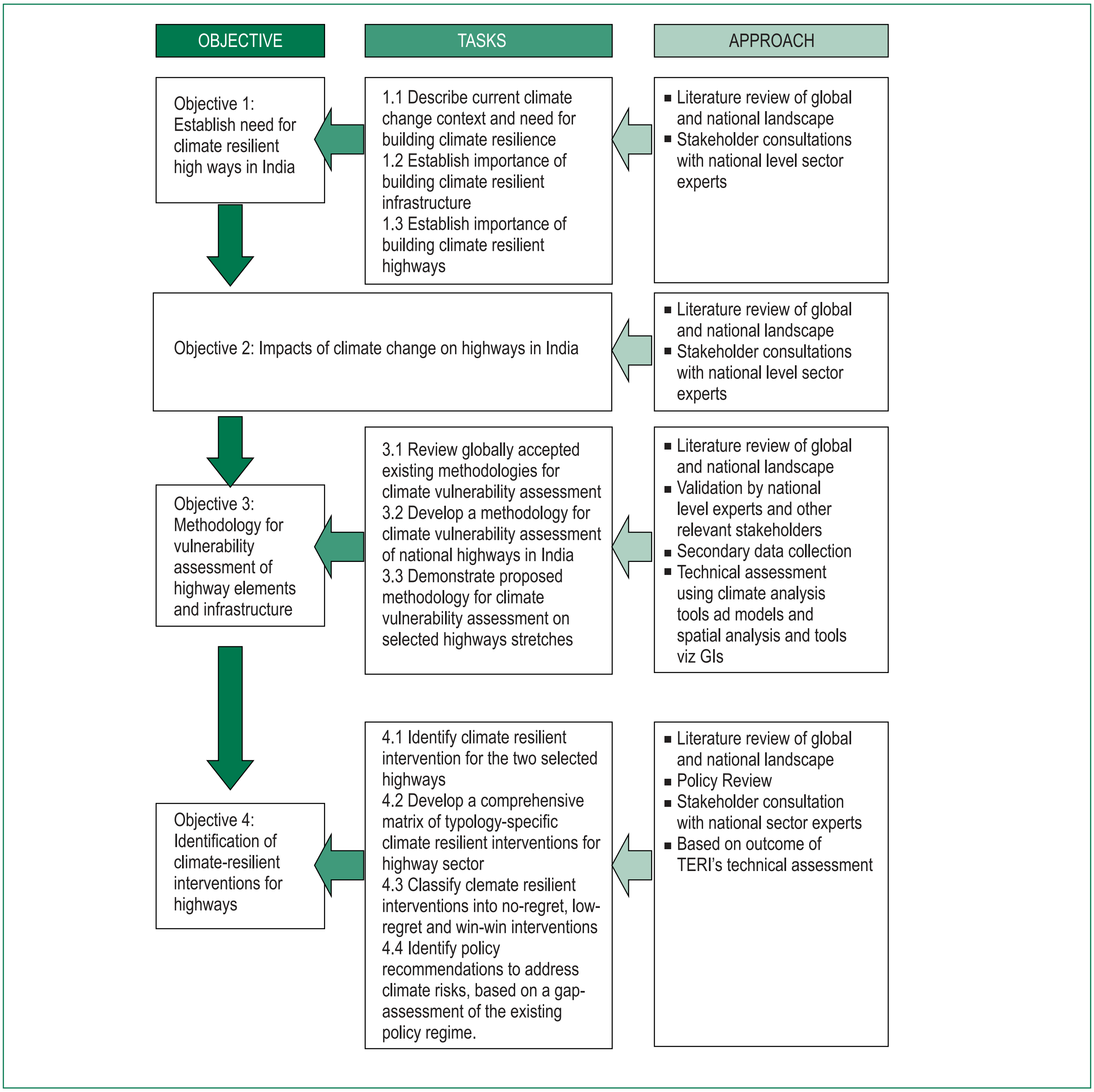

Figure 1 Methodology of Study

of flooding lead to the damage and destruction of infrastructure and property which impacts economic growth. Sea level rise and associated coastal flooding harms vital coastal ecosystems. Climate change impacts a broad spectrum of functions, infrastructure, and services and is responsible for compounding and aggravating the existing non-climatic stresses, such as urbanization, population growth, migration, water demand, sanitation, etc. Hence, climate change poses a challenge of managing risks that affect people, infrastructure, and ecosystems. To successfully tackle these risks, it becomes imperative to shift from reactive responses to proactive, systematic, and integrated risk management (World Bank, 2013).

In developing countries, climate change impacts usually exacerbate existing vulnerabilities and India is no exception. The evidence of climate change in India has generally been consistent with the analyses and future scenarios developed in the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports (IPCC, 2014). These impacts of climate change include rising maximum and minimum temperatures, higher mean temperatures, increasing frequency of extreme temperature events, marked rainfall variability, and increase in incidences of extreme precipitation events (Indian Network for Climate Change Assessment [INCCA], 2010). It has also been estimated that the Indian coasts will experience a sea level rise of 1.3 mm per year (Indian Network for Climate Change Assessment [INCCA], 2010). In India, the incidences of disasters and extreme weather events with increased intensities have become more frequent due to climate change (Give2Asia, 2016). Approximately 85% of India's area is vulnerable to natural hazards, with 68% vulnerable to droughts, 57% to earthquakes, and 12% to floods (Give2Asia, 2016). The country is constantly affected by floods which are identified as the most recurring hazard, leading to maximum economic losses. This is followed by cyclones and storms and nearly 5,700 km of India's coastline, out of 7,500 km, is prone to cyclones and other storms (NDMA, GoI, 2016). India, like any other developing country, is coping to deal with climate variability and extreme weather events.

The country's economic exposure to extreme climate-related events is highlighted by the extent of economic losses caused by the cyclone Hudhud and the Jammu and Kashmir floods. As per a UN report, Hudhud was the second costliest disaster of 2014 in the Asia-Pacific region, causing losses worth USD 11 billion (*The Economic Times*, 2015). The floods in Jammu and Kashmir that occurred in September 2014 caused an immediate loss of around ₹570 billion to the state's economy (*Down To Earth*, 2014). India's vulnerability to climate change and associated extreme events unquestionably undermine the development goals of the country. As per IPCC's Fifth Assessment Report, it is projected that there will be an increase in intensity and frequency of extreme weather events due to climate change (IPCC, 2012), thereby clearly indicating India's future condition of increased vulnerability to extreme weather events. Taking this vulnerability into account, there has been a significant focus on climate change adaptation and resilience building in India's Intended Nationally Determined Contributions (INDCs) in the Paris Agreement (Ernst & Young, 2016). Presently, India spends 3% of its GDP on climate change adaptation and the INDCs suggest the need for enhanced investment in this domain.

This calls for clear action and efforts to minimize the risks posed by climate change and incorporate climate change considerations in the development goals of the country. To achieve this, climate-resilient development should be at the forefront of any development (Box 1).

The agenda for climate-resilient development should be multisectoral and should include strategies that integrate both the management of risk and the ability to respond to climate change and its impacts. Climate resilient-development should look at addressing vulnerabilities, implementing climate change adaptation measures, and facilitating governance and financial mechanisms that enable an environment for climate-resilient development.

BOX 1: CLIMATE-RESILIENT DEVELOPMENT

"Climate resilient development is about adding considerations of climate variability and climate change to development decision-making in order to ensure that progress towards development goals includes consideration of climate impacts" (USAID, 2014)

The need for climate-resilient infrastructure

Infrastructure is undoubtedly an integral element required for sustaining the development needs of a country. Public infrastructure is multifunctional and caters to a range of diverse stakeholders spread over a wide geographic area. It directly or indirectly provides critical social and economic services required towards meeting the development needs of people and the economy. Interruptions in infrastructure services have significant implications as it leads to severe negative economic impacts. In most developing countries, infrastructure is vulnerable to the destruction that occurs due to climate-induced extreme events and disasters. Given that infrastructure investments have an economic life expectancy of 30 years or more, it should be realized that it is sensitive to both climatic conditions prevailing at the time of its construction as well as to the climate variations over the decades of use (UNDP, 2011).

Climate-induced extreme events threaten vital infrastructure, such as roads, bridges, rails, drains, airports, ports and harbours, etc. Rising temperatures can lead to deterioration of pavements due to melting of bitumen, thermal expansion of bridges and rail tracks, and buckling of joints. Increase in the intensity and frequency of extreme precipitation events can affect drainage capacities, road pavements, bridges, airports, and ports and harbours. Cyclone-associated winds and rainfall can inundate roads and also impact rails, airports, ports and harbours, road signage, and disruption of evacuation operations. Sea level rise affects coastal roads, rails, airports, and ports and harbours situated in coastal areas.

A significant proportion of the economic costs of an extreme weather event are attributed to its impacts on public and private infrastructure, including public works, bridges, dams, roads, schools, hospitals, etc. Considering the heavy cost implications associated with the damage of infrastructural services, it is important to establish infrastructure that not only work effectively in the present, but are also equipped to deal with the future challenges of climate change which in turn calls for the need to climate proof infrastructure. Table 1 shows the impact matrix between transport infrastructure and climate stressors, and thereby depicting such (transport) infrastructures that are vulnerable and need to be climate proofed (marked with an 'x').

Table 1 clearly indicates that precipitation, storms, and cyclones are the most prominent climate parameters impacting all types of infrastructure and rendering it vulnerable. Taking into account the vulnerability of infrastructure to climate change impacts, it is imperative that climate change concerns are a key consideration while designing infrastructure. Typically, infrastructure is designed to withstand the most extreme or close-to-the-most extreme events. However, in light of the changing climate and increasing frequency and intensity of climate-induced extreme events, the existing design considerations fall short. Studies indicate that the current infrastructure design standards do not meet the demands of climate change and emphasize the need to introduce new design standards to accommodate future climate scenarios and construct infrastructure in vulnerable locations with higher standards (Regmi and Hanaoka, 2009). Climate proofing infrastructure (Box 2) adds a new layer to sustainable development as it safeguards human lives and assets in the context of climate change.

BOX 2: CLIMATE PROOFING

" 'Climate proofing' refers to actions that make infrastructure more resilient and resistant to anticipated scenarios of long-term climate change, as well as the risks associated with geological hazards and climate variability and extremes. It includes internalization of the risks and opportunities that alternative climate change scenarios are likely to imply for the design, operation and maintenance of infrastructure." (UNDP, 2011)

Table 1: Impact matrix of climate events and vulnerable transport infrastructure

Vulnerable Infra-structure	Pave-ments	Bridges	Drains	Rail Tracks	Cul-vert	Side Slopes	Costal Roads/ Rails	Ports / Harbour	Air-port	Water Trans-port	Road Sign-age
Rising Temperature	x	x		x			x	x	x		
Precipitation (Rainfall/ Snowfall)	x	x	x	x	x	x	x	x	x	x	x
Wind		x							x	x	x
Storm/ Cyclone	x	x	x	x	x	x	x	x	x	x	x
Sea Level Rise		x					x	x	x	x	

Source: Regmi and Hanaoka, 2009

Climate proofing infrastructure is not a new concept, but there are several challenges that need to be addressed. For developed countries, the challenge mostly lies in retrofitting existing infrastructure and siting and protecting new developments along coasts and rivers. For developing countries, the challenge lies in planning for infrastructure taking climate change adaptation into account (Rosenzweig, 2014).

Civil engineering inherently requires the design of infrastructure to be in coalescence with the environment. However, the current challenge lies in upholding this practice while accounting for climate change. The key design parameters that need to be considered in order to factor in climate change and develop climate-resilient infrastructure is indicated in Table 2.

Therefore, the development of climate-resilient infrastructure calls for the need to revisit standards and incorporate design parameters that consider extreme climatic factors for roads and highways, railways, and other transport infrastructure. The modified design parameters and standards should be such that the current and future challenges of climate change are addressed. For instance, flash floods are now a recurring phenomenon, but in the current design considerations for infrastructure, flash floods are not taken into account. Hence while designing bridges, culverts, and drains, design parameters, such as frequency and intensity of rains and high flood level (HFL) of bridges needs to be increased. While designing coastal roads, predicted sea level rise should be considered and while designing roads in flood plains, adequate slope stabilization, river bank protection works should be provided and embankment heights raised.

Need for climate-resilient highways

Roads and highways are designed based on historic climate data; however, during their design life they could be subjected to a varying climate which may be different from past climate trends. The climate is projected to change at an increasingly rapid pace over the coming decades and is likely to alter long-term climatic averages and the frequency and severity of extreme weather events, all of which play an important role in the planning, design, operations,

Table 2: Key design parameters to be considered for climate proofing transport infrastructure

Infrastructure and elements	Design parameters
Road and pavement	• Camber to facilitate water flow • Stiff bitumen to withstand heat • Soil moisture and maintenance planning
Bridge	• Flood estimation, design period, design discharge • High Flood Level (HFL) • Free board (clearance above HFL) • Length of waterway • Design load, wind load • Foundation, river and bank protection • Corrosion protection
Drains	• Discharge estimation (return period) • Size and shape of drain • Drain slope
Rail track	• Heat resistance material • Rail line joints • Expansion joints
Culverts	• Discharge estimation (flood return period) • Size and discharge capacity • Cross slope • Free board (clearance)
Side slope	• Slope protection work • Subsurface drains • Catch drains
Coastal roads/ rails	• Protection wall • Warning signs • Realignment • Edge strengthening
Ports/Harbour	• Height of platform • Protection work • Design for storm and surge actions
Airports	• Wind direction • Runway alignment • Snow and ice removal plan • Pavement material • Drainage capacity
Water transport	• Bridge clearance • Dredging • Flood protection at sea entrance
Road signage	• Wind load • Structural design • Foundation • Corrosion protection

Source: Regmi and Hanaoka, 2009

maintenance, and management of highways (Meyer *et al.* 2012 cited in Meyer *et al.* 2014).

In India, the design of highways and other road networks are guided by the Indian Roads Congress (IRC) codes. As per the IRC codes, it is recommended that national and state highways be designed for a life of 15 years. The IRC codes very aptly prescribe the drainage measures that need to be adhered to, considering the fact that the performance of pavements can be seriously affected due to moisture accumulation. Some measures taken towards facilitating good drainage conditions include maintenance of transverse section to facilitate a quick run off of surface water and provision of appropriate surface and sub-surface drains wherever required. Drainage measures are given particular importance if the road is built on a solid base with low permeability and if it is situated in a heavy rainfall or snowfall precipitation area. The IRC codes also specify that the difference between the bottom of the subgrade level and the level of water table/ high flood level should be at least 0.6 m to 1 m. However, there is a need to relook at these standards and codes in the light of emerging climate uncertainties. As far as highways are concerned, the impacts of climate change effect can be seen on highway elements, such as pavement, embankment and shoulder, drainage and traffic control and safety infrastructure, namely, crash barriers, road signs, lighting, kilometre stones, etc. Moreover, the impacts of climate change on highways vary depending on the type of pavements. For instance, asphalt (bitumen) pavements are vulnerable to surface damage due to increased temperature while concrete pavements are less susceptible to damage due to infiltration of water but are exposed to the risk of expansion of joints in high temperatures. Prevailing climatic conditions also often interact with other factors which further influence deterioration. For example, a combination of heavy traffic and extreme temperatures can lead to more severe rutting. Often, highway drainage is found to be incapable of coping with prolonged and heavy rainfall, resulting in increased flooding and deterioration of the pavement structure (Willway *et al.* 2008). A detailed discussion of the impacts of climate change on highways has been included in Chapter 2 ' Impact of Climate Change on Highways'.

Though NHs constitute only about 2% of the road network in the country, they carry about 40% of the total road traffic (NHAI, 2014). They provide transit to freight, cargo, tourists and locals, and serve as exodus routes when citizens need to evacuate during an extreme event threat, such as cyclone threats and mandatory evacuations. Typically, in hilly regions, a single road serves as the only connectivity route and the blockage of this road, due to landslides, severely hampers economic activity and obstructs the passage of relief and (re)construction material from reaching the destination (Roychowdhury, 2015). Taking into account the significance of roads and highways, it is important that these remain functional throughout the year. In order to minimize the disruptions and economic cost implications due to climate impacts and associated extreme events, it is imperative that highways be planned to adapt to the changing climate. Several studies conducted all over the world highlight the need to adapt highways to the changing climate. Climate change adaptation interventions will help to reduce operations and maintenance costs, improve safety for travellers, and safeguard the large investments made in the transportation system infrastructure. India regularly witnesses damage to its roads and highway infrastructure during extreme weather events. The extreme weather events in the past clearly indicate the vulnerability of Indian highways and roads to the risks posed by climate change (Table 3). This illustrates the climate vulnerability of Indian highways and emphatically stresses on the need to enhance the resilience of highways to the changing climate.

Through Table 3 and the literature review conducted for this study, with respect to extreme climate events, it is evident that the coastal and hilly regions are the most vulnerable regions in India. Both hilly and coastal regions are susceptible to hydro-meteorological extreme events and its associated impacts. Hence, it is recommended that the highway network situated in the hilly and coastal areas be made climate resilient. In the NH network, around 4%–5% of the highways are located in hilly regions, and so, are vulnerable to climate change impacts (MoRTH).

At present, in India, there is no specific, comprehensive climate-resilience policy for the highways or road sector in India. However, there are a few guidelines which

Table 3: Impact of past extreme weather events on road and highway infrastructure in India		
Sl. No.	**Climate Induced Event**	**Region**
1	Cyclone 'Vardha' that hit Chennai in Dec 2016 uprooted several trees and electric poles, thereby blocking connectivity. A section of NH 45 was blocked by fallen trees and 8 toll plazas sustained severe damage. Lack of storm water drains also lead to water logging and stagnation on roads affecting traffic and connectivity.	Coastal
2	The floods in Chennai in 2015 caused severe damage to NH 16 between Chennai and Nellore leaving a cut for over 20 metres causing major traffic disruptions on both sides (*The Hindu*, 2015).	Coastal
3	The Cyclone Hudhud in 2014 left a trail of destruction; loss to roads, horticulture, agriculture, and water works is to the tune of ₹2,000 crore (*Business Standard*, 2014). Uprooted trees blocked highway connectivity (*The Economic Times*, 2014).	Coastal
4	Uttarakhand floods in June 2013 destroyed over 1,000 kilometres of Uttarakhand's one-way-in, one-way-out highways (*Circle of Blue*, 2014).	Hilly
5	Heavy rainfall in Uttarkashi in August 2012 washed away a number of stretches of the Rishikesh–Gangotri National Highway. Connectivity to as many as 85 villages was disrupted. The National Highways of Uttarkashi, Gangotri, and Yamunotri also remained closed during July–August.	Hilly
6	Assam witnessed massive floods in June and September 2012. The floods along with landslides damaged several National Highways (NIDM, GoI, 2012).	Hilly
7	The 2008 Kosi floods in Bihar reported significant damage to road infrastructure. All categories of roads ranging from National Highways to village roads were affected; 31.7 km of National Highway was fully damaged and 30 km was partly damaged. (GFDRR, 2010).	Plains (River Basin Zone)

Source: (U.S. Department of Transportation, Federal Highway Administration, 2016), (Scott Wilson, 2008), (Forum of European Highway Research Laboratories (FEHRL), 2013), (National Cooperative Highway Research Program), (Jonathan Dowds, 2015), (World Bank, 2010), (Deccan Chronicle, 2016) TERI stakeholder interactions (2015–17)

have attempted to factor in climate parameters. There are specific IRC codes which provide guidelines and standards for constructing roads, taking into account rainfall intensity and flooding. IRC 034-2011 provides recommendations for road construction in areas affected by water logging and flooding for prolonged periods. IRC 28-1967 provides specifications for the construction of roads in areas of moderate rainfall (not exceeding 150 cm per annum) in areas of high rainfall (exceeding 150 cm per annum). Both IRC and the Bureau of Indian Standards have come out with guidelines that look at addressing landslides and rock-fall risks. The Landslide Control Guidelines (IS. 14680:1999), Recommended Practices for Treatment of Embankment and Roadside Slopes for Erosion Control (IRC: 56 - 2011), State of The Art: Design and Construction of Rock fall Mitigation Systems (IRC Highway Research Board–Special Report 23-2014), State of The Art: Landslide Correction Techniques (IRC Highway Research Board–Special Report 15 - 1995), and the Hill Road Manual (IRC: SP-48-1998), all provide guidelines on planning and designing and recommended interventions that address both climatic and non-climatic vulnerabilities of roads in hilly terrain. Addressing the perils of flooding, the National Disaster Management Plan 2016 recommends investing in structural measures, such as waterways and drainage systems for roads, highways, and expressways. The plan also clearly states the responsibilities of both Central and State agencies for implementing these structural measures. The central agencies, such as MoRTH, NHAI, Ministry of Defence (MoD), and Border Roads Organisation (BRO), are responsible for the proper alignment and design of roads for implementing these measures. The state agencies, such as States/UTs, SDMA, CoR, Revenue Department, PWD, DDMA, Panchayats, and ULBs are responsible for coordination with the central agencies for implementing the projects and also ensuring proper alignment and design of roads for the state projects. The Green Highways (Plantation, Transplantation, and Beautification & Maintenance) Policy, 2015, looks at arresting soil erosion at the embankment slopes. Even though the main focus of the policy is beautification and maintenance of highways, it can contribute to enhancing the resilience of highways.

Considering climate change is a critical concern, it is imperative to strengthen the inter-linkage of improved planning and management of roads and climate-resilience measures at a policy level. It is important that climate change concerns be integrated in the planning, designing, construction, and maintenance of roads and highways. This calls for a comprehensive policy to steer the current and future course of highway management, that will ensure the mainstreaming of climate change concerns into the highways sector.

2 Impact of Climate Change on Highways

2

Impact of Climate Change on Highways

Typically, highways and other transportation infrastructure are designed keeping in mind the local weather and past climatic trends. Given that the lifespan of highways is 30 years on an average, it becomes necessary that the future impacts of climate change are also considered while planning and designing highway networks (UNDP, 2011). In order to incorporate climate change considerations into the highway network planning and management, it is important to understand climate stressors and the potential risks they pose to highways.

For roads and highways, the climate variables that typically pose risks on pavements are temperature (average and extreme), precipitation, and soil moisture. However, the type and scale of impacts will vary depending on the topography, geology, drainage, pavement condition, and traffic flow. These climatic and non-climatic stressors can cause significant damage and disruption of services. For instance, in areas where prolonged flooding takes place, the subgrade gets saturated due to water percolation, thereby reducing its bearing capacity. In the case of flexible pavements, prolonged contact with water strips the binder of the pavement and in concrete pavements, the percolation of water in subgrades leads to pumping and cracking of the pavement. In case of concrete roads, high temperatures can lead to buckling of roads. Occurrences of buckling in the USA show that there is no specific temperature that causes a road to buckle, but it is usually seen to occur at temperatures ranging from 70°–90° F, which are considered as high temperatures in the North American context.

In order to incorporate climate change considerations in the Indian highways sector, it is important to understand impacts specific to the Indian scenario. However, studies that explore the impacts of climate change on Indian roads and highways are practically non-existent. Therefore, in order to document the impacts of climate change on Indian highways, information collected from the field, through interactions with stakeholders, and international literature has been utilized (Table 4).

It is important to note here that international literature indicates temperature as the key climate stressor for rigid pavements; while in the case of flexible pavements, precipitation has been found to be the primary stressor. Also, stakeholder discussions with respect to hilly and coastal regions indicated that extreme rainfall has been observed to be the primary climate stressor for highways in these regions of India.

Table 4: Impact of climate change on highways

Region	Climate stressors	Impact on highway elements and infrastructure	Impact on operations, maintenance and safety
All regions	High Temperatures	• Softening of pavements resulting in rutting and shoving • Buckling, heaving at the joints of the pavements • Cracking of pavements, thereby rendering it more vulnerable to the rains as rainwater percolates to the layers below and thus affects the structural stability of roads	• Vehicle overheating and increased risk of tire blowouts • Closing of roads because of increased wildfires • Increase in accident rates (most likely due to slow reaction time or loss of concentration and alertness) • The growing season for deciduous trees that shed their leaves may be extended, thereby causing more slipperiness on roads and visual obstructions and also increasing maintenance costs • Breaks soil cohesion and increases dust volume which causes accidents
Coastal, hill, and plain	Intense rainfall/ Extreme precipitation events	• Erosion and subsidence of paved roads • Increase of hydrodynamic pressure on roads resulting in revelling of pavement surface • Infiltration of rainwater into the layers below and thus damaging the structural stability of the road • Reduced capacity of drainage system due to debris accumulation, sedimentation, erosion, scour piping and conduit structural damage, and hence flooding of roads • Water overtopping and washing away of road pavements • Risk of landslides, rock falls, slope failures, and floods from runoff	• Slightest rains can slow traffic and decrease the capacity of roads to handle traffic. • Tree root damage and landslips • Reduces road safety by impairing visibility and mobility and also increasing livelihood of hydroplaning
	Storms/dust storms and stronger winds	• Clogging of roadside drains due to debris from destruction	• Damages trees, lampposts, overhead cables, other roadside infrastructure
			• Increases accident risk, travel delays, low visibility
Coastal	Sea level rise and storm surges	• Coastal road flooding and subsequent damages • Erosion of coastal road base • Increased frequency of flooding rendering the drainage system less effective	• More frequent disruptions of transport services • Increased maintenance costs and probabilities of structural failure during extreme events
Desert	Drought	Cracking and splitting of pavements	Health hazards due to the movement of dust during dry conditions
Plains and hills	Winter storms	Changes in freeze and thaw cycle making road surfaces more susceptible to potholes and rutting	Increase in road maintenance due to potholes, cracking, and rutting

Source: (U.S. Department of Transportation,Federal Highway Administration, 2016), (Scott Wilson, 2008), (Forum of European Highway Research Laboratories [FEHRL], 2013), (National Cooperative Highway Research Program), (Dowds, 2015), (World Bank, 2010), TERI stakeholder interactions (2015–17)

3 Climate Vulnerability Assessment of Highways

3

Climate Vulnerability Assessment of Highways

This chapter presents the methodology developed by TERI for vulnerability assessment (VA) of NHs in India, also one of the key objectives of this study. To this end, an international review of methodologies used for conducting climate vulnerability and risk assessment of infrastructure assets has been carried out. The methodologies have been reviewed to identify and understand the essential elements and approach steps for assessing the vulnerability of highway infrastructure to climate change.

3.1 Review of globally accepted climate vulnerability assessment approaches

This section presents a discussion on the key components and takeaways from the reviewed methodologies. The authors would like to note here that, mostly, only international studies and methodologies for vulnerability assessment (VA) of highways and infrastructures was found during the review process and the same have been discussed here. It was found that similar approaches or studies for highways or regional roads are practically non-existent in India. As the next best alternative, to study the Indian context, TERI's own methodology for VA of urban infrastructure (including urban roads) was considered.

It may also be noted that the discussion presented here does not include methodologies which were found to be very data intensive and involved a lot of modelling-based studies. For instance, the 'Impact of Climate Change on Road Infrastructure' (Harvey *et al.*, 2004), a study conducted in Australia, utilized modelling tools (Pavement Life Cycle Costing (PLCC) model and the Highway Development and Management Version 4 (HDM-4) model) for drawing the connection between climate projections and road system component. It utilized data, such as road inventory, traffic information (e.g., annual average daily traffic), pavement type (e.g., materials, strength, and thickness), and pavement condition (e.g., age, initial pavement roughness) in order to undertake the detailed VA. Another study, 'Evaluating Climate Change Impacts on Low Volume Roads in Southern Canada' (Tighe *et al.*, 2008), analyses pavement performance over a 20-year period using the Mechanistic-Empirical Pavement Design Guide (M-E PDG) to determine how climate changes in precipitation and temperature will affect the pavement performance indicators of international roughness index (IRI), longitudinal cracking, transverse cracking, alligator cracking, asphalt concrete (AC) deformation, and total deformation. This analysis requires traffic, structural, and material property datasets to represent current stressors and pavement conditions. Such data- and time- intensive methodologies were not considered for review, to develop VA methodology for this study. This is mainly attributed to the fact that the proposed VA methodology is intended as a quick decision-making tool for planners and practitioners in the field of highway development in India who may not typically have access to such detailed data and technical assessment models and the capacity to utilize them. Therefore, the scope of this study focussed on the review of methodologies and approaches that do not need very detailed data or complex software for conducting the VA and are user friendly and easy to adopt/ adapt for the highways sector in India.

The following methodologies were found to be most relevant for this study and have been discussed in detail.

- ADB Guidelines for Climate Proofing Investment in the Transport Sector—Road Infrastructure Projects (ADB, 2011)
- Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase II (U.S. Department of Transportation, Federal Highway Administration, 2015)
- Adapting to Climate Change: Canada's First National Engineering Vulnerability Assessment of Public Infrastructure (Canadian Council of Professional Engineers, 2008)
- The Federal Highway Administration's (FHA's) Climate Change and Extreme Weather Vulnerability Assessment Framework (U.S. Department of Transportation, 2012)
- Dorset County Council's approach for building resilience in local highways (UK) (Climate UK, 2013)
- TERI's Methodology and Framework for urban risk assessment, developed for Guwahati city (TERI, 2013)

Table 5 summarizes these methodologies in terms of the objectives and scope of assessment, key steps involved, and the geographical context and scale. The column titled 'Relevance' comments on the strengths and gaps of the methodologies in terms of their application for VA of highways in India. A detailed

Table 5: Reviewed VA methodologies

Study Title	Objectives and scope of assessment	Key steps involved	Geo-graphical context	Scale	Relevance
Guidelines for Climate Proofing Investment in the Transport Sector—Road Infrastructure Projects, ADB	Guidance tool for climate proofing investment in the transport sector. Applicable to new or proposed projects	• Constructing climate change scenarios: Identifying the relevant climate variables needed for the impact assessment • Learning from the past: Establishing the climate baseline; using climate projections from general circulation models • Downscaling: From global to local climate projections	Flexible	Project scale	The ADB guidelines specify the steps involved in impact assessment and climate vulnerability assessment and aim to identify and evaluate, in qualitative terms, the effects of climate change on the road infrastructure
Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase II	To understand the impacts of climate change on transportation infrastructure in Gulf coast region and identify appropriate adaptation strategies. Relevant for VA of new/ proposed as well as existing infrastructure assets	• Criticality assessment • Gather and process climate information • Screen for vulnerability • Conduct detailed engineering assessments	Coastal region	Regional assessment	This methodology is of direct relevance to the current study because it studies the impacts of climate change on various transportation networks including highways

Table 5: Reviewed VA methodologies					
Study Title	**Objectives and scope of assessment**	**Key steps involved**	**Geo-graphical context**	**Scale**	**Relevance**
Adapting to Climate Change: Canada's First National Engineering Vulnerability Assessment of Public Infrastructure	A five-step protocol for conducting a VA of public infrastructure to climate change for making investment decisions. Applicable to new or proposed projects	• Project definition • Data gathering and sufficiency • Vulnerability assessment • Indicator analysis • Recommendations	Flexible	Project scale	It is a fairly simple methodology to follow with only five key steps. It is useful in terms of identifying indicators for conducting the vulnerability and risk assessment of roads, and prioritizing adaptation options
The Federal Highway Administration's (FHWA's) Climate Change and Extreme Weather Vulnerability Assessment Framework	It is a guide for transportation agencies for assessing their vulnerability to climate change and extreme weather events. Relevant for VA of new/proposed as well as existing infrastructure assets	• Defining the study objectives and scope • Selecting and characterizing relevant assets • Checking data availability • Delineating which assets to examine • Assessing asset criticality • Obtaining climate information • Developing information on asset sensitivity to climate • Identifying and rating potential vulnerabilities • Considering adaptive capacity • Incorporating likelihood and risk • Identifying, analysing, and prioritizing adaptation options	Flexible	Project scale	This methodology is of direct relevance to the current study and many steps can be directly be applied in Indian context
Dorset County Council's approach for building resilience in local highways	They adopted a sequential approach to assessing climate risk with the objective of building adaptation and resilience into their highways asset management plan. Relevant for VA of new/proposed as well as existing infrastructure assets.	• Local Climate Impacts Profile (LCLIP) • Identifying climate risks and priorities for adaptation • Comprehensive climate change risk assessment • Highways climate change detailed risk assessment • Climate threshold investigation • Highways asset climate threshold data analysis • Sector-specific adaptation plans • Highway asset management plan	Flexible	Project scale, local level highways	This methodology is reasonably detailed and is of direct relevance to the study because of its focus on the highway sector. The highways asset prioritization is derived from both quantitative and qualitative components

Table 5: Reviewed VA methodologies

Study Title	Objectives and scope of assessment	Key steps involved	Geo-graphical context	Scale	Relevance
TERI's Methodology and Framework for urban risk assessment	Development of methodology and its application (Case Study). Relevant for VA of new/proposed as well as existing infrastructure assets in a city.	• Identification of hazards and challenges • Vulnerability Analysis • Identification of hotspots • Future climate and socio-economic projections • Current and future risk profile of the city • Identification of adaptation and resilience options to address the risks • Review of existing policies and legislations to identify gaps in addressing to risks • Identification of means of integrating and mainstreaming policies for risk reduction in the existing policy framework	Hilly region	City-level assessment for Guwahati city, Assam	It is a city- level assessment framework but can be useful for understanding the basic steps involved for climate vulnerability assessment of infrastructure assets

discussion on the individual methodologies are as follows:

Guidelines for Climate Proofing Investment in the Transport Sector— Road Infrastructure Projects (ADB, 2011)

The guidelines by ADB have been developed with an objective to outline a methodological approach for investments on climate change adaptation in the transport sector. The methodology is divided into six different sets of activities which include climate vulnerability assessment as one of the core activities (Figure 2). The ADB guidelines focus on the identification and evaluation of climate change impacts on road infrastructure at a project scale in qualitative terms (ADB, 2011). The guidelines were of particular interest for the current study with respect to the approach adopted for VA of roads.

Key Takeaways

The methodology highlights the importance of climate analysis and projections for the region as a key to understand the present and future climate vulnerability of a road stretch. The study recommends adopting or downscaling of the available climate change scenarios developed as part of existing national and regional climate change initiatives, such as the national communications to the UNFCCC, as developing such projections at the regional level can be costly and time consuming. Also, in some cases, it is observed that even the most up-to-date climate models would not be able to provide the desired precision or accuracy at the project level due to topographical variability and uncertainty related to climate change projections. However, in all cases, understanding the history of climate (temperature, rainfall, storm surges, and extreme weather events) is always a necessary first step. Another key step is to assess the likely impacts of various probable climatic events on the infrastructure.

Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase II (U.S. Department of Transportation, Federal Highway Administration, 2015)

The U.S. Department of Transportation (U.S. DOT) conducted a comprehensive study on the impacts of climate change on the transportation infrastructure in the Gulf coast region for the identification of

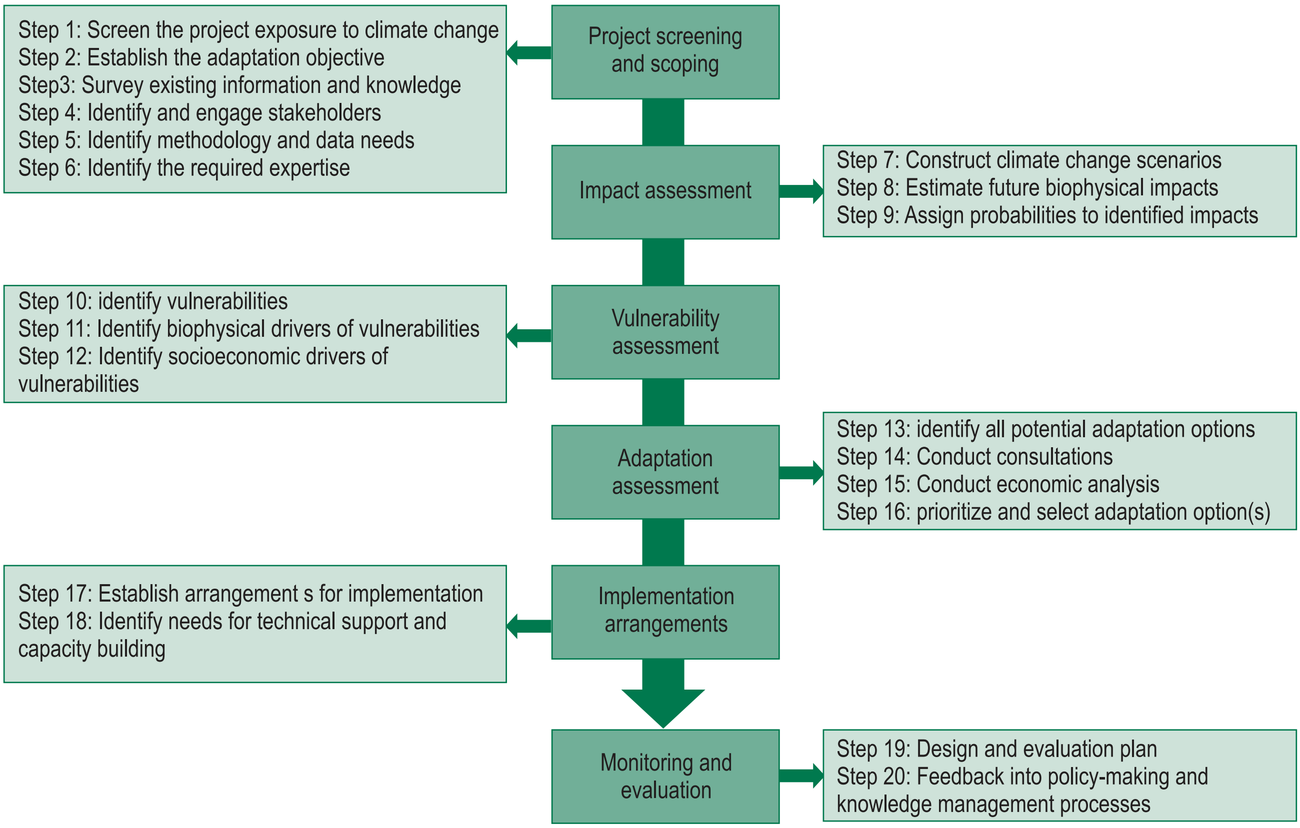

Figure 2 Activities and steps involved in climate proofing transport investment

Source: Guidelines for Climate Proofing Investment in the Transport Sector—Road Infrastructure Projects, August 2011, ADB, Philippines

appropriate adaptation strategies. As part of this study, the climate change impacts on various transportation networks, including highways, were evaluated based on the projected changes in precipitation, temperature, sea level rise, storm surge, and intensity and frequency of storms (U.S. Department of Transportation, Federal Highway Administration, 2015). Table 6 outlines the key tasks undertaken for VA under this study.

Key Takeaways

This methodology highlights the importance of conducting a criticality assessment of the transportation systems for vulnerability and risk assessment of infrastructural assets. In order to determine the criticality, the evaluation criteria were developed for three broad categories (Table 7).

Table 6: Vulnerability assessment task/stages

Tasks	Objectives
Criticality assessment	Identification of the most critical assets from a socio-economic, operational, and health and safety viewpoint
Gathering and processing climate information	Projection of key climate stressors—temperature, precipitation, sea level rise, storm surge, and wind over a time period; Identification of relevant climate data formats
Screening for vulnerability	Identification of the most vulnerable critical assets to climate change; Identification of system-level vulnerabilities, such as regions that are particularly vulnerable, climate stressors, timeframes of particular concern
Conducting detailed engineering assessments	Development and testing of a detailed climate impact assessment process to evaluate the climate vulnerabilities and possible adaptation strategies; Documentation of specific findings relevant to engineering practices

Table 7: Criticality criteria for highways			
	Socio-economic	**Use/Operational**	**Health/Safety**
Highways	Locally identified priority corridors Serves areas and economic centres	Functional classification (Interstate, etc.) Usage (Average Daily Traffic)	Evacuation route Component of disaster relief and recovery plan

- Socio economic importance
- Use and operational characteristics
- Health and safety role in community

The criticality was then evaluated based on the scoring of each criterion. The scoring was based on the volume of traffic, traffic modelling, expert judgments, and other allied parameters. An overall criticality score of high, medium, and low was given to the assets.

On similar lines of the ADB methodology, U.S. DOT's methodology also recommends analysing multiple climate change scenarios in order to minimize the uncertainty in climate change impacts projected for the future. All the information gathered on criticality of assets, projections of climate stressors, and asset sensitivity to climate change is then compiled based on a scoring approach to come up with a vulnerability index in order to identify assets which will be most vulnerable to climate change. The technical assessment and vulnerability indices for various assets are further refined and finalized after validating the results with experts and various stakeholders (U.S. Department of Transportation, Federal Highway Administration, 2015).

While the vulnerability assessment methodology developed by ADB limits to a broad assessment at the project scale for identifying resilience options, this methodology goes a step further to conduct detailed engineering assessments of the vulnerable assets for a detailed evaluation of the structural integrity and effectiveness of adaptation measures. Overall, this methodology is of direct relevance to the current study because it studies the impacts of climate change on various transportation networks, including highways.

Adapting to Climate Change: Canada's First National Engineering Vulnerability Assessment of Public Infrastructure (Canadian Council of Professional Engineers, 2008)

Under this Canadian study, the vulnerability assessment of four categories of infrastructure, namely, water resources, storm water and waste water, roads and associated infrastructure, and buildings was conducted. As a result of the study, 'The Engineering Vulnerability Assessment Protocol' was developed. This five-step protocol (Figure 3) provides the methodology to be adopted while conducting an assessment of vulnerability of infrastructure to climate change. The methodology is of relevance to the current study as it provides an approach for vulnerability assessment, particularly for roads among other infrastructure.

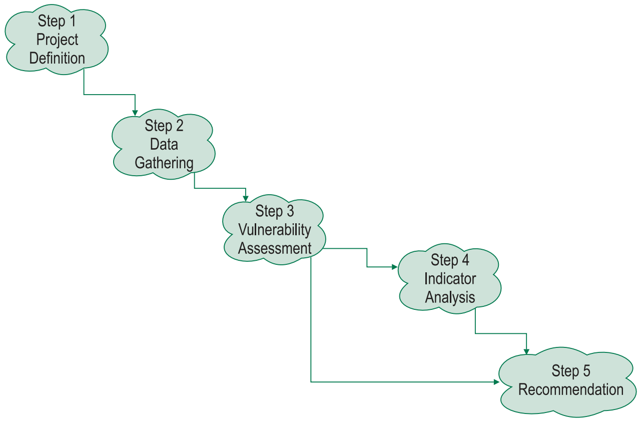

Figure 3 Five-step protocol adopted by the study

Source: Adapting to Climate Change: Canada's First National Engineering Vulnerability Assessment of Public Infrastructure. Canadian Council of Professional Engineers, 2008

Key Takeaways

One of the key components and takeaways from this methodology is the project definition or scoping exercise that is conducted as the first step prior to any climate or non-climate data analysis. This step helps in defining the boundaries and geographical scale of assessment based on the location of infrastructure, load, age, and historic climatic data. This step also involves identifying relevant information, documents, and data formats (Canadian Council of Professional Engineers, 2008). Another key feature of this methodology is an indicator-based risk assessment of road infrastructure assets. This involves an evaluation of the impacts of relevant climate events and factors on the key infrastructure elements and performance of road assets in terms of 'high' and 'medium' vulnerability based on the number of cases/ incidence of past events (Figure 4) (Canadian Council of Professional Engineers, 2008). Remedial actions for the upgradation of infrastructure, management actions, and monitoring of performance are identified based on this assessment.

Relevant Infrastructure Elements	Performance Response	Relevant climate Events and other Environmental Factors
Arterial Roads Collector Roads Local Urban Roads Local Rural Roads • Surface • Surface Treatment • Surface Gravel • Curb • Sidewalk • Traffic Signals • Street Lighting • Utility Poles • Boulevards and Shoulders • Bike Paths • Embankments/Suts • Bridge/Structures • Signage • Sub-Base • Storm Sewer Systems • Catch Basins • Culverts • Ditches • Distribution Systems • Maintenance Holes • Undergrounds Utilities • Administration/Personnel • Maintenance • Winter Maintenance • Records • Trees • Guide Rails	Structural Integrity Serviceability Functionality Operations and Maintenance Emergency Response Risk Insurance Considerations Policies and Procedures Economics Public Health and Safety Environmental Effects	High Temperature Low Temperature Extreme Temperature Range* Precipitation as Rain Precipitation as Show Wind Ice Accretion Ice Force* Hail Freeze-Thaw Cycles Ground Water Flooding Fog* Temperature + Relative Humidity Heavy Winter Snow + Early Spring + Heavy Rain = Major Flooding Snow + Freeze Temp = Heavy/Dense Snow
Bridges Operations & Maintenance • Regular Maintenance Crew* • Maintenance Equipment* • Snow Removal Personnel* • Snow Removal Equipment/Material* Deck • Cast-in-place Concrete* • Reinforcement* • Wearing Surface • Water-proofing Membrane • De-icing System/Approach*		

Figure 4 Factors considered for the vulnerability assessment of roads

Source: Adapting to Climate Change: Canada's First National Engineering Vulnerability Assessment of Public Infrastructure. Canadian Council of Professional Engineers, 2008

The Federal Highway Administration's (FHA's) Climate Change and Extreme Weather Vulnerability Assessment Framework (U.S. Department of Transportation, 2012)

The Federal Highway Administration's (FHA's) Climate Change and Extreme Weather Vulnerability Assessment Framework is a guide for transportation agencies for assessing their vulnerability to climate change and extreme weather events. The framework is of relevance to this study as it outlines a step-by-step methodology for vulnerability and risk assessment of highways in any geographical context. The framework broadly comprises of three key steps—defining study objectives and scope, assessing vulnerability, and incorporating results into decision-making (Figure 5).

Key Takeaways

A key learning from this methodology is its first step which focuses on defining the objectives and scope of the assessment study. The methodology argues that this step is a pre-requisite for VA of highway infrastructure as it helps in determining the data and level of detail required in the analysis. This will also be important from the perspective of monitoring and assessing the impacts/success of identified adaptation measures. This step also includes identifying the relevant infrastructure assets and delineating the geographical scale for which the assessment is to be conducted based on objective of the assessment. The framework recommends delineation of the geographical scope based on administrative jurisdiction or geographic vulnerability. It may also be done such that it includes the relevant infrastructure for assessment, for instance, old, stressed or most critical infrastructure (U.S. Department of Transportation, 2012).

The methodology also highlights the importance of a combined approach for establishing the criticality of the infrastructure assets prior to VA, wherein a desk review identifies an initial list of critical assets based on commonly available data, such as average daily traffic or economic information for the region (e.g.,

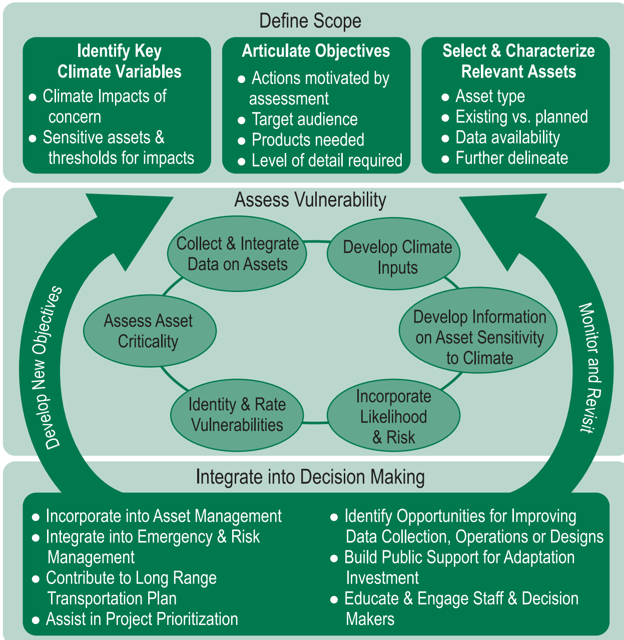

Figure 5 : Climate Change and Extreme Weather Vulnerability Assessment Framework

Source: U.S. Department of Transportation, 2012

		Consequence				
		1	2	3	4	5
Likelihood	1	2	3	4	5	6
	2	3	4	5	6	7
	3	4	5	6	7	8
	4	5	6	7	8	9
	5	6	7	8	9	10
Risk	Low		Moderate		High	

High Risk (Red)

Unacceptable, major disruption likely; priority management attention required.

Moderate Risk (Orange)

Some disruption; additional management attention may be needed.

Low Risk (Green)

Minimum impact; minimum ovesight needed to ensure risk remains low.

Figure 6 Risk Rating Matrix

Source: *Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project, November 2011*

data on imports/exports from a particular port). The project team then utilizes the results of the desk review to inform and structure feedback from stakeholders and local experts. The methodology recommends consideration of the exposure,[1] sensitivity,[2] and adaptive capacity[3] to develop a risk rating matrix (Figure 6). This helps in identifying the likelihood and extent of impacts of climate change factors and events on vulnerable assets as well as prioritizing adaptation options. It is suggested that the sensitivity to climate change may be assessed based on identification of climate thresholds in terms of the kind and level of climate factors and events which may affect an asset. This particular step is relevant for the current study due to the absence of such thresholds for the highways sector in the Indian context. The FHA methodology recommends a detailed analysis of design standards and the extent of loss and damage caused in the past by climate events to identify these climate thresholds. In order to develop climate information, the methodology recommends referring to the existing climate knowledge developed by others or working with climate modellers to develop projections tailored to the project's need, however, it notes that the latter is a resource-intensive approach (U.S. Department of Transportation, 2012). The climate and asset information is combined by overlaying the climate projections in a GIS-based format. Adaptation strategies are evaluated based on their feasibility, efficacy, and the ability to withstand a range of climate hazards, costs, and co-benefits (U.S. Department of Transportation, 2012).

Dorset County Council's Approach for Building Resilience in Local Highways (Climate UK, 2013)

A sequential approach to assess climate risks was adopted by Dorset County Council in UK with an objective of making investment decisions for building climate-resilient highways and formulating a highways asset management plan. The study followed a broad approach of assessing comprehensive climate risks at the county, district, and borough level and then conducting a detailed risk assessment for highways at the local level to come up with a sector-specific adaptation plan and asset management plan (Figure 7). The detailed risk assessment included the likely impacts of climate change factors and events on

[1] Exposure refers to whether the asset or system is located in an area experiencing direct impacts of climate change, such as temperature and precipitation changes, or indirect impacts, such as sea level rise.

[2] Sensitivity refers to how the asset or system fares when exposed to an impact.

[3] Adaptive capacity refers to the system's ability to adjust to cope with the existing climate variability or future climate impacts.

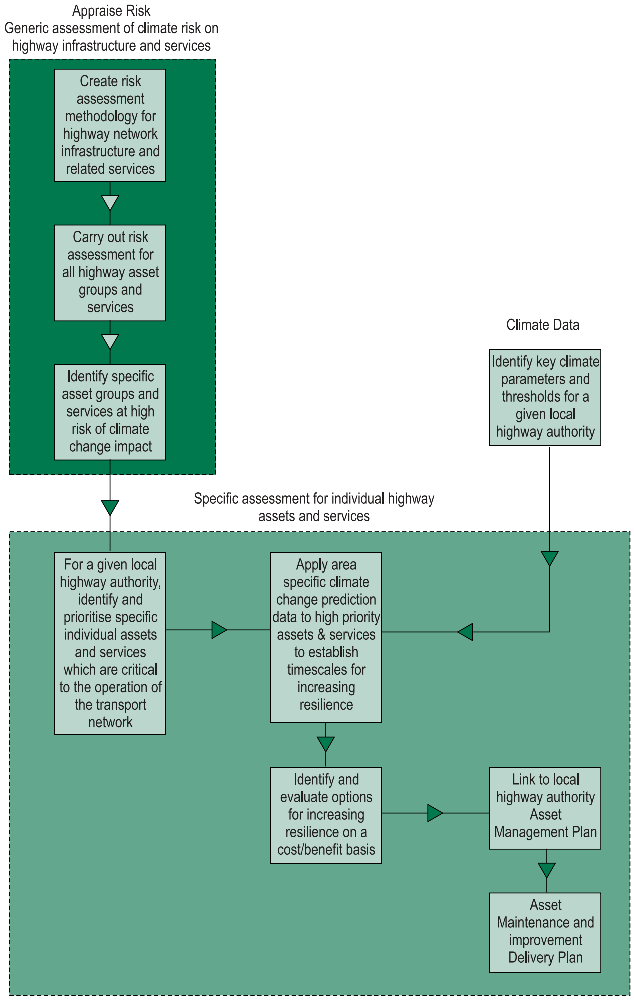

Figure 7 Assessment framework; Dorset County Council, UK

Source: Climate UK, 2013

physical assets, such as road surfaces as well as impacts on end user and operations due to failures of the asset (Climate UK, 2013).

Key Takeaways

The methodology highlights the importance of prioritizing highways assets in terms of their critical role in supporting communities and the economy and the impact of its failure on the delivery of all other local government services. This was carried out with two objectives. First, to scope the relevant highway assets for VA and second, prioritizing adaptation actions and formulating the asset management plan. Another key learning from this methodology was the approach adopted for identifying climate thresholds. Thresholds were chosen based on their relevance to highway assets and operations based on first, the identification of specific climate factors that are likely to impact highways and second, the extent of likely impact. For instance, projected information on high and low temperatures, precipitation, and drought for each decade up to the 2080s was combined with highway information in a GIS-based format to build scenarios of the likely extent of risk. Moreover, the methodology recommended the use of previous climate change risk assessments and local insights in addition to future climate projections to understand the vulnerability and likely risks, and thereby developing a management plan for each highway assets group.

TERI's Methodology and Framework for Urban Risk Assessment (TERI, 2013)

The methodology was developed with an objective to understand the existing and future risk profile of an urban area—infrastructure, assets, and communities—based on a city-scale vulnerability assessment to climatic and non-climatic hazards and stressors. The methodology is intended as a quick, easy-to-use, step-by-step guide for city-level practitioners and decision-makers and primarily relies on local secondary data and consultations with relevant stakeholders (Figure 8). Though a detailed climate analysis, based on globally accepted scientific climate models, is a key step in understanding the present and future risks and vulnerabilities of the case study city, the methodology notes that such capacity may not be available at the city level. Therefore, it suggests using the available climate knowledge at the state or national level as an alternative. Identification of vulnerable hotspots and communities is done by overlaying the future climate and socio-economic projections on the existing risk profile of the city (TERI, 2013). This leads to the identification of structural and non-structural (policy) resilience options to address the vulnerabilities of different infrastructure assets and communities.

Key Takeaways

As stated earlier, there are no specific studies conducted in respect of climate vulnerability assessment of the road sector in India. Since TERI has successfully developed and applied this methodology of vulnerability assessment of urban infrastructure, including roads, it has been considered for discussion

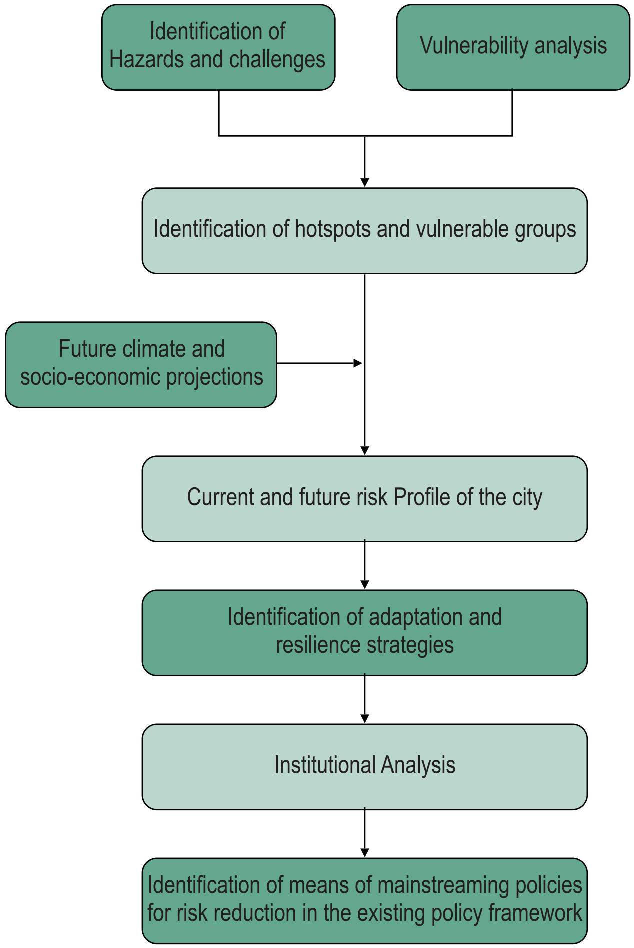

Figure 8: Risk Assessment Framework for urban infrastructure and communities

Source: Risk Assessment and Review of Prevailing Laws, Standards, Policies and Programmes to Climate Proof Cities-Synthesis Report for Guwahati, TERI, 2013.

here. The methodology is simple to use and can be easily customized to help in the vulnerability assessment of NHs.

3.2 Conceptualizing the proposed methodology for vulnerability assessment of highways in India

A review of the aforementioned methodologies provides an understanding of the type of approaches used in assessing vulnerability in the context of road and highway infrastructure. The key takeaways from the review of relevant methodologies have been contextualized and adopted for developing new and customized methodology for climate vulnerability assessment of NHs in India. These key takeaways have been discussed as follows:

- **Need for VA and resilience building of highways**—All reviewed methodologies iterate the importance of VA and resilience building of roads and highways for making investment decisions and identifying adaptation options in view of the climate change impacts, extreme events, and resulting likely risks to highway infrastructure assets. This has also been highlighted by the loss and damage caused by multiple recent climate events in India as discussed in Chapter 2 'Impact of Climate Change on Highways'. At the network level, VAs will help in prioritizing investment decisions. At the stretch level, detailed risk assessments will help in identifying appropriate engineering interventions for retrofitting.
- **Importance of identifying objectives and scope of the VA methodology**—Four methodologies (ADB, U.S. DOT, Canadian Council of Professional Engineers, FHA) out of the six, discussed in the preceding section, highlight the importance of defining objectives and boundaries or scope of the study. It is observed that this exercise is important for delineating the relevant geographical extent and assets and services that may be impacted by climate change. The objectives and scope of the study, and whether the VA is being carried out to develop a new highway or retrofit an existing one, will also help in determining the relevant data and level of details required for the assessment.
- **Developing climate scenarios**—Development of multiple climate scenarios is recommended based on analysis of past/existing trends of climate parameters and events as well as future projections. However, most methodologies recommend that regional climate change information should be adopted from the existing national and regional climate change initiatives or studies, as developing such projections at the regional level can be costly and time consuming.
- **Criticality assessment**—A criticality assessment of the highway networks and infrastructure is highlighted by multiple methodologies reviewed above as a key step (U.S. DOT, FHA, and Dorset County Council). This is considered important by

the authors, especially at the l network level, for prioritizing investment decisions for resilience building of highways. Criticality may be defined in the context of the socio-economic and regional importance of the highway, operations, etc.

- **Risk assessment**—The methodology adopted by the Canadian Council of Professional Engineers, FHA, and Dorset County Council recommend a risk assessment for ranking the vulnerability of specific highway elements and infrastructure. This has typically been done using qualitative matrices or systems of scoring and weightages. This step is also considered important by the authors for the current study for identifying appropriate engineering interventions for the vulnerable stretches/sections.

Besides, identification of low and high thresholds for climate parameters, such as temperature, precipitation, drought, storm surges, etc., has been done in the case of methodologies recommended by the FHA and Dorset County Council. This step is also considered important by the authors for a detailed vulnerability and risk assessment of NHs and prioritizing areas of investments and interventions. However, identification of such thresholds will require further detailed studies and is recommended as a way forward for mainstreaming climate change concerns in the highway and road development policy and guidelines, such as IRC Codes.

3.3 Proposed methodology for carrying out climate vulnerability assessment of NHs sector in India

Based on the key takeaways from the review of VA methodologies, a broad framework for VA of highways in India has been developed by TERI which has been discussed in the subsequent section. The proposed approach adopts the good practices from the reviewed methodologies to develop a new and customized methodology for vulnerability assessment of NHs in India. The proposed methodology may be applied for vulnerability assessment of both new and existing highways, including highway alignment, expansion, and upgradation.

It is also observed that vulnerability assessment for resilience building of highways, both at network and stretch levels, is a good practice. Accordingly, the proposed methodology suggests the approach and key steps for ensuring VA of highways at both levels. It is recommended that climate VA should be an integral part of investment planning and development of any highway network, especially in areas with higher likelihood of climate change impacts and hydro-meteorological extreme events. This will include the Himalayan terrain, coastal and desert regions, and high flood-risk areas.

Though the proposed methodology is intended as a step-by-step guide that can be applied across the country, it is to be noted that the methodology will need to be contextualized based on the topographical and climatic/hydro-meteorological factors. Local insights from experts and stakeholder consultations will play a key role in this exercise.

Moreover, as discussed earlier, the proposed VA methodology is intended as an easy and quick decision-making tool for planners and practitioners in the field of highway development in India and, therefore, does not recommend primary data collection or the use of complex analytical tools for climate assessments.

Given the fact that NHs account for only about 2% of the total roads network in India, it is suggested that the Ministry of Road Transport and Highways (MoRTH), Government of India, may recommend this methodology for vulnerability assessment and resilience building of roads and highways sector in India to other relevant agencies at national, state, and city level, apart from the National Highways Authority of India (NHAI). Figure 9 presents the VA methodology that has been developed by TERI—both for network and stretch/local levels—and the step-by-step approach is discussed below.

Step 1: Defining objectives

The first step of a VA exercise for the highways sector would be to identify the objectives, and some examples of study objectives for VA of highways sector could be:

- Vulnerability assessments at the network level for:

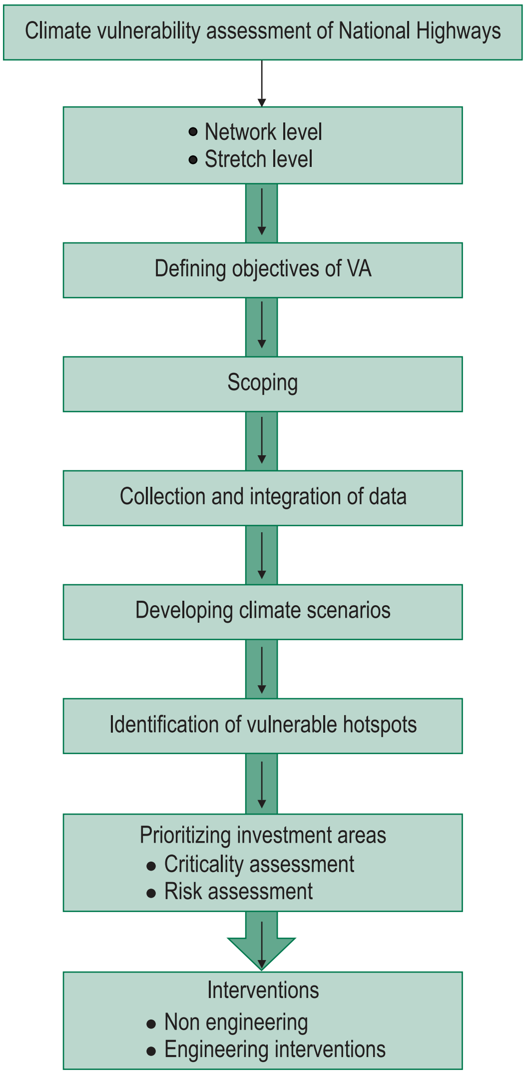

Figure 9: Methodology for Climate Vulnerability Assessment of Highways

- Planning a new highway network in a region
- Identifying stretches at risk to climate change impacts on the existing highway network for prioritizing investments
- Identifying effective adaptation strategies for existing or new highways

■ Local vulnerability assessment at stretch level for:

- Prioritizing retrofitting measures on the existing risk-prone highway stretches
- Identifying evacuation routes and formulating plans for disaster risk management

Therefore, the first step is proposed both for network level and stretch/local level assessments. It is important to define the objectives at this stage as this will facilitate delineation of the geographical limits and determine the data and level of details required in the study. For instance, planning a regional-level highway network will be more of a strategic decision-making exercise requiring planning scale analysis and data, such as land use, regional importance and traffic demand analysis, etc. On the other hand, identification of retrofitting measures for existing highway assets would require more detailed information at the design and engineering scale, for instance, construction materials, detailed contours and slopes, etc. Identification of the specific objectives will help in relevant and seamless implementation of the methodology at subsequent stages.

Step 2: Scoping

The scoping exercise would define the scope of the study and boundaries for VA; which in turn would help in focussing the assessment to significant and relevant climate parameters and geographical extent. This step is proposed both for network level and stretch/local level assessments. The project proponent can carry out the scoping exercise with inputs from technical experts, public representatives, local communities, and other stakeholders. This step should result in the following:

■ **Delineation of geographical limits**—The geographical limit of the study will be contingent on the highway stretch in consideration and objective of the study. For instance, for planning and finalizing alignment of a new highway stretch, the study area will need to be defined in such a way to include all the key settlements/ nodes to be connected. On the other hand, for identifying stretches or assets at risk to climate change impacts on existing highways, the study area will need to include all the key infrastructure assets for which the outcomes of vulnerability assessment are relevant, such as transport terminals, economic hubs, settlements, etc. Similarly, low-lying areas in case of coastal stretches are more vulnerable to flooding from sea-level rise or river flooding. The study might focus on these areas to quickly limit the analysis to the highway elements and infrastructure most likely to be affected by climate changes (U.S. DOT, 2012). The delineation of the geographical limits will thus differ for each study or stretch based on the objective and context of the VA and jurisdiction of the proponent of the study. However, to start with, the proponent may consider including the right of way (ROW) as well as the areas falling within a minimum of 500 m on both sides of the ROW. This is in line with the existing approaches for transport corridor assessment studies in India, such as Environment Impact Assessment (EIA).

- **Identification of key issues and parameters (climate and non-climatic) to be considered**—For the purpose of assessing the vulnerability of the highway stretch, it is suggested that both climatic and non-climatic parameters/stressors should be identified at this stage. Inputs from local experts and stakeholders may be used for identifying the most relevant issues/ parameters to be considered.
  - **Climate stressors**

    In order to analyse climate stressors for any region, it is important to understand the past and future climate variability over the region by looking at historical trends of key climate parameters, such as temperature, rainfall, past history of extreme events, etc. For instance, in case of coastal areas, inundation caused by sea level rise will be an important consideration. For this purpose, tide gauge data to understand the historical sea level rise, and cyclone frequency and intensity data along with surge data provides useful information. Also, precipitation variability and wind speed are other key climate parameters to be considered. For hilly areas, it would be relevant to study the past incidences of extreme precipitation and flooding events resulting in landslides. Even though landslide events are a result of multiple factors, it is important to consider them as extreme climate events have been observed to aggravate their occurrence.
  - **Non-climatic stressors**

    Non-climatic stressors for the highways may include but not be limited to the terrain, drainage, and material and construction technique of the highway stretch in consideration.
- **Identification of the sources of data and local knowledge**—Identification of data sources at this stage will enable easy and quick collection of data at the next stage. Sources of information can be identified on the basis of key issues and parameters identified in the previous stage. For instance, all climate data can be sourced from the meteorological department, data on sea level rise is usually available with port authorities and Survey of India as a tide gauge dataset. It can also be accessed via the open source database available online (e.g. PSMSL website[4]) It is also observed that some of the data needed for vulnerability assessment is typically not recorded. In such cases, discussion with local experts can provide a lot of insights. These sources of local knowledge should also be identified at this stage. It is recommended to rely on secondary data sources rather than primary surveys. It may also be noted here that resilience building of highways would require multi-sectoral data and coordination with other national and state line departments such as meteorological department, environment and climate change department, disaster management agencies, etc., multi-stakeholder consultations are therefore recommended.
- **Identification of relevant analytical tools and techniques**–Relevant analytical tools and techniques may be identified at this stage based on the timeline of study and details of outcomes required. For instance, a detailed climate and SLR projection modelling exercise typically takes 6-8 months and therefore, should be used in case of an extended study timeframe (of more than 1 year) or in the of requirement of detailed assessments. However, for a rapid vulnerability assessment, it is more suitable to use available regional climate change information from existing national or regional climate change initiatives or studies. Similarly, in case spatial assessments are needed, GIS-based vulnerability mapping techniques are recommended for identification of specific vulnerable hotspots.

4 PSMSL: Permanent Service to Mean Sea Level http://www.psmsl.org/, last accessed on September 5, 2017.

Step 3: Collection & Integration of Data

This step is proposed both for network level and stretch/local level assessments. It would involve collection and integration of the data required for the vulnerability assessment as identified in Step 2. This would include the data related to climatic and non-climatic parameters. It will include:

- Climate data on parameters including temperature, rainfall, past history of extreme events, etc.
- Material and construction techniques
- Highway elements, drainage, traffic control and safety infrastructure
- Criticality parameters – socio-economic importance, use and operational characteristics, and health and safety role

This data will help to create the exposure profile pertaining to climate impacts over the study area. A detailed data checklist for vulnerability assessment of a highway stretch may be referred from Annexure 1.

Step 4: Developing climate scenarios

This step relies on the available climate information for the future time periods over the selected highway stretch. As discussed under the 'Scoping' section above, the past climate information can be developed by using the historical observational datasets available either from the Indian Meteorological Department (IMD) or via the open source datasets available online (reanalyses datasets). The historical dataset analysis forms an important part of the methodology as it helps to understand the existing climate profile and vulnerability of the study area and also to choose the relevant climate variables to be analysed for the future time periods (for e.g. SLR values for coastal and extreme precipitation for hilly areas). In case the relevant datasets are not available, it is recommended to use the datasets from the nearest meteorological station as first approximation. In case of non-availability of relevant datasets, gridded dataset[5] over the region can be utilized as next level of approximation. The gridded datasets are available from IMD on payment basis. The climate profile publications from IMD for that area also forms a useful information source in case of data unavailability. For analysis of future climate and its impacts, datasets from high resolution (smaller grid size i.e. of the order of 50 kms or less) regional climate model becomes essential. Future projections of relevant climate variables and their probable changes provide the necessary information for analysing an impact or vulnerability over the study area. Since climate modelling requires special infrastructure that includes high performance computers and storage, it is recommended to emphasize on these capabilities before initiating the study. In case the required infrastructure to develop the primary dataset (future climate data) is not available, the next best option is to approach the Indian Ministry of Earth Sciences to request for availability of high resolution climate projection data for future time periods over the study area. Alternately, relevant datasets may also be retrieved from open source modelling databases. However, availability of such datasets over the study area and at higher resolution may be a challenge. Hence, it is imperative to utilise primary dataset via modelling exercise or information from an existing study, which can be either from the government (for example: INCCA report of 2010) or from a research institute (TERI studies on coastlines and future projections over various states). It should be noted here that any high resolution modelling study for assessing future (say 30 years from present) climate impacts ideally requires more than 1 year of total time including computational time (considering an average level fast super computer) and post processing of model data with analysis.

This step is proposed both for network level and stretch/local level assessments. Based on this approach, the outcomes of this step will entail:

- Past and future climate profile over the highway stretches
- Past and future profile for extreme climate events
- Sea level rise and storm surge assessment (over coastal stretches)

Step 5: Identification of vulnerable hotspots

This step is proposed both for network-level and stretch/local-level assessments. It would result in identification of vulnerable hotspots, that is, vulnerable sections of the highway stretch based on the climate

[5] IMD gridded dataset: IMD provides gridded datasets at two horizontal resolutions. It's advised to take 0.25 degree rainfall datasets for the analyses. http://www.imd.gov.in/advertisements/20160219_advt_12.pdf

scenarios developed in Step 4. An exposure profile of the study area will be created outlining how known climatic conditions are affecting the system and highway functioning based on an understanding of the impacts, loss and damage caused by past climate and extreme events. This would involve overlaying of past climate profile and the information related to the existing baseline (condition of pavements, traffic control and safety infrastructure, vegetation, capacity of drainage, topography, etc.) on a GIS platform. The future climate scenarios developed in Step 4 will then be overlaid onto the exposure profile for assessing the vulnerability of the highway to future climate impacts.

The vulnerability mapping exercise will result in identification of vulnerable hotspots, that is, vulnerable stretches at the network level and vulnerable sections on the stretch level. Besides, consultations with local experts and stakeholders will be an integral part of this step. This will help in validating the outcomes of the technical assessment and in prioritizing adaptation options at a later stage.

Step 6: Prioritizing areas for investment and interventions

Assessments conducted in this step will help in identifying areas for investments and interventions. In case of a network level assessment, a criticality assessment of highway network will be conducted to prioritize the 'critical' highway stretches for investments in resilience building. In the context of a stretch level assessment, a detailed risk assessment exercise will be conducted to prioritize highway elements requiring engineering interventions or retrofit measures.

Criticality Assessment

Criticality assessment would be particularly relevant for the network level vulnerability assessment of National Highways. Critical highway stretches will be identified with respect to the three main broad sets of parameters (U.S. DOT, 2012) in the vulnerable areas mapped in Step 5:

a) Economic importance

b) Operations

c) Health and Safety

Table 8 presents an indicative checklist of these parameters for the Indian scenario. However, these parameters maybe further qualified and refined based on the context. Criticality assessment will help in prioritizing investment decisions for resilience building in regions vulnerable to climate change.

Risk Assessment

A risk assessment of highway elements and infrastructure is recommended at the stretch level to prioritize highway elements requiring engineering interventions or retrofit measures. This step would result in identification of most risk prone highway elements to climate impacts due to high temperature, precipitation, storm surges, etc. This will be based on the sensitivity (the likely extent of impact of the specific climate risks) of the vulnerable stretches identified in Step 5. The existing exposure profile developed in Step 5 can provide an understanding of the kind and extent of climate impacts to which highway elements are sensitive to. For instance, a storm surge threshold could be a surge value (in metres) that causes inundation of 10 per cent of the highway stretch thereby causing loss and damage to pavements or highway elements such as drains, lighting, etc. Based on this, a risk assessment matrix can be developed that classifies risks into three categories (low, moderate, high). This classification may be done based on the following considerations (U.S. DOT, 2012, Table 9):

- **Low risk**—Highway elements and infrastructure that have a low likelihood of being impacted by a future climate condition with a low consequence of the impact may be classified as 'low risk'.
- **Moderate risk**—Highway elements and infrastructure that have a low likelihood of being impacted by a future climate condition with a high consequence of the impact may be classified as 'moderate risk'

OR

- Highway elements and infrastructure that have a high likelihood of being impacted by a future climate condition with a low consequence of the impact may be classified as 'moderate risk'.
- High risk - Highway elements and infrastructure that have a high likelihood of being impacted by a future climate condition with a high consequence of the impact may be classified as 'high risk'.

Table 8: Indicative checklist of criticality assessment parameters

Parameters
Economic Importance
Intermodal connectivity –provides access to airport, port or rail
Connects Industries/Power Plants
Serves economic centres- SEZ/ route for a primary economic activity
Connects major settlements, for instance, million plus cities, state capitals, popular tourist cities, pilgrimage cities etc
Operational Characteristics
Functional classification [6]
Usage- Annual Average daily traffic
Health and Safety
Provides access to regional health facilities such as Super Speciality Hospitals, Regional Speciality Health Centres/ Medical Colleges, etc.
Part of Disaster relief and recovery plan, for instance, Identified Evacuation route or key connection during emergency situations
Component of the National Defence System, for instance, National Highways connecting border roads and critical national defence areas

Table 9: Risk assessment assumptions for highway elements and infrastructure

Risk		Consequence	
		Low	High
Likelihood	Low	Low	Moderate
	High	Moderate	High

The risk assessment matrix will help in identifying appropriate resilient building strategies required towards step 8 and prioritize them accordingly.

Step 7: Identifying interventions for resilience building

This step would involve identification of the most relevant measures/solutions for resilience building of highway stretches. These would include engineering interventions (such as 'resilient' new assets, retrofitting existing assets, more intensive maintenance schedules, improved operations plans, etc.) at the stretch level and non-engineering interventions (viz. policy, institutions, capacity building, etc.) at the network level.

Moreover, it is desirable that the proposed interventions should be classified into short and long-term in the context of the identified highway stretches based on their feasibility, efficacy, ability to withstand a range of climate hazards, and co-benefits.

This methodology for VA as discussed above may be used as a step-by-step guide for understanding climate change risks and identifying adaptation options for the roads sector, both at the network and stretch level in India. However, as observed earlier, it may be contextualized to suit the specific requirements based on the objectives and expected outcomes, and topographical/ hydro-meteorological regions and settings.

As part of this study, the proposed methodology will be demonstrated at the country level on the entire National Highway network and for two NH stretches in the local context—hilly (Shimla–Moorang on NH 5 in Himachal Pradesh) and coastal (Kathipudi–Ongole on NH 216 in Andhra Pradesh). The next chapter gives a detailed discussion on the approach and outcomes of the VA exercise conducted.

[6] For the purpose of this study since the scope is limited to National Highways this parameter will not be applicable. However, when being used for other roads, stretches with greater functional importance such as National highways or State Highways will have a higher functional importance as compared to other roads (MDRs, PWD roads, urban roads, etc)

4 Applying the Proposed Methodology for Vulnerability Assessment of Highways

4

Applying the Proposed Methodology for Vulnerability Assessment of Highways

This chapter gives a detailed discussion of the approaches and outcomes of the demonstrative vulnerability assessment (VA) exercise conducted both at the network and stretch level. In the network context, the methodology has been applied for the country-level NH network and in the local context it has been demonstrated over two NH stretches- hilly (Shimla–Moorang on NH 5 in Himachal Pradesh) and coastal (Kathipudi–Ongole on NH 216 in Andhra Pradesh). Section 5.1 focusses on the country-level assessment; section 5.2 and 5.3 discuss the outcome of VA of the hilly stretch – Shimla-Moorang on NH 5 in Himachal Pradesh and the coastal stretch of Kathipudi–Ongole on NH 216 in Andhra Pradesh, respectively.

4.1 Vulnerability Assessment of National Highways at the Country Level in India

Step 1: Defining Objectives

Based on the overall scope of the study, the objective and outcomes of the VA include:

- Identifying NH stretches that are at risk to climate change impacts at the country level.
- Recommending non-engineering interventions for building climate resilience of the NH network.

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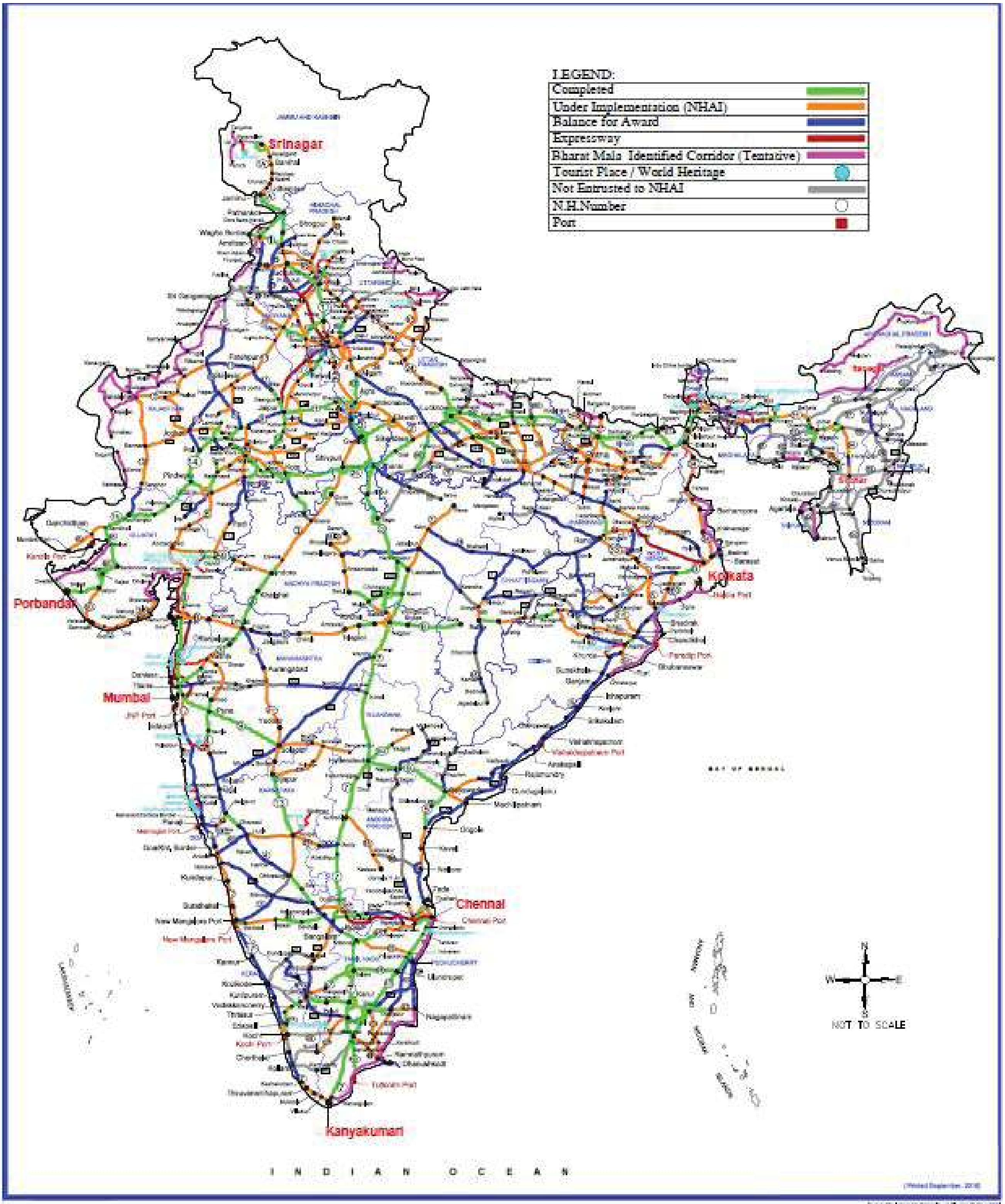
Step 2: Scoping

A scoping exercise has been conducted at this step to define the geographical boundaries as well as the study parameters, data sources, and tools and techniques of assessment for the purpose of this study.

- **Delineation of geographical limit**—Since the exercise is being conducted at the country level the geographical scope aligns with national boundaries and includes all the NHs in the country (Map 1).
- **Identification of key issues and parameters (climatic and non-climatic)**—Existing literature suggests that the key parameters relevant for understanding climate change impacts in the Indian context include temperature, precipitation, and pattern of extreme events (MoEF, 2010). In terms of the non-climate parameters, slope instability is one of the key stresses on highways and roads. This has been understood in terms of topography (elevation) and seismic activity as it decreases stability by tectonic movements and decomposition of the geologic materials (CPWD Engineers Association, 2012). Besides, built parameters, including settlements and infrastructure, will play a key role in deciding the vulnerability and extent of risk of the highways.
- **Identification of sources of data and local knowledge**—Identification of sources of secondary data and expert stakeholders was done at this stage. These include MoRTH and NHAI who will also be the primary users of the outcomes of this study. Other relevant data sources at the national level include Indian



Map 1: Geographical delineation - National Highways at the country level in India

Source: NHAI

Meteorological Department (IMD) and National Disaster Management Authority (NDMA). For future climate information, data has been derived from the existing literature on future climate scenarios from India. This includes scientific papers and 4X4 Assessment Report of the Indian Network for Climate Change Assessment (MoEF, 2010). Apart from this, certain open data sources, such as BHUVAN hosted by ISRO/ NRSC, and Aster Global Digital Elevation Model which is freely available through UGCS[7] have been used for sourcing physiological information. A detailed discussion on data collection and sources is presented in Step 3.

- **Identification of Analytical Tools and Techniques for Vulnerability Assessment**—The overall spatial vulnerability mapping exercise has been conducted using an Arc GIS platform. The input layers to the mapping exercise have been developed based on secondary information received from various agencies and open data sources as mentioned in the preceding paragraph. Detailed technical methodology and considerations for each step of mapping and assessments have been discussed through Steps 4–6.

Step 3: Collection and Integration of Data

One of the key steps to conduct the VA is to identify the kind of data that needs to be collected. The data collection was primarily aligned towards developing an exposure profile of the entire NH network to various climate and non-climate parameters identified in Step 2. For this purpose, the NH network map was obtained from the NHAI. In order to develop the exposure profile for the NH network, and identify vulnerable highways stretches in different regions and critical highways that need to be prioritized for building climate resilience, the following datasets were available and have been collated:

- Climate parameters:
  - Projected changes in mean and extreme precipitation over very wet days sourced from a study titled 'Projected Changes in Mean and Extreme Precipitation Indices over India' (Rao *et al.* 2013). The findings of this paper have also been found to be consistent with other relevant literature, such as Krishna Kumar *et al.* (2011) and the 4X4 Assessment Report (MoEF, 2010) .
  - Hydro-meteorological extreme events—Wind and Cyclone Hazard map sourced from the National Disaster Management Authority.
- Non-climate parameters:
  - Seismic Zonation sourced from the National Disaster Management Authority
  - Physiographic map of India sourced from Survey of India
  - Settlement Pattern—Cities with population more than one million have been mapped, based on the data obtained from Census 2011
  - Key infrastructure—Locations of ports and airports have been mapped based on the information taken from Google Earth[8]
  - Operations—The Indian Highways Management Company Limited has been approached for collecting the data related to traffic on the entire highway network. However, the data is awaited

Step 4: Developing Climate Scenarios

For understanding and spatial mapping of future climate scenarios for the country, existing literature, such as scientific papers and study reports, have been referred. These include the 4X4 Assessment Report of the Indian Network for Climate Change Assessment (MOEF, 2010), and other pioneering research such as (Rao *et al.* 2013) and (Krishna Kumar *et al.* 2011). These literatures indicate projected climate change information for the Indian subcontinent, based on an ensemble mean approach obtained from PRECIS driven by IPCC A1B (business-as-usual) scenario for mid and end 21st century.

PRECIS simulations indicate an all-round warming over the Indian subcontinent associated with increasing GHG concentrations with a high likelihood of daily maximum and daily minimum temperatures intensifying over the century. The region shows a small increase in annual precipitation with respect to the

[7] United States Geological Survey

[8] Google Earth displays satellite images of varying resolution of the Earth's surface, allowing users to see cities, houses, infrastructure, etc.

baseline, that is 1970s. Although the frequency of rainy days may decrease, the intensity of rainfall on a rainy day may increase in the future. Moreover, as per IPCC (2013) and MoEF (2010), there is a high likelihood of increase in extreme hydro-meteorological events, such as cyclones, and their intensity on the eastern coast of India in the future.

For the purpose of this exercise, it is imperative to understand exposure of NHs to the future climate scenarios as discussed earlier. To this end, a spatial assessment of changes in rainfall (Map 2) and hydro-meteorological extreme events, that is, cyclone and wind hazard (Map 3) has been conducted. Additional climate information/parameters, including past trends of temperature and precipitation, may further be considered to refine the results of this climate VA.

Map 2 shows the projected changes in mean and extreme precipitation indices over India using PRECIS (Rao *et al.*, 2013). It depicts the ensemble mean of percentage change in rainfall over very wet days[9] of monsoon season for the future scenario (2071–2098) with respect to baseline simulations for 1960–1990.[10] Thus, towards the end of the century, rainfall on very wet days may increase substantially over the majority of the Indian landmass. This result is consistent with the findings of Krishna Kumar *et al.* (2011) that the intensity of rainfall on a rainy day may increase in the future.

Map 3 is derived from cyclone and wind hazard profile mapping of the National Disaster Management Authority (NDMA).[11] It depicts 5 categories of risk zones which are vulnerable to combined effect of cyclone and wind hazards in India. Coastal areas, especially those located on the eastern coast, show high vulnerability as a result of cyclonic and super cyclonic events combined with high wind speeds. Vulnerability of NHs in these regions is likely to aggravate in the future in light of the findings of IPCC, 2013 and MoEF (2010) which indicates an increase in the frequency and intensity of cyclonic events on the eastern coast of India.

[9] As per Rao (2013), extreme précis, 95th percentile of precipitation on wet days (R95p) is defined as the total rainfall on very wet days. Hence very wet days are the days on which the rainfall exceeds the 95th percentile.

[10] (Rao et al. 2013).

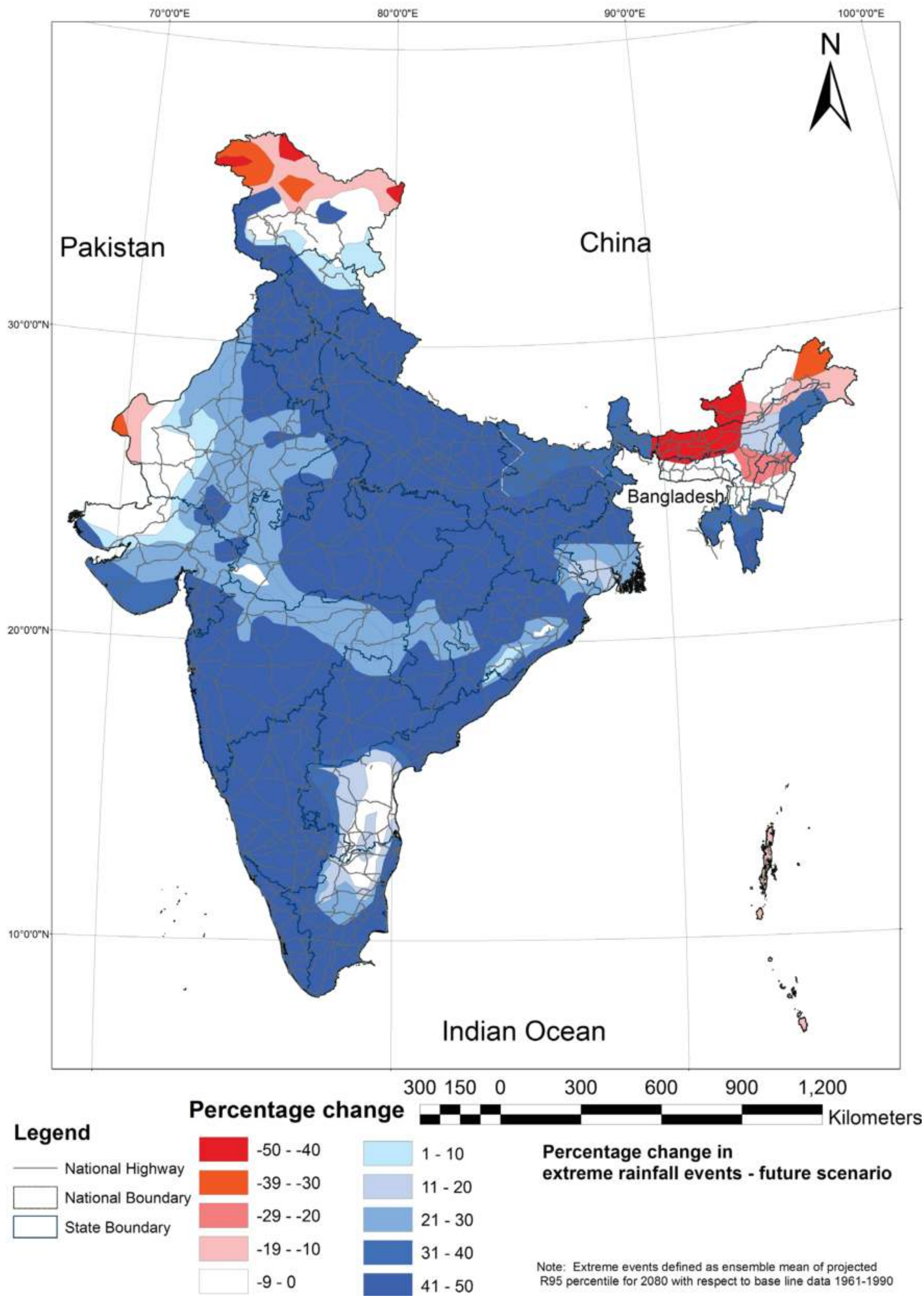
[11] Map derived from (NDMA,GoI, 2016)

Step 5: Identification of Vulnerable Hotspots

A VA mapping of the NH network in the country has been conducted based on climate and non-climate stresses/ parameters identified in Step 2, which provides an overview of the vulnerability criteria considered for these parameters.

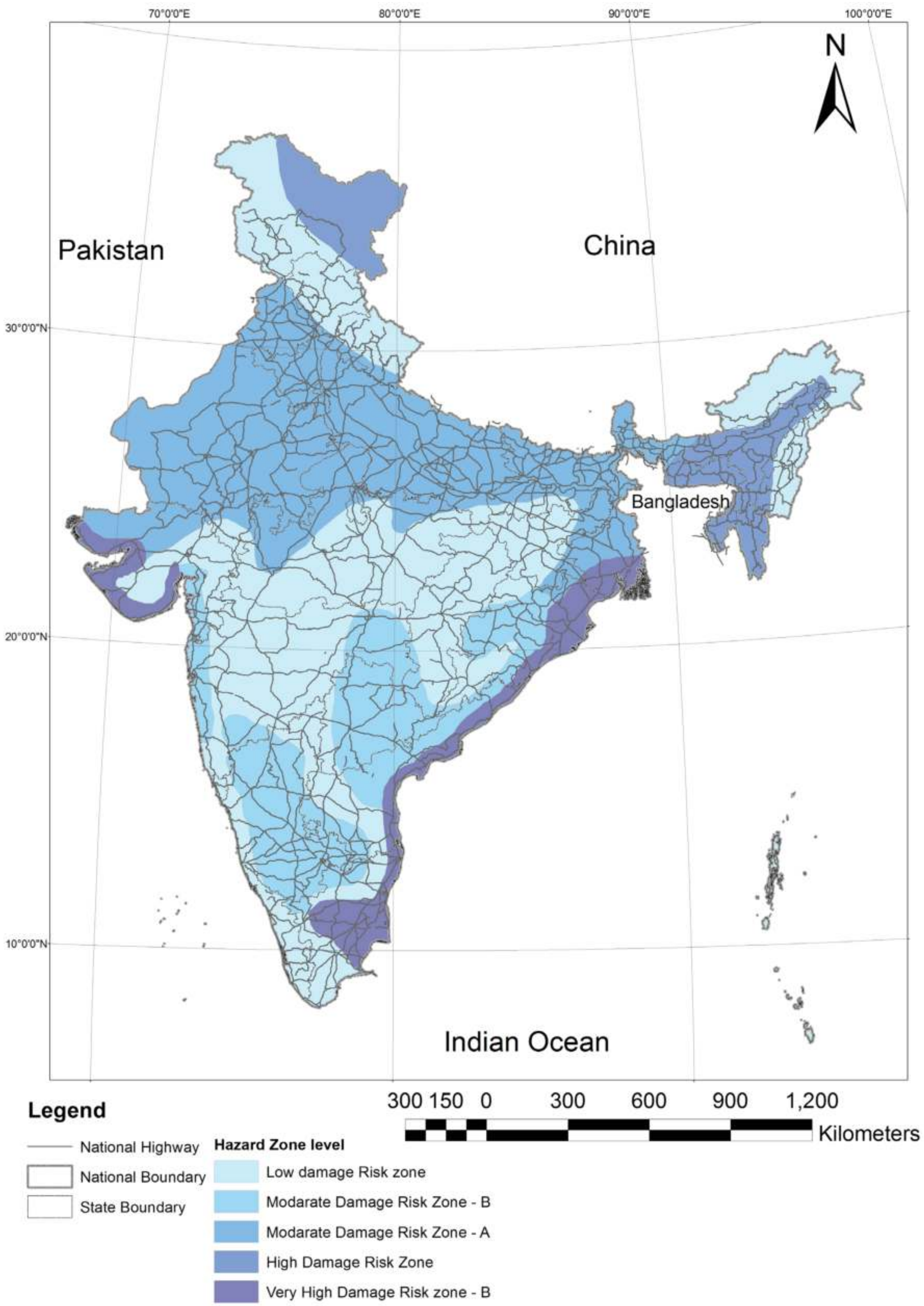
To begin with, an exposure profile for NHs network in India has been created by mapping the climate and non-climate stressors/parameters as enumerated in Table 10. A detailed discussion on the outcomes and an exposure analysis of NHs with respect to earthquakes, wind and cyclones and future rainfall anomalies is given below.

- Exposure of NHs to earthquake hazard: The exposure profile (Map 4) has been created by superimposing the earthquake zonation sourced from earthquake hazard maps of NDMA over the NH network in Arc GIS. Based on frequency and intensity of seismic activities in the past, the country is divided into 4 seismic zones wherein very high seismic activity is found in very high damage risk zone - V and viz. high, moderate, and low seismic activity is found in high damage risk zone – IV, Moderate damage risk zone – III, and Low damage risk zone – II, respectively.
- Exposure of NHs to cyclone and wind hazard: The exposure profile (Map 3) has been created by superimposing the cyclone and wind hazard profile mapping sourced from NDMA over the NH network in Arc GIS. It depicts 5 categories of risk zones which are vulnerable to combined effect of cyclone and wind hazard in India. Based on the frequency and intensity of cyclonic events and wind speeds, the country has been spatially classified into 5 categories—Very high damage risk zone –B, High damage risk zone, Moderate damage risk zone –A, Moderate damage risk zone –B, and Low damage risk zone.
- Exposure of NHs to change in rainfall over very wet days in future: The exposure profile (Map 2) has been created by superimposing the projected ensemble mean of percentage change in rainfall over very wet days in future (2071–2098) over the NH network in Arc GIS. In the future scenario, the rainfall map shows there may be increase in amount of rainfall received on very wet days over major parts of India.



Map 2: Percentage change in extreme rainfall events -future scenario

Source: TERI, 2014



Map 3: Cyclone and wind hazard map of India

Source: (NDMA,GoI, 2016)

Table 10 Parameters for country level vulnerability assessment of NH

			Vulnerability Ranking			
Sl.No	**Parameters**	**Criteria**	**Classification**	**Score**	**Classification**	**Score**
Non-climate stressors/ parameters						
1	Earthquake hazard	Seismic Zonation based on frequency and intensity	Low damage risk zone - II	1	High damage risk zone - IV	2
			Moderate damage risk zone -III		Very high damage risk zone - V	
Climate stresses/ parameters						
2	Wind and Cyclone hazard	Wind speeds; frequency and intensity of cyclones	Low damage risk zone	1	High damage risk zone	2
			Moderate damage risk zone -B		Very high damage risk zone -B	
			Moderate damage risk zone -A		Very high damage risk zone - A	
3	Change in rainfall over very wet days in future	Percentage change	-50 to -40	1	0 to 10	2
			-40 to -30		10 to 20	
			-30 to -20		20 to 30	
			-20 to -10		30 to 40	
			-10 to 0		40 to 50	

As an outcome of this step, the three exposure profiles were overlaid to understand the overall vulnerability of NHs (Map 5). The final vulnerability map depicts the most vulnerable NH stretches based on scoring. The vulnerability scoring has been derived based on the following pointers:

- Equal weightage have been accorded to all the vulnerability parameters (Table 10).
- A score of 1 and 2 has been assigned to the vulnerability rankings of low, moderate, high, and very high risk zones, respectively for each parameter (Table 10).
- The total scores have been classified in the ranges of 2–3, 3–4, 4–5, and 5–6 and have been assigned a ranking of low, moderate, high, and extremely high vulnerability, respectively.

Based on this assessment, it may be observed that the NHs falling in the Himalayan region, north eastern states, eastern coast of India, and the coastline of Gujarat, Maharashtra, and Goa on the west coast are found to be highly vulnerable, that is around 37% of NHs are vulnerable. These vulnerable highways have been enlisted in Table 11.

Step 6: Prioritizing areas for investment and Interventions—Criticality Assessment

Step 5 aided in identification of the vulnerable NHs for the study. However, in order to prioritize for investment and interventions for resilience building, a criticality assessment of the NHs should be carried out, based on the indicative checklist presented in Table 8. It may be noted that criticality parameters to be considered for this exercise are not restricted to these enlisted parameters and may be further refined and expanded based on the context and objective of assessment.

Step 7: Identifying interventions for resilience building

Being a network-level assessment, the interventions for building resilience of NHs sector in India are primarily non-engineering in nature. Building resilient roads and highways is a multi-step process

Table 11: Vulnerable National Highway stretches		
Highway region	**New National Highways**	**Stretch**
Eastern Coast	NH 85	Tiruvadanai and terminating at Tondi Port town - Muthupatti
	NH 532	Salem road
	NH 48	Chennai–Santhvellae
	NH 18	Bharagora–Baripada–Betonti–Baleshwar
	NH 16	Kharagpur–Kolkata
	NH 132	Villupuram–Tindivanam
	NH 16	Baleshwar–Bhubaneshwar–Vishakhapatnam–Vijaywada–Nellore–Chennai
	NH 49	Baharagora–Kharagpur
	NH 65	Machilipatnam–Vuyyuru
	NH 116	Junction with old National Highway No. 6 near Kolaghat-Haldia Port
	NH 38	Tiruchirapalli–Villupuram(NH38)
	NH 332	Villupuram–Pondicherry
	NH 38	Trichy–Melur
	NH 36	Junction with old NH 132 near Vikravandi–Panruti–Vadulur–Neyveli–Township-Sethiathop–Kumbakonam–Thanjavur
	NH 87	Dhanushkodi–Manamadurai
	NH 16	Baleshwar–Nikursini
	NH 77	Pondy–Tindivanam–Gingee–Thiruvanamalai-Krishinagir
	NH 81	Tiruchchirappalli–Mayanur
	NH 316	Bhubaneshwar–Puri–Konark
	NH 316	Junction with old NH 203 at Puri, connecting Bramhagiri and terminating at Satpada
	NH 716	Chennai–Thiruvallur
	NH 336	Trichy–Pudukottai
	NH 216	Kathipudi–Kakinada–Pamarru
	NH 216	Junction of old NH 214 near Digamarru connecting Narasapur–Machilipatnam–Challapalle–Avanigadda–Repalle Bapatla–Chirala and terminating at its junction with NH 5 near Ongole
	NH 57	Junction with old NH 5 near Khorada and connecting Nayagarh
	NH 36	Thanjavur–Pudukottai–Sivaganga–Manamadurai
	NH 136	The highways starting from Perambalur connecting Perali, Keelapalur, Ariyalur, Kunnam, Thiruvaiyaru, Kandiyur and joining with old NH 226 at Thanjavur
	NH 81	Thiruchirapalli–Lalgudi–Chidambaram road
	NH 32	Tindivanam–Chennai
	NH 32	Pondicherry–Chidambaram–Nagapattinam
	NH 536	Pudukottai–Devakottai
	NH 26	Natavalasa –Ramabhadrapuram
	NH 83	Manapparai–Tiruchirapalli
Western Coast	NH 48	Pune–Kagal highway junction
	NH 53	Haridaspur–Paradip Port
	NH 44	Commorin (Kanyakumari)–Levinjupuram

Table 11: Vulnerable National Highway stretches

Highway region	New National Highways	Stretch
	NH 66	Hedge–Honnavar and Ankola–Betkuli and Manoor– Katapady and Karivelha–Thalipavambn and Kozikode–Vellimukku and Gurvayoor–Talikulam and North Pavvor–Junction with old NH 47 near Edapally
	NH 566	Ponda–Verna
	NH 66	Junction with old NH 17 and NH 47–Allepy
	NH 220	Kottayam to Chagnassery
	NH 66	Junction with old NH 7 near Cortalim–Murmugao
Hilly	NH 44	Madhopur–Jammu–Banihal
	NH 244	Batote–Doda–Kistwar–Symthan pass –Khanabal
	NH 144	Domel–Katra
	NH 1	Srinagar–Kargil–Leh
	NH 10	Sivok–Gangtok
	NH 17	North Salmara–Junction with old NH 37 near Jogighopa
	NH 27	Nowgong–Daboka
	NH 17	Goalpara–Guwahati
	NH 127	Guwahati–Kaliabor
	NH 715	Kaliabor–Jorhat
	NH 715	Kuarital–Junction with old NH 52 near Tezpur
	NH 315	Mukum–Ledo–Lekhapani
	NH 129	Numaligarh–Dimapur
	NH 6	Nongstoin and connecting Shillong–Passi Badarpur
	NH 108	Aizawl–Manu
	NH 217	Paikan–Mundal
	NH 15	Baihata–Charali–Tezpur-Bander Dewa–North Lakhimpur–Kulajan
	NH 515	Kulajan–Pasighat
	NH 415	Banderdeva–Itanagar–Gohpur
	NH 15	Kulajan–Dibrugarh
	NH 27	Dabaka–Lumding
	NH 302	Theriat–Lunglie
	NH 7	Haridwar–Badrinath–Mana
	NH 2	Kohima–Wokha–Mukokchung–Jhanji
	NH 217	Rongjwng–Dudhnai
	NH 102B	Churachandpur–Singhat–Singhat–Sinzawl–Tuivai Road–upto Mayanmar Road
	NH 127B	Srimrampur–Dhuburi–Phulbari–Tura–Rongram–Ronjeng–Nongston
	NH 2	Aizawl–Churachandpur
	NH 127A	Patacharkuchi–Bhutan border
	NH 315	Ledo–Lekhapani–Indo / Myanmar–Border
	NH 202	Junction of old NH 61 near Mokokchung and connecting Tuensang–Sampurre–Meluri
	NH 315A	Tinsukia on old NH15 – Naharkatia – Hukanjuri – Khonsa
	NH 154	Pathankot – Mandi

Table 11: Vulnerable National Highway stretches

Highway region	New National Highways	Stretch
	NH 303	The highways starting from Nagrota at the junction of NH 20 connecting Ranital
	NH 105	Pinjore–Nalagarh–Swarghat
	NH 5	Kalka–Shimla–Narkanda–Rampur–Indo-China Border near Shipkila
	NH 3	Dharampur –Mandi
	NH 707	The highways starting from Paonta at the junction of old NH 72 connecting Rajban, Shillai and passing through Minus, Tuini in Uttarakhand and terminating at Hatkoti in Himachal Pradesh
	NH 34/NH 934	Kanpur–Chhatarpur–Hirapur
	NH 934	Hirapur–Sagar
	NH 34	Rishikesh–Ampata –Tehri–Dharasu
	NH 34	Dharasu–Uttarkashi–Gangotri Dham
	NH 507	Junction with old NH 72 connecting Vikasnagar- Kalsi-Barkot and terminating at junction with old NH 94 near Barkot bend
	NH 8	Dhaleshwar–Uptakhali
	NH 1	Baramula–Uri
	NH 29	Daboka–Dimapur
	NH 715	Jorhat–Jhanji
	NH 2	Jhanji–Dibrughar
	NH 15	Dibrughar–Makum–Wakro
	NH 29	Dimapur–Kohima
	NH 8	Passi Badarpur–Agartala–Sabroom
	NH 13	Pasighat-Tezu-Sitapani Junction with old NH 37 near Saikhoaghat
	NH 2	Kawanpuri–Aizawl–Tuipang
	NH 503	Ranital, Dehra and terminating at Mubarikpur at the junction of NH 70
	NH 146	Sagar-Bhopal
	NH 134	Dharasu–Kuthnaur –Yamnotri
	NH 2	Junction with old NH 306A Kanpui
	NH 10	Junction with new NH 27 near Siliguri Junction with new NH 17 –Chalsa
	NH 17	Chalsa–Nagarkata–Goyerkata–Dalgaon–Birpara
	NH 317	Birpara–Hasimara–Salsabari junction with New NH 27
	NH 13	Wakro–Roing
Plains	NH 44	Delhi–Ambala–Jalandhar
	NH 44	Delhi–Mathura–Agra
	NH 519	Sikandra–Bhognipur
	NH 31	Bhaktiarpur–Mokameh–Kora
	NH 27	The highway starting from old NH 31 near Siliguri and joining NH 31C near Salsalabari via Fulbari, Mainaguri, Dhupguri, Falakata and Sonapur
	NH 12	Junction with old NH 31 near Dalkola- Farakka and Kolkata–Chakdana

Table 11: Vulnerable National Highway stretches

Highway region	New National Highways	Stretch
	NH 112	Barasat–Bangaon–Indo–Bangladesh Border
	NH 27	Muzaffarpur–Darbhanga–Forbesganj–Purnia
	NH 527	Junction of old NH 57 near Forbesganj and terminating at Jogbani
	NH 9	Delhi–Ghaziabad
	NH 34	Ghaziabad–Meerut
	NH 14	Kharagpur–Bishnupur
	NH 22	Hajipur–Sitamarhi–Sonbarsa
	NH 33	Mokamah–Rajmahal–Farakka
	NH 31	Kora–Katihar–Malda
	NH 120	Gaya–Biharsharif
	NH 22	Patna–Jehanabad
	NH 531	Chhapra–Siwan–Gopalganj
	NH 722	Chhapra–Rewaghat–Muzaffarpur
	NH 322	Hajipur–Mushrigharari
	NH 227	Chakia–Sitamarhi–Jaynagar–Narharia
	NH 131	Birpur–Madhepura–Bihpur
	NH 116B	Nandakumar–Contai–Digha
	NH 12	Junction with old NH 6 connecting Kona Expressway–Vidyasagar Setu–Kolkata–Diamond Harbour–Kulpi–Namkhana and terminating at Bokkhali
	NH 730	Pilibhit on old NH 74–Puranpur–Kutar–Gola Gokharnath–Lakhimpur–Isanagar –Nanpara (on NH 28C) Bahraich on NH 28C Balrampur –Maharajgang–Pandaruna on NH 28
	NH 730A	Puanpur–Pawayan–Maikalganj (NH 24)
	NH 48	Delhi–Bawal
	NH 10	Delhi–Bahadurgarh
	NH 54	Pathankot–Amritsar– junction with SH 15
	NH 31	Patna–Chappra
	NH 152	Ambala–Panchkula
	NH 9	Delhi–Rampur
	NH 122	Junction with old NH 31 near Barauni Muzaffarpur
	NH 527D	Junction with old NH 28 near Pipra Kothi–SagauliRaxaul-Indo/Nepal Border
	NH 727	Junction with old NH 28 A from Chhapwa connecting Bettiah, Lauriya, Bagaha, Chhitauni Rail cum road bridge and terminating at its junction with old NH 28 near Kushinagar
	NH 24	Barhalganj–Gorakhpur–Pharenda and terminating at Sunali
	NH 319	Junction with NH 2 near Mohania–Arrah
	NH 431	Phatuha–Chandi–Harnaut–Barh
	NH 7	Chandigarh–Rajpura–Patiala
	NH 152	Ambala–Ismailabad
	NH 3	Jalandar–Hoshiarpur–Hamirpur
	NH 703	Jalandar–Moga

Table 11: Vulnerable National Highway stretches

Highway region	New National Highways	Stretch
	NH 919	The highway starting from the junction of old NH 71 near Rewari in the state of Haryana and connecting Dharuhera and passing through Rajasthan and connecting Taoru -Sohna and terminating at its junction with old NH 2 near Palwa
	NH 7	Ambala - Punjab border-Nahan-Paonta Sahib-Dehradun
	NH 307	Chhutmalpur-Biharigarh-Dehradun
	NH 344	Roorkee-Saharanpur-Yamuna Nagar-Saha-Dhanana
	NH 907	The highway starting from the junction of old NH 73 near Yamuna Nagar in the state of Haryana and connecting Jagadhri – Mustafabad – Ledi – Darpur and terminating at its junction with old NH 72 near Paontasahib in the State of Himachal Pradesh
	NH 30	Bareilly–Pilibhit–Sitarganj
	NH 9	Sitarganj–Kichcha–Rudrapur
	NH 34	Ghaziabad–Aligarh–Eta
	NH 509	Agra–Aligarh–Babrala–Chandausi–Moradabad
	NH 5	Kharar (Chandigarh)–Ludhiana–Jagaron–Ferozepur
	NH 331	Chhapra–Baniapur–Mohamadpur
	NH 34	Junction with old NH 58 near Meerut and connecting Bijnor–Najibabad
	NH 9	Junction with old NH 74 near Sitarganj and connecting Khatima–Tanakpur and terminating at Pithoragarh
	NH 28	The highway starting from India/Nepal border (connecting to Lumbani) via Naugarh, Sidarthnagar, Bansi, Basti,
	NH 334	The highway starting from Meerut connecting Hapur, Gulawthi and terminating at Bulandshahr
	NH 3	Jalandhar–Amritsar–Indo-Pak Border
	NH 231	Kora–Purnia
	NH 334	Meerut–Haridwar
	NH 33	Biharsarif–Mokama
	NH 5	Panchkula–Kalka
	NH 530	Rampur–Bareilly–Lucknow
	NH 27	Muzaffarpur–Pipra Kothi–Gorakhpur–Lucknow
	NH 922	Arrah–Bihta–Patna
	NH 7	Dhanana–Panchkula
	NH 309	Rudrapur–Kashipur
	NH 734	Kashipur–Najibabad
	NH 34	Najibabad–Haridwar
	NH 534	Najibabad–Kotdwara–Bubakhal
	NH 309	Bubakhal–Pauri and terminating at its junction with old NH 58 near Srinagar
	NH 231	Kora–Purnia
	NH 27	Purnia–Dalkola–Siliguri–amingaon
	NH 20	Nawada–Bhaktiarpur

Table 11: Vulnerable National Highway stretches

Highway region	New National Highways	Stretch
Plateau	NH 55	Angul Junction with old NH 5 near Cuttack
	NH 83	Dindigul
	NH 81	Karur–Coimbatore
	NH 79	Salem–Vadachennaimalai
	NH 149	Talcher–Pal Lahar
	NH 83	Oddanchatram–Dindigul
	NH 20	Panikoli–Keonjhar
	NH 532	Cuddalore–Vridhachalam–Vadechennaimalai
	NH 49	Pal Lahar–Chandikhol

that requires interventions and inter-departmental coordination, both at national and sub-national levels and during all the phases of a road project—planning, construction, and operations. As stated in Chapter 2 'Impact of Climate Change on Highways', although climate parameters, such as rainfall intensity, have been acknowledged and addressed in specific IRC Codes, they are out dated and do not include new state-of-the-art technology options that are globally available. Moreover, in the absence of a specific, comprehensive policy on climate resilience of the roads and highways sector, there are no mandates and implementation mechanisms to ensure the integration of climate resilience in the roads sector. Mainstreaming climate resilience in the roads and highways sector will need a multi-pronged approach through the following measures.

- Mainstreaming in the planning and approval processes.
- Formulation of construction and maintenance guidelines for building climate resilience of highways.
- Updating and enforcement of the existing IRC Codes.
- Inter-departmental coordination at the national and sub-national levels, including various committees of IRC, for information sharing and policy making.
- Data management—Collection and integration of data for resilience building of the highways sector was found to be a challenging process during the course of this study. Therefore, it is recommended that specific data for the purpose may be recorded and updated regularly.
- Research and capacity development.

A detailed discussion on these non-engineering measures is provided in Chapter 5 'Recommendations for Building Resilience of the Highways Sector in India'.

4.2 Vulnerability assessment for Shimla–Moorang stretch on NH 5

Step 1: Defining objectives

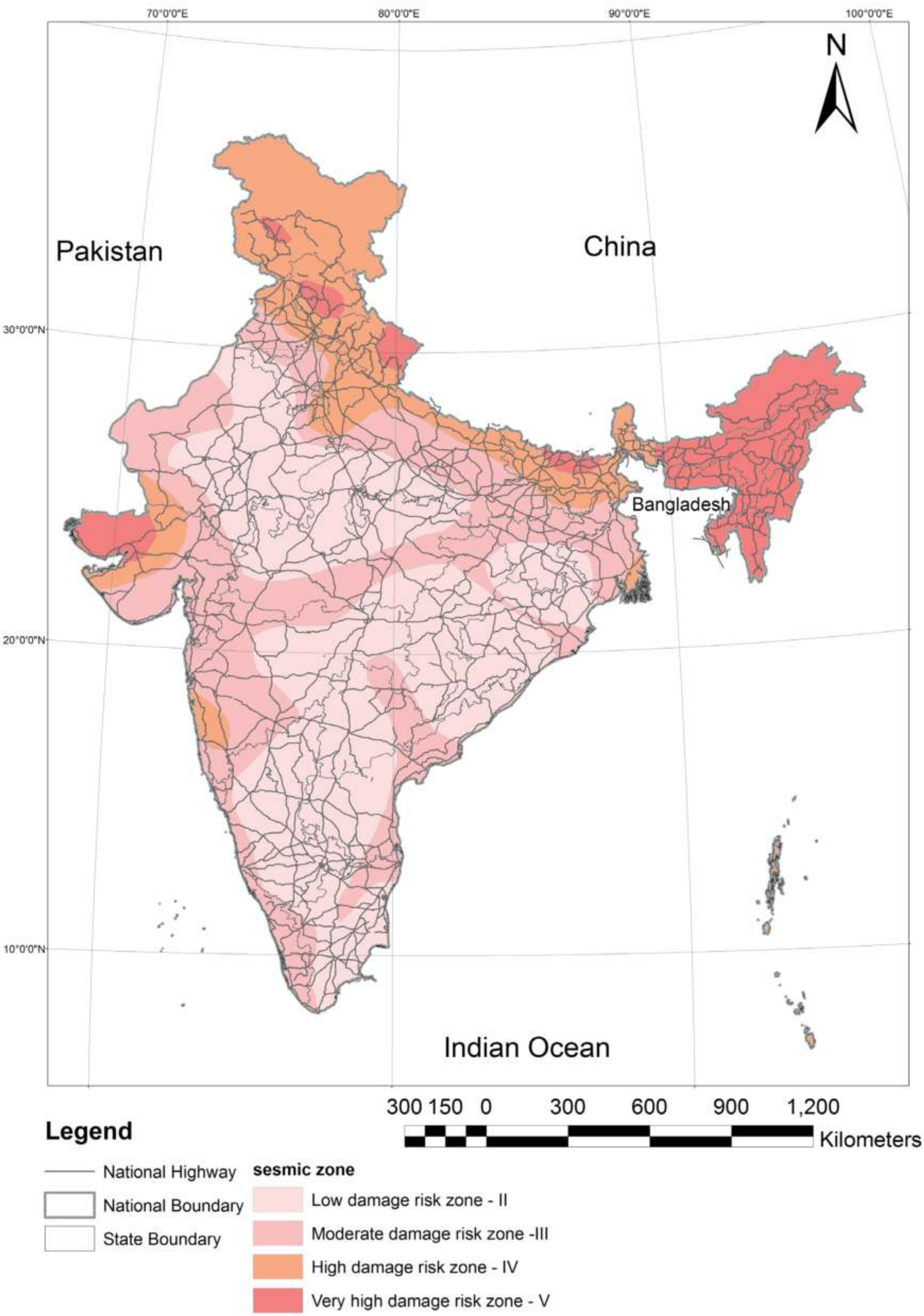
Based on the overall scope of the study, the objective and outcomes of the VA include the following:

- Identifying sections or highway elements and infrastructure at risk to climate change impacts on the highway stretch
- Identifying effective engineering interventions for adaptation to address the climate vulnerability of the highway stretch

Step 2: Scoping

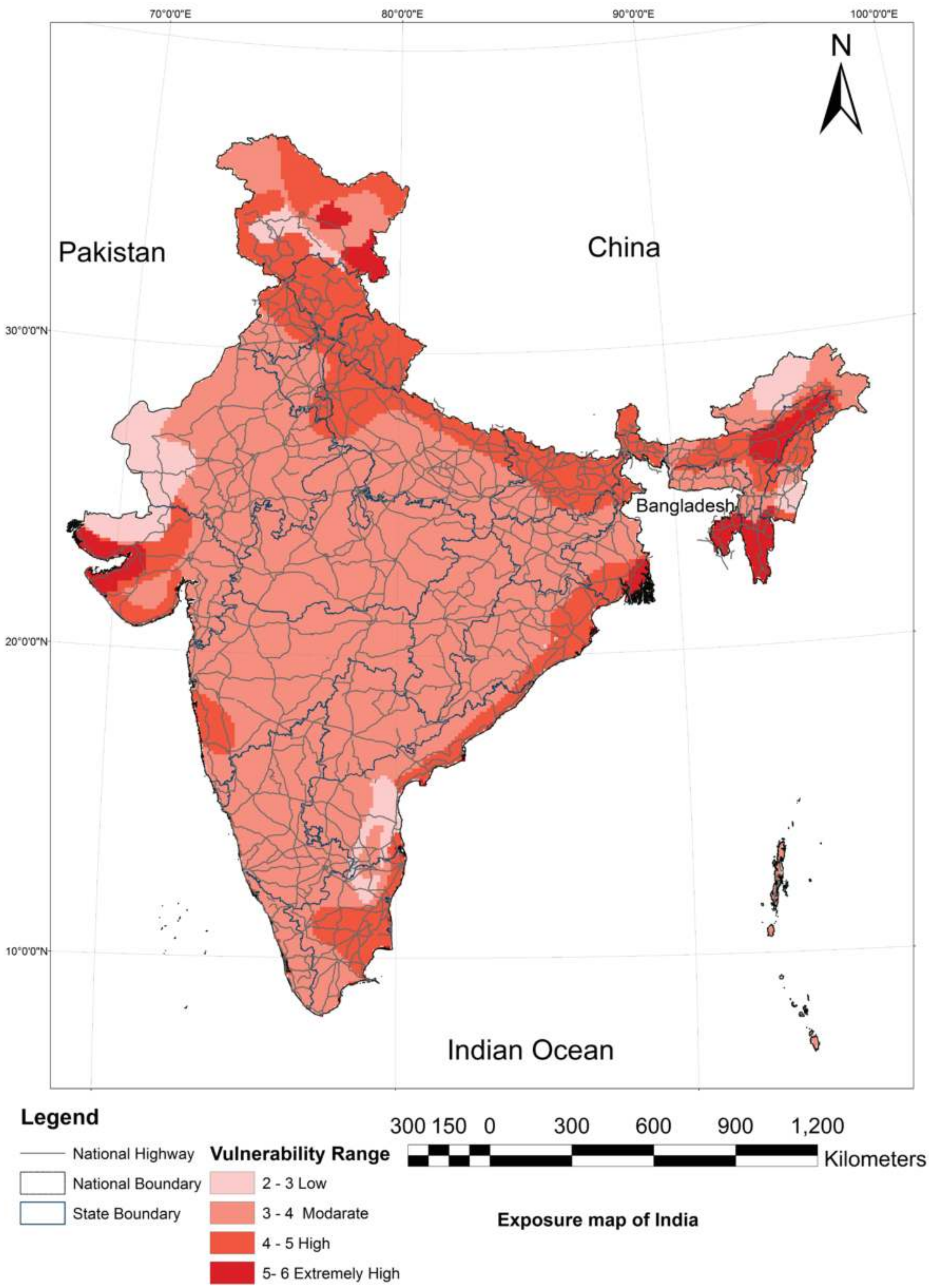
A scoping exercise has been conducted at this step to define the geographical boundaries as well as the study parameters, data sources, and tools and techniques of assessment for the purpose of this study.

- **Delineation of geographical limit**—The geographical delineation of the study stretch has been conducted based on inputs from NHAI, HP PWD, HP Disaster Management Department,



Map 4: Earthquake hazard map of India

Source: (NDMA,GoI, 2016)



Map 5: Vulnerability mapping for National Highways

Source: TERI Analysis, 2016

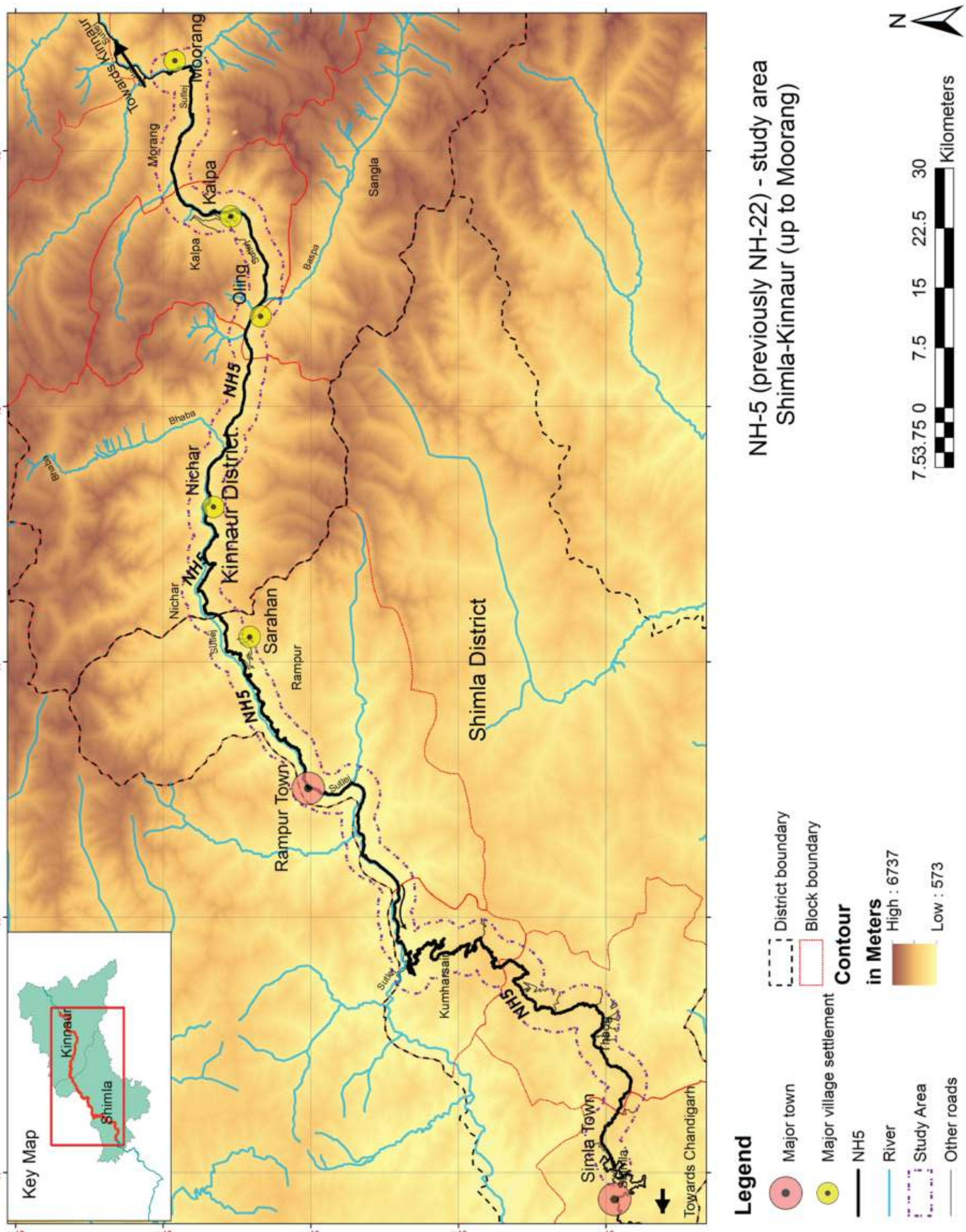
and sector experts and practitioners. Based on interactions with relevant stakeholders, a stretch of 253 km (from Shimla to Moorang in Kinnaur district) has experienced maximum loss and damage from extreme hydro-meteorological events in the past and is, therefore, selected as the case study stretch in light of its vulnerability (Map 6). An area, approximately within 2 km distance on both sides of the highway ROW has been delineated. A key consideration has been to include the important social and physical infrastructure (viz. large-scale industries, hydropower projects, schools and health facilities) and settlements abutting the highway for which it plays a critical role in connectivity. These settlements include Shimla, Theog, Rampur, Kumharsain in Shimla district, and Nichar, Kalpa, Oling and Morag in Kinnaur district. Moreover, from the point of view of hazard risk, the mountain ridge and flood plain of River Sutlej has also been included at the points adjoining the study area boundary.

- **Identification of key issues and parameters (climate and non-climatic) to be considered**—During the stakeholder interactions (refer Annexure 3) it was observed that, this hilly stretch, located in the Himalayan belt, is prone to extreme precipitation events, landslides, and avalanches. The inherent unstable geology coupled with extreme rainfall and snowfall makes it extremely vulnerable to landslides. It would, therefore, be relevant to study the past trend of rainfall variability, incidences of extreme precipitation events viz. rainfall and snowfall, occurrence of thunderstorms, wind speeds, avalanches and flooding events resulting in landslides. To assess the future vulnerability of the highway stretch, assessment of future climate information would also be imperative. In terms of the non-climatic parameters, the physiological and built parameters including topography, settlements, and infrastructure will play a key role in deciding the vulnerability and extent of risk of the highway stretch. A study of past incidents of climate-related disaster events and their impacts would also indicate towards understanding the highway's vulnerability to climate change impacts. At the engineering level, highway characteristics such as materials, nature and condition of highway elements and infrastructure will also play a key role in the level of vulnerability of the highway stretch. Based on this preliminary understanding of parameters to be considered for assessment, data collection and analysis of the same has been conducted in the subsequent steps.
- **Identification of sources of data and local knowledge**—Identification of sources of secondary data and expert stakeholder insights was done at this stage. These include national and state line departments, such as the Indian Meteorological Department, HP state environment and climate change department and disaster management department, and HP PWD, among others. For future climate information, data has been derived from TERI's earlier study on Climate Resilient Green Growth Strategies for Himachal Pradesh (TERI, 2015). Apart from this, certain open data sources, such as Aster Global Digital Elevation Model, freely available through UGCS[12] have been used for sourcing physiological information. A detailed discussion on data collection and sources is presented in Step 3.
- **Identification of analytical tools and techniques for vulnerability assessment**—The overall spatial vulnerability mapping exercise has been conducted using an Arc GIS platform. The input layers to the mapping exercise have been developed based on secondary information received from various government departments and agencies at the national and state levels as mentioned above, open data sources, such as Aster Global Digital Elevation Model, and future climate information derived from IPCC regional data sets referred from TERI's study (TERI, 2015). Detailed technical methodology and considerations for each step of mapping and assessments has been discussed through Steps 4–6.

Step 3: Collection and Integration of Data

A key element of the study was to identify the data required for conducting a typical vulnerability analysis. The data collection was primarily aligned towards developing an exposure profile of the highway to

[12] United States Geological Survey



Map 6: Study area: NH 5 Shimla-Kinnaur (up to Moorang)

Source: TERI Analysis, 2016

extreme events, understanding the impacts and extent of damage of the past extreme events on highways, and determining past and future climate profile over the highway stretch.

Two weather stations—Shimla and Kalpa—and a rain gauge station at Rampur were identified along the selected stretch for the purpose of collecting climate data. Table 12 enumerates the climate parameters that were identified and the data that was received from the Regional Meteorological Centre, Shimla, towards the exercise of VA.

Table 12 : Meteorological Data for study stretch of NH 5

Sl. No.	Climate Variables	Time period	Stations
1	Daily rainfall	1986–2015	Shimla, Rampur, Kalpa
2	Maximum daily temperature	1986–2015	Shimla, Kalpa
3	Minimum daily temperature	1986–2015	Shimla, Kalpa
4	Daily snowfall	2009–2015	Shimla, Kalpa
5	No. of days of occurrence of thunderstorms	1986–2010	Shimla, Kalpa
6	Monthly average wind speed	1986–2007	Shimla, Kalpa

Due to the time constraint in generating primary modelling dataset for this study, the future climate information for the demonstration stretch has been drawn from TERI's study on Climate Resilient Green Growth Strategies for Himachal Pradesh,[13] conducted in collaboration with Global Green Growth Institute, wherein IPCC regional data sets and models were used. The future climate information for the relevant stretch has been extracted from TERI's block-level future climate dataset and has been plotted on the demonstration stretch for the time period 2020–50.

Data related to past extreme events and disasters, such as disruptions and damages on the highways due to landslides, flash floods, and avalanches has been collated along with highway locations experiencing the impacts. This data was sourced from the Himachal State Disaster Management Authority (HSDMA), disaster management plans, and other similar literature.

To understand the terrain of the selected stretch, an Aster Global Digital Elevation Model of 30 metre contour interval, freely available through UGCS,[14] was used for generating the contours. Data received from the revenue department[15] of the State provided information on physical features, such as road network, amenities, government buildings, large-scale industries, hydro power plants, forest cover, along with major settlements.

The NH division of the Public Works Department of the state was approached for collecting the data related to traffic and operation, and material characteristics, inventory of highway elements and infrastructure. However, no data was received.

Step 4: Developing climate scenarios

Past climate profile

As discussed in Chapter 3 'Climate Vulnerability Assessment of Highways', to analyse climate variability over a region, it is important to understand the past and future climate profile of the region. The past climate profile of the highway stretch has been prepared, based on an analysis of the available past climate data received from the three IMD stations on the stretch—Shimla, Rampur, and Kalpa. A study of the past extreme events and disasters indicates that the region is prone to landslides and flash floods. It may be noted here that although landslide events are a result of multiple factors, extreme climate events have been observed to aggravate their occurrence. Hence, past data on rainfall parameters has been analysed in detail in this study (refer to Annexure 2). Although snowfall is also one of the significant precipitation parameters that should be studied for hilly areas, a detailed analysis on the same could not be conducted for the selected stretch due to an insufficient record and maintenance

[13] CRGGS (2015). Climate Resilient Green Growth Strategies for Himachal Pradesh. Implemented by The Energy and Resources Institute in collaboration with the Global Green Growth Institute and nodal support from Department of Environment, Science & Technology, Government of Himachal Pradesh.

[14] United States Geological Survey

[15] Himachal Pradesh government website, URL: http://www.himachal.nic.in/ accessed on August 26, 2016.

of data by RMC. Considering the relevance of snowfall as a climate parameter for hilly regions, it is recommended that the Indian Meteorological Department or the Regional Meteorological Centres regularly maintain this data for holistic understanding of climate variability.

Seasonal rainfall trends—summer (March–May), monsoon (June–September), and winter (December–February) were analysed over the region. It is observed that the annual mean of the total monthly rainfall for the 29 year (1986–2015) period shows a slight increase over the region which may not be significant. The rainfall pattern is also observed to be highly variable ,especially during the recent past 10 years, with more than 85% of the daily maximum rainfall events and thunderstorm days occurring in the monsoon season.

It may be noted here that although Kalpa shows a decreasing overall trend in maximum 24-hour daily rainfall, the individual events occurring over the station have a higher intensity than Shimla and Rampur. For Kalpa, the data shows two Extremely Heavy Rain (EHR) events. The EHR events are not seen over Shimla and Rampur datasets. Also, the summer season shows a relatively larger number of maximum 24-hourly rain events and thunderstorm days in case of Kalpa as compared to Rampur and Shimla. A detailed analysis on the past climate trends over the three stations may be found in Annexure 2. To spatially plot the past climate profile over the highway stretch, the maximum rainfall received in a day has been mapped for the period 1986–2015 (Map 7).

Future climate profile

Once the past climate profiling over the region has been understood well, it is imperative to understand the future climate variability over the region as well. The future climate information for the demonstration stretch has been extracted from TERI's study on Climate Resilient Green Growth Strategies for Himachal Pradesh (TERI, 2015), conducted in collaboration with Global Green Growth Institute. The objective of the cited study was to analyse the state's future climate using the regional model simulations at 25 km × 25 km resolution, for which Providing Regional Climates for Impacts Studies (PRECIS) model, developed at UK Met Office Hadley Centre, was used. It is an atmospheric and land surface model of limited area and high resolution and is applicable to a typical horizontal grid size of 50 km, which can be lowered as per the requirement of the study. It has been tuned to simulate the baseline runs from 1970 to 2000 and future runs of the 2030s (2020–2040) under the A1B SRES4 scenario.[16] This scenario assumed a business-as-usual state in the near future and hence has been taken as the optimum climate scenario for simulation. PRECIS is highly relevant for scientists involved in vulnerability and adaptation studies, particularly for national communication documents and have been extensively used throughout the world in numerous regional modelling experiments.

The climate modelling exercise conducted for the state as part of the cited study shows a large spatial variation for future seasonal precipitation. The regional climate model projects a precipitation change in the range of -8% to 12% for the monsoon months, (<-10% to over 30%) for winter months, <-15% to over 30% during post monsoon months, and between 5% to 30% for summer months in the future time period of 2020–2050. Also, the model projections show an increase in the extreme rainfall in future over the state (Figure 10).

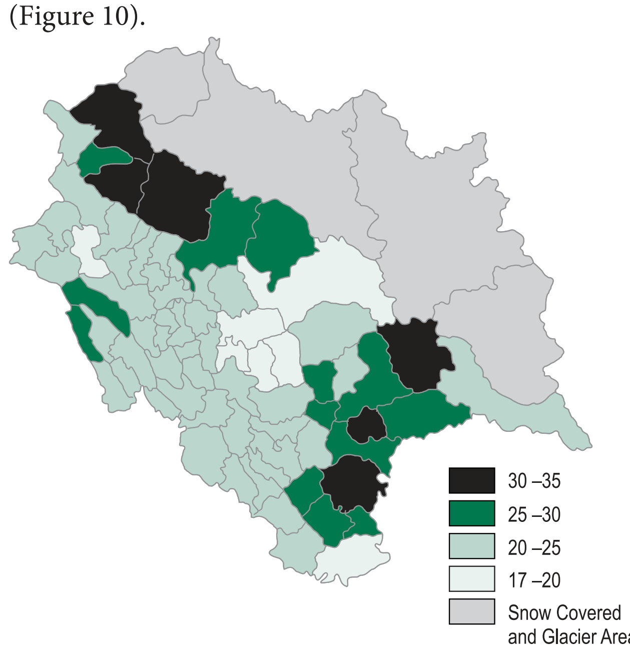
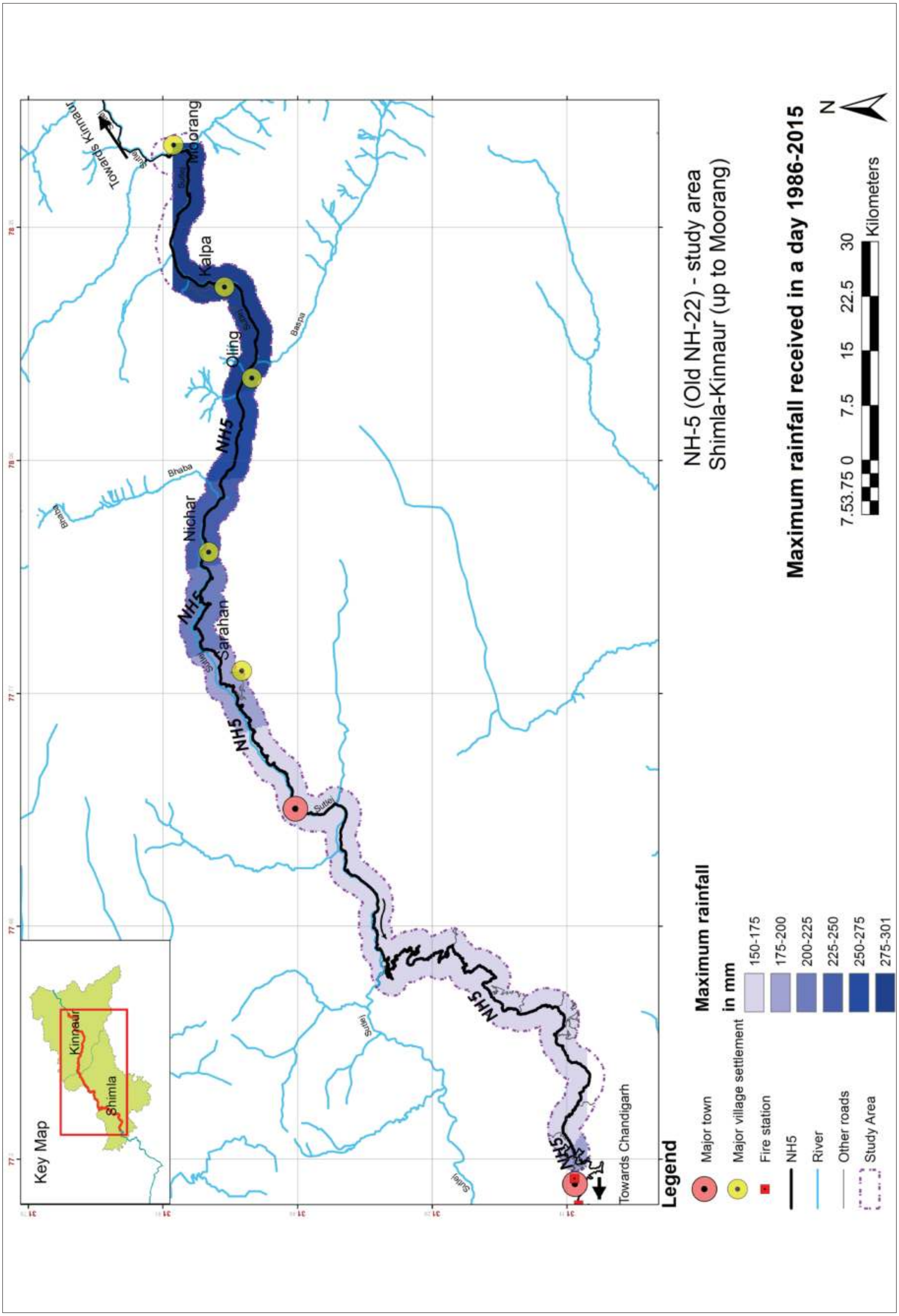


Figure 10: Extreme wet days contribution to the total rainfall in the near future (2020–2050)

Source: (TERI, 2015)

[16] A1B scenario assumed a balance emphasis on all energy sources under the A1 emission scenario characterized by rapid economic growth with quick spread of new and efficient technology. In other words, this scenario assumed a business-as-usual state in the near future and hence has been taken as the optimum climate scenario for simulation.



Map 7: Maximum rainfall received in a day during 1986–2015

Source: TERI Analysis 2016 based on IMD data

To assess the future climate vulnerability of the selected stretch for the purpose of this study, the future extreme rainfall scenario in terms of the contribution of extremely wet days to the total rainfall in the near future time period 2020–50 has been plotted on the selected stretch (Map 8). An increase of 15% to 30% is observed in the extreme wet days contribution to the total rainfall for the overall stretch. The stretch between Rampur to Oling is likely to receive an even higher increase of 25%–30% in the contribution of extreme wet days in a year.

Based on the analysis of past climate trends and future climate scenario, there is a high likelihood of an increase in extreme rainfall events on the selected stretch in the future, in particular, the Rampur to Oling section. This information, along with other non-climate parameters, will be utilized for identifying the most vulnerable sections of the selected stretch in the subsequent steps.

Step 5: Identification of Vulnerable Hotspots

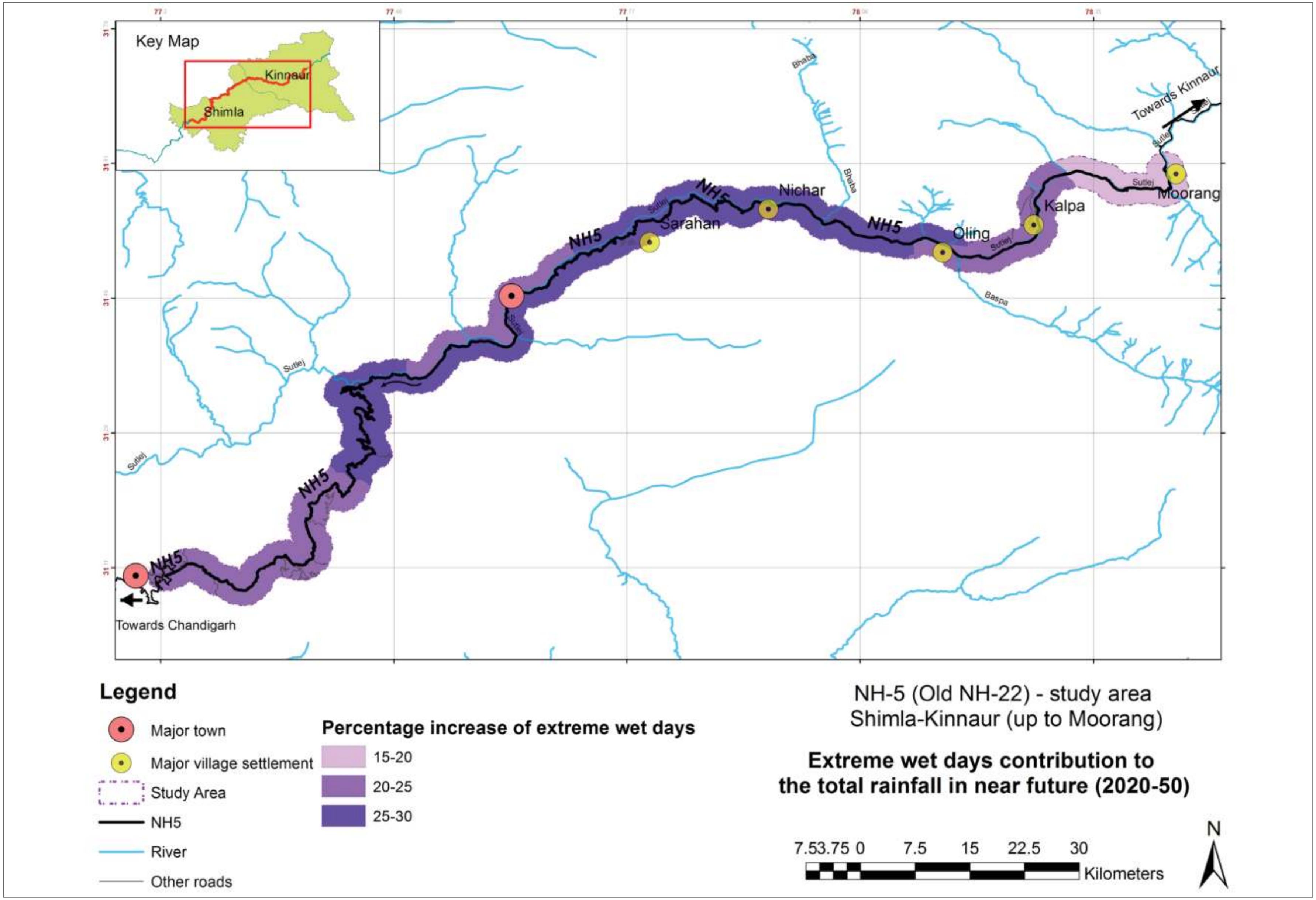
To identify vulnerable hotspots, a VA mapping of the study area has been conducted based on climatic and non-climatic parameters discussed in Step 2. Table 13 gives an overview of the vulnerability criteria considered for the parameters

To begin with, an exposure profile of the selected stretch has been developed with respect to topography, past landslide events, and past extreme events, such as avalanches and flash floods. A detailed discussion on the outcomes of the exposure analysis based on the these three parameters topography, past landslide events, and past extreme events is given below:

- Topography—An analysis of the slope variation has been considered for developing the exposure profile with respect to topographical features. The slope variation in the selected stretch has been classified into four categories, viz., 0–15, 15–30, 30–45 (Map 9). A vulnerability ranking of low, moderate, and high has been assigned to the slope ranges 0°–30°, 30°–45°, and 45° and above, respectively. Typically, construction on slopes more than 30 degrees is risky. It is observed that a major section of the stretch Rampur and Moorang has a slope of more than 30 °. This undesirable slope when combined with extreme rainfall events and loose soil aggravates the risk of landslides, and thereby the vulnerability of the road.
- Past landslide events—Highways in the mountainous and hilly terrains are typically vulnerable to landslides due to a combination of factors, such as extreme rainfall events, non-compliance of safety standards of road construction, and geological characteristics. For developing the exposure profile with respect to landslides, locations of the past events have been plotted on

Table 13: Vulnerability parameters for study stretch of NH

			Vulnerability Ranking					
Sl.No.	**Parameters**	**Criteria**	**Low**	**Score**	**Moderate**	**Score**	**High**	**Score**
1	Slope Analysis	Degree of slope	0°–30°	0	30°–45°	1	45° and above	2
2	Past landslides	Spatial location of landslides	No history		Outside the 1 km radius		A radius of 1 km from the point location	
3	Past events-Avalanches and flash floods	Spatial location events occurred	No history		Outside the 1 km radius		A radius of 1 km from the point location	
4	Extreme wet day contribution to the total rainfall 2020–2050	Percentage increase of extreme wet days	15–20		20–25		25–30	



Map 8: Extreme wet days contribution to the total rainfall in the near future

Source: TERI, 2015

the selected stretch in Arc GIS platform (Map 10). A vulnerability ranking of high, moderate, and low has been assigned to the areas falling within 1 km radius of past landslide locations, areas outside the 1 km radius and if there has been no history of landslides respectively. It is observed that the section from Rampur to Nichar and Kalpa to Moorang is most risk prone to landslides

- Past extreme events— Point locations of past extreme events, such as avalanches and flash floods which have caused major damage have been plotted to understand the exposure of the selected stretch to these extreme events based on their occurrences during 1973-2016 (Map 11). Table 14 gives an overview of the losses and damages caused on the roads due to these past extreme events. A vulnerability ranking of high, moderate, and low has been assigned to the areas falling within 1 km radius of past extreme event's point locations, areas outside the 1 km radius and if there has been no history of extreme events respectively.

In order to assess the future climate vulnerability of the selected stretch, the future extreme rainfall scenario in terms of extreme wet days' contribution to the total rainfall in near future has been plotted on the stretch

Table 14: Loss and damage of past events for study stretch of NH 5

Past event	Year	Location	Remarks/ loss and damage
Landslide	1993	Jhakari	NH 22 was washed away due to flash floods and could be restored only after two months
Landslide	1995	Chirgaon	Road Rohroo to Chirgaon was washed away due to flash floods and could be temporarily restored only after 15 days
Flash floods	1973	Nathapa rock fall	Data not available
Flash floods	1993	Jhakari	1 km of NH 5 and forest land public property destroyed.
Flash floods	2000	Rampur	140 human deaths, 1673 cattle death (60 feet above normal level)
Flash floods	1973	Sanjay power house	₹45 million estimated loss due to Nahpa rock fall on Sanjay Power House
Flash floods	1975	Sumdo and Kaurik fault line.	60 m height and 150 m length blockage due to landslide after earthquake
Flash floods	1988	Soldan Village	2 km of NH 22 damaged
Flash floods	1991	Soldan Khad	32 killed, 15 houses and 35 bigha agricultural area destroyed, 20 m bridge collapsed
Flash floods	2005	Pareechhu Lake outburst	10 bridges and several section of NH 22 destroyed incurring a loss of ₹610 crores
Flash floods	1995,1991	Tapri	Damaging NH 22. Tow erosion to NH 22
Flash floods	1995	Baspa river	NHs damaged at numerous places, loss to government and private property, roads, and bridges estimated US$ 182 million
Flash floods	2000	Panwi Khad	19 houses, 3 buses, HRTC workshop and damaged HP PWD rest house
Flash floods	2000	Khab	Extensive damage to 200 km of NH 22, washed away 20 bridges, 22 Jhulas and badly damaged 12 bridges. 135 people and 1,673 cattle lost their lives. The total estimated loss was to the tune of ₹1,466.26 crore
Avalanches	Different years	Pyala Nalla (Jangi) and Ralli	Accidents and human deaths

Source: *(District Disaster Management Authority, Kinnaur, 2012)*

(Map 8). It is observed that an increase of 15% to 30% is observed in the extreme wet days' contribution to the total rainfall for the overall stretch. The stretch between Rampur to Oling is likely to receive an even higher increase of 25%–30% in the contribution of extreme wet days in a year. For extreme wet days' contribution, a vulnerability ranking of low, moderate, and high has been assigned to the ranges 15%–20%, 20%–25%, and 25%–30%, respectively.

As an outcome of this step, three exposure maps with respect to topography, past landslide events, and past extreme events were overlaid with the future climate information (Map 12). The final vulnerability map depicts the most vulnerable sections of the selected stretch, based on a total vulnerability scoring. The vulnerability scoring has been derived based on the following:

- Equal weightage has been accorded to all the vulnerability parameters
- A score of 0, 1, and 2 has been assigned to the vulnerability rankings of low, moderate, and high, respectively, for each parameter (refer the Table 13 vulnerability parameters).
- The total scores have been classified in the range of 0–4, 4–7, and 7–11 and assigned a ranking of low, moderate, and high vulnerability, respectively.

Based on the score, it may be observed that, although the overall stretch is vulnerable to climate change, the section from Rampur (31°23'20.66"N 77°36'53.37" E) Oling (31°29'49.36"N 78°12'41.53E) is found to be the most vulnerable.

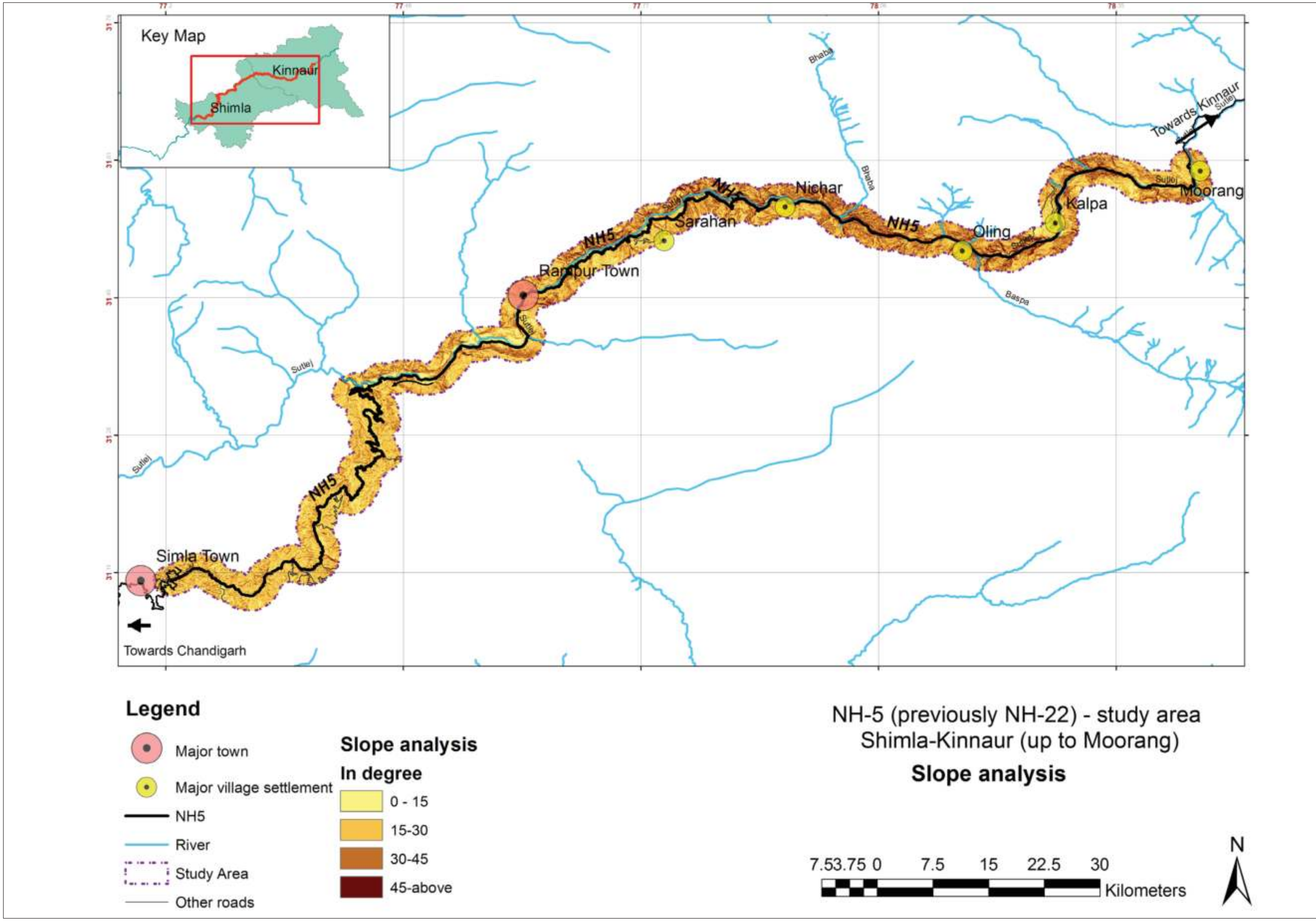
Step 6: Prioritizing areas for investment and interventions—Risk assessment

Based on the vulnerability mapping conducted in Step 5, the most vulnerable section of the selected stretch has been identified (Map 13). This step provides a discussion on the outcomes of the risk assessment of the most vulnerable section for prioritizing areas/ highway elements for investment and interventions. As stated in Chapter 3, 'Climate Vulnerability Assessment of the Highways' the objective of this risk assessment is to identify highway elements and infrastructure that are most risk prone and this step is recommended when detailed retrofit measures are needed for an existing stretch with high climate vulnerability. To this end, in line with the proposed methodology, the recommended approach would be to collect detailed data of the highway elements and infrastructure along the vulnerable section. Data should also be collected on the extent of loss and damage borne by the highway elements and infrastructure during past extreme events. This will provide an understanding of the extent of climate impacts the highway elements and infrastructure are sensitive to and assist in developing the risk assessment matrix as an outcome of this step. The highway elements and infrastructure to be considered for risk assessment may include, but not limited to, are:

- Pavements
- Shoulder
- Embankments
- Protection works
- Retaining walls/engineering stabilization works
- Drainage
- Lighting
- Crash barriers
- Road Signs
- Kerbs
- Kilometre stones

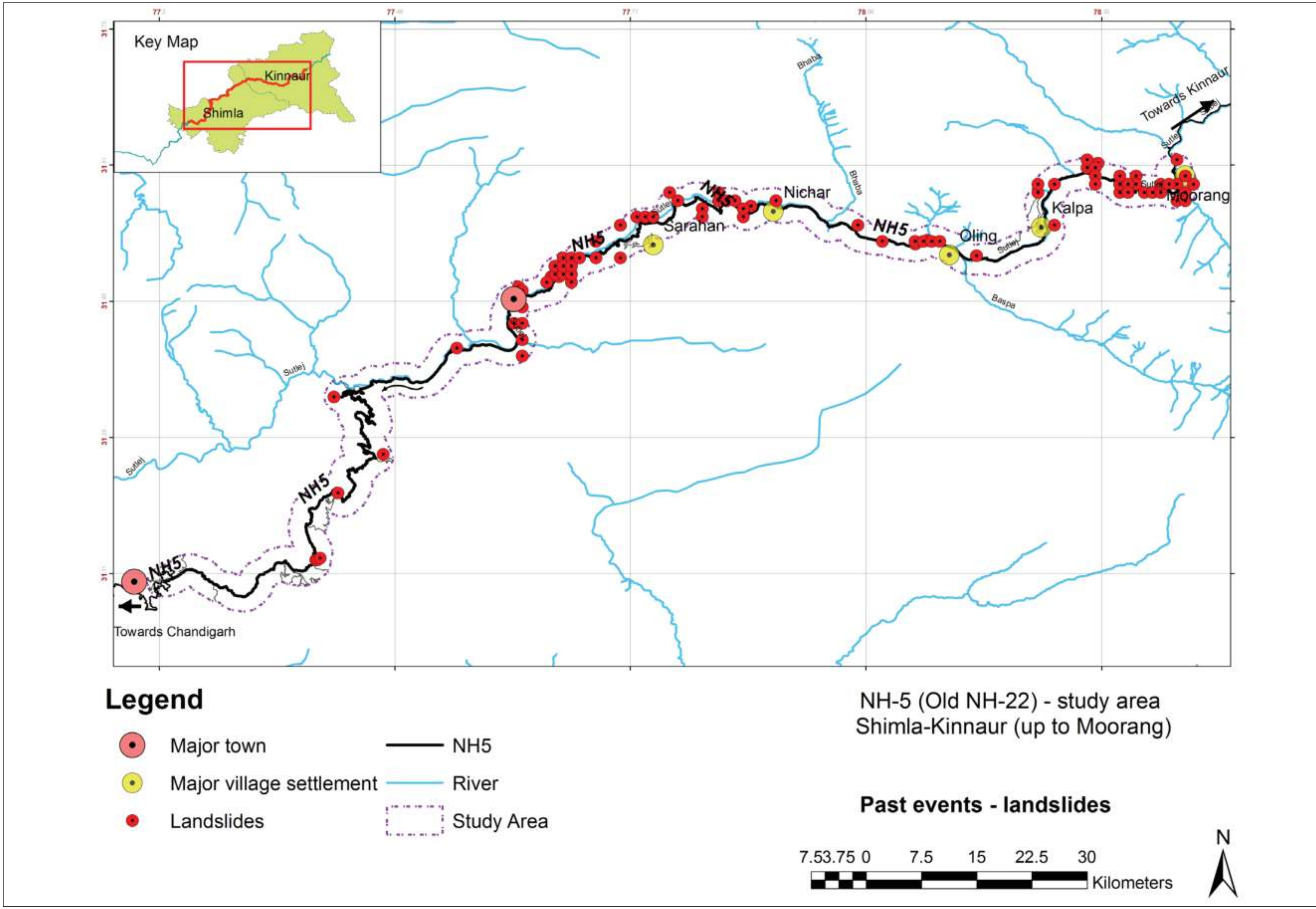
The data received for the risk assessment exercise for this stretch was inadequate and could not be utilized. Hence, only a broad risk assessment of highway elements and infrastructure could be conducted for the most vulnerable section. To this end, national level stakeholders and sector experts have been consulted, based on the assumptions presented in Table 9, to broadly identify the risks of the highway elements and infrastructure. Table 15 presents a broad risk assessment which is based on the consultations.

Extreme rainfall and landslides triggered by rainfall are the most prominent risks to which this stretch is prone. Therefore, the highway elements and infrastructure, such as drainage, protection works, retaining walls, pavements, and shoulders, which have high probability of impact and are directly affected by extreme rainfall due to inundation and damages caused by landslides fall under high risk. The assets,



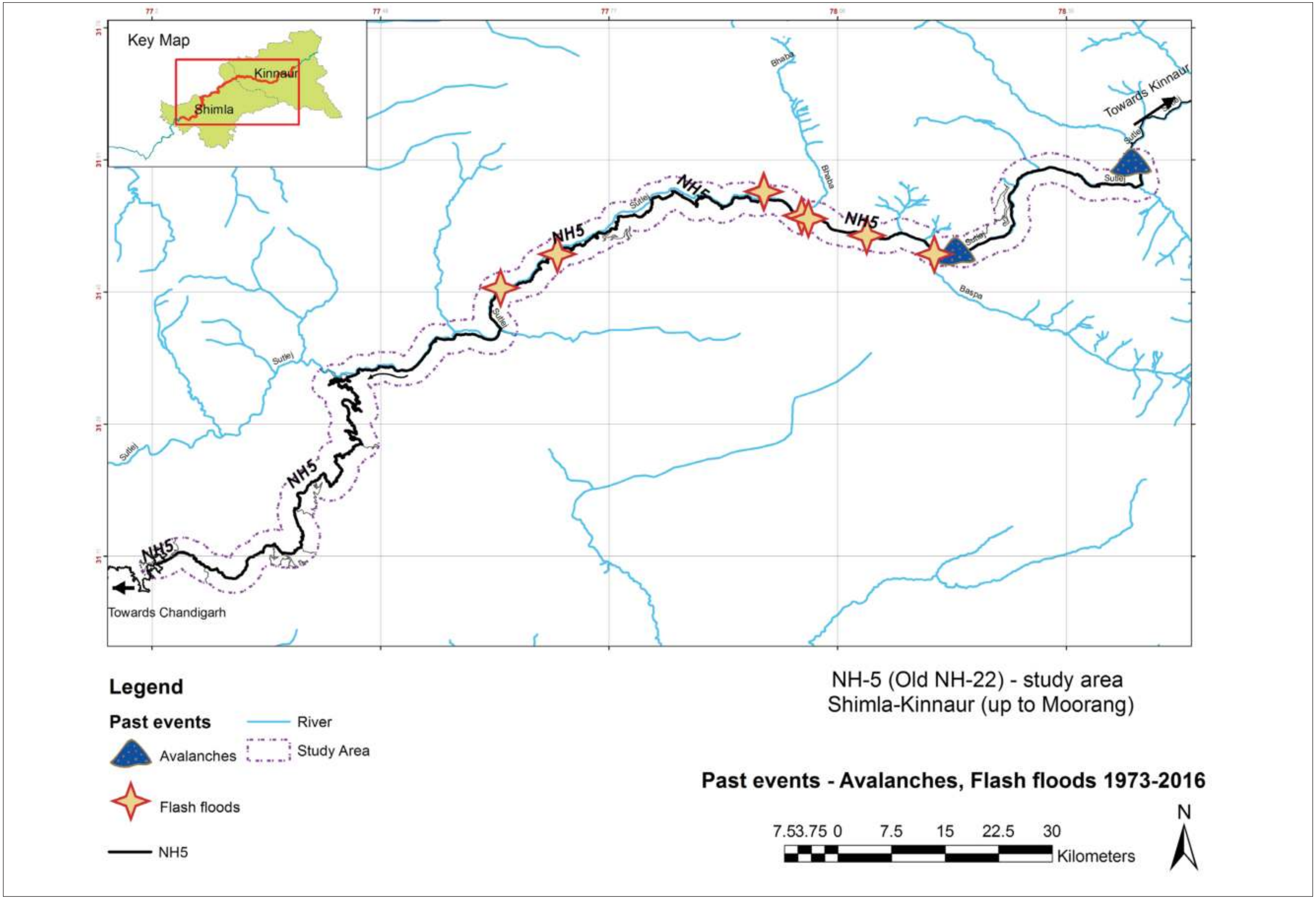
Map 9: Slope Analysis

Source: TERI Analysis, 2016



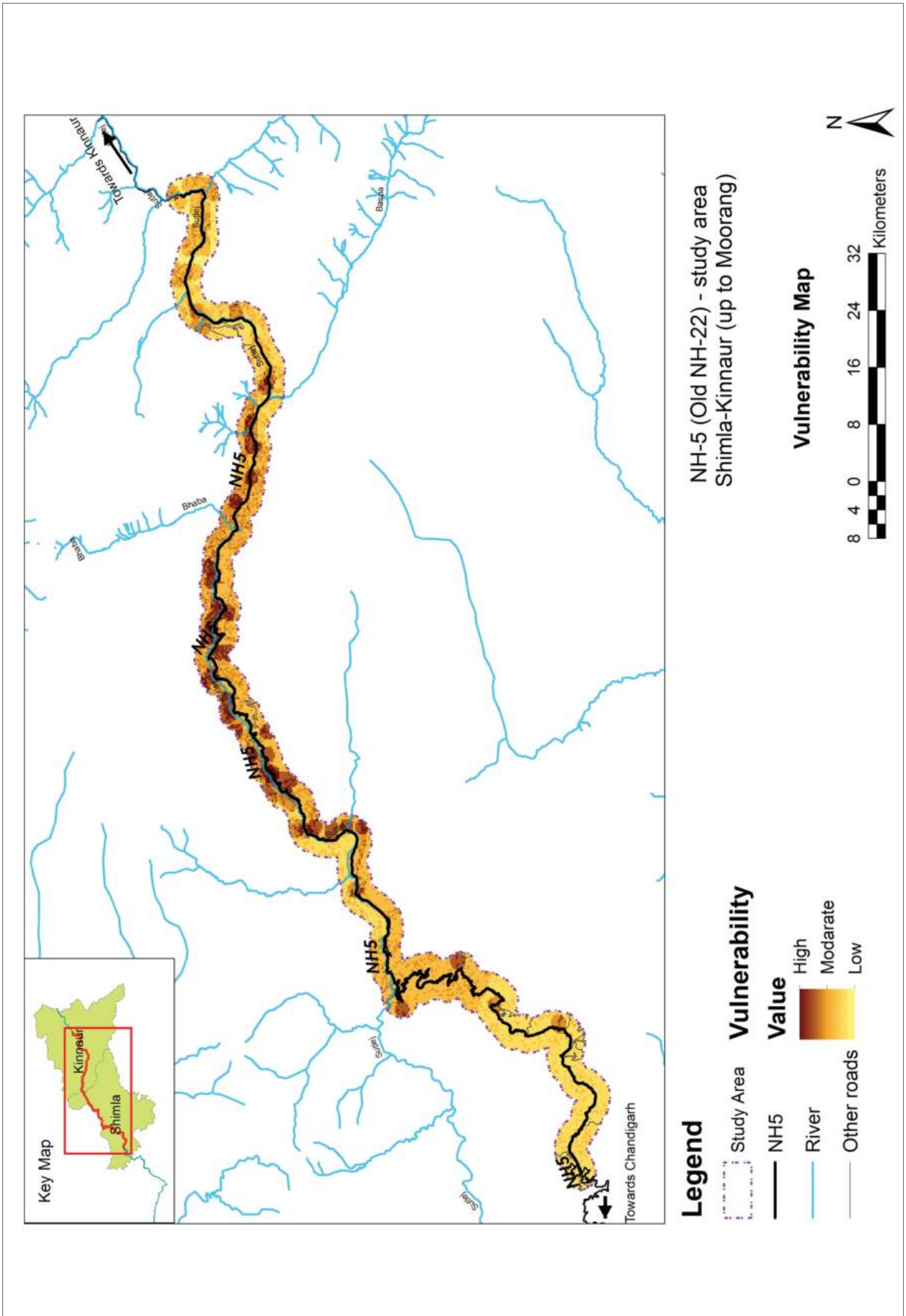
Map 10: Past events – landslides

Source: (District Disaster Management Authority, Kinnaur, 2012)



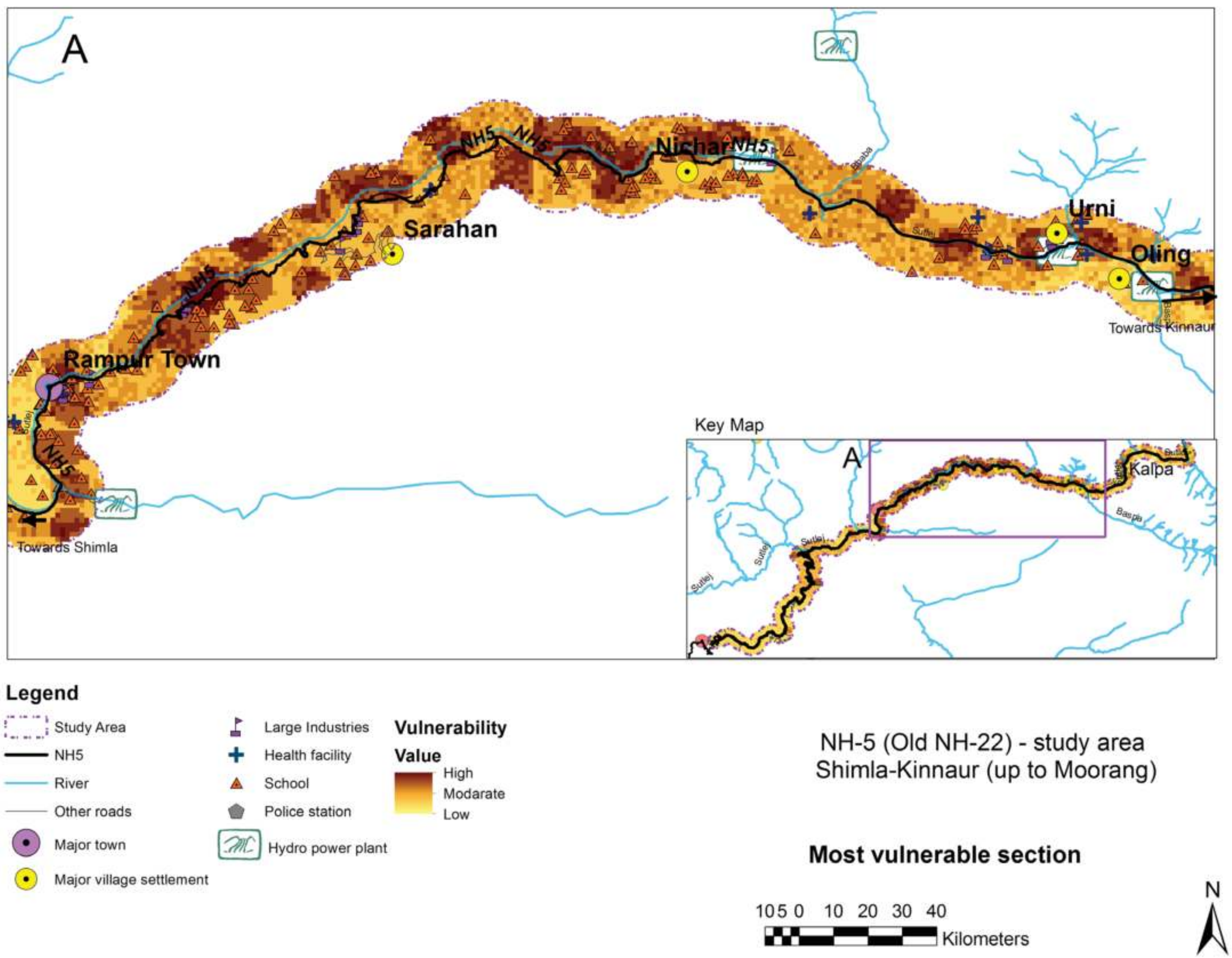
Map 11: Past events —Avalanches, Flash floods 1973–2016

Source: Kinnaur, 2012; Revenue & Disaster Management Department, Government of Himachal Pradesh, 2016



Map 12: Vulnerability Map

Source: TERI Analysis, 2016



Map 13: Most vulnerable section of the study stretch

Source: TERI Analysis 2016

Table 15: Risk assessment matrix for study stretch of NH 5

Highways assets and components	Low	Moderate	High
Pavements			■
Shoulder			■
Embankments		■	
Protection works			■
Retaining wall/engineering stabilization works			■
Drainage			■
Lighting	■		
Crash barriers		■	
Road signs	■		
Kerbs		■	
Kilometre stones		■	

such as lighting and road signs which have less probability of being impacted and are not directly affected, fall under low risk.

Step 7: Identifying interventions for resilience building

This last step identifies interventions for enhancing climate resilience of the selected highway stretch. From Step 5, the most vulnerable section within the selected highway stretch is identified. Accordingly, this highway section is accorded top priority for implementing the recommended engineering interventions during construction, upgradation, and maintenance stages. Similarly, implementation of interventions may be time-phased over the highway stretch, based on the vulnerability ranking.

The risk assessment (Step 6) conducted for the most vulnerable section shows drainage, protection works, retaining walls, pavements, and shoulders as high-risk elements; the recommended engineering interventions can focus on these elements. The engineering interventions primarily include structural measures that focus on increasing the slope stability to address landslides. The slope stability can be increased by reducing or eliminating the effects of any contributing factor causing sliding and reducing the contact of rainfall with soil. There are several engineering interventions that can be implemented in landslide-prone areas. However, whether specific interventions are optimal and feasible for this stretch/section can be determined only through a further detailed analysis which could not be conducted in the available time for this study. However, considering the drainage, protection works, pavements, and shoulders of this stretch are at a high risk, the engineering interventions that are recommended to be adopted are:

- Treatment for slope stabilization and erosion control by:
  - Construction of restraining structures, such as retaining walls of concrete and masonry, gabion walls, and piling to prevent landslides. For instance, retaining walls, when erected, ensure greater stability to dangerous slopes or also support existing landslides (Bureau of Indian Standards, 1999).
  - Interval slope reinforcement with rock bolts, soil nailing, anchors, and grouting
  - Modification of slope geometry by removal of material from the upper areas, reduction of slope angle, and trimming of loose surface material
  - Use of erosion control mats/blankets and other bio-engineering measures, such as hydro seeding methods, mulching, etc.
- Control of water percolation by providing appropriate surface and subsurface drainage. The drainage capacity can be improved through the following (Roychowdhury, 2015):
  - Geo-composite drainage systems for both drainage under pavements and drainage behind retaining walls
  - Improve slope stability through installation of drainage systems, mostly horizontal weep
  - Annual and periodic maintenance of drainage, particularly in pre-monsoon and monsoon period
- Rock fall mitigation measures which prevent the rocks from falling directly onto the road, either by containing them or directing the rocks to a ditch or other catching structures (Bobrowsky, 2008), such as:

- Geo-nets /drapery systems
- Falling rock protection barriers including catchment shoulder
- Rock bolts
- Rock sheds, barriers, and tunnels
- Wire mesh
- Use of erosion control mats/blankets and other bio engineering measures, such as hydro seeding methods, mulching, etc.

4.3 Vulnerability assessment for Kathipudi to Ongole stretch on NH 216

Step 1: Defining objectives

Considering the overall scope of the Study, the objectives of conducting VA on the highway stretch are:

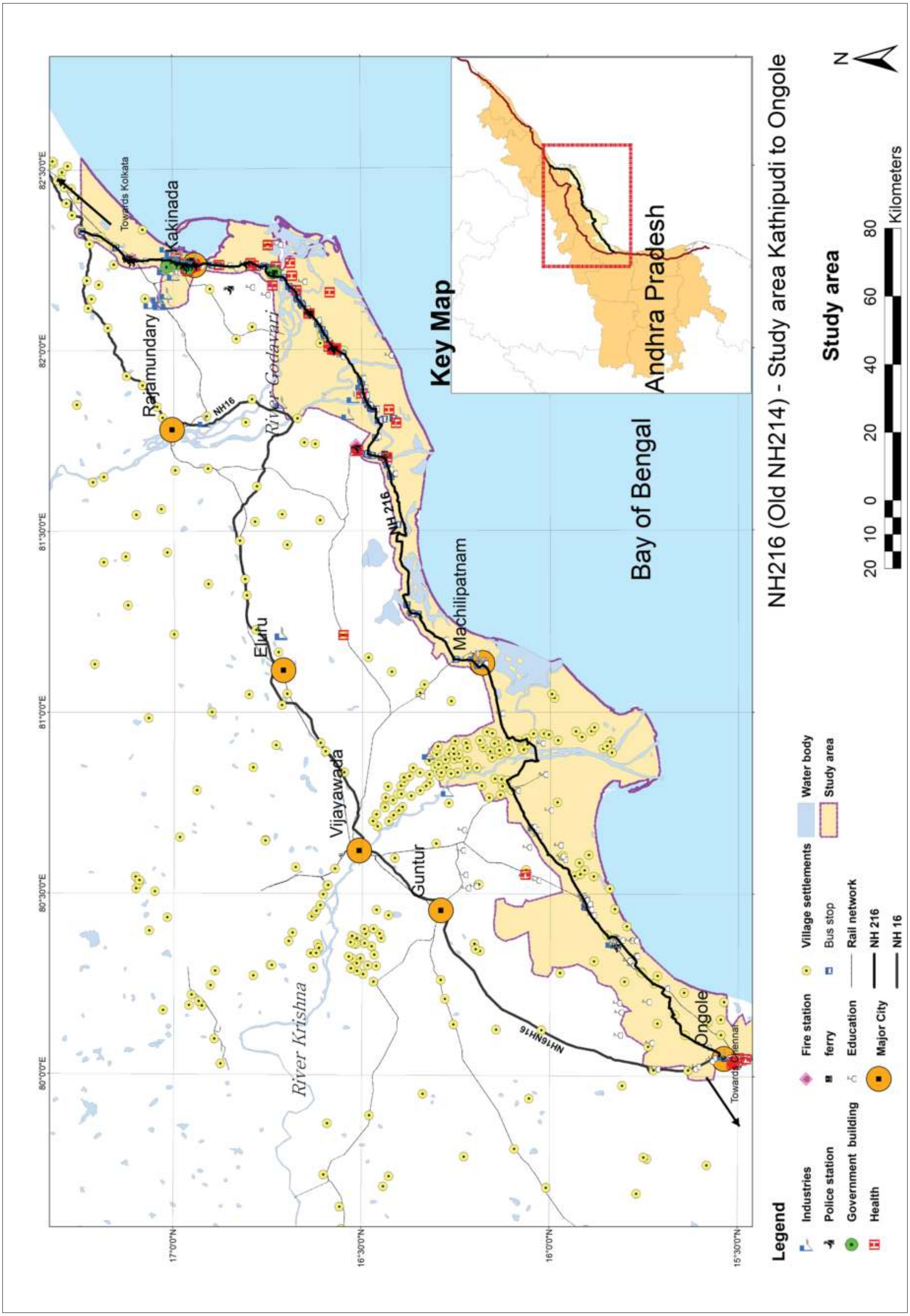
- To identify sections or highway elements and infrastructures on these highway stretches that is at risk to the impacts of climate change.
- To identify and recommend effective engineering interventions for climate change adaptation, and thereby address the climate vulnerability of the highway stretch.

Step 2: Scoping

A scoping exercise has been conducted at this step to define the geographical boundaries as well as the study parameters, data sources, and tools and techniques of assessment for the purpose of this study.

- **Delineation of geographical limit**—The geographical delineation of the study stretch has been conducted based on inputs from NHAI, AP PWD, AP Disaster Management Department, National Remote Sensing Centre, Hyderabad, and other sector experts and practitioners. Based on interactions with relevant stakeholders, a stretch of 397 km (Kathipudi to Ongole in Andhra Pradesh) has experienced maximum loss and damage from extreme hydro-meteorological events in the past and is, therefore, selected as the case study stretch in light of its vulnerability (Map 14). For delineating the study area on both sides of the highway ROW, locations of important social and physical infrastructure (viz. large-scale industries, power projects, schools and health facilities, etc.) and settlements abutting the highway for which it plays a critical role in connectivity have been taken into consideration. These settlements include Kakinada, Amalapuram, Kalipatnam, Machilipatnam, and Bapatla. Moreover, locations of inundation-prone areas[17] based on the past trend of hydro-meteorological extreme events (2012–2016) have also been one of the key criteria. On the seaward side, all the areas up to the coastline have been included in the geographical scope of the study.
- **Identification of key issues and parameters (climate and non-climatic) to be considered**—During the stakeholder interactions (refer to Annexure 3) it was observed that, located in the coastal areas, this stretch is prone to coastal flooding as a result of multiple hydro-meteorological events, including extreme precipitation events and cyclones and storm surges. It would, therefore, be relevant to study the past trends of rainfall variability, incidences of extreme precipitation events, and occurrence of cyclones and storm surges. To assess the future vulnerability of the highway stretch, assessment of future climate information would also be imperative. In terms of the non-climatic parameters, locations of settlements and infrastructure will play a key role in deciding the vulnerability and extent of risk of the highway stretch. A study of past incidents of climate-related disaster events and their impacts would also indicate towards understanding the highway's vulnerability to climate change impacts. At the engineering level, highway characteristics, such as materials, nature and condition of highway elements, and infrastructure, will also play a key role in the level of vulnerability of the highway stretch. Based on this preliminary understanding of parameters to be considered for assessment, data collection, and analysis of the same has been conducted in the subsequent steps.
- **Identification of analytical tools and techniques for vulnerability assessment** —The overall spatial vulnerability mapping exercise has been conducted using an Arc GIS platform. The input layers to the mapping exercise have

[17] Source: NRSC, Hyderabad



Map 14: Study area map

Sources: TERI Analysis, 2016

been developed based on secondary information received from various government departments and agencies at the national and state levels as mentioned above, open data sources, such as Aster Global Digital Elevation Model/ BHUVAN, and future climate information referred from 4X4 Assessment Report of the Indian Network for Climate Change Assessment (MoEF, 2010) and TERI's study (TERI, 2014). A detailed technical methodology and considerations for each step of mapping and assessments have been discussed through Steps 4–6.

Step 3: Collection and Integration of Data

Data collection was conducted in line with the requirements towards developing an exposure profile of highways to extreme climate events, the impacts of these events on the highway, extent of damage, and loss caused due to these extreme events, and past and future climate profile over the highway stretch.

Six weather stations—Bapatla, Kakinada, Machilipatanam, Narsapur, Ongole, and Tuni were identified along the selected stretch for collecting past climate data. Table 16 lists the climate parameters that were collected from IMD, Pune, for the purpose of conducting VA.

Data related to past extreme events, such as high-intensity cyclonic events and the areas affected by them, has been collected for the time period, 1980–2015. This data was sourced from the Regional Specialized Meteorological Centre for tropical cyclones in the northern part of the Indian Ocean, IMD.

Spatial location of areas inundated in the delineated study area due to past events (2012–2016) was obtained from the National Database for Emergency Management under 'Bhuvan', the Indian Geo-Platform of ISRO.

The future climate information for this stretch has been drawn from the existing studies and literature. Future rainfall variability has been referred from the study titled '*Projected Changes in Mean and Extreme Precipitation Indices over India using PRECIS*' (Rao *et al.*, 2013). The information extracted from the above-mentioned study has been plotted on the demonstration stretch for the time period 2070–2100. TERI's study titled 'Climate Resilient Infrastructure Services' (TERI, 2014) has been referred to for building future storm surge and consequent inundation scenarios for the time period 2070–2100.

To understand the terrain of the selected highway stretch, an Aster Global Digital Elevation Model of a 30 metre contour interval was used for generating the contours, which is freely available through USGS.[18]

Data drawn from Google Earth was utilized for identifying administrative boundaries, physical features, such as road network, amenities, government buildings, large-scale industries, hydropower plants,

<table>
<tr><th colspan="6">Table 16: Meteorological Data for study stretch of NH 216</th></tr>
<tr><th>Sl. No</th><th>Climate Variables</th><th>Tuni</th><th>Machilipatnam and Kakinada</th><th>Narsapur,</th><th>Bapatla, Ongole</th></tr>
<tr><td>1</td><td>Daily rainfall</td><td rowspan="8">1996–2009</td><td rowspan="4" colspan="3">1980–2009</td></tr>
<tr><td>2</td><td>Maximum daily temperature</td></tr>
<tr><td>3</td><td>Minimum daily temperature</td></tr>
<tr><td>4</td><td>Daily average wind speed</td></tr>
<tr><td>5</td><td>Monthly mean/highest maximum temperature</td><td rowspan="4">1901–2009</td><td rowspan="4">1988–2009</td><td rowspan="4">1980–2009</td></tr>
<tr><td>6</td><td>Monthly mean/lowest minimum temperature</td></tr>
<tr><td>7</td><td>Total monthly rainfall (month wise)</td></tr>
<tr><td>8</td><td>Monthly heaviest rainfall in 24 hours</td></tr>
</table>

[18] United States Geological Survey

forest cover along with major settlements in the delineated study area.

Also, data related to the highway stretches, such as traffic, operations, highway materials and characteristics, inventory of highway elements, etc., was collected. Project Implementation Units of NHAI for NH 216 in the state of Andhra Pradesh were approached for collecting these data.

Step 4: Developing climate scenarios

Past climate profile

This step presents the climate variability profile of the highway stretch in terms of past and future climate profiles. The past climate profile of the highway stretch has been prepared based on an analysis of the available past climate data (1980–2009) received from the six IMD stations on the stretch—Kakinada, Machilipatanam, Narsapur, Bapatla, Tuni, and Ongole. A study of the past extreme events and disasters indicates that the region is prone to coastal flooding as a result of multiple hydro-meteorological events including extreme precipitation events and cyclones and storm surges. Hence past data on rainfall parameters, cyclones, and wind speeds has been analysed in detail in this study (refer to Annexure 2).

Rainfall and wind speed pattern

The analysis of the past climate data on rainfall and wind speeds indicates a slight decreasing trend of the total annual rainfall for the 29-year rainfall dataset analysed (1980–2009) during the monsoon and post-monsoon seasons showing a larger contribution towards the total rainfall over the stations. Despite the decreasing rainfall trend over the region, the maximum rainfall is seen to increase in the time period with most of the events seen under very heavy and heavy rainfall event category of IMD.[19] Also, most of the high rainfall events in a day are seen in monsoon and post monsoon seasons. Relatively high wind speeds are found to occur in the monsoon months of June, July, and August and also in the months of November and December. Average seasonal wind speeds have slightly decreased over the region in the observed time period although the variability is quite high. The monsoon months show relatively higher wind speeds than other months over the six stations. A detailed analysis on the past climate trends over the six stations may be found in Annexure 2. To spatially plot the past climate profile over the highway stretch, the maximum rainfall received in a day has been mapped for the time period 1980–2009 in Arc GIS platform (Map 15).

Cyclones and storm surges

Data related to past cyclonic events and the areas affected by them was collected for the time period (1980–2015) from the Regional Specialized Meteorological Centre for tropical cyclones in northern part of the Indian Ocean, IMD. As per IMD and NDMA, the eastern coast of India is relatively more risk prone to cyclones and storm surges as compared to the western coast. To map high intensity cyclonic events, the areas affected by severe cyclones, extremely severe cyclones and super cyclones during 1980–2015, were plotted over the study area in Arc GIS platform. The affected areas were identified based on the path and land fall points of the cyclones (Map 16). A detailed list of all cyclonic events may be found in Annexure 2. Existing literature[20] suggests average storm surge heights, as a result of high intensity cyclonic events and high wind speeds, in the range on 2.5 m–6 m over Andhra Pradesh stretch of the eastern coast of India.

Future climate profile

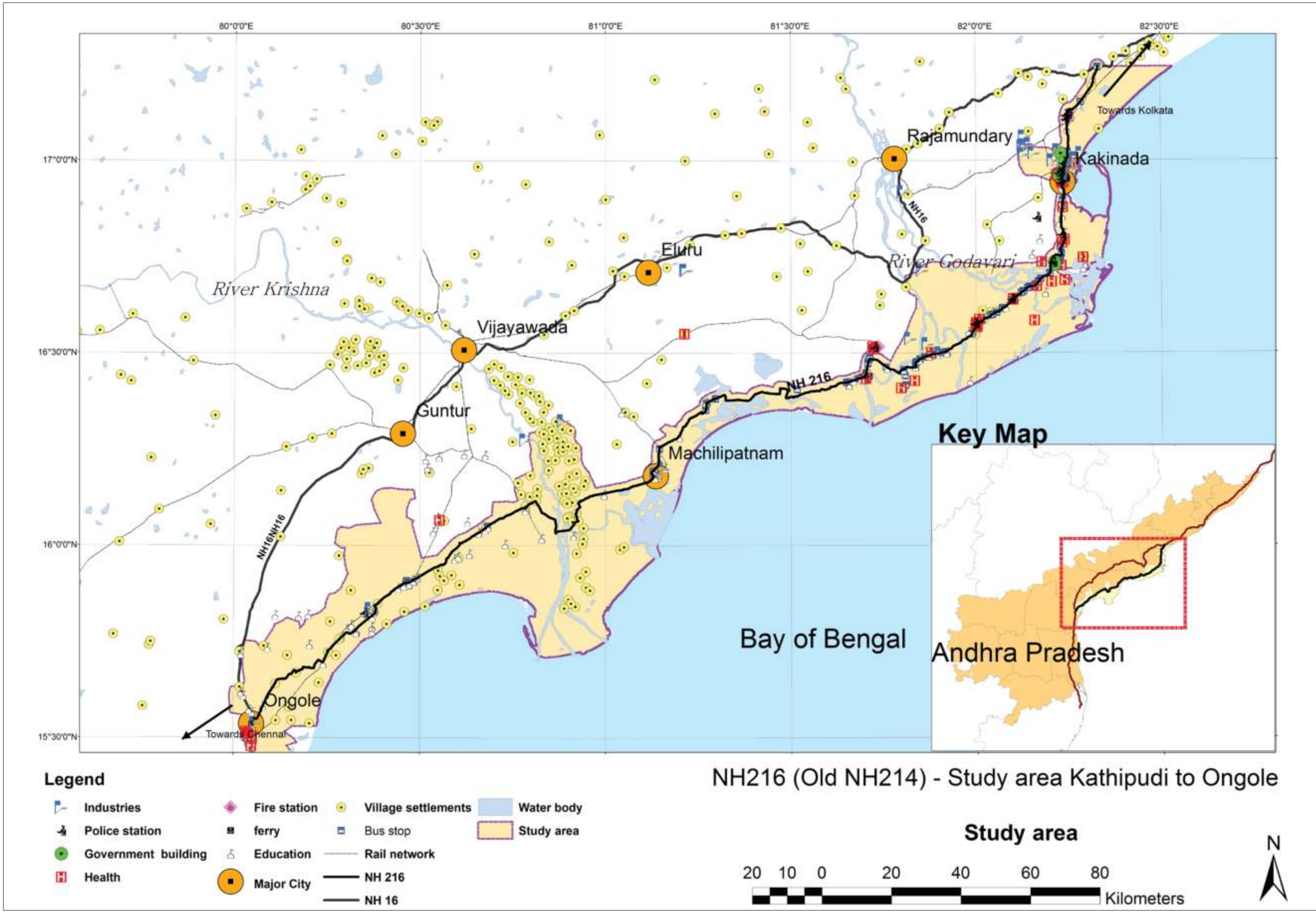
Once the past climate profiling over the region has been well understood, it is imperative to understand the future climate variability over the region as well. To this end, a spatial assessment of changes in future rainfall (Map 17) and hydro-meteorological extreme events, that is, storm surges resulting from high intensity cyclones (Maps 18 and Map 19) has been conducted. The future climate information for building these scenarios has been drawn from existing studies and literature.

Rainfall variability

Information on future rainfall variability has been referred from the study titled 'Projected changes in mean and extreme precipitation indices over India using PRECIS' (Rao *et al.* 2013). It depicts the ensemble mean of percentage change in rainfall over very wet days of monsoon season for the future scenario (2070–2100) with respect to baseline simulations for 1960–1990. The information extracted

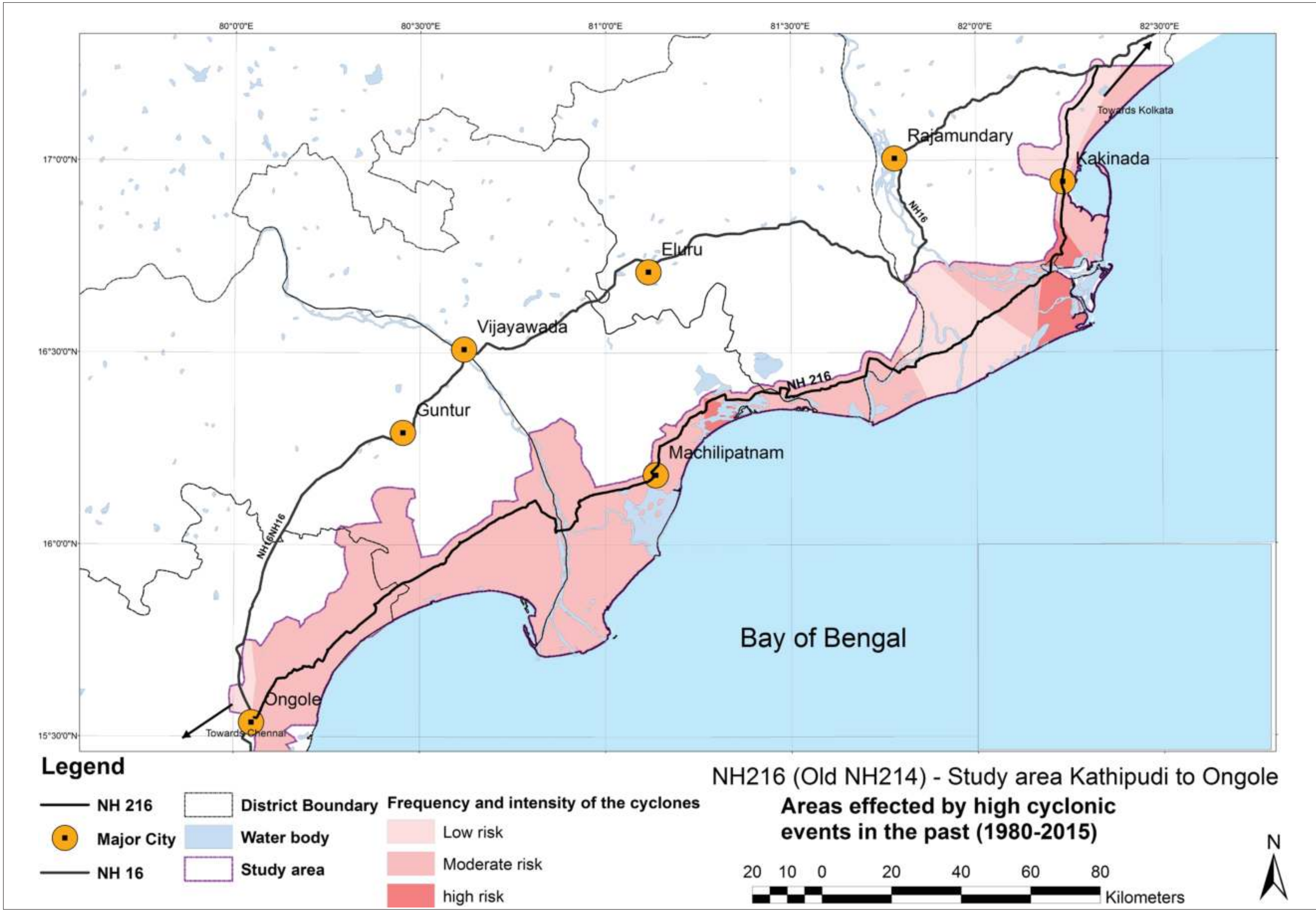
[19] http://www.imdpune.gov.in/weather_forecasting/glossary.pdf

[20] Andhra Pradesh State Action Plan on Climate Change; Revenue (Disaster Management) Department, GoAP



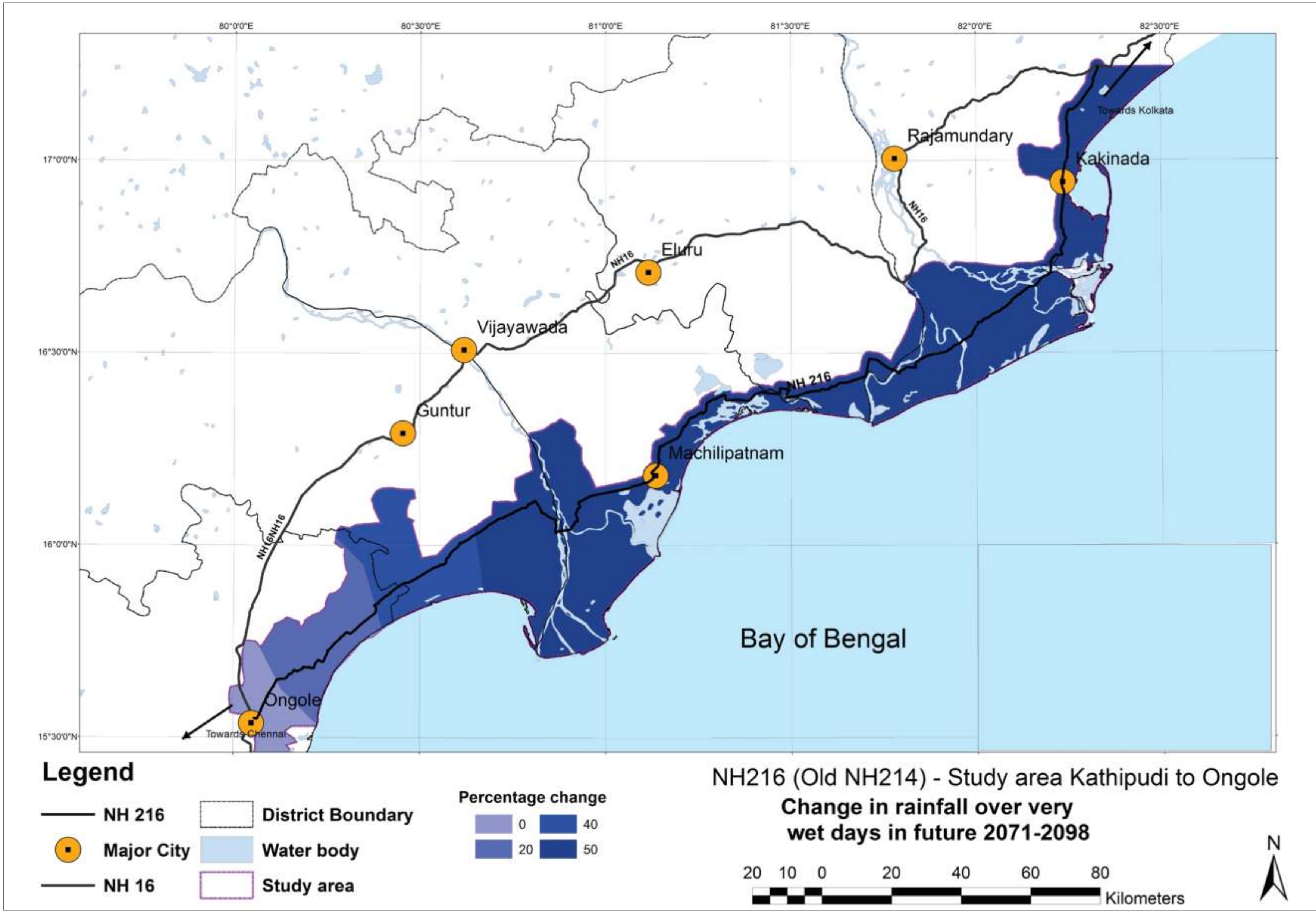
Map 15: Maximum rainfall received in a day for the time period 1980–2009

Source: TERI Analysis 2016 based on IMD data



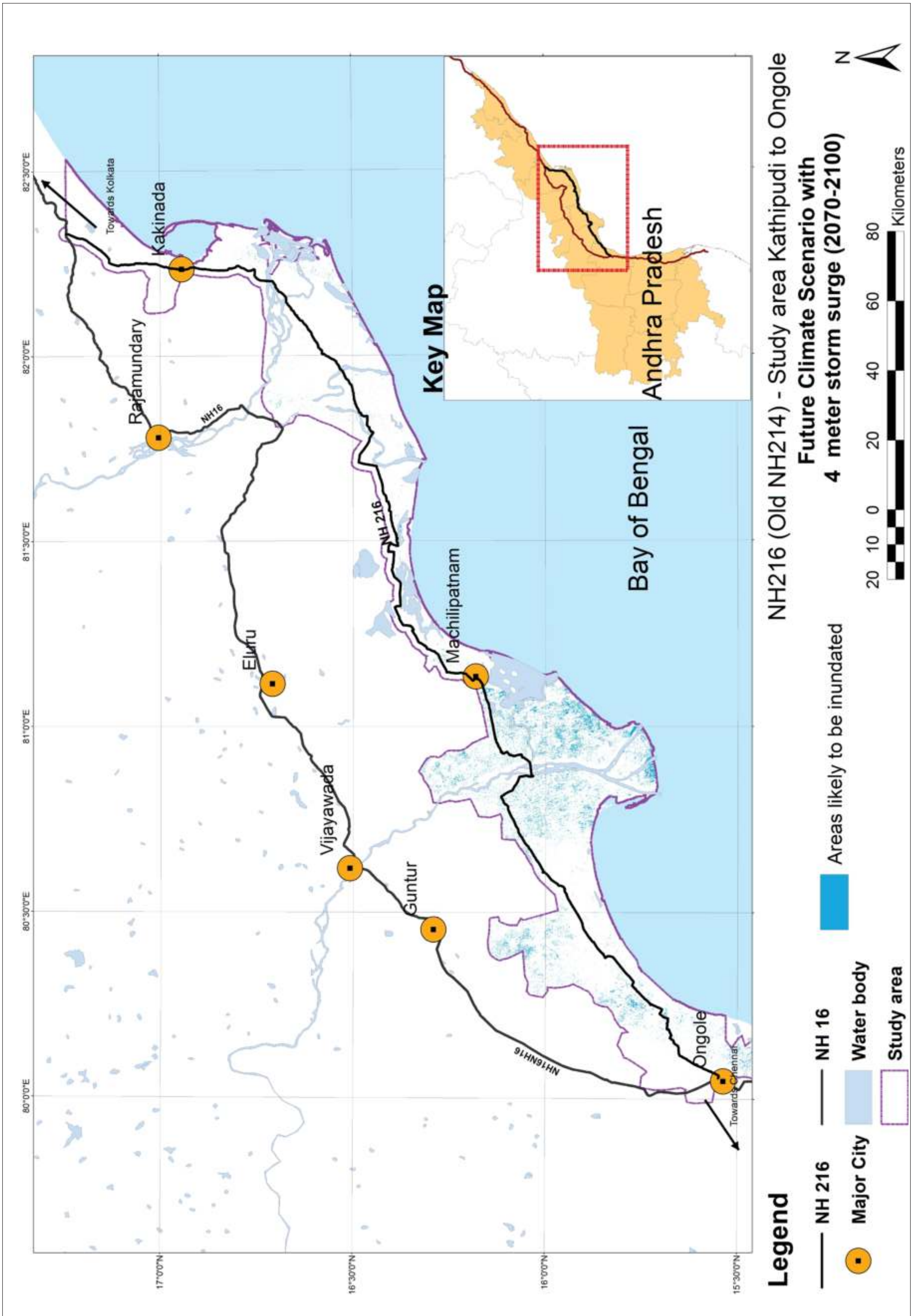
Map 16: Areas effected by high cyclonic event in the past (1980–2009)

Source: TERI Analysis 2016 based on IMD data



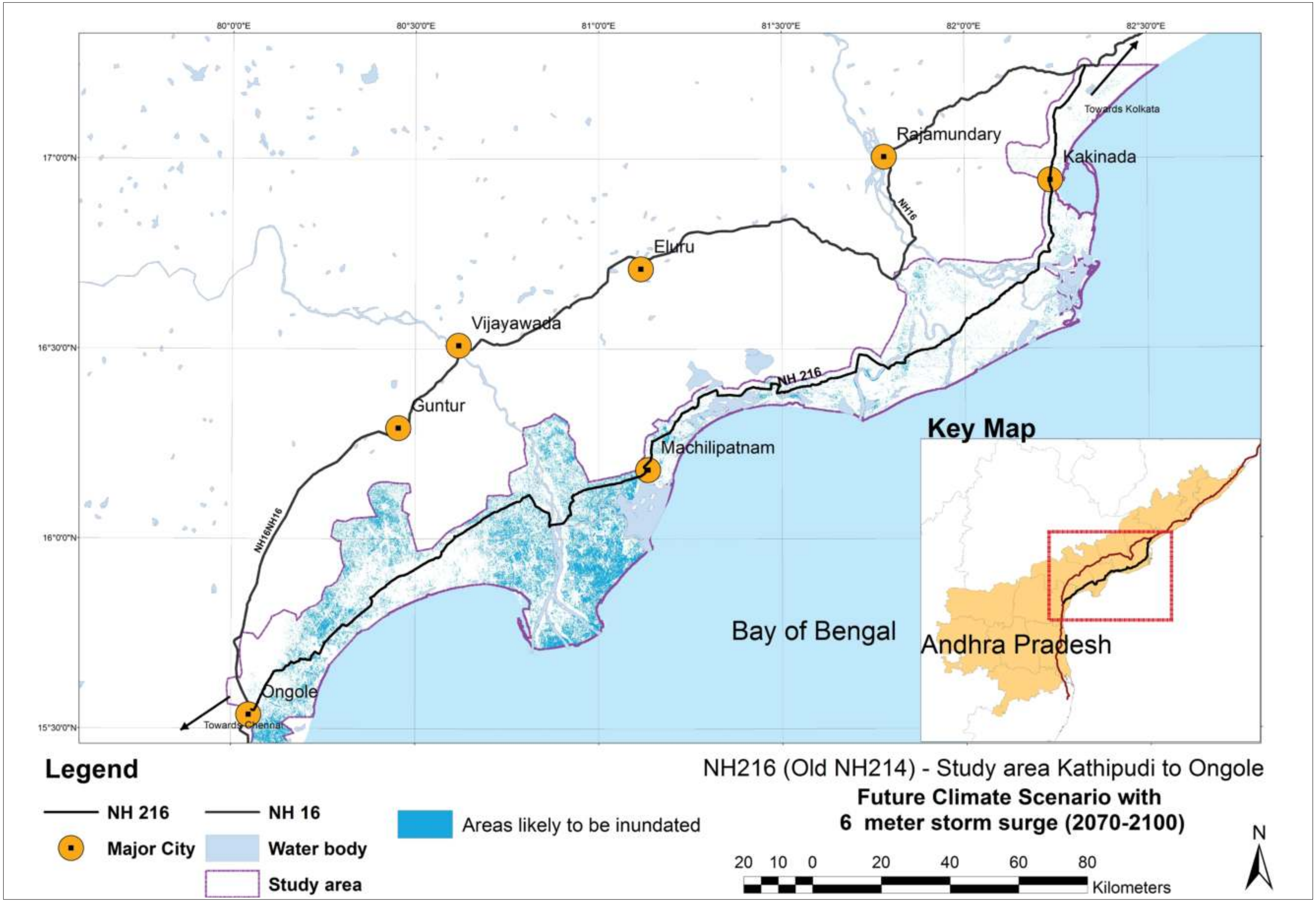
Map 17: Change in rainfall over very wet days in future (2070–2100)

Source: TERI Analysis 2016 based on (Rao et al., 2013)



Map 18: Future Climate Scenario with 4 m storm surge

Source: TERI Analysis (2017) 2016



Map 19: Future Climate Scenario with 6 m storm surge

Source: TERI Analysis (2017) 2016

from the above mentioned study has been plotted on the demonstration stretch for the time period 2070-2100 (Map 17). It is observed that an increase of upto 50% is observed in the extreme wet day's contribution to the total rainfall for the overall stretch in the future, especially the stretch between Kakinada to Bapatla. Thus towards the end of the century, the rainfall on very wet days may increase substantially over the study stretch. This result is consistent with the findings of Krishna Kumar *et al*. (2011) that the intensity of rainfall on a rainy day may increase in the future over most of the Indian sub-continent.

Cyclones and storm surges

TERI's study titled 'Climate Resilient Infrastructure Services' (TERI, 2014) has been referred for building future storm surge and consequent inundation scenarios for the time period 2070–2100 (Maps 18 and Map 19). Vulnerability of roads and highways in the study area is likely to aggravate in the future in light of the findings of IPCC, 2013 and MoEF (2010) which indicate an increase in the frequency and intensity of cyclonic events on the eastern coast of India. It is also understood that a Category 5 cyclone can cause a surge height of 4 m and above, depending on the wind speed (MoEF, 2010). Based on these considerations, two storm surge scenarios of 4 m and 6 m were taken into account for mapping the future exposure profile of the study stretch to cyclones and resulting storm surges. The storm surge scenarios were plotted on the USGS DEM dataset in Arc GIS 10 platform. Maps 18 and 19 depict the areas that are likely to be inundated in the storm surge scenarios for 4 m and 6 m surge above mean sea level over the study stretch as demarcated through this mapping exercise.

Step 5: Identification of vulnerable hotspots

A VA mapping of the study area has been conducted based on climatic and non-climatic parameters discussed in Step 2 to identify vulnerable hotspots. Table 17 gives an overview of the vulnerability criteria considered for the parameters

To begin with, an exposure profile of the selected stretch has been developed with respect to inundation and past hydro-meteorological extreme events (cyclones). A detailed discussion on the outcomes exposure analysis based on these two parameters is detailed as follows:

- Inundation-prone areas—Highways in the coastal areas are typically vulnerable to inundation/ flooding due to a combination of factors, such as topography (low-lying areas), extreme rainfall events, and storm surges as a result of cyclones and high wind speeds. In order to develop the exposure profile with respect to inundation/ flooding, the locations have been plotted based on historical data (2012–2016) sourced from NRSC,

Table 17 Vulnerability Parameters for study stretch of NH 216

Sl.No	Parameters	Criteria	Vulnerability Scoring					
			Low	Score	Moderate	Score	High	Score
1	Inundation prone area based on past events (2012–2016)	Inundated areas in the past	Other areas (non-affected areas)	0	-	1	Affected areas	2
2	Areas effected by high cyclonic event in the past (1980–2015)	Frequency and intensity of the cyclones	Low risk		Moderate risk		High risk	
3	Future Climate Scenario with a 6 m storm surge, (2070–2100)	Elevation from Mean Sea Level	Above 6 m		-		Below 6 m	
4	Change in rainfall over very wet days in the future (2070–2100)	Percentage change	Up to 0 %		0–20%		20%–50%	

Hyderabad, over the selected stretch in Arc GIS platform (Map 20). A vulnerability ranking of high and low has been assigned to the affected and non-affected areas, respectively, based on past data. It is observed that the section from Machilipatnam to Ongole is most risk prone to inundation.

- Past extreme events (cyclones)—To map the areas at risk to high intensity cyclonic events, the areas affected by severe cyclones, extremely severe cyclones, and super cyclones during 1980–2015 were plotted over the study area in Arc GIS platform. The affected areas were identified based on the path and land fall points of the cyclones (Map 16). It is understood from the discussion in Chapter 2, 'Impact of Climate Change on Highways', that such high-intensity cyclones have caused major damage to roads and highways in the past. A vulnerability ranking of high, moderate, and low has been assigned to the areas effected by high cyclonic events in the past (1980–2015) based on the frequency and intensity of cyclonic events.

In order to assess the overall climate vulnerability of the selected stretch, the two exposure profiles were overlaid with the future extreme rainfall scenario in terms of the contribution of extreme wet days to the total rainfall in the near future (Map 17) and the future storm surge scenario with 6 m surge height (Map 19) have been plotted on the stretch. For Map 17, change in rainfall over wet days a vulnerability ranking of low, moderate, and high has been assigned to the ranges of up to 0%, 0%–20%, 20%–50%, respectively. For Map 19, a vulnerability ranking of high and low has been assigned to the areas above 6 m elevation and below 6 m elevation from mean sea level, respectively based on past data.

As an outcome of this step, the overall vulnerability of the highway stretch has been plotted in Map 21. This final vulnerability map depicts the most vulnerable sections of the selected stretch based on a total vulnerability scoring. The vulnerability scoring has been derived based on the following:

- Equal weightage has been given to all the vulnerability parameters
- A score of 0, 1, and 2 has been assigned to the vulnerability rankings of low, moderate, and high, respectively for each parameter (refer to Table 17).
- The total scores have been classified in the ranges—0–3, 3–5, and 5–7 and have been assigned a ranking of low, moderate, and high vulnerability, respectively.

Based on the score, it may be observed that although the overall stretch is vulnerable to climate change, the sections from Narsapur (15°49'33.92"N 80°22'48.93"E) to Bapatla (16°27'45.29"N 81°49'39.19"E) and Kakinada (16°36'7.72"N 82°2'55.00"E) to Amalapuram (16°55'17.19"N 82°14'15.04"E) are found to be the most vulnerable.

Step 6: Prioritizing areas for investment and interventions: Risk assessment

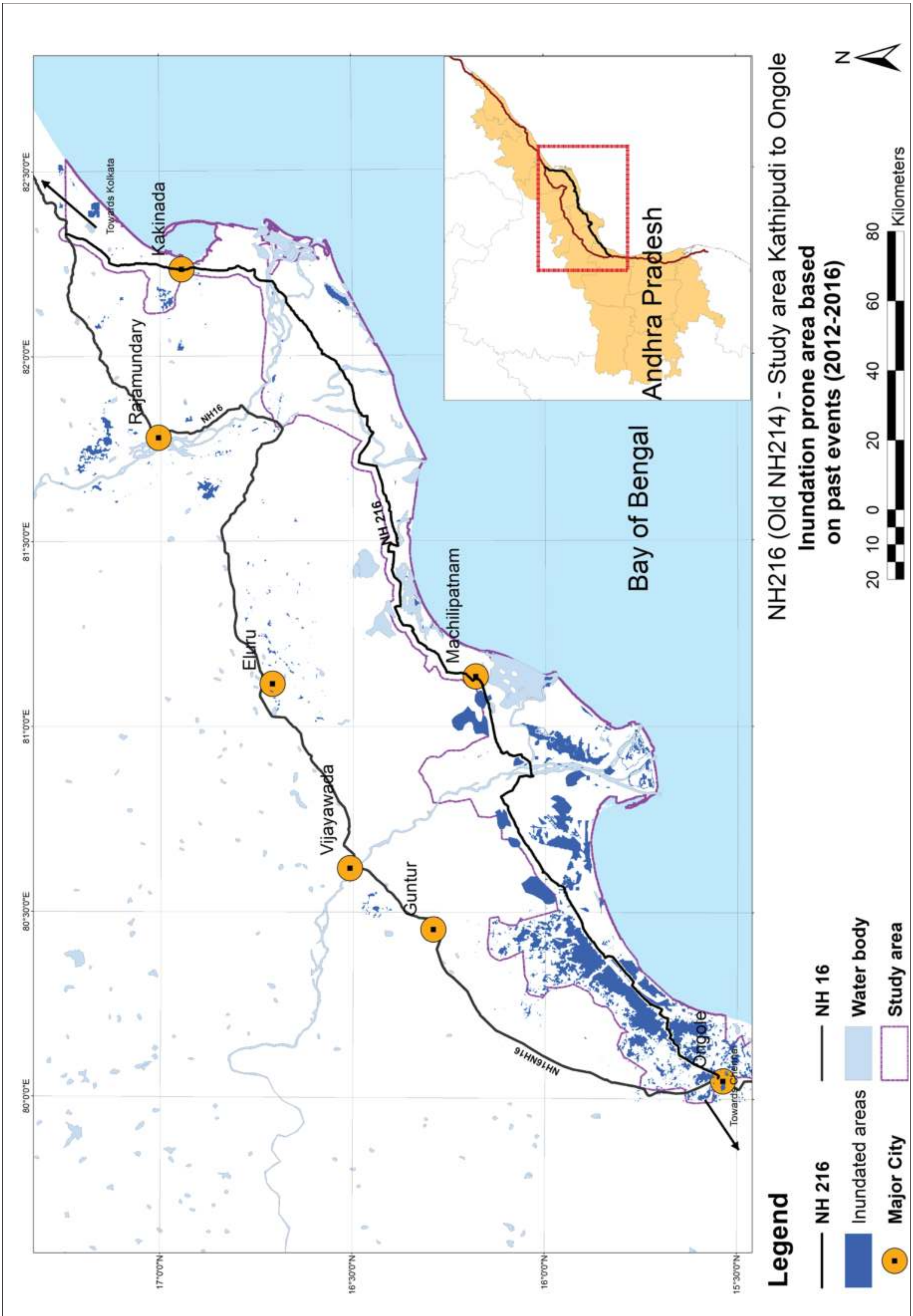
Based on the vulnerability mapping conducted in Step 5, the most vulnerable sections of the selected stretch have been identified (Maps 22 and 23). As stated in Chapter 3, 'Climate Vulnerability Assessment of Highways', the objective of this risk assessment is to identify highway elements and infrastructure that are most risk prone.

As the data that was received for the risk assessment exercise for this stretch was not adequate and could not be utilized, only a broad risk assessment of highway elements and infrastructure could be conducted for the most vulnerable sections. To this end, national level stakeholders and sector experts have been consulted based on the assumptions presented in Table 9, to broadly identify the level of risk the highway elements and infrastructure are prone to. Table 18 presents a broad risk assessment which is based on the consultations.

Table 18: Risk Assessment Matrix for study stretch of NH 216

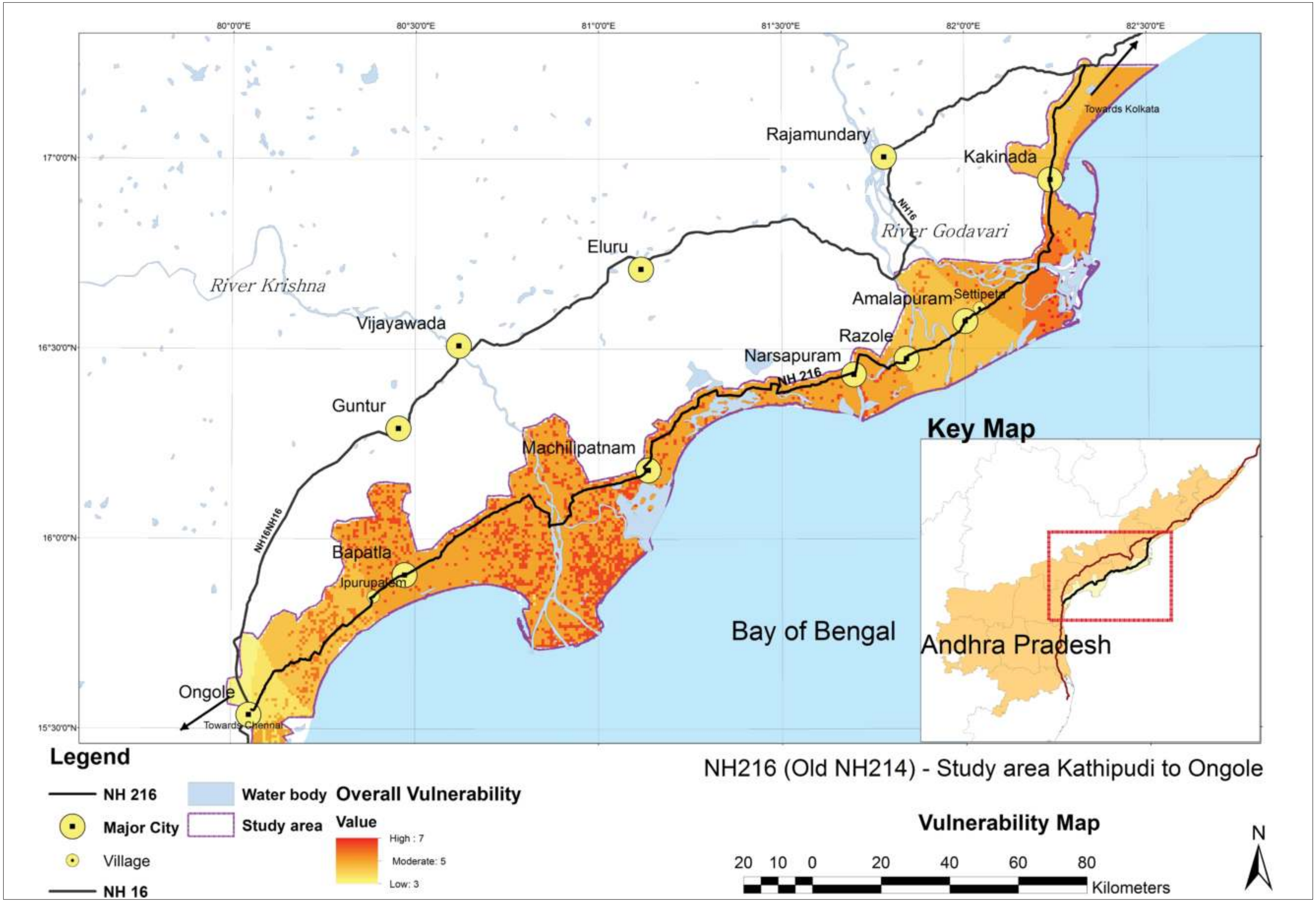
Highways assets and components	Low	Moderate	High
Pavements			
Shoulder			
Embankments			
Drainage			
Lighting			
Road signs			
Kilometre stones			

Flooding due to extreme rainfall and storm surges due to cyclones are the most prominent risks to which this stretch is prone. Therefore, the highway elements and infrastructure, such as drainage, pavements, and



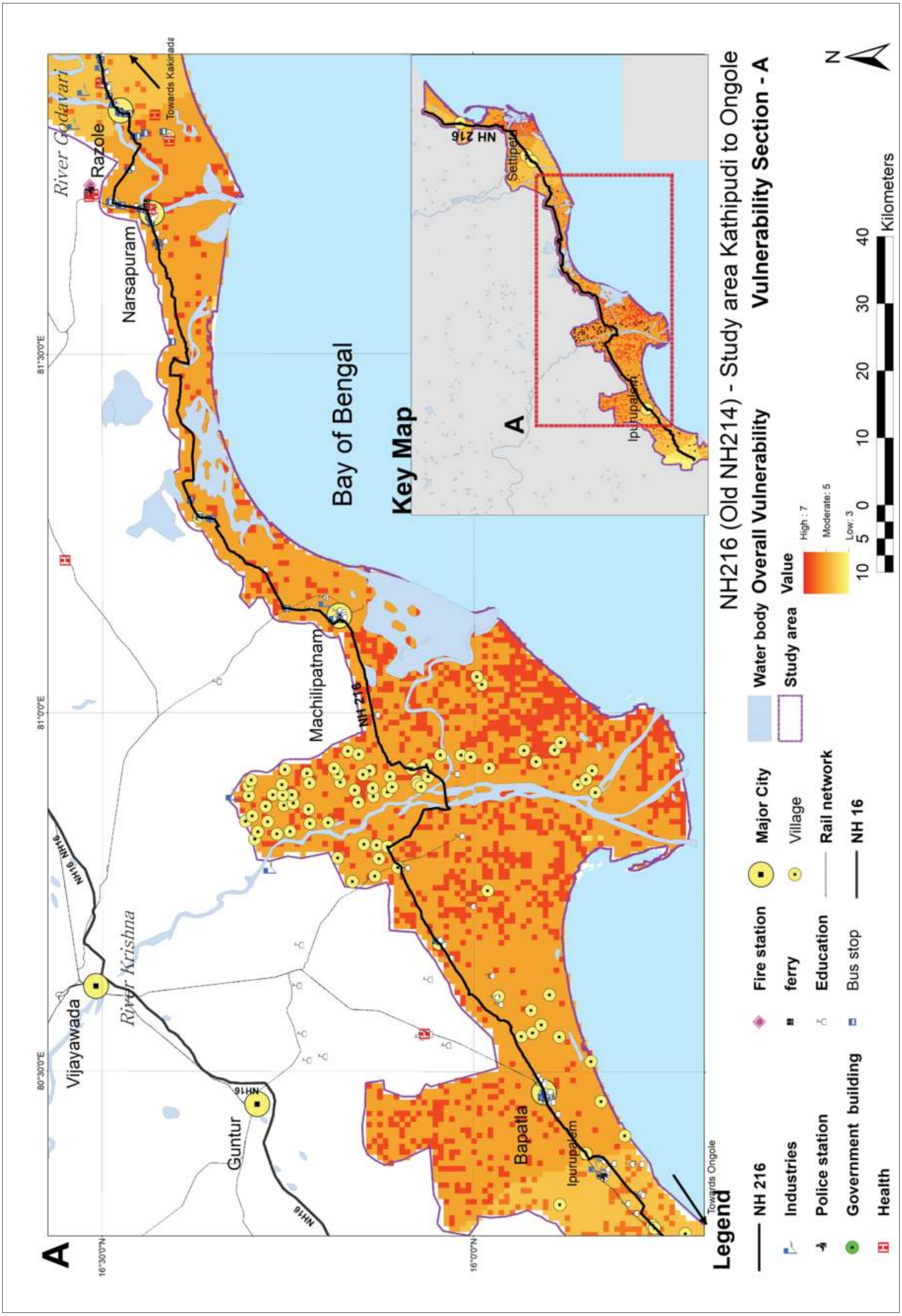
Map 20: Inundation prone area based on past events

Source: TERI Analysis 2016 based on Bhuvan National Remote Sensing Centre (2016)



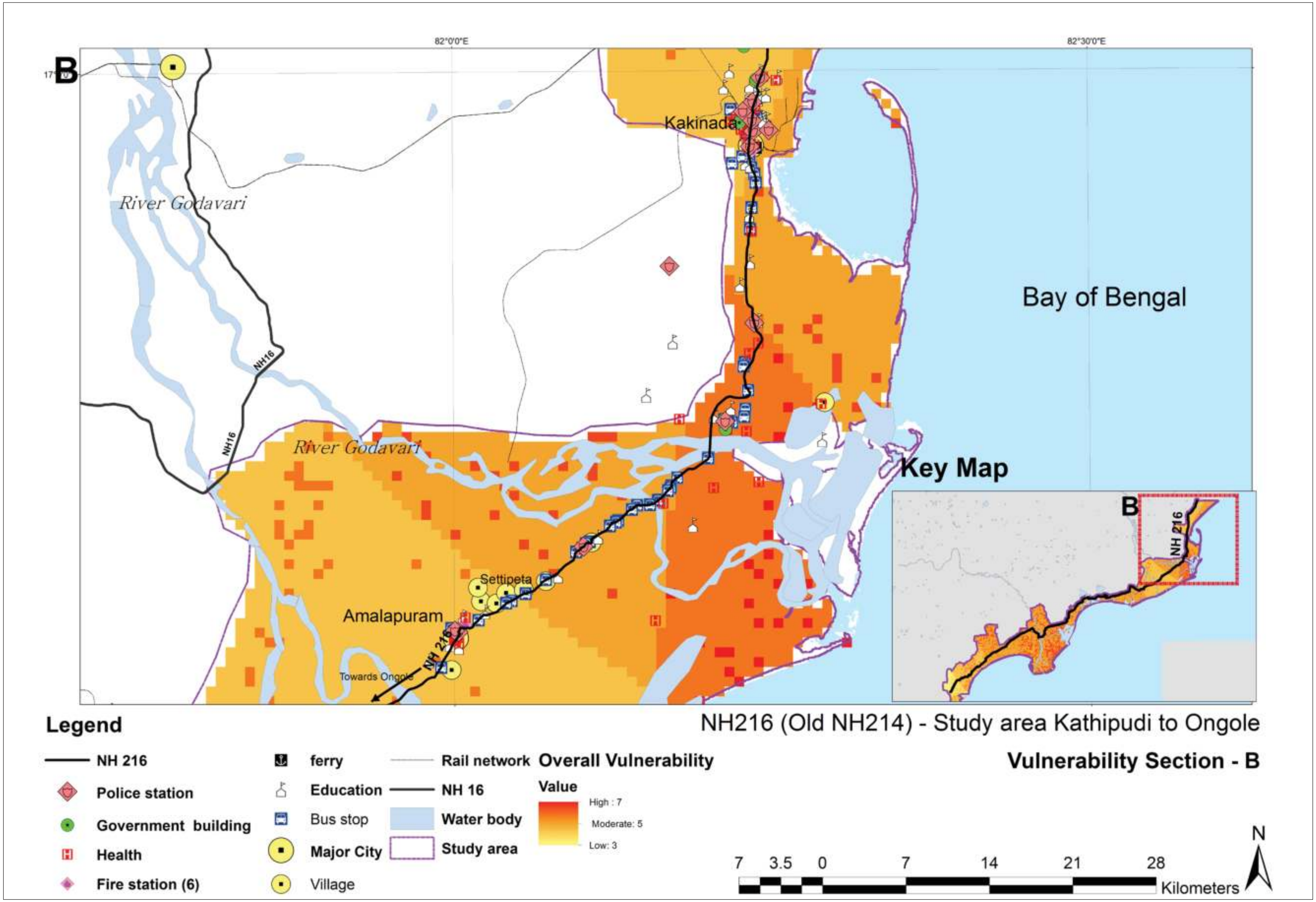
Map 21: Overall vulnerability mapping for NH 216

Source: TERI Analysis 2016



Map 22: Highly vulnerable section A for NH 216 - Narsapur to Bapatla

Source: TERI Analysis 2016



Map 23: Highly vulnerable section B for NH 216 - Kakinada to Amalapuram

Source: TERI Analysis 2016

shoulders, which have a high probability of being directly affected by flooding, fall under high risk. Assets, such as lighting and road signs which have less probability of being impacted and are not directly affected, fall under low risk.

Step 7: Identifying interventions for resilience building

Based on the outcomes of VA (Step 5), the most vulnerable section within this demonstration stretch has been identified. This particular section, which qualifies as the most vulnerable stretch must be prioritized when implementing the recommended engineering adaptation solutions during upgradation and maintenance stages. Similarly, based on the vulnerability ranking, implementation of interventions on the remaining sections may be time-phased over the highway stretch.

The outcomes of the risk assessment conducted (Step 6) for the most vulnerable section indicates drainage, pavements, and shoulders as high-risk elements. Hence, the recommended engineering interventions can focus on these elements. The engineering interventions primarily include structural measures that focus on reducing impacts of climate hazards or protecting the highway from flooding/inundation and erosion as a consequence of extreme rainfall, storm surges, and sea level rise. There are several engineering interventions that can be recommended to address coastal hazards affecting roads. However, it is important to note that even though coastal adaptation measures can reduce vulnerability to coastal hazards, total protection from coastal flooding and erosion is not achievable.

In this study, however, specific interventions that are optimal and feasible for this stretch/ section have not been recommended. This is possible only through a further detailed analysis which could not be conducted in the time available for this study. The interventions that can be adopted in this stretch should focus on drainage, pavements, and shoulders, considering they are at high risk. Therefore, the recommended engineering interventions for the coastal stretch to prevent coastal road base erosion, and coastal road flooding are:

- Embankment slope vegetation to protect and minimize damages on highways due to coastal flooding and erosion.
- Greening of coastal belt which acts as a buffer and provides protection/ reduces damages due to cyclone related flooding and winds.
- Use of spun concrete electric poles instead of the normal electric poles in order to better withstand extreme winds
- Improve redundancy of the highway by the construction of a by-pass route—On field, highway experts recommended that retrofitting to enhance the resilience of the existing roads is generally not a financially viable option; hence, the construction of an alternative route taking into consideration appropriate height and alignment in the context of flooding is recommended.

Apart from the above, there are other interventions which serve the purpose of minimizing climate risks and also have added social, environmental and economic benefits. However they are generally very costly to implement and may require a cost benefit analysis. A few have been listed below:

- Coastal armouring, such as building sea walls, breakwater, storm surge barriers, etc.
    - Seawalls are structures which function as coastal defences. Besides, they also prevent erosion of the shoreline and are built parallel to the shore and aim to hold or prevent sliding of the soil while providing protection from wave action.
    - Sea dykes are hard-engineering structures built to protect low-lying, coastal areas from inundation by the sea under extreme conditions.
    - Breakwaters—Artificial offshore structure protecting infrastructure from the action of waves.
    - Surge barriers are movable or fixed barriers or gates which are closed when an extreme water level is forecast in order to prevent flooding.
- Use of geo tubes and geo containers for storm surge protection, also for breakwaters
- Underground cabling of electricity and other communication lines.

5 Recommendations for Building Resilience of Highways Sector in India

5

Recommendations for Building Resilience of Highways Sector in India

Based on the findings of the literature review, stakeholder consultations, and VA of the demonstration stretches, this chapter documents the engineering and non-engineering interventions for resilience building of the NH in India. The chapter also classifies these interventions based on the impacts of climate change on NHs in various regions across India, namely, hilly, coastal, desert, plains, etc. These are further classified into no-regret, low-regret, and win-win solutions for prioritizing resilience-building options.

5.1 Engineering interventions

Specific interventions for the two demonstration stretches—hilly and coastal—have been suggested in this chapter. However, given the fact that NHs carry about 40% of the total road traffic (NHAI, 2014), it is important that appropriate resilience-building interventions are identified for NHs in other regions of the country as well. To this end, engineering interventions have been recommended to address climate change impacts in different regions across India. Table 19 indicates the suggested region-wise engineering interventions that can be adopted in these regions in line with the impacts of climate change on NHs as tabulated in Chapter 2, 'Impact of Climate Change of Highways' (Table 4). Table 19 also provides a list of guidelines, codes, and standards and manuals, wherein the engineering interventions, recommended as part of the study, already exist. This provides an overview of the potential entry points for mainstreaming climate resilience in NHs, also stressing on the need to enforce and revise IRC guidelines and codes to take the resilience agenda forward.

5.2 Non-engineering interventions for mainstreaming climate resilience in the National Highways sector

Building resilient roads and highways is a multi-step process that requires interventions and inter-departmental coordination at both national and sub-national levels and during all the phases of a road project—planning, construction, and operations. At present, in the absence of a specific, comprehensive policy on climate resilience of roads and highways sector, there are no mandates and implementation mechanisms to ensure the integration of climate resilience in the roads sector. There are only a few guidelines which have attempted to factor in climate parameters. As stated in Chapter 1, 'Introduction', the Indian Roads Congress (IRC) has come out with codes that provide guidelines to address climate parameters and associated climate risks. However, IRC is only an advisory body for the planning and designing, transportation, legislation, and research associated with the development and maintenance of roads and does not mandate the use of the codes. Also, the codes are out dated with no inclusion of new state-of-art technology options available globally.

Table 19: Region-wise engineering interventions

Region	Climate stressors	Impact on highway elements and infrastructure	Engineering intervention	References in the existing codes and guidelines	Proof of concept
Desert, plains, coastal	High temperatures	• Softening of pavement resulting in rutting and shoving • Buckling, heaving at joints of the pavements • Cracking of pavements rendering it more susceptible to rains and potholes, and also affecting structural stability	• Use of road surface grids, such as glass grids, composite geo grids, steel meshes, etc., for structural reinforcement of asphalt pavements to provide lateral restraint to asphalt, hence improving resistance to rutting and shoving • Use of paving fabrics as a moisture barrier to reduce cracking • Use of appropriate asphalts and asphalt binders to prevent cracking of pavements	• MoRTH specification for roads and bridge works; Section 700-Geosynthetics and Reinforced work • IRC: SP: 59-2002 (currently under revision) to cover all geo synthetics and not just geotextiles	• Laying of geo grid at Gharni–Nitur–Nilanga Road SH-167, Latur, Maharashtra[i]* • Use of glass grids in Lucknow–Sitapur NH 24 and Cochin International Airport, Kerala[ii,iii]
			• Microsurfacing technology (cold mix asphalt, defined aggregate, and bitumen emulsion), helps in preserving pavement strength and preventing cracks	• IRC: SP:81-2008 Tentative Specification for Slurry Seal and Micro surfacing	• Belgaum–Maharashtra Border road project NH 4 (Maintained by North Karnataka Express Ltd)
			• Use of crack sealing materials, such as asphalt emulsion slurry seal, asphalt cements and fiberized asphalt, self-levelling silicone, etc. to prevent the intrusion of water through the crack	• IRC 57-2006 Recommended Practice for Sealing of Joints in Concrete Pavements	• Usage of asphalt emulsion slurry seal for crack sealing and periodic maintenance of New Delhi Municipal Corporation roads[iv]
			• Patching- Process of repairing potholes to prevent water seepage.[21] Materials for patching include hot mix asphalt, asphalt emulsion mixes, stockpile patching mixes, and proprietary patching mixes	• IRC 116: Specifications for Readymade Bituminous Pothole Patching Mix Using Cut-Back Bitumen	• Pot holes are repaired by patching mix, used for NH 2, Sukhdev Vihar, Delhi[v]

[21] Basically Patching is done in two ways-Full-depth patching where entire pavement surface layer over the patching area is removed and deep patching where four or more inches of the pavement surface course is removed. For asphalt pavements both full-depth and deep patching are applicable but for concrete roads only full depth patching is applicable.

Table 19: Region-wise engineering interventions

Region	Climate stressors	Impact on highway elements and infrastructure	Engineering intervention	References in the existing codes and guidelines	Proof of concept
Coastal, hill and plain	Intense rainfall/ Extreme Precipitation events	• Increase of pore pressure in pavement layers of roads resulting in revelling of pavement surface	• Use of water soluble, UV and heat-stable chemical soil modifier to reduce swelling. These soil modifiers waterproofs compacted soil and prevents revelling of pavements surface. However, the longevity of this treatment is yet to be established	Reference of chemical stabilizers in IRC: 37-2013–2015- Design of Flexible Pavement	Kulesra–Surajpur road section of the DSC road of Greater Noida
		• Erosion and subsidence of paved roads.	• Increased soil stabilization through compaction, drainage, mechanical stabilization, and chemical stabilization to increase soil strength and the resistance of soil to softening by water	IRC 28-1967: Tentative specifications for the construction of stabilized soil roads with soft aggregate in areas of moderate and high rainfall IRC 88-1984: Recommended Practice for Lime Fly ash Stabilized Soil base/Sub-base in Pavement construction IRC SP-89-2010: Guidelines for Soil and Granular Material Stabilization using Cement Lime and Fly Ash IRC 56-2011: Treatment of embankment slope for erosion control	Usage of lime fly ash to stabilize soil base/sub-base in pavement construction of NH 4 Satara to Kolhapur stretch (Mukherjee and Gaurang, 2013).
			Using natural or synthetic erosion control mat for the prevention of erosion of side slopes of the pavement section		Treatment of the embankment slope at NH7 Karur–Madurai, Tamil Nadu

Table 19: Region-wise engineering interventions

Region	Climate stressors	Impact on highway elements and infrastructure	Engineering intervention	References in the existing codes and guidelines	Proof of concept
		Infiltration of rainwater into the layers below and thus damaging the structural stability of the road	Geo-composite drainage systems for both drainage under pavements and drainage behind retaining walls i.e. fin drains. To improve drainage capacity Provision of impermeable interlayer, i.e., Paving fabrics which works as a moisture barrier to prevent cracking	IRC 34-1970: Road Construction in water logged area IRC SP: 42- 2014: Guidelines for urban drainage IRC SP 59-2002: Guidelines for use of geotextiles in road pavements and associated works	Geotextile for sub grade Stabilization at Jejuri - Morgon Road MDR-65[vi] Geotextile for separation, filtration and drainage at Link Road between Paithan Road to Nagar Road, Aurangabad, Maharashtra[vii]
		Water overtopping and wash away of road pavement	Proper geometric design (slope, camber) and provision of side drains of required capacity.	Manuals for Specifications and & Standards for 2, 4 and 6 lanes	4 Laning of Pathankot–Amritsar section of NH 15
		Reduced capacity of drainage system due to debris accumulation, sedimentation, erosion, scour piping, and conduit structural damage, thereby resulting in flooding of roads	Annual and periodic maintenance of drainage, particularly in pre monsoon and monsoon period. Provision of causeways and vented causeways to cater to HFLs and flash floods	IRC 34-2011: Recommendations for road construction in waterlogged areas. IRC SP: 42-2014 Guidelines of road drainage IRC: SP:83-2008 guidelines for maintenance, repair and rehabilitation of cement concrete pavements IRC: SP: 73-2015, IRC: SP-84-2014, IRC: SP -87-2013, Manuals for Specifications and Standards for 2, 4, and 6 lanes, respectively	
	Storms/dust storms and stronger winds	Clogging of roadside drains due to debris from storm	Annual and periodic maintenance of drainage	IRC SP: 42-2014 Guidelines of Road Drainage IRC SP: 83-2008 Guidelines for maintenance, repair and rehabilitation of cement concrete pavements	

Table 19: Region-wise engineering interventions

Region	Climate stressors	Impact on highway elements and infrastructure	Engineering intervention	References in the existing codes and guidelines	Proof of concept
Hills	Intense rainfall/ Extreme Precipitation events	Risk of landslides, rock falls, and floods from run off Slope failures	Protection measures–Containing or directing the rocks to ditch or other catching structures, such as Geo-nets/ Drapery systems, wire meshes, rock bolts, berms and benching, rockfall ditches and trenches, rock sheds and tunnels, rockfall barriers, and embankments (gabion walls, structural walls, etc.) Protection measures–Use of erosion-control mats/blankets and other bio-engineering measures, such as hydro seeding methods, mulching, etc. Retention Measures–Use of slope reinforcement with rock bolts, soil nailing, mesh with anchors and grouting, etc. Prevention measures–Modification of slope geometry by removal of material from the upper areas, reduction of slope angle and trimming of loose surface material, reinforcing slope face, benching etc. Prevention Measure–Improving slope stability through the installation of drainage systems, that most often consist of horizontal weep	IRC HRB Special Report 23 B 23 State of the Art-Design and Construction of Rock fall Mitigation Systems IRC: SR:15 State of the Art: Landslide correction Techniques IRC SR:21 State of the Art: Use of Just Geotextiles in Road Construction and Prevention of Soil Erosion/Landslides IRC:SP: 106-2015- Engineering Guidelines on Landslide Mitigation Measures for Indian Roads IRC 56-2011: Treatment of embankment slope for erosion control IRC SP: 48 1998 Hill Road Manual IRC SP: 102- 2014 Guidelines for Design and Construction of Reinforced Retaining walls	Rock fall mitigation works along Mumbai –Pune expressway usage of (Mono oriented Reinforced Steel Wire Mesh, Rhomboidal Cable Wire Rope Panels, Dynamic Rock fall Barrier:[viii] Landslip Repair at Mahabaleswar–Tapola Road and Widening of Hill Road at Kelghar Ghat under Maharashtra Public Works Department Protection measures by planting of shrubs and trees in a phased manner for erosion control in intense landslides zone between Kotdwara–Dugadda road, Pauri of Uttarakhand [ix]

Table 19: Region-wise engineering interventions

Region	Climate stressors	Impact on highway elements and infrastructure	Engineering intervention	References in the existing codes and guidelines	Proof of concept
Coastal	Sea-level rise, cyclones, and storm surges	Coastal road flooding and subsequent damages Erosion of coastal road base	Embankment slope vegetation to protect and minimize damages on highway due to coastal flooding and erosion. Greening of coastal belt which act as a buffer and provides protection/ reduces damages due to cyclone related flooding and winds. Coastal armouring, such as building sea walls, breakwater, groynes, storm surge barriers, etc. Use of geo tubes and geo containers for storm surge protection, also for breakwaters	Ganga Flood Control Commission Guidelines for Use of Geotextiles/ Geotextile bag / Geotextile tubes in Construction of Flood Management Works Central Water Commission guidelines–Handbook for Flood Protection, Anti Erosion and River Training Works CRRI Report 2013 -Guidelines for Planning and Construction of Roads in Cyclone Prone Areas	Construction of beach protection bund and groyne using geotextile tubes at Petronet LNG Ltd, Kochi, Kerala, India[x]
		Electric poles, and trees falling on roads	Underground cabling of electricity and other communication lines Use of spun concrete electric poles instead of the normal electric poles in order to better withstand extreme winds	Manuals for Specifications and & Standards for 2, 4 and 6 lanes recommends to follow provisions as per IRC98-2011 Guidelines on Accommodation of Utility Services on Roads in Urban Areas, for accommodating underground utilities	
Plains, hills	Extreme Temperatures and Permafrost	Changes in freeze and thaw cycle making road surfaces more susceptible to potholes and rutting. Extreme high temperatures resulting in cracking of pavements	Use of precautionary measures as per IS 7861- Part 1(hot weather) and Part 2 (cold weather) for extreme weather concreting	IS 7861- Part 1(hot weather) and Part 2(cold weather) for extreme weather concreting	

* Footnotes i–x have been referred in Annexure 4 of this Report.

Sources: (Nanotechnology for water resistant soil bases, 2017), (New technology for dust control, erosion resistance and water resistance , 2017), (Zydex Road Solutions, 20017),Rajesh S. Gujar, et al. (2013), (Bobrowsky, 2008), (Roychowdhury, 2015), (Bureau of Indian Standards, 1999), (ndian Roads Congress, 1998), (The Indian Road Congress, 2011), (TERI's stakeholder interactions 2017), (Indian Road Congress, 2017)

Considering that climate change is of critical concern, it is important that these concerns be integrated in the planning and management of roads and highways. There is a need to strengthen the interlinkage of planning, design, construction, and maintenance of roads and climate-resilience measures at the policy level. This calls for a comprehensive climate mainstreaming plan to steer the current and future course of highways management.

Mainstreaming climate resilience (Box 3) in the roads and highways sector will need a multi-pronged approach.

BOX 3: MAINSTREAMING

Mainstreaming can be defined as the "integration of climate change related policies and measures into developmental planning process and decision-making." (Eriksen, 2005)

Institutionalizing a dedicated climate change unit in the Ministry of Road Transport and Highways (MoRTH), Government of India; the primary objective of this will be reducing carbon footprint and enhancing resilience of NHs. The unit will be the nodal point for coordinating research and development activities, data management and information sharing, formulation, and enforcement of codes and guidelines for resilience building of NHs in the country. The unit will also coordinate with other government agencies and stakeholders, including the NHAI, IMD, NIDM, NDMA, ISRO/ NRSC, and state-level departments, such as disaster management/ revenue departments, PWD, environment and forest departments, and state transport department, to name a few. The unit will become an interface for the state PWDs on issues pertaining to climate adaptation and resilience. The unit will also play a key role wherein studies and actions on climate resilience will be conducted and streamlining and financing of the same will be facilitated. It is recommended to empanel a set of consultants /expert agencies that can support the unit in conducting these VA studies. The unit will also act as an interface between external aid agencies and technical agencies, such as research and academic institutes that aid in developing knowledge and technical capacities to build resilience. Figure 11 presents the proposed interlinkages for institutionalization of the unit .

- **Mainstreaming planning and approval processes**—Climate change considerations should be included as one of the key parameters during the planning and design stage of the highway network and projects. Identification and mapping of vulnerable areas at the regional scale and detailed risk assessment studies for high vulnerability stretches should be made mandatory by MoRTH as part of the planning and approval process for expansion and upgradation of roads and highways. It is advised that stretch-level VA should be conducted for all highway stretches. However, to start with, it is recommended that stretch level VA should be made mandatory for all highway stretches falling in the vulnerable regions identified under the network level VA conducted for this study. To this end, it is recommended that Vulnerability Assessment should be included in the ToR prepared by the project proponents for the DPR consultants and also be incorporated in IRC-SP: 19-2001: Manual for survey, investigation and preparation of road projects. This will ensure that the Vulnerability assessment will be conducted as part of the feasibility study. Then based on the recommendations that emerged from the VA

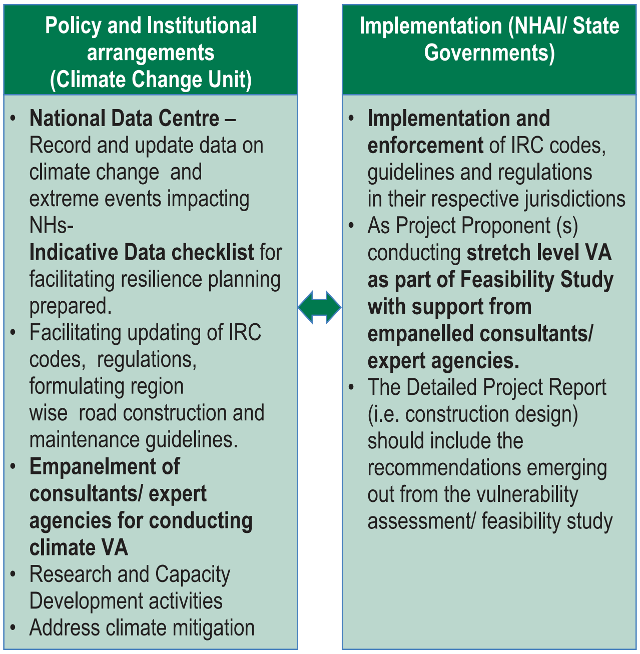


Figure 11: Mainstreaming of proposed institutional changes

carried out as part of the feasibility study, the Detailed Project Report (DPR) should include the cost of the engineering interventions that need to be implemented for enhancing the climate resilience of the highways.

- **Formulation of region-wise construction and maintenance guidelines**—The stakeholder consultations conducted as part of this study indicate that the current construction and maintenance practices for NHs are not sensitive to the changing climate. The study also indicates that climate change impacts on roads and highways vary across different regions in the country. Moreover, it is observed that appropriate maintenance practices and schedules will play an integral role in resilience building of roads and highways. Therefore, it is suggested that region-wise construction and maintenance guidelines be formulated by the MoRTH, with support from the proposed climate change unit and Indian Roads Congress (IRC) and be implemented and enforced by National Highways Authority of India (NHAI) and State PWDs depending on their jurisdiction.
- **Facilitating updating and enforcement of existing Codes**—IRC codes are a set of guidelines for road development in India. However, these codes are outdated and do not include new technology options (Roychowdhury, 2015). They also do not address emerging concerns such as climate change. It is recommended that relevant codes and guidelines be updated by the IRC with assistance from the proposed climate change unit and its provisions be made mandatory by the MoRTH to address construction and maintenance practices in the light of climate change impacts. For instance, IRC Codes: SP-48-1998, IRC 56, IRC 104, IRC 034-2011, IRC 28-1967, etc., pertaining to the development of roads in hilly regions may be updated and enforced to build climate resilience of hilly highways. Other relevant codes that need to be enforced include IS Codes, such as 7861-Part 1 (hot weather) and Part 2 (cold weather). These updated codes and regulations shall be implemented and enforced by the NHAI and State PWDs depending on their jurisdiction.
- **Interdepartmental coordination at national and subnational levels**—Resilience building of the highways sector requires coordination amongst multiple departments at the national and subnational levels, especially with respect to information sharing and policymaking. These will include IMD, MoRTH, NHAI, State PWD, disaster management department, etc. The proposed climate change unit will play a key role in this process. Similarly, coordination between various committees of the IRC will also be imperative to ensure climate resilient road development in India.
- **Data management**—Collection and integration of data for resilience building of the highways sector was found to be a challenging process during the course of this study. In most cases, the required data was not available, for instance, data on risk-prone locations based on past events, measures adopted for the same, operational data, etc., and if it was available, it was not in an appropriate format. Therefore, it is recommended that specific data for the purpose may be recorded and updated regularly by relevant highway authority. To start with, a broad data checklist has been developed based on the learning and experience from this study and presented in Table 20 with an objective of facilitating resilience planning efforts for the NH sector in India.

  Moreover, existing data efforts on climate and non-climate parameters related to NHs by other departments and agencies also need to be collated by the proposed unit. For example, the IMD maintains a data set on daily weather forecast specific to highways, which when combined with other vulnerability parameters, has the potential to be developed into an early warning system for contingency planning for highways.
- **Research and capacity development**—It is recommended that research and capacity development is required to explore alternative construction materials and technologies and also bridge knowledge and capacity gaps of highways engineers, practitioners, and consultants. International literature review and interactions with relevant stakeholders indicate numerous capacity gaps, identified as follows, at various

Table 20: Indicative data checklist for facilitating resilience planning efforts for the NHs sector in India	
Parameters	**Data required**
Climate Data	• Temperature (maximum and minimum): daily (for the past 20–30 years), Temperature extremes: last 20–30 years • Rainfall/precipitation: Daily (past 20–30 years), Highest 24-hourly rainfall: last 20–30 years • Other precipitation: snow • Wind speed daily: last 5 years
Extreme events and disasters	• Past history of extreme events and natural disasters: last 20–30 years • Damage caused during extreme events • Cost incurred to rebuild and renovate post the extreme event/disaster
Future Climate projections	• Data to be extracted from previous national and international studies for future climate projections
Physiography	• Physical terrain: topography, slopes, and geological and geo-hydrological characteristics
Land use	• Surrounding settlements, forest cover, eco-sensitive areas agricultural land, water bodies, industrial areas, services, and infrastructure
Highways elements and infrastructure	• Drainage, embankment, pavement thickness, crash barriers, sign boards, etc.
Highways materials and construction techniques	• Material used for road construction, details of the construction technology used for constructing the road.
Traffic data	• Annual Average daily traffic (AADT) in PCUs differentiated by vehicle categories for the last 5 years • Peak traffic period of the year (monthly data) • Peak traffic recorded (in PCUs) during the peak period (specify in terms of Average Daily Traffic)
Highway infrastructure assets	• Location and condition of the various elements of infrastructure that comprise the highway network: • Street lights – numbers and distance • Storm water drainage system – type • Safety barriers and their types • Trees/ vegetation – type and numbers
Location of cities and infrastructure	• Million plus cities, other important cities with respect to tourism, trade, pilgrimage, etc. • Airports, ports, railway stations, etc.

levels for the resilience building of the highways sector in India.

- Lack of updated climate thresholds for extreme rainfall
- Flood levels impacting roads
- Factors for defining the criticality of roads
- Climate VA at national or subnational level for the roads/ highways sector
- Viable technology options for highway resilience in India

As a way forward, it is recommended that the MoRTH addresses these gaps for capacity development in the highways sector. This will also help in identifying specific entry points for mainstreaming climate change considerations in the IRC codes. Training and capacity building of highway engineers, practitioners, and consultants is also required to address resilience building of highways.

It may be noted that these recommendations are based on stakeholder consultations, discussions with sector experts, international literature review, and the outcomes of VA of the two demonstration stretches (hilly and coastal). Although this study only focusses on the NH sector, it is suggested that the MoRTH may recommend these interventions for resilience building of roads and highways sector in India to other relevant agencies at the national, state, and city levels, apart from the NHAI.

5.3 Identifying no-regret, low-regret, and win-win options for building the resilience of the highways sector in India

The existing literature suggests that climate proofing infrastructure to make it resilient to future climate risks and uncertainties will require additional financial costs. A World Bank study estimates that the price tag between 2010 and 2050 for adapting to an approximately 2 °C warmer world by 2050 will be in the range of $70 billion to $100 billion a year (World Bank, 2010a). Out of this, infrastructure sector, including roads and highways, has accounted for the largest share of adaptation costs based on past studies (World Bank, 2010a). At the same time, it is generally accepted that $1 of preventive measures equals to $5 of repairs (Pacific Region Infrastructure Facility, 2013). Therefore, in order to prioritize investment decisions, it is imperative to quantify and understand the economics of adaptation—the costs and co-benefits. As per the IPCC, adaptation cost is 'the cost of planning, preparing and facilitating and implementing climate change adaptation measures including transition costs" and benefits as 'the avoided damage costs or the accrued benefits following the adoption and implementation of adaptation measures' (United Nations Framework Convention on Climate Change, 2011). Specific tools and methodologies for quantifying these costs and benefits are still emerging (World Bank, 2015).

In the Indian scenario, such cost-benefit assessments for climate adaptation in the infrastructure sector are practically non-existent. Moreover, this study revealed that post-disaster assessments of loss and damage are typically limited to direct physical impacts and repair costs only. For instance, the data collected for hilly stretches reveal that the repair cost for addressing the direct physical loss and damage due to extreme rainfall in June 2013 was to the tune of ₹13.9 lakh/ km (Public Works Department, Himachal Pradesh, 2013). However, no data was recorded for the overall accrued economic losses as a result of the damage to the highway. This presents a challenge in quantification of the benefits of adaptation interventions, and subsequent classification of the proposed interventions into no-regret, low-regret, and win-win options. Therefore, a review of the existing literature on classification approaches adopted globally and inputs from national sector experts have been utilized for the same.

What are no-regret, low-regret, and win-win adaptation options?

When it comes to identifying appropriate adaptation measures, it must be understood that out of the several adaptation options, the most viable options are the ones that result in effective adaptation and are cost-effective (UK Climate Impacts Program, 2007). Moreover, given the uncertainities surrounding climate change outcomes and long-term projections of social and economic development, policies that typically give priority or co-benefits towards development goals or focus on preventing or minimizing risks should be targetted (UK Climate Impacts Program, 2007) . These options are generally referred to as no-regret, low-regret, and win-win adaptation options.

No-regret adaptation options

No-regret adaptation options deliver socio-economic benefits irrespective of future climate change outcomes (United Nations Framework Convention on Climate Change, 2011). These type of options include measures that are cost-effective in the current context of climate variability and risks. No-regret adaptation options focus on near-term projections and objectives and their implementation can provide immediate benefits. Such no-regret adaptations options include actions focussing on building overall adaptive capacities and minimizing risks, for instance avoiding building in high risk areas, improving efficiency and better management of infrastructure systems, such as drainage, etc. Such measures/strategies will require investments but are most cost effective when the immediacy of the targetted risks and realized benefits are considered (UK Climate Impacts Program).

Low-regret adaptation options

Adaptive measures for which the associated costs are relatively low and for which the benefits, although primarily realised under projected future climate change, may be relatively large (UK Climate Impacts Program, 2007). Such options target at maximizing the return on investments by focusing on building the resilience of most vulnerable sectors, assets and communities (World Bank, 2010a). Measures will include options, such as restricting the type and extent of development in flood-prone areas, implementing improved technical standards and use of climate-appropriate technologies in risk-prone areas, developing partnerships and financial/insurance mechanisms for offsetting risks and incentivizing adaptation, etc.

Win-win adaptation options

Win-win adaptation options include measures that have the desired result in terms of minimizing the climate risks but also have other social, environmental, or economic benefits. These types of measures include those that are introduced primarily for reasons other than addressing climate risks but also deliver the desired adaptation benefits (UK Climate Impacts Programme, 2007). Examples include awareness generation and capacity building programmes, flood management and disaster planning, development of data management systems, promoting resource efficiency, climate-proofing new infrastructure, etc. It may be noted here that some of the options would qualify both under categories, that is, no-regret and win-win solutions as they are cost-effective and will have both immediate and long-term impacts and co-benefits.

Table 21 summarizes the parameters that determine the classification of the interventions into the three categories.

No-regret, low-regret and win-win options for building resilience of highways sector in India

Based on the parameters that differentiate no- regret, low-regret, and win-win solutions, both engineering and non-engineering interventions recommended in the study have been classified. Table 22 indicates the different categories under which the recommended interventions have been classified. This classification is primarily based on qualitative assessment (through consultations and discussions with experts/contractors/construction companies) and literature review.

Table 21: Parameters for classifying adaptation interventions

Classification	Time frame	Cost	Benefits
No regret	Immediate benefit; relevant in current climate variability and risk irrespective of the future climate change scenario	Most cost effective for addressing immediate risks	Minimizing risk, building overall capacities, and delivering socio-economic benefits
Low regret	Benefits realized under the projected future climate change scenarios	Additional cost with maximum returns by focussing investments on most vulnerable sectors, areas, and communities	Potentially large benefits under the projected climate change scenarios by offsetting climate risks of the most vulnerable
Win-win	Benefits realized under the projected future climate change scenarios	Additional cost	Desired results for minimizing future climate risks along with social, economic, and environmental co-benefits

Table 22: Classification of interventions

Interventions	No regret	Low regret	Win-Win
Engineering			
Use of road surface grids for the structural reinforcement of asphalt pavements to provide lateral restraint to asphalt, hence improve resistance to rutting and shoving		■	
Use of appropriate asphalts and asphalt binders, depending on the weather conditions to prevent cracking of roads	■		
Use of Micro-surfacing technology to preserve the pavement strength and preventing cracking of pavements		■	
Use of crack-sealing materials to prevent the intrusion of water through the crack into the underlying pavement structure	■		
Patching for repairing potholes and hence preventing water from seeping into the subgrade	■		
Use of water soluble, UV, and heat-stable soil chemical modifier to waterproof compacted soil surface up to 10 mm depth and to reduce swelling and thus prevent revelling of the pavement surface		■	
Increased soil stabilization to help improve the soil strength and increase the resistance of soil to softening by water		■	
Proper geometric design (slope, camber) and provision of side drains of required capacity to prevent water overtopping of pavement and wash away of pavements			■
Provision of causeways and vented causeways to cater to HFLs and flash floods		■	
Improving drainage capacity through the use of geo-composite drainage systems for both drainage under pavements and drainage behind retaining walls, i.e. fin walls			■
Annual and periodic maintenance of drainage, particularly in pre-monsoon and monsoon period	■		
Containing or directing the rocks to ditch or other catching structures, such as Geo-nets/ Drapery systems, wire meshs, rock bolts, Rock sheds, barriers and tunnels, and half tunnels		■	
Use of slope reinforcement with rock bolts, soil nailing, anchors and grouting, etc			■
Modification of slope geometry by removing material from the upper areas, reduction of slope angle and trimming of loose surface material, benching, etc		■	
Coastal armouring, such as building sea walls, breakwater, storm surge barriers, etc			■
Use of geotubes and geo containers for storm-surge protection			■
Greening of coastal belt for cyclone protection			■
Embankment slope vegetation to protect the highway from coastal flooding and erosion			■
Underground cabling of electricity and other communication lines			■
Use of spun concrete electric poles instead of the regular electric poles in order to better withstand extreme winds.		■	
Non-Engineering			

Table 22: Classification of interventions

Interventions	No regret	Low regret	Win-Win
Constitution of a dedicated unit in the MoRTH with an objective of enhancing resilience of NHs			
Planning and approval—Climate change considerations should be included as one of the key parameters during the planning and design stage of highway networks and project. Identification and mapping of vulnerable areas at the regional scale and detailed risk assessment studies for high vulnerability stretches for expansion and upgradation of roads and highways.			
Formulation of region-wise construction and maintenance guidelines			
Updation and enforcement of the existing IRC and IS codes to address and modify construction and maintenance practices in the light of climate change impacts			
Interdepartmental coordination at the national and subnational levels with respect to information sharing and policymaking			
Data management—Collection and integration of data for resilience building of highways sector. Specific data for the purpose may be recorded and updated regularly by the NHAI			
Conducting research and capacity development in the sector			

6 References

American Association of State Highway and Transportation Officials. 2016. *Understanding Transportation Resilience: A 2016–2018 Roadmap.* American Association of State Highway and Transportation Officials.

Anil P, Rakesh K, and Kiran. 2001. The Disaster Management. Himalayan Environment Studies and Conservation Organisation. Uttarakhand.

Asian Development Bank (ADB). 2011. *Guidelines for Climate Proofing Investment in the Transport Sector: Road Infrastructure Projects.* Metro Manila, Philippines: ADB.

Bhuvan National Remote Sensing Centre. 2016. Retrieved December 2016, from Disaster Services(NDEM Public): http://bhuvan-noeda.nrsc.gov.in/disaster/disaster/disaster.php

Bobrowsky, L M. 2008. *The Landslide Handbook: A Guide to Understanding Landslides.* US Geological Survey.

Bureau of Indian Standards. 1999. Indian Standard: Landslide Control Guidelines.

Business Standard. 2014. Cyclone Hudhud damage in AP estimated at ₹8,000 cr; death toll rises to 24.

Canadian Council of Professional Engineers. 2008. *Adapting to Climate Change: Canada's First National's Engineering Vulnerability Assessments of Public Infrastructure.*

Central Road Research Institute. (2009–2010). *Annual Report on Flexible Pavements.* New Delhi: Central Road Research Institute.

Circle of Blue. 2014, May 8. *Uttarakhand Flood Disaster Made Worse By Existing Hydropower Projects, Expert Commission Says*. Retrieved from Circle of Blue: http://www.circleofblue.org/2014/world/uttarakhand-flood-disaster-made-worse-existing-hydropower-projects-expert-commission-says/

Climate UK. 2013. Creating and Managing Resilient Local Highways. Climate Change Northwest.

Cynthia Rosenzweig, W D. 2014. *Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network.*

D Meyer, M. n.d. *Design Standards for U.S. Transportation Infrastructure: The Implications of Climate Change.*

Deccan Chronicle. 2016, December 13. Cyclone Vardah leaves trail of damage across Chennai.

Department of Environment, Science & Technology, Government of Himachal Pradesh. 2012. *State Strategy & Action Plan on Climate Change, Himachal Pradesh.* Shimla: Department of Environment, Science & Technology, Government of Himachal Pradesh.

Down to Earth. 2014. *Floods in 4 states lead to economic loss of ₹19,000 crore in past one year*. Retrieved from *Down to Earth:* http://www.downtoearth.org.in/news/floods-in-4-states-lead-to-economic-loss-of-rs-19000-crore-in-past-one-year-46847.

Dowds, Jonathan and L. A.-H. 2015. *Challenges and Opportunities for integrating climate adaptation efforts across state, regional and local transportation agencies.* U.S. Department of Transportation.

Environment Protection Training and Research Institute (EPTRI). 2012. *State Action Plan on Climate Change for Andhra Pradesh.* Hyderabad: EPTRI.

Eriksen S E H, N L. 2005. Portfolio Screening for Mainstreaming Adaptation to Climate Change. *International Conference on Climate and Development.* Hamburg: Hamburg Institute of International Economics.

Ernst & Young LLP. 2016. *The Paris Agreement; A Universal Call to Action for Governments and Businesses;What it means for India.* Kolkata: Ernst & Young LLP.

Federal Highway Administration, U.S. Department of Transportation. 2017. *Synthesis of Approaches for Addressing Resilience in Project Development.* Washington D.C.: U.S. Department of Transportation.

Federal Highway Administration, U.S. Department of Transportation. 2017. *Transportation Infrastructure Resiliency: A review of practices in Denmark, the Netherlands and Norway.* Washington DC: U.S. Department of Transportation.

Forum of European Highway Research Laboratories (FEHRL). 2013. *The Resilient Road: A Roadmap for Research; An Element of the Forever Open Road.* Belgium: FEHRL Secretariat.

Geofabrics. 2015. *Rockfall Protection.* Retrieved from Geofabrics: http://www.geofabrics.co.nz/civil/rockfall-protection/.

Global Fund for Disaster Risk Reduction (GFDRR). 2010. *Bihar Kosi Floods (2008), Needs Assessment Report.* Retrieved from Global Fund for Disaster Risk Reduction: https://www.gfdrr.org/sites/gfdrr/files/publication/GFDRR_India_PDNA_2010_EN.pdf

Give2Asia. 2016. *Disaster Preparedness and Resiliency: India.* Retrieved from Give2Asia: http://www.give2asia.org/disaster-preparedness-and-resilience-india/

Harvey, M, Whetton P, McInnes K L, Cechet B, McGregor J L, Nguyen K, Houghton N, Lester C, Styles E, and Michael N. 2004. "Impact of climate change on road infrastructure. Austroads, Report no. AP-R243/04." Austroads and the Bureau of Transport and Regional Economics, Sydney.Impacts of Climate Change on Transport and Adaptation in Asia (PDF Download Available). Available from: https://www.researchgate.net/publication/228888356_Impacts_of_Climate_Change_on_Transport_and_Adaptation_in_Asia (accessed September 11, 2017).

INCKAH Infrastructure technologies for road operation and maintenance. n.d. *Slurry Seal.* Retrieved July 21, 2017, from Inckah Maintenance. Conservation. Innovation: http://inckah.com/our-services/slurry-seal-2/

Indian Network for Climate Change Assessment (INCCA). (2010). *Climate Change and India: A 4×4 Assessment: A Sectoral and Regional Analysis for 2030s.* New Delhi: Government of India.

Indian Roads Congress (IRC). 2017. *Annual Report 2015-16.* New Delhi: IRC.

Intergovernmental Panel on Climate Change (IPCC). 2012. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation.*

Intergovernmental Panel on Climate Change. 2014. *Climate Change 2014: Synthesis Report.*

Kinnaur, D D. 2012. *District Disaster Management Plan Kinnaur.*

Krishna Kumar, K, Patwardhan, S K, Kulkarni, A, Kamala, K, and Koteswara Rao. 2011. Simulated projections for summer monsoon climate over India. *Current Science*, 312–326.

National Cooperative Highway Research Program. n.d. *Climate Change, Extreme Weather Events and the Highway System: A Practitioner's Guide.*

NDMA,GoI. 2016. *Hazard, Risk and Vulnerability*. Retrieved January 2017, from National Disaster Management Authority, Government of India: http://www.ndma.gov.in/en/vulnerability-profile.html

NIDM, GoI. 2012. Retrieved from National Institute of Disaster Managment: http://nidm.gov.in/PDF/pubs/India%20Disaster%20Report%20 2012.pdf.

Maccaferri India. 2015. *CH-CP-IN-Extension of existing Breakwater, Construction of Beach protection bund and Groyne using Geotextile Tubes, Petronet, Kochi*. Retrieved July 2017, from Maccaferri India: https://www.maccaferri.com/in/download/ch-cp-extension-existing-breakwater-construction-beach-protection-bund-groyne-using-geotextile-tubes-petronet-kochi-rev01-july15/.

Mukherjee, S, and Gaurang, V. 2013. Exploring Fly Ash Utilization in Construction of Highways in India. *IOSR Journal of Mechanical and Civil Engineering* 8(4): 23–32.

Koteswara Rao K, Patwardhan, S K, Kulkarni, A, Kamala, K, Sabade, S S, Krishna Kumar, K 2013. Projected changes in mean and extreme precipitation indices over India. *Global and Planetary Change* 113: 77–90.

Pacific Region Infrastructure Facility. 2013. *Infrastructure Maintenance in the Pacific.*

Public Works Department, Himachal Pradesh. 2013. *Loss and Damages on Highways in Monsoons*.

Regmi, Madan B and Hanaoka, Shinya. 2009. Impacts of Climate Change on Transport and Adaptation in Asia. *Proceedings of the Eastern Asia Society for Transportation Studies.*

Revenue & Disaster Management Department, Government of Himachal Pradesh. 2016. Hazard, Vulnerability and Risk Assessment (HVRA) Himachal Pradesh.

Roychowdhury, D. 2015. Construction of disaster resilient roads in land slide prone areas.

Singh, N T. 2016. *Rock fall mitigation measures for hill roads*. IIT Bombay.

Techfab India. n.d. *Subsurface Drainage With Geosynthetic For Separation, Filtration & Drainage*. Retrieved July 21, 2017, from Techfab India: https://www.techfabindia.com/case_studies/Subsurface-Drainage-With-Geosynthetic-For-Separation-Filtration-&-Drainage.php

TERI. 2013. *Risk Assessment and Review of Prevailing Laws, Standards, Policies and Programmes to Climate Proof Cities: Synthesis Report for Guwahati.* New Delhi: TERI.

TERI. 2014. *Planning Climate Resilient Coastal Cities: Learnings from Panaji and Visakhapatnam, India.* New Delhi: TERI.

TERI. 2015. *Climate Resilient Green Growth Strategies for Himachal Pradesh.* New Delhi: TERI.

The Economic Times. 2014. Hudhud effect: Road link between Koraput and Andhra Pradesh restored.

The Economic Times. 2015. Cyclone Hudhud caused $ 11 billion worth of losses: UN. Retrieved from *The Economic Times*: http://articles.economictimes.indiatimes.com/2015-02-26/news/59541541_1_natural-disasters-asia-pacific-region-cyclone-hudhud

The Indian Roads Congress. 1998, July. IRC:SP-48-1998-Hill Road Manual.

The Indian Roads Congress. 2011. IRC 56-2011-Recommended Practices for Treatment of Embankment and Roadside Slopes for Erosion Control.

The United Nations Office for Disaster Risk Reduction (UNISDR). 2015. *Climate Change Adaptation*. Retrieved February 5, 2016, from The United Nations Office for Disaster Risk Reduction (UNISDR): https://www.unisdr.org/we/advocate/climate-change.

Tighe, Susan, Smith, James, Mills, Brian, and Andrey, Jean. 2008. Evaluating Climate Change Impacts on Low-Volume Roads in Southern Canada. *Transportation Research Record: Journal of the Transportation Research Board*. Vol. 2053.

UK Climate Impacts Program. 2007. *Identifying adaptation options.*

U.S. Department of Transportation. 2012. Climate Change and Extreme Weather Vulnerability Assessment Framework.

U.S. Department of Transportation, Federal Highway Administration. 2016, February 17. *Virtual Framework for Vulnerability Assessment*. Retrieved February 2016, from Climate Adaptation: https://www.fhwa.dot.gov/environment/climate_change/adaptation/adaptation_framework/modules/index.cfm?moduleid=2

U.S. Department of Transportation,Federal Highway Administration. 2015. *U.S. DOT Gulf Coast Study, Phase 2*. Retrieved from U.S. Department of Transportation, Federal Highway Administration: http://www.fhwa.dot.gov/environment/climate_change/adaptation/case_studies/gulf_coast_study/engineering_and_tasks/case12.cfm

United Nations Development Programme (UNDP). 2011. *Paving the way for climate resilient infrastructure.*

United Nations Framework Convention on Climate Change. 2011. *Assessing the Costs and Benefits of Adaptation Options: An Overview of Approaches.*

UNISDR. 2017, February. *Terminology*. Retrieved July 2017, from United Nations Office for Disaster Risk Reduction: https://www.unisdr.org/we/inform/terminology

USAID. 2014. *Climate-Resilient Development: A framework for understanding and addressing climate change .*

Wilson, Scott. 2008. *The 3 Countries Alliance Partnership (3CAP):The Effect of Climate Change on 3CAP's Highway Network Policies and Standards.* London, United Kingdom: Scott Wilson.

World Bank. 2010a. *Economics of Adaptation to Climate Change.* Washington D.C.: The World Bank.

World Bank. 2010b. *Making Transport Climate Resilient: Country Report Mozambique.* Washington D.C.: The World Bank.

World Bank. 2013. *Integrating Climate and Disaster Risk into Development.* Washington D.C.: The World Bank.

World Bank. 2015. *Moving Towards Climate Resilient Transport* . Washington D.C.: The World Bank.

World Bank. 2017. *Prioritizing Climate Resilient Transport Investments in a Data-Scarce Environment: A Practitioners' Guide.* Washington D.C.: The World Bank.

7
Annexures

Annexure 1 – Data Checklist

General

Number of districts (with population) which the highway passes through	
District	**Total Population and density**

Climate Information

Data	Source
Temperature (Maximum and minimum): Daily (for the past 20-30 years)	Indian Meteorological Centre (IMD), Regional Meteorological Centre (RMC)
Rainfall/precipitation: Daily (past 20-30 years)	
Other Precipitation-Snow	
Wind speed Daily: last 5 years	
Highest 24-hourly rainfall: last 20-30 years	
Temperature extremes: last 20-30 years	
Past Flood incidences : last 20-30 years	National Disaster Management Authority / State Disaster Management Authority/ NHAI
Past history of extreme events and natural disasters: last 20-30 years	
Damage caused during extreme events	
Cost incurred to rebuild and renovate post the extreme event/ disaster	MoRTH, NHAI

Traffic Operations and volume

Data	Source
Annual Average daily traffic (AADT) in PCUs- differentiated by vehicle categories. For the last 5 years	
Peak traffic period of the year (monthly data)	
Peak traffic recorded (in PCUs) during the peak period (specify in terms of Average Daily Traffic)	
Number of accidents - For the last 5 years	
Fatalities due to accidents - For the last 5 years	

Highway Characteristics

Data	Source
Highway infrastructure assets - Location and condition of the various elements of infrastructure that comprise the highway network	
1. Street lights – numbers and distance	
2. Storm water drainage system – type	
3. Safety barriers and their types	
4. Trees/ Vegetation – type and numbers	

Questionnaire:

1. Locational attributes

Does this highway connect any of the below option (tick appropriate)		
Ports	**Industries**	**Power Plants**
Airports	High density settlements	

Does this highway pass through any protected or ecologically sensitive areas? (tick appropriate)		
Biodiversity Parks	**Wildlife Sanctuary**	**National Parks**
Wetlands	Mangroves	Backwaters
Beaches	Forest	Others (Specify)…………

Does this highway pass through any hazardous areas/ industries? (tick appropriate)		
Thermal Power Plants	**Nuclear Plants**	**Other Hazardous Industries**
Others (Specify)…………		

Are any vulnerable settlements or groups located along the Highway? (tick appropriate)		
Slums	**Unauthorized settlements**	**Housing colonies**
Hospitals	Other Vulnerable population	

- Is this stretch a part of any evacuation route or part of the disaster relief and recovery plan?
- In case of traffic disruption of this highway, which alternative route is used?

II. Climate vulnerability

- What is the history of past extreme events/disasters and disruptions (for past 5 years)?

Year	Events (Flood Incidences, landslides, extreme events, etc.)	Duration of Disruption		Damage to highway		Accidents		Remarks
		From	To	Type of damage	Monetary terms (Rs)	Number of accidents	Fatalities in these accidents	

What are the impacts this highway faces due to high temperature? (tick appropriate)		
Rutting and shoving of pavements	**Heaving at joints of the pavements**	**Cracking of pavements**
Safety and health impacts	Heat stress affecting traffic operation	Rapid growth of the Roadside vegetation, hence increased maintenance
Others (Specify)…………		

- Does the highway segment face any specific impacts such as rutting and shoving of pavements, heaving at joints of the pavements, cracking of pavements, etc., with increase in temperature? If yes, specify the temperature and the kind of impacts faced?

What are the impacts this highway faces due to heavy rainfall/ precipitation/ flooding? (tick appropriate)		
Erosion and subsidence of paved roads.	**Leaking of rain-water under the pavement and damaging the pavement.**	**Flooding due to lack of maintenance and capacity of drainage system**
Landslides/Landslips	Accidents	Tree damage
Others (Specify)………….		

- Does the highway segment face any specific impacts such as erosion and subsidence of paved roads, leaking of rain-water under the pavement and damaging of pavements, flooding due to lack of capacity of drainage system, etc. due to extreme rainfall? If yes, specify the rainfall range and the kind of impacts faced?

What are the impacts this highway faces face due to high winds? (tick appropriate)		
Debris from destruction clogs drainage.	**Trees damage,**	**Accidents due to low visibility**
Buildings and other roadside infrastructure		

- Any other issues the highway encounters due to climate related events.
- Is the highway performance as expected under current climatic conditions and design assumptions?
- If no, what are the shortfalls?
- What should be the adaption options in order to counter the shortfalls?
- Is there a plan in place to deal with in the occurrence of extreme events e.g.: alternative route, evacuation routes, etc.?

III. Design Characteristics and Others

- Are any temperature thresholds considered while designing the pavement? If yes the rationale behind using the threshold?
- Are any rainfall/precipitation thresholds considered while designing the pavement? If yes the rationale behind using the threshold?
- What other climatic parameters are considered while designing the pavement and what is the rationale behind using these parameters?
- What are the climatic parameters taken into consideration while designing the storm water drainages?
- What materials are used for constructing the highways/pavements? (impervious/pervious)
- What are the measures in place that look at the maintenance of the highway assets
  - Storm water Drainage
  - Street lights
  - Roadside vegetation
  - Safety barriers
  - Others

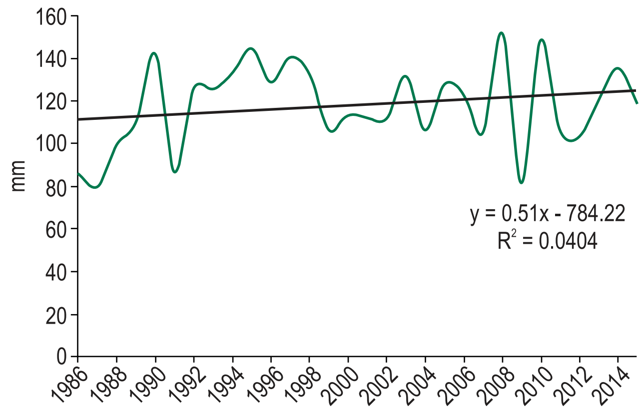
Annexure 2 – Past climate analysis for demonstration stretches

Shimla-Moorang

Shimla Station

Total rainfall

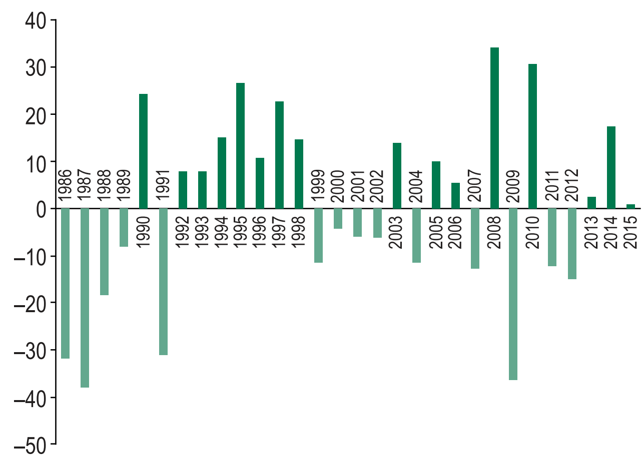
The annual mean of total monthly rainfall for the 29 year (1986-2015) period shows a slight increase over station of Shimla which may not be significant. However, as seen from the Graph 1 the rainfall over the station is highly variable especially during the recent 10 years in the past.



Graph 1: Shimla annual mean of total monthly rainfall

Annual rainfall anomaly

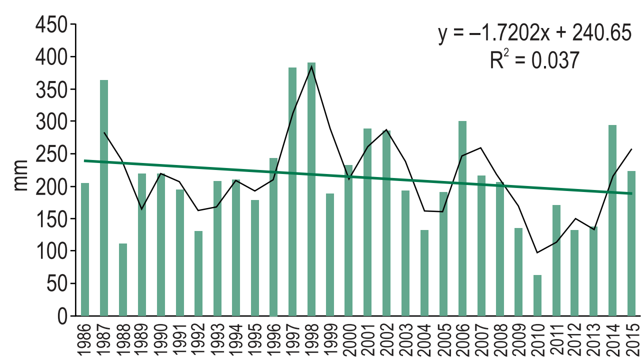
The annual rainfall anomaly over Shimla also shows a highly variable rainfall with alternate negative and positive anomalies during the entire dataset. No clear trends can be seen over the rainfall in recent years.



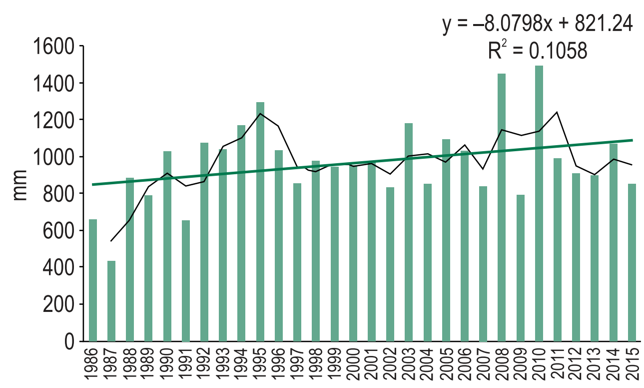
Graph 2: Shimla annual rainfall anomaly

Seasonal Rainfall Trends

The seasonal rainfall trends over Shimla shows that the summer (March, April & May) rainfall over the station has decreased in the last 29 years of analysed dataset. However, the monsoonal (June, July, Aug & Sept) rainfall over the station shows an increase with winter (December, Jan & Feb) not showing any trend. Hence for Shimla, monsoon rainfall is contributing the most towards the increasing trend of annual mean rainfall. It may be noted that the seasonal rainfall for a particular year is defined as the sum total rainfall amount received for those months in that year. For calculating seasonal amount for winter months of a particular year, the January and Feb contributions from the next year have been considered.



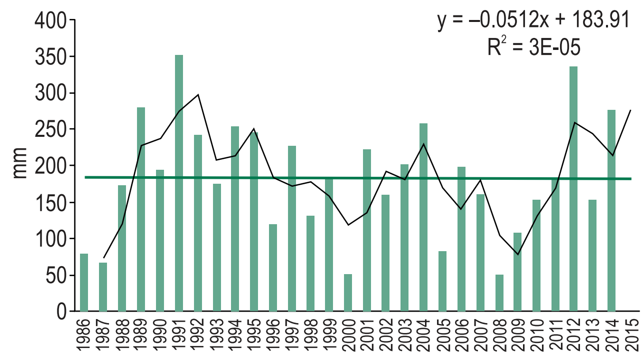
Graph 3: Shimla summer rainfall



Graph 4: Shimla monsoon rainfall

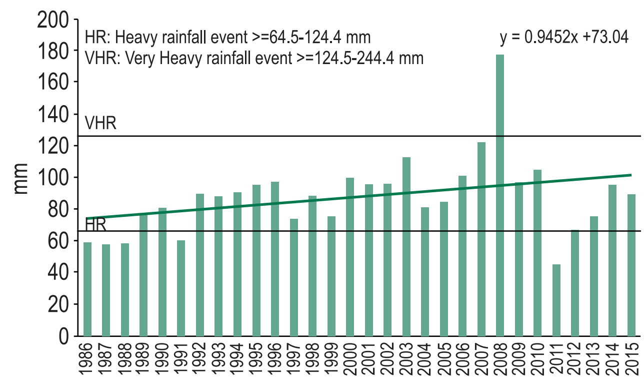
Rainfall Extreme

The maximum rainfall received in a day over Shimla also shows an increase trend in the past 29 yrs (1986-2015). Over 80% of all maximum daily rainfall recorded over Shimla falls in the Heavy Rainfall (HR)



Graph 5: Shimla winter rainfall

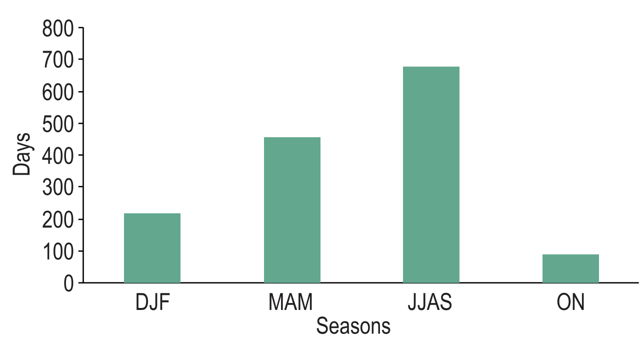
category with one event in Sept 2008 falling in the Very Heavy Rainfall (VHR) event category[22] It may be also be noted that in the past 30 years, more than 85% of these daily maximum rainfall events have occurred in monsoon season.



Graph 6: Shimla maximum rainfall

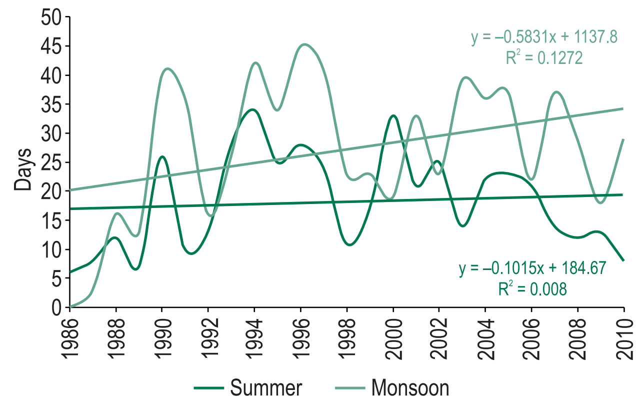
Thunderstorms

Summer and monsoon seasons experiences relatively higher thunderstorm days as compared to other seasons. Hence, further analysis was carried out for these two seasons which shows an increasing trend of growing thunderstorm days during the monsoon season as compared to the summer season for the Shimla station.

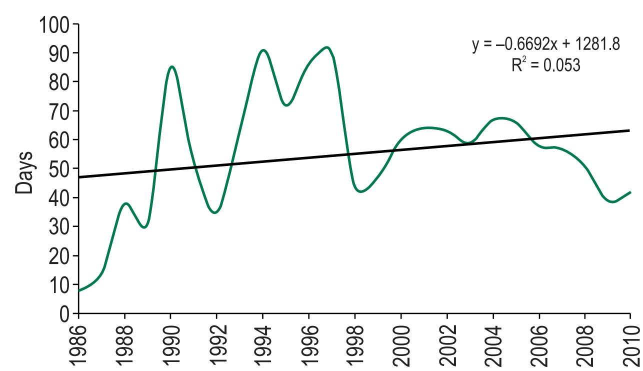


Graph 7: Shimla seasonal thunderstorm days

The total thunderstorm days in a year for Shimla also show an increasing trend for the 30 year data analysed. Hence, from the analysis above, it can be deduced that monsoon season in Shimla has seen not only an increase in rainfall amounts but also increase in extreme events and thunderstorm days as compared to other seasons.



Graph 8: Shimla seasonal thunderstorm days



Graph 9: Shimla total thunderstorm days in a year

Rampur Station

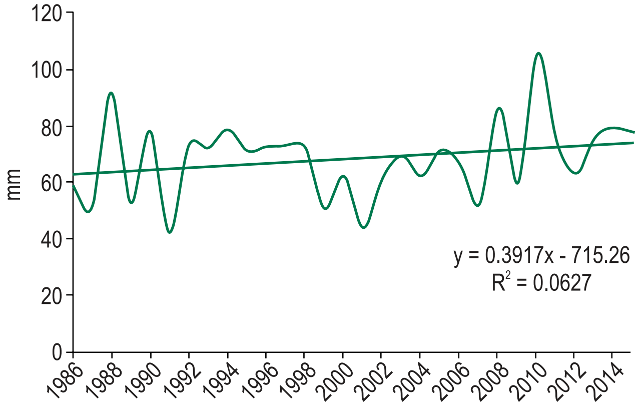
Total rainfall

The total rainfall over Rampur from 1986–2015 shows a slight increase in the past 29 year climate period. Although the increase may not be significant but the past 10 years have shown an increase relative to the late 90s to early 2000s period.

Rainfall (total) anomaly

The yearly total rainfall anomaly over Rampur shows positive anomalies from long term mean for the recent

[22] (IMD definition: http://www.imdpune.gov.in/weather_forecasting/glossary.pdf).



Graph 10: Rampur total rainfall

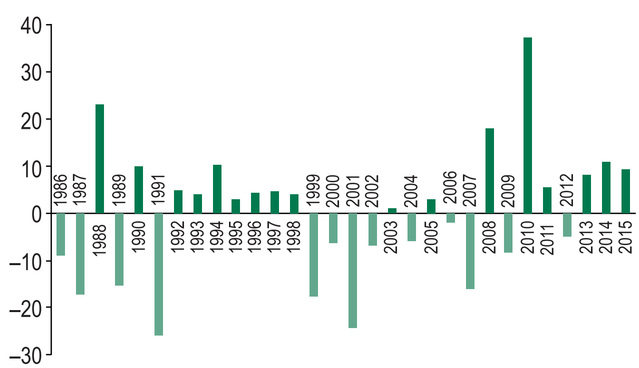
years relative to the 1999–2005 period. This may be responsible for an increasing trend seen in the rainfall over the past 29 year data period.

Seasonal Rainfall Trends

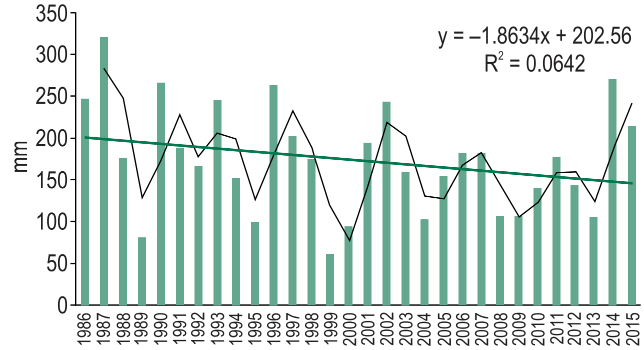
The seasonal rainfall trends over Rampur show that although the summer (March, April, and May) rainfall seems to be decreasing in the past 29 years, the monsoon (June, July, August, and September) and winter (December, January & February) rainfall shows an increase for the same period with monsoon rainfall showing a relatively higher increase. It may be noted that the seasonal rainfall for a particular year is defined as the sum total rainfall amount received for those months in that year. For winter months, the contribution for the months of January and February in the next year are considered in the winter months of the previous year.

Rainfall Extreme

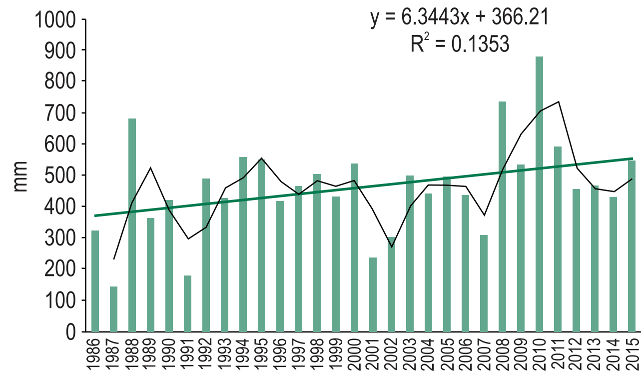
The maximum rainfall received in a day over Rampur also shows an increase based on the analysis of the data for the past 29 years. It is also seen that approx.



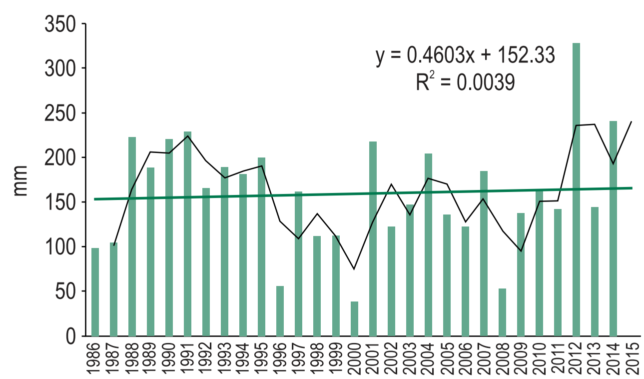
Graph 11: Rampur total yearly rainfall anomaly



Graph 12: Rampur summer rainfall (total)



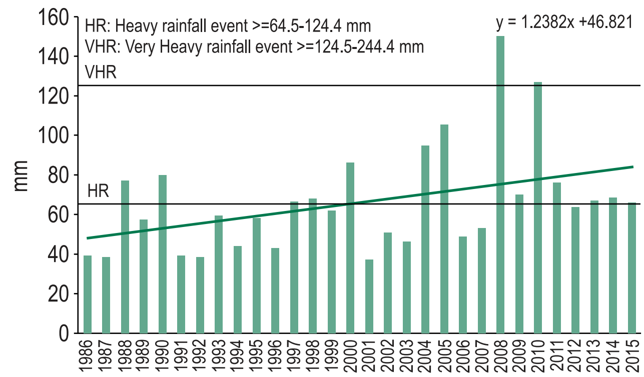
Graph 13: Rampur monsoon rainfall (total)



Graph 14: Rampur winter rainfall (total)

48% (14 out of 29) of these maximum rainfall events lie under the Heavy Rainfall (HR) events.[23] Also, two events are seen to be Very Heavy Rainfall (VHR) events. It may be noted here that out of the past 29 years, the recent 10 years show higher number of VHR events. Most of the events (22 out of 29 analysed) have occurred in the monsoon.

[23] (IMD definition: http://www.imdpune.gov.in/weather_forecasting/glossary.pdf).

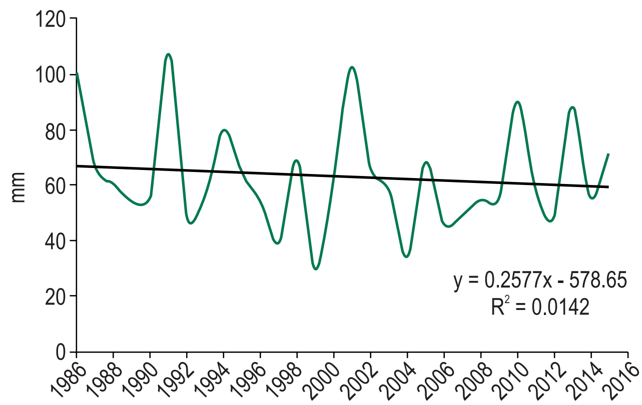


Graph 15: Rampur maximum rainfall event

Kalpa Station

Total rainfall

The annual mean of total monthly rainfall over Kalpa station shows a high variability in the 1986–2015 time period. As seen from Graph 16, the annual rainfall does not follow any clear trend for the time period analysed.

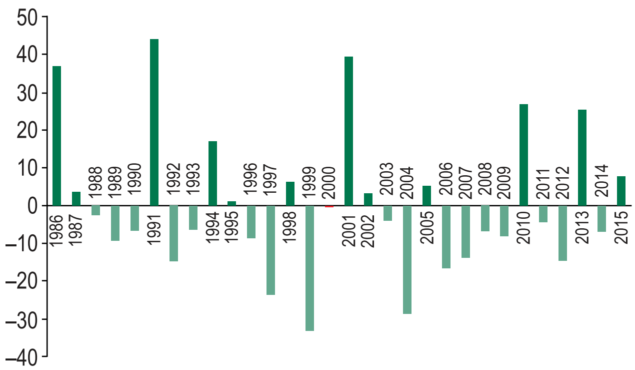


Graph 16: Kalpa annual mean of total monthly rainfall

The rainfall anomaly show more negative anomalies as compared to the positive ones. However, the positive anomalies are larger in comparison to the negative anomalies which shows that although the annual rainfall has been lesser than the long-term mean for the 1986–2015 period, the cases where the rainfall have exceeded the long-term normal, have been a large deviation.

Seasonal Rainfall Trends

Unlike the case of Shimla and Rampur where monsoon rainfall seems to have the largest contribution towards the annual rainfall component, Kalpa's seasonal rainfall does not show any similar dominance from any of the individual seasons (Graph 18). Although the trends in the summer rainfall shows a decrease in

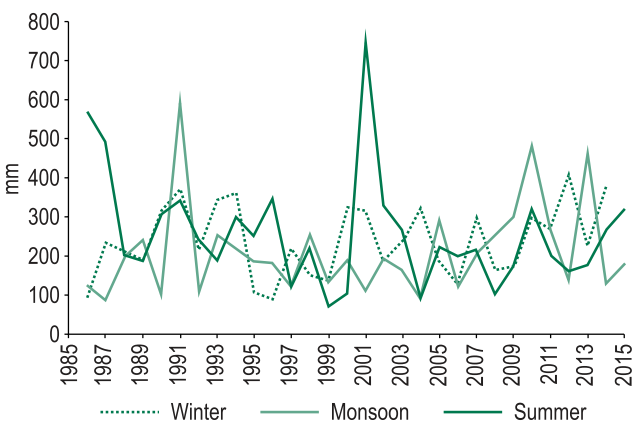


Graph 17: Kalpa annual rainfall anomaly

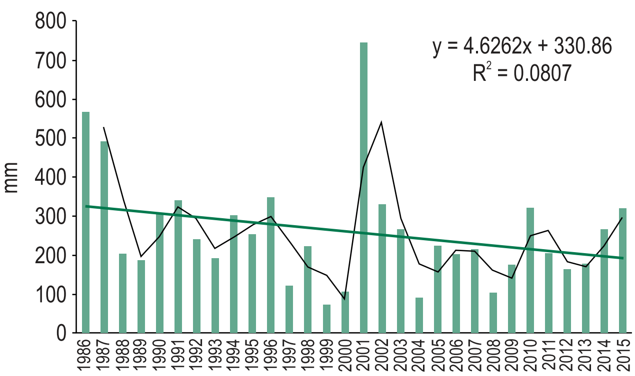
contrast to the other two seasons, viz. monsoon and winter that shows an increasing trend, the summer rainfall has a relatively higher contribution towards the annual total rainfall as compared to the other two seasons (Graph 18).

Rainfall Extreme

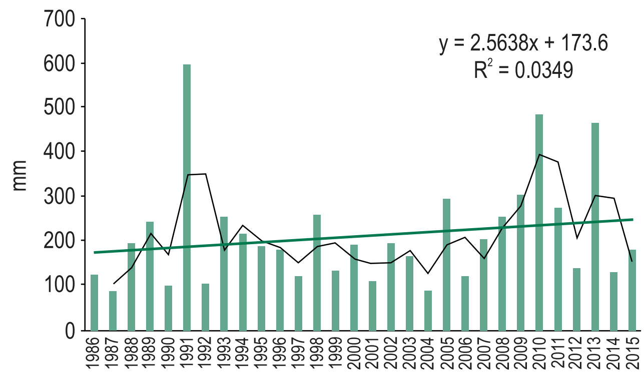
Although the overall trend in maximum 24-hourly daily rainfall over Kalpa shows a decreasing trend



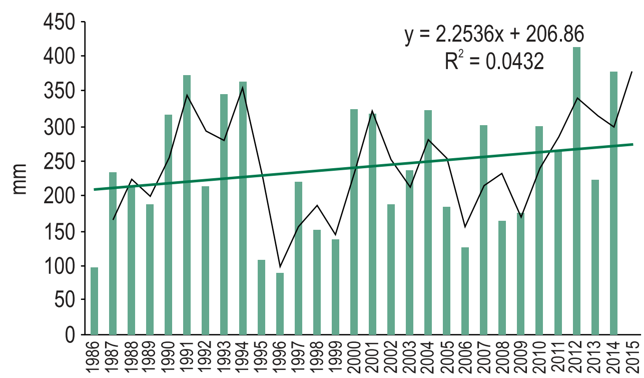
Graph 18: Kalpa seasonal total rainfall



Graph 19: Kalpa summer rainfall (total)



Graph 20: Kalpa monsoon rainfall (total)

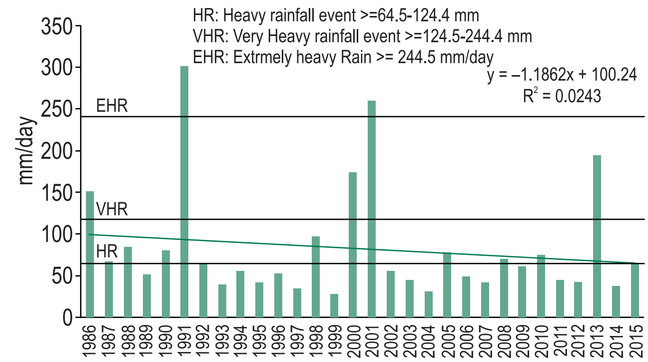


Graph 21: Kalpa winter rainfall (total)

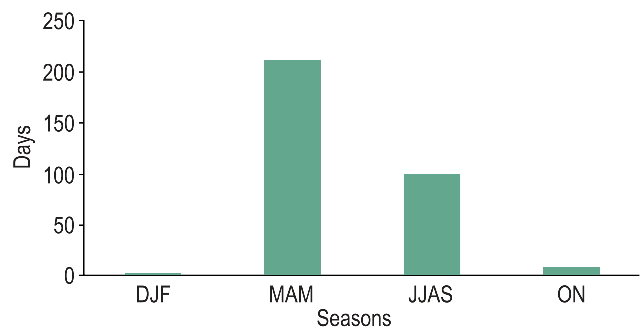
over the 1986–2015 time period, the individual events occurring over the station have higher intensity than Shimla and Rampur. For Kalpa, the data shows 8 HR events, 3 VHR events, and 2 Extremely Heavy Rain (EHR) events. The EHR24 events are not seen over Shimla and Rampur datasets. Also, the summer season shows a relatively higher number of maximum 24-hourly rain events in case of Kalpa, as compared to the stations of Rampur and Shimla.

Thunderstorms

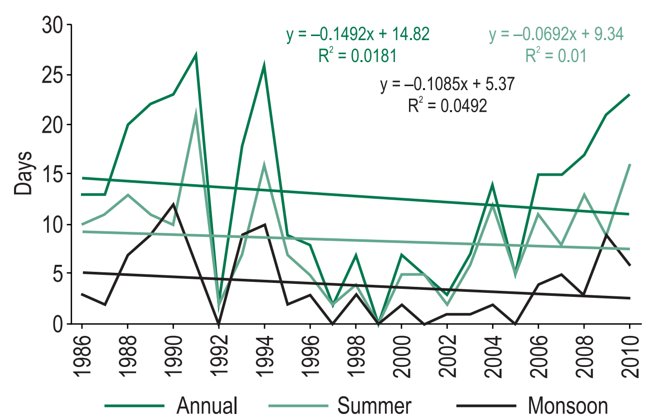
As seen in Graph 24 summer and monsoon seasons experience relatively higher thunderstorm days as compared to other seasons. Hence, further analysis was carried out for these two seasons which shows a slight decreasing trend of thunderstorm days in the past 30 years. Also, it is seen that unlike Shimla station, the summer season at Kalpa shows higher number of thunderstorm days as compared to monsoon season.



Graph 22: Kalpa maximum rainfall



Graph 23: Kalpa seasonal thunderstorm days



Graph 24: Kalpa thunderstorm days (seasonal)

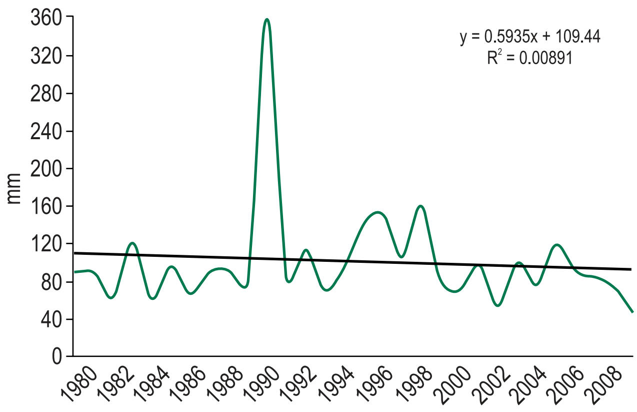
Kathipudi–Ongole

Kakinada Station

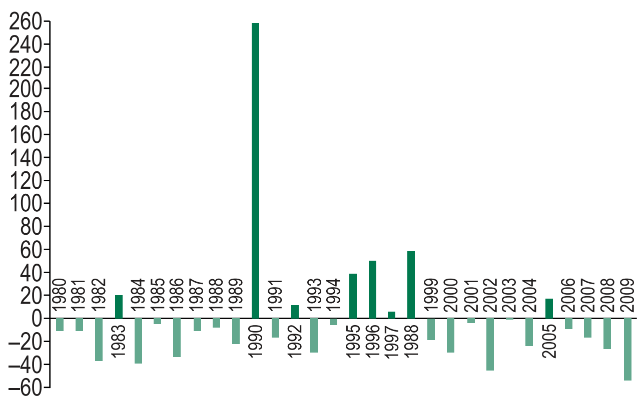
Total Annual Rainfall

The total rainfall over Kakinada shows a slight decreasing trend for the 29-year rainfall dataset analysed (1980–2009). The annual rainfall variability is also seen over the station with a very high value seen for the year 1990 which is also the year of cyclone activity over the coast. Barring the high value seen for 1990, most of the years show a lower than normal rainfall over the station.

[24] IMD definition: http://www.imdpune.gov.in/weather_forecasting/glossary.pdf)



Graph 25: Kakinada annual mean of total monthly rainfall



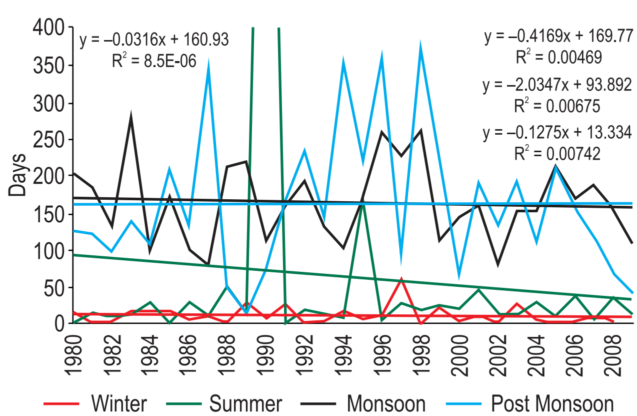
Graph 26: Kakinada annual rainfall anomaly

Seasonal Total Rainfall

Monsoon and post monsoon seasons show a larger contribution towards the total rainfall over the station. The high value in 1990 corresponds to the cyclonic activity seen in the month of May.

Annual Maximum Rainfall

Despite the decreasing rainfall trend over the station, the maximum rainfall is seen to increase in the 29 year data of the station. Also, most of the high rainfall events in a day are seen in monsoon and post monsoon seasons over the station, barring the highest maximum rainfall in a day event in 1990 which was seen in summer season. The station also witnessed in total, four events in EHR event category of IMD which is the largest amongst all the station data analysed for this study.



Graph 27: Kakinada seasonal total rainfall

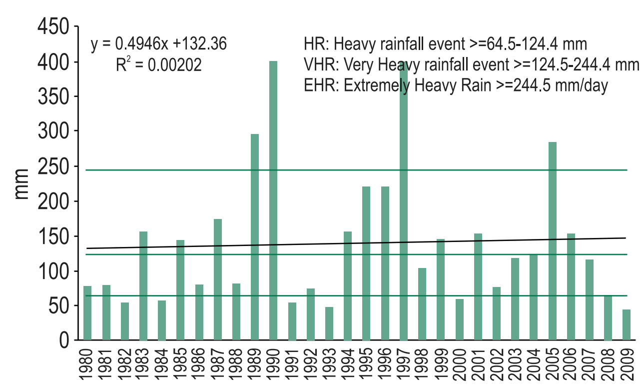
Wind speeds

The winter season witnesses relatively higher wind speeds, followed by monsoon season for Kakinada station. Post-monsoon and winter seasons have seen higher wind speeds for most of the years in the 29 year time period. However, the latter part of the analysed dataset, especially 2000 onwards have witnessed monsoon season having higher wind speeds over the station.

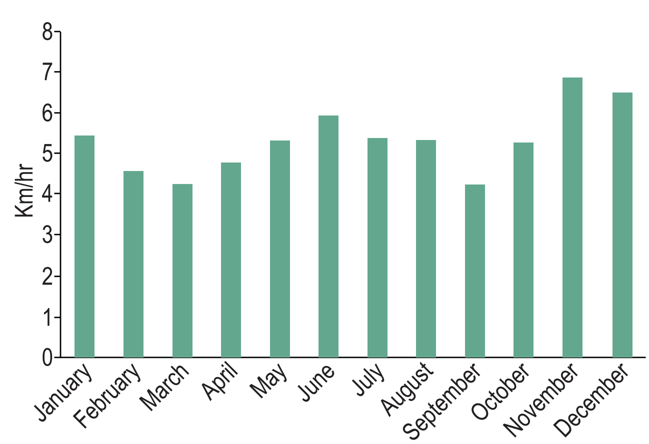
Machilipatnam station

Total Annual Rainfall

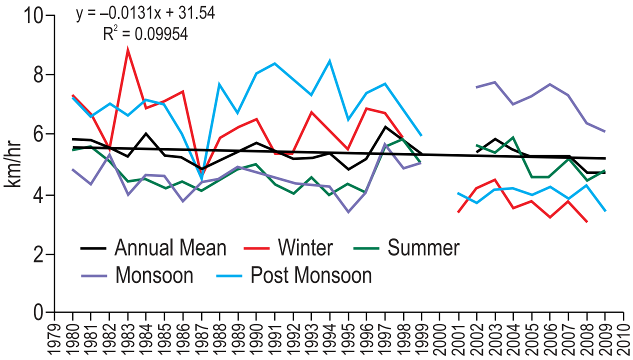
The annual mean of total monthly rainfall over



Graph 28: Kakinada Annual Maximum Rainfall



Graph 29: Kakinada monthly climatology of average winds



Graph 30: Kakinada seasonal average wind speeds

Machilipatnam station show a high variability over the entire 1980–2009 time period of available data. As seen from Graph 31, the annual rainfall shows a very slight increasing trend over the entire time period analysed.

The rainfall anomaly also shows a large variability of rainfall over the station. Although the total rainfall over the entire 29 year time period shows a slight increasing trend, the initial and the latter part of the data shows more negative anomalies, i.e. years having lower than normal rainfall.

Seasonal Total Rainfall

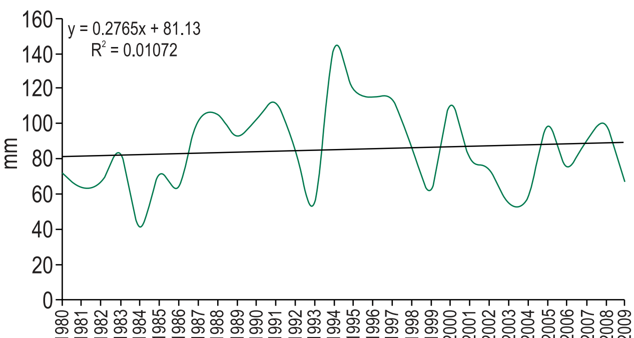
Monsoon and post-monsoon total rainfall together contribute the largest towards the annual rainfall component with post monsoon providing the highest contribution over the Machilipatnam station.

Annual Maximum Rainfall

The heaviest 24 hourly rainfall over the station shows an increasing trend with most of the events seen under VH and HR event category of IMD (see - http://www.imdpune.gov.in/weather_forecasting/glossary.pdf). Most of these heavy and VH rainfall events are seen during the monsoon and post-monsoon seasons.

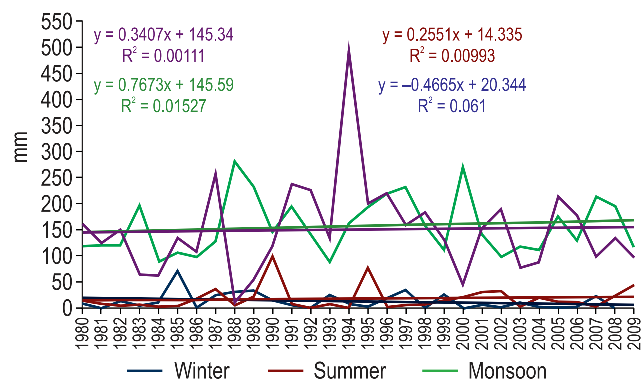
Wind speeds

As seen in Graph 35, relatively high wind speeds over Machilipatnam occur during summer and monsoon months of April, May, and June. In the past 30 years, it is seen that the average seasonal wind speeds over the station have slightly decreased, although the variability is quite high. The summer and monsoon months have

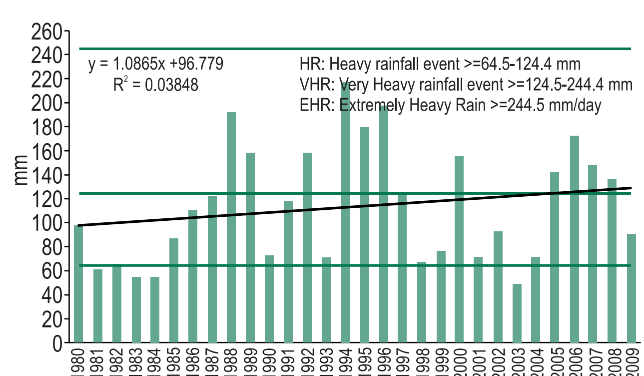


Graph 31: Machilipatnam annual mean of total monthly rainfall

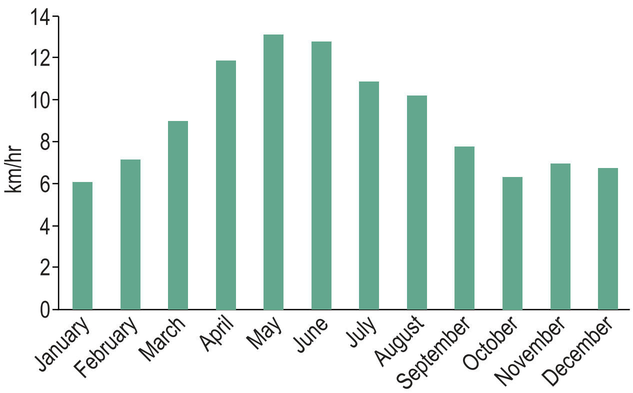
Graph 32: Machilipatnam annual rainfall anomaly



Graph 33: Machilipatnam seasonal total rainfall



Graph 34: Machilipatnam annual maximum rainfall



Graph 35: Machilipatnam monthly climatology of average winds

also shown relatively higher wind speeds than other months in the past 30 years.

Narsapur station

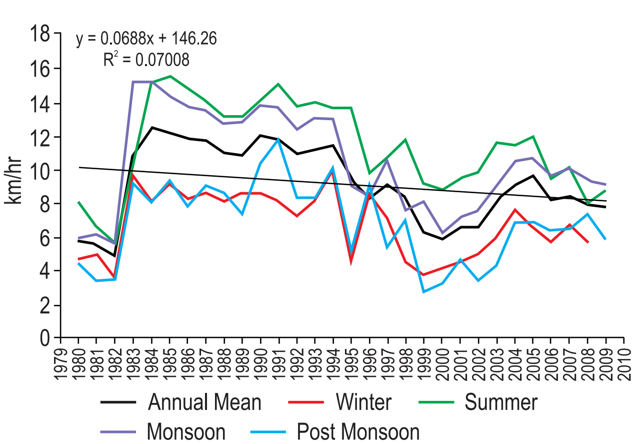
Total Annual Rainfall

The annual mean of total monthly rainfall over Narsapur analysed using the dataset available for the 1988–2009 time period shows a decreasing rainfall trend over the 21 year time period.

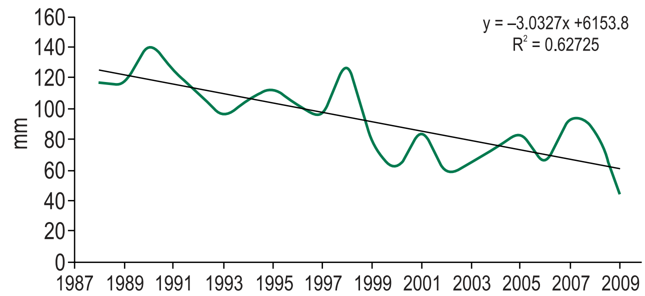
Most of the decreasing trend on total rainfall seen over the station is primarily due to the negative anomalies, i.e. lower than normal rainfall seen over the later years from 1999 onwards till 2009. This is clearly seen in the anomaly plot above where red shows the negative anomalies and blue shows the positive anomalies.

Seasonal Total Rainfall

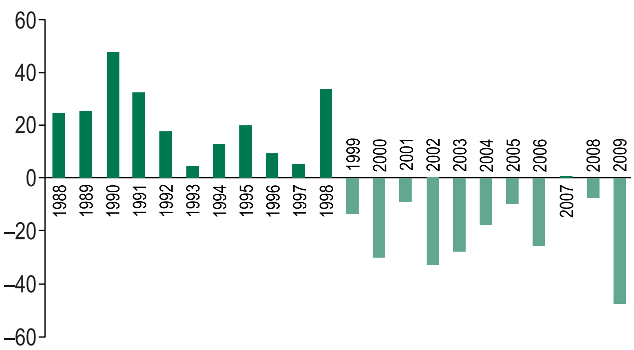
During monsoon and post-monsoon, total rainfall together contributes the largest towards the annual



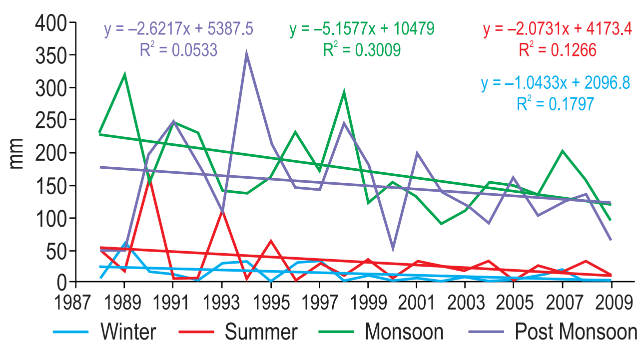
Graph 36: Machilipatnam seasonal average wind speeds



Graph 37: Narsapur annual mean of total monthly rainfall



Graph 38: Narsapur annual rainfall anomaly



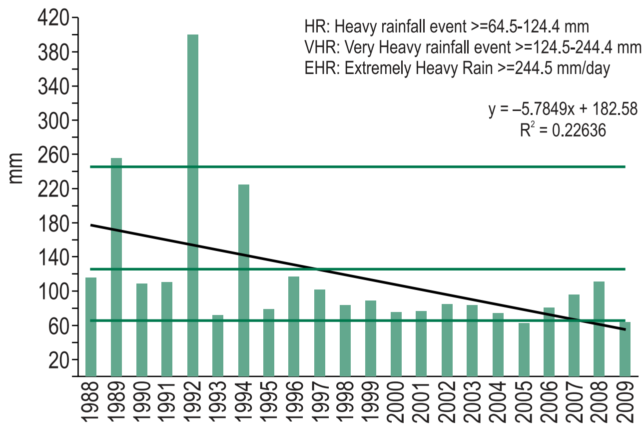
Graph 39: Narsapur seasonal total rainfall

rainfall component over the Narsapur station. All the seasons show a decreasing trend similar to the annual total rainfall trends over the station.

Annual Maximum Rainfall

The maximum 24-hourly daily rainfall over Narsapur also shows a decreasing trend for the available data of 1988–2009. Most of the individual maximum 24-hourly rain events occurring over the station have high intensity and fall within the heavy rainfall event category as per IMD definition.[25] Although two events in the given data time period had recorded extremely heavy rain events (for 1989 and 1992) and one event of 1994 recording under VHR event, most of the heaviest

[25] http://www.imdpune.gov.in/weather_forecasting/glossary.pdf



Graph 40: Narsapur annual maximum rainfall

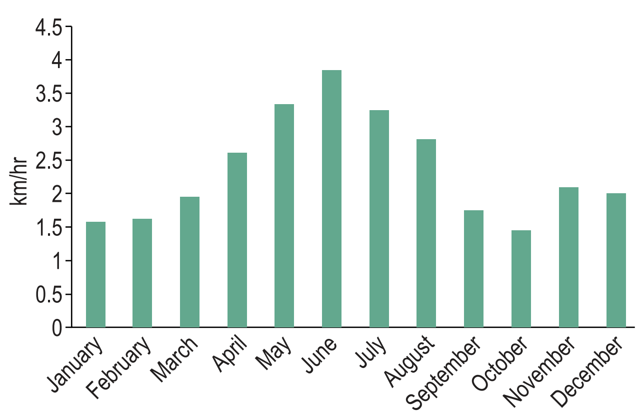
rain 24 hourly events fall within the heavy rainfall category of IMD. Also, most of the heavy rainfall events for the station are seen for monsoon and post-monsoon seasons over the station.

Wind speeds

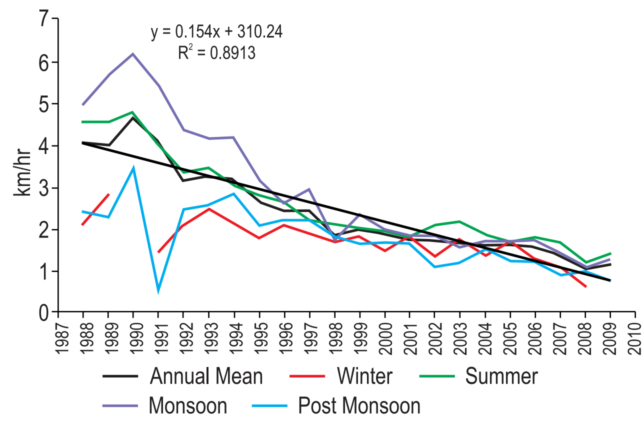
As seen below, relatively high wind speeds over Narsapur occur in the monsoon months of June, July, and August as well as in November and December. In the past 21 years of analysed data, it is seen that the average seasonal wind speeds over the station have slightly decreased although the variability is quite high. The monsoon months show relatively higher wind speeds than other months over the station.

Tuni Station

Only 13 years of data (1996–2009) was available for the station which also had few data gaps, hence the time length of the dataset is not sufficient to draw conclusive information on climate information for the station.



Graph 41: Narsapur monthly climatology of average winds

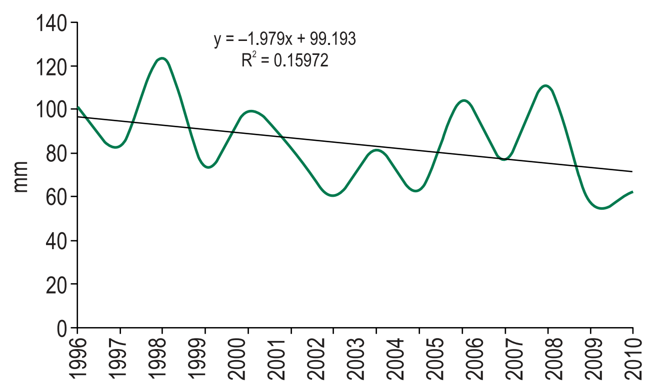


Graph 42: Narsapur seasonal average wind speeds

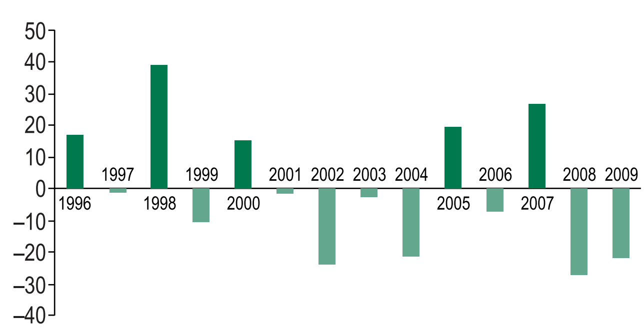
Total Rainfall

The rainfall for the 13-years of analysed dataset shows a decreasing trend over the station, although the variability is seen to be high.

Data over the past few years shows a higher than normal rainfall over the station but most of the years in the available data depicts negative anomalies, i.e. lower than normal rainfall for the station.



Graph 43: Tuni annual mean of total monthly rainfall



Graph 44: Tuni annual rainfall anomaly

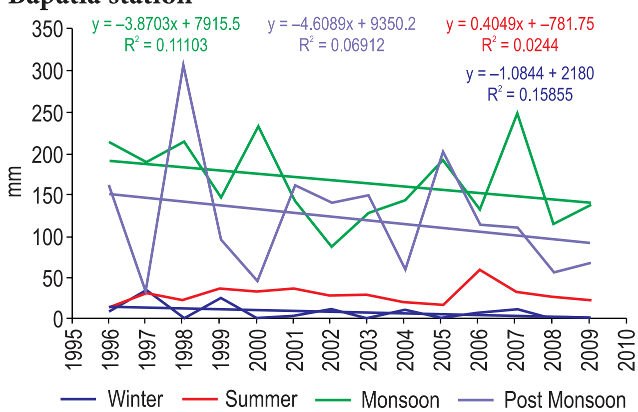
Seasonal Total Rainfall

Monsoon and post-monsoon have the largest share towards the total rainfall component over the station.

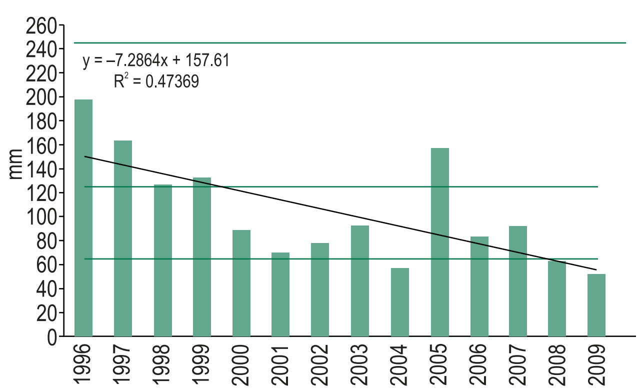
Annual Maximum Rainfall

The maximum 24-hourly rainfall also shows a decreasing trend over the station but the 13 year data is insufficient to clearly depict this as climate information over the station.

Bapatla station



Graph 45: Tuni seasonal total rainfall

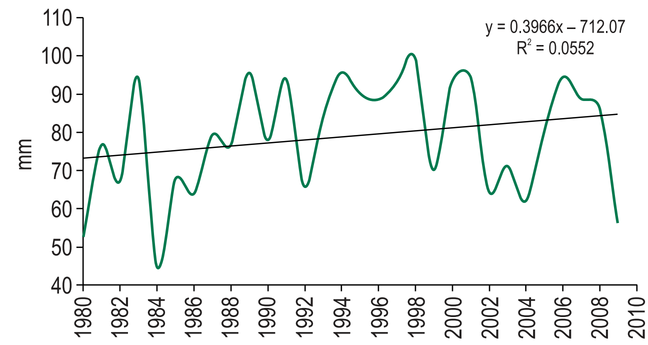


Graph 46: Tuni annual maximum rainfall

Total Annual Rainfall

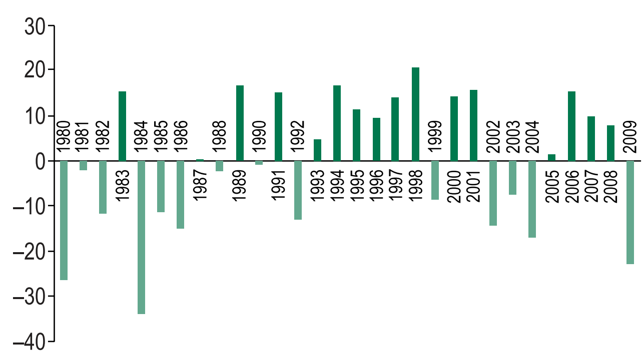
The annual mean of total monthly rainfall over Bapatla station show a high variability over the entire 1980–2009 time period of available data. As seen from Graph 47, the annual rainfall shows a slight increasing trend over the entire time period analysed.

The rainfall anomaly shows relatively higher number of positive anomalies as compared to negative ones for the stations although the share of both is nearly equal. This signifies that the station depicts high



Graph 47: Bapatla annual mean of total monthly rainfall

rainfall variability. It is also seen that barring few years, viz. 1980, 1982, 2009 where the negative anomalies have been large, i.e. larger deviation from long-term normal rainfall that signified poor annual rainfall, the magnitude of the negative anomalies have been smaller than the positive ones. This shows that although the rainfall does not follow any long-term trend, the magnitude of good rainfall years have been larger than those of bad monsoon years.



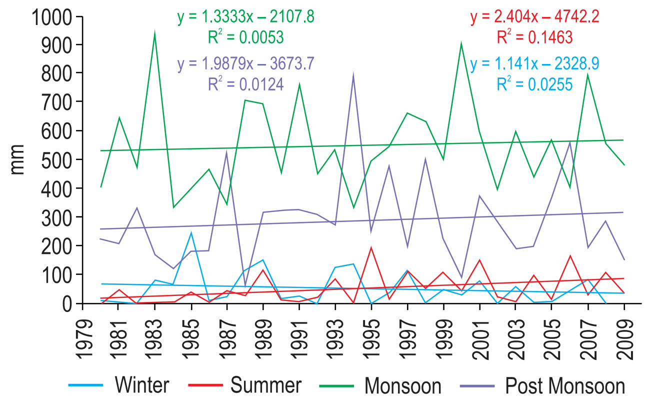
Graph 48: Bapatla annual rainfall anomaly

Seasonal Total Rainfall

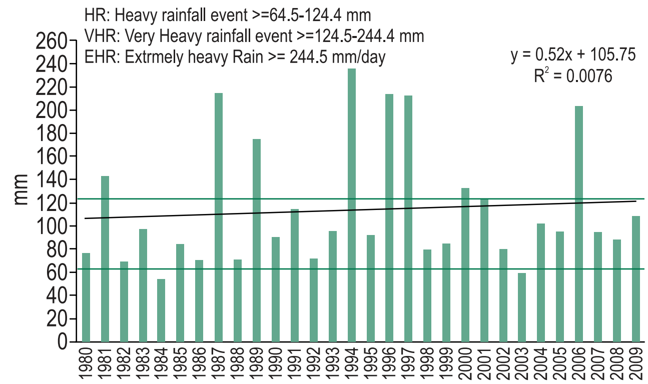
Monsoon and post-monsoon total rainfall together contributes the largest towards the annual rainfall component over the Bapatla station. Barring winter season, all the other seasons show an increasing trend in rainfall similar to the annual increasing trend. The rainfall variability is seen to be high for all the seasons.

Annual Maximum Rainfall

The maximum 24-hourly daily rainfall over Bapatla shows an increasing trend for the available data of 1980–2009. Most of the individual maximum 24-hourly rain events occurring over the station have



Graph 49: Bapatla seasonal total rainfall

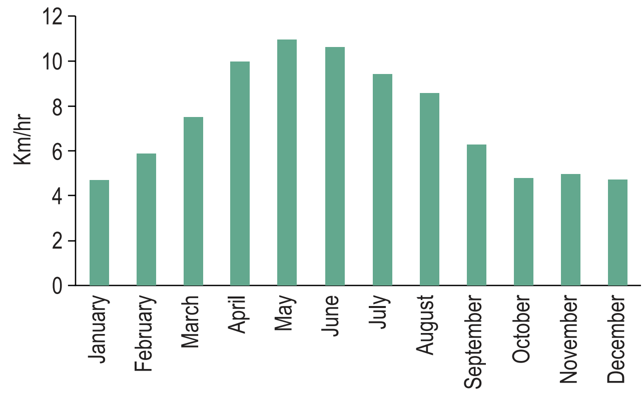


Graph 50: Bapatla annual maximum rainfall

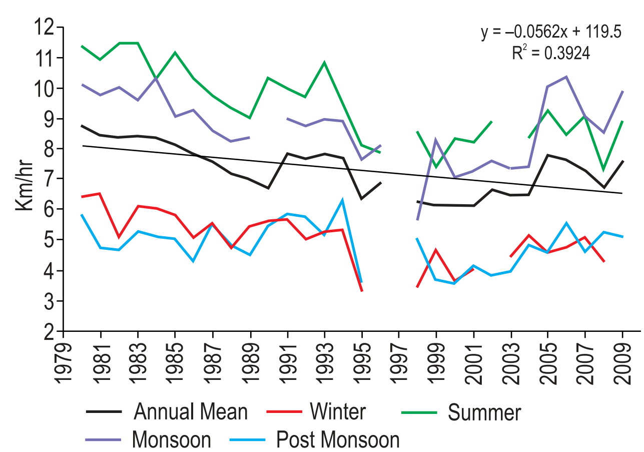
high intensity. The data shows 20 HR events and 8 VHR events as per IMD definition of rainfall events.[26] Also, most of the heavy rainfall events are seen for monsoon and post-monsoon seasons over the station.

Wind speeds

As seen in Graph 51, relatively high wind speeds over Bapatla occur in the summer and monsoon months of April, May, and June. In the past 30 years, it is seen that the average seasonal wind speeds over the station have slightly decreased although the variability is quite high. The summer and monsoon months have also shown relatively higher wind speeds than other months in the past 30 years.



Graph 51: Bapatla monthly climatology of average winds



Graph 52: Bapatla seasonal average wind speeds

Ongole Station

Total Annual Rainfall

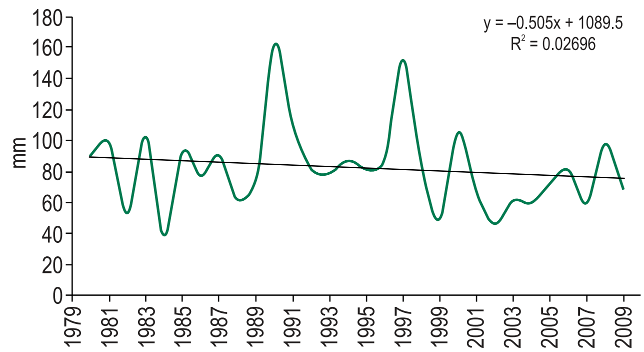
The annual mean of total monthly rainfall over Ongole station shows a high variability over the entire 1980–2009 time period of available data. As seen from Graph 53, the annual rainfall shows a very slight decreasing trend over the entire time period analysed.

The rainfall anomaly shows relatively higher number of negative anomalies as compared to positive anomalies, thereby signifying that lower than normal rainfall years have exceeded in number over the higher than normal rainfall years for the Ongole station. However, the rainfall during the years 1990 and 1997 have had very high positive anomalies, which neither of the negative anomalies has witnessed in the entire analysed dataset. Of the entire 29 years of analysed dataset, the trend of occurrence of negative anomalies has been seen during the latter part of the dataset.

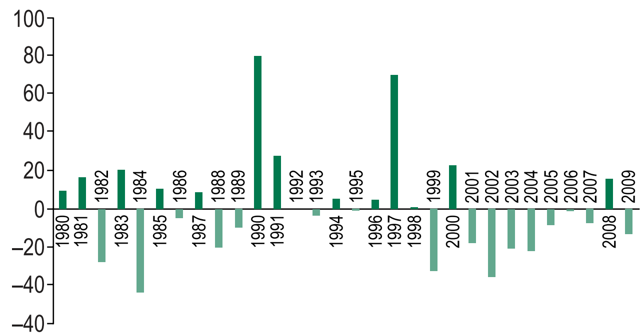
Seasonal Total Rainfall

Monsoon and post-monsoon total rainfall together contributes the largest towards the annual rainfall component as well as towards the negative trends of annual rainfall over the Ongole station. The summer and winter seasonal rainfall does not exhibit any significant trend in total rainfall.

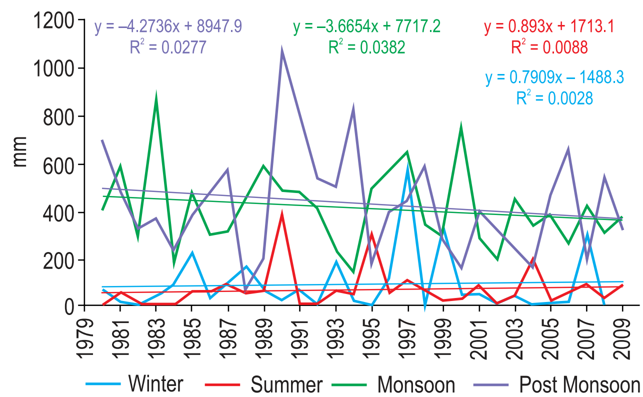
[26] http://www.imdpune.gov.in/weather_forecasting/glossary.pdf



Graph 53: Ongole annual mean of total monthly rainfall



Graph 54: Ongole annual rainfall anomaly



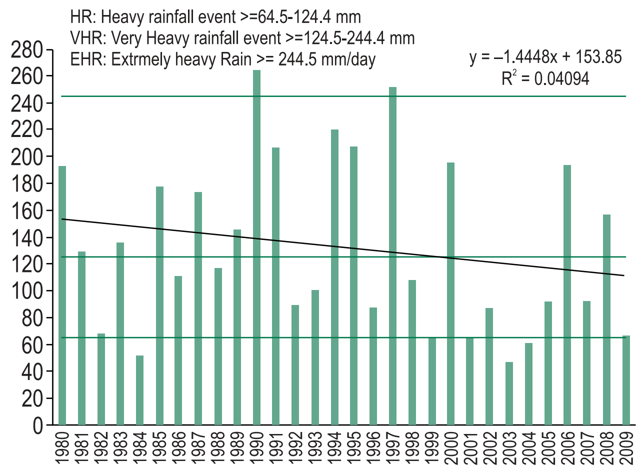
Graph 55: Ongole seasonal total rainfall

Annual Maximum Rainfall

Although similar to total rainfall and seasonal rainfall trend, the heaviest rainfall in 24 hours also exhibit negative trend for the Ongole station, but the station shows many events under the VHR event category apart from the two events in the year 1990 and 1997 falling under the EHR category of IMD. Also, most of the heavy rainfall events are seen for post-monsoon season over the station.

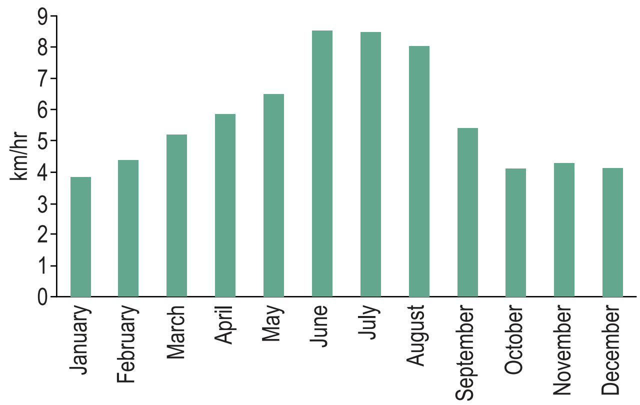
Wind speeds

As seen below, relatively high wind speeds over

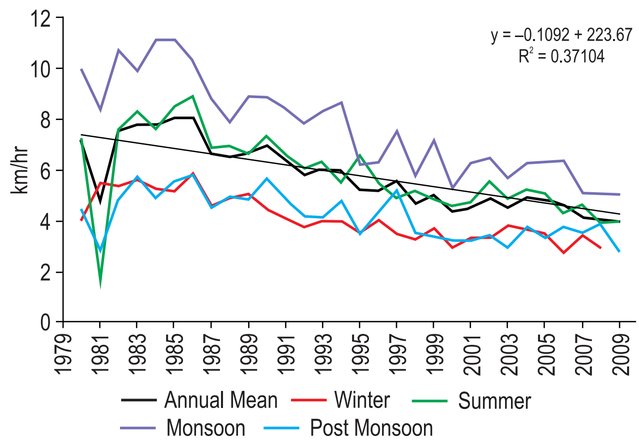


Graph 56: Ongole annual maximum rainfall

Ongole occur in the monsoon months of June, July, and August. In the past 30 years, it is seen that the average seasonal wind speeds over the station have slightly decreased although the variability is quite high with monsoon showing the highest value of wind speeds followed by summer season.



Graph 57: Ongole monthly climatology of average winds



Graph 58: Ongole seasonal average wind speed

Past cyclonic events affecting NH 216 (1990–2015)

Serial Number of system during year	Basin of origin	Name	Date(DD/MM/YYYY)	Time (UTC)	Latitude (lat)	Longi-tude (Long)	CI No [or "T. No"]	Estimated Central Pres-sure (hPa) [or "E.C.P"]	Maximum Sustained Surface Wind (kt)	Grade
1	BOB	LAILA	17/05/2010	0600	10.50	88.50	1.5	1004	25	D
1	BOB	LAILA	17/05/2010	1200	11	88	2.0	1000	30	DD
1	BOB	LAILA	17/05/2010	1800	11.50	87.50	2.0	998	30	DD
1	BOB	LAILA	18/05/2010	0000	11.50	86.50	2.5	998	35	CS
1	BOB	LAILA	18/05/2010	0300	12	85.50	2.5	996	40	CS
1	BOB	LAILA	18/05/2010	0600	12.50	84.50	3.0	992	45	CS
1	BOB	LAILA	18/05/2010	0900	13	84	3.0	992	45	CS
1	BOB	LAILA	18/05/2010	1200	13	83.50	3.0	990	45	CS
1	BOB	LAILA	18/05/2010	1500	13	83	3.0	990	45	CS
1	BOB	LAILA	18/05/2010	1800	13	82.50	3.0	990	45	CS
1	BOB	LAILA	18/05/2010	2100	13	82	3.0	990	45	CS
1	BOB	LAILA	19/05/2010	0000	13.50	82	3.0	990	45	CS
1	BOB	LAILA	19/05/2010	0300	13.50	82	3.0	990	45	CS
1	BOB	LAILA	19/05/2010	0600	13.50	81.50	3.5	986	55	SCS
1	BOB	LAILA	19/05/2010	0900	14	81.50	3.5	986	55	SCS
1	BOB	LAILA	19/05/2010	1200	14	81.50	3.5	986	55	SCS
1	BOB	LAILA	19/05/2010	1500	14	81.50	3.5	986	55	SCS
1	BOB	LAILA	19/05/2010	1800	14.50	81	3.5	986	55	SCS
1	BOB	LAILA	19/05/2010	2100	14.50	81	3.5	986	55	SCS
1	BOB	LAILA	20/05/2010	0000	15	81	3.5	986	55	SCS
1	BOB	LAILA	20/05/2010	0300	15.50	80.50	3.5	986	55	SCS
1	BOB	LAILA	20/05/2010	0600	15.70	80.50	3.5	986	55	SCS
1	BOB	LAILA	20/05/2010	0900	15.80	80.50	3.5	986	55	SCS
1	BOB	LAILA	20/05/2010	1200	16	80.50	-	990	45	CS
1	BOB	LAILA	20/05/2010	1500	16	80.50	-	990	45	CS

1	BOB	LAILA	20/05/2010	1800	16	80.50	-	990	45	CS
1	BOB	LAILA	20/05/2010	2100	16	80.70	-	990	40	CS
1	BOB	LAILA	21/05/2010	0000	16.20	80.80	-	990	35	CS
1	BOB	LAILA	21/05/2010	0300	16.50	81	-	995	30	DD
1	BOB	LAILA	21/05/2010	0600	17	81.50	-	999	20	D
04	BOB	--	07/10/2010	0300	16.50	84.50	1.5	998	25	D
04	BOB	--	07/10/2010	0600	17.50	84.50	1.5	998	25	D
04	BOB	--	07/10/2010	1200	18.50	85	1.5	996	25	D
04	BOB	--	07/10/2010	1800	19	85.50	1.5	996	25	D
04	BOB	--	08/10/2010	0000	20	86.50	1.5	998	25	D
04	BOB	--	08/10/2010	0300	21	87.50	1.5	998	25	D
04	BOB	--	08/10/2010	0600	22	89	1.5	998	25	D
04	BOB	--	08/10/2010	1200	23.50	90.50	--	1000	25	D
04	BOB	--	08/10/2010	1800	24.50	91	--	1002	25	D
05	BOB	--	13/10/2010	0600	17.50	90	1.5	1002	25	D
05	BOB	--	13/10/2010	1200	17.50	89	1.5	998	25	D
05	BOB	--	13/10/2010	1800	18	88.50	1.5	998	25	D
05	BOB	--	14/10/2010	0000	18	88.50	1.5	998	25	D
05	BOB	--	14/10/2010	0300	18	88.50	1.5	998	25	D
05	BOB	--	14/10/2010	0600	18	88.50	1.5	998	25	D
05	BOB	--	14/10/2010	1200	18	88	1.5	996	25	D
05	BOB	--	14/10/2010	1800	18	88	1.5	996	25	D
05	BOB	--	15/10/2010	0000	18.50	87.50	1.5	996	25	D
05	BOB	--	15/10/2010	0300	19	87	2.0	996	30	DD
05	BOB	--	15/10/2010	0600	19.50	86	2.0	996	30	DD
05	BOB	--	15/10/2010	1200	19.50	85.50	2.0	995	30	DD
05	BOB	--	15/10/2010	1800	19	84.50	--	996	30	DD
05	BOB	--	16/10/2010	0000	19	84	--	998	25	D
06	BOB	GIRI	20/10/2010	1200	17.50	91.50	1.5	1002	25	D
06	BOB	GIRI	20/10/2010	1800	17.50	91.50	1.5	1002	25	D

06		BOB	GIRI	21/10/2010	0000	17.50	91.50	1.5	1002	25	D
06		BOB	GIRI	21/10/2010	0300	17.50	91.50	2	1000	30	DD
06		BOB	GIRI	21/10/2010	0600	17.50	91.50	2.5	998	35	CS
06		BOB	GIRI	21/10/2010	0900	17.50	91.50	2.5	996	40	CS
06		BOB	GIRI	21/10/2010	1200	18	92.00	3	990	45	CS
06		BOB	GIRI	21/10/2010	1500	18	92.00	3	990	45	CS
06		BOB	GIRI	21/10/2010	1800	18	92.00	3	988	50	CS
06		BOB	GIRI	21/10/2010	2100	18.50	92.50	3	984	55	CS
06		BOB	GIRI	22/10/2010	0000	18.50	92.50	3.5	980	60	SCS
06		BOB	GIRI	22/10/2010	0300	19	93.00	4.5	974	80	VSCS
06		BOB	GIRI	22/10/2010	0600	19	93.00	5	964	90	ESCS
06		BOB	GIRI	22/10/2010	0900	19.50	93.50	5.5	950	105	ESCS
06		BOB	GIRI	22/10/2010	1200	19.80	93.50	5.5	950	105	ESCS
06		BOB	GIRI	22/10/2010	1500	20	93.50	--	966	80	VSCS
06		BOB	GIRI	22/10/2010	1800	20.50	94.00	--	976	70	VSCS
06		BOB	GIRI	22/10/2010	2100	20.50	94.00	--	986	55	SCS
06		BOB	GIRI	23/10/2010	0000	21	94.50	--	992	45	CS
06		BOB	GIRI	23/10/2010	0300	21.50	95.00	--	996	35	CS
06		BOB	GIRI	23/10/2010	0600	22	95.50	--	998	25	D
07		BOB	JAL	04/11/2010	0000	8	92	1.5	1002	25	D
07		BOB	JAL	04/11/2010	0300	8.50	91	1.5	1002	25	D
07		BOB	JAL	04/11/2010	0600	8.50	90.50	1.5	1002	25	D
07		BOB	JAL	04/11/2010	1200	8.50	90	1.5	1002	25	D
07		BOB	JAL	04/11/2010	1800	8.50	89.50	1.5	1002	25	D
07		BOB	JAL	05/11/2010	0000	9	88.50	2.0	1000	30	DD
07		BOB	JAL	05/11/2010	0300	9	88	2.0	1000	30	DD
07		BOB	JAL	05/11/2010	0600	9	87.50	2.5	998	35	CS
07		BOB	JAL	05/11/2010	0900	9	87.50	2.5	996	40	CS
07		BOB	JAL	05/11/2010	1200	9.50	87	2.5	994	45	CS
07		BOB	JAL	05/11/2010	1500	9.50	87	3.0	994	45	CS
07		BOB	JAL	05/11/2010	1800	10	86.50	3.0	992	50	CS

07		BOB	JAL	05/11/2010	2100	10	86	3.5	990	55	SCS
07		BOB	JAL	06/11/2010	0000	10	85.50	3.5	990	55	SCS
07		BOB	JAL	06/11/2010	0300	10	85.50	3.5	990	55	SCS
07		BOB	JAL	06/11/2010	0600	10	85	3.5	990	55	SCS
07		BOB	JAL	06/11/2010	0900	10	85	3.5	990	55	SCS
07		BOB	JAL	06/11/2010	1200	11	84.50	3.5	988	60	SCS
07		BOB	JAL	06/11/2010	1500	11	84.50	3.5	988	60	SCS
07		BOB	JAL	06/11/2010	1800	11	84	3.5	988	60	SCS
07		BOB	JAL	06/11/2010	2100	11	84	3.5	988	60	SCS
07		BOB	JAL	07/11/2010	0000	11	83.50	3.5	988	60	SCS
07		BOB	JAL	07/11/2010	0300	12	83	3.5	990	55	SCS
07		BOB	JAL	07/11/2010	0600	12	82.50	3.0	992	45	CS
07		BOB	JAL	07/11/2010	0900	12	81.50	2.5	994	40	CS
07		BOB	JAL	07/11/2010	1200	13	81	2.0	996	30	DD
07		BOB	JAL	07/11/2010	1500	13	80.50	2.0	998	30	DD
07		BOB	JAL	07/11/2010	1800	13	80	--	1000	30	DD
07		BOB	JAL	08/11/2010	0000	14	79	--	1002	25	D
07		BOB	JAL	08/11/2010	0300	15	78	--	1004	25	D
08		BOB		07/12/2010	0300	14	82	1.5	1000	25	D
08		BOB		07/12/2010	0600	14.50	82	1.5	1000	25	D
08		BOB		07/12/2010	1200	15	81.50	1.5	1000	25	D
08		BOB		07/12/2010	1800	15.50	81	1.5	1000	25	D
08		BOB		08/12/2010	0000	16	80	1.5	1000	20	D

Annexure 3—Stakeholder Consultations

Prior to the stakeholder interactions/interviews, a questionnaire was prepared which has been included in Annexure 1. Based on this questionnaire, the comments were received from the different stakeholders. These comments have been tabulated as follows.

Sl. No.	Name	Designation	Key comments
1	Mr Prasad Negi	Executive Engineer Public Works Department (NH Division), Himachal Pradesh	• Discussions were held with Mr Negi regarding National Highways. Key points are summarized below: • National Highway 5 is the only route that links Shimla to the Indo-Tibet border. • The Ministry has initiated work on constructing a by-pass road to address the issue of traffic disruption. • In the year 2011–12, as per the figures from MoRTH, the monetary losses due to floods were to the tune of ₹1,30,12,000. • The impacts the Highway faces due to high temperature included rutting and shoving of pavements, heaving at joints of pavements, and cracking of pavements. • The most prominent impact the Highway faces due to heavy rainfall is erosion and subsidence of paved road. Three such events were reported in July 2016 (the same month as this interaction happened). • The other impacts include infiltration of rainwater into the layers below and thus, damaging the structural stability of the road, tree damage, landslides and landslips. • Flooding of Highways due to lack of maintenance and insufficient drainage capacity. It was also pointed out that the Highway currently has kaccha and pakka drains. • The impact the Highway faces mainly due to high winds is tree damage. • He opined that the performance of the Highway was not as expected under the prevailing climatic conditions and design assumptions. • The functioning of the Highway is affected due to the limited availability of funds for repair and maintenance, lack of machinery suited for hilly terrain and common IRC being used for highway construction on different terrains. • He stated that the Ministry has proposed construction of a by-pass road as an alternative route, as a measure to deal with extreme events. • In hilly regions, cloudbursts are a common occurrence. Also landslides, especially during monsoons are common.
2	Mr Manas Dwivedi	State Project Officer, Himachal Pradesh State Disaster Management Authority	• Discussions were held with Mr Dwivedi regarding risks and hazards related to National Highways. Key highlights of discussions are summarized as follows: • Landslides, flash floods, and cloudbursts are key climate risks in hilly regions. Disaster risks due to these are likely to increase in future with increasing rainfall variability.

			• Rampur–Kinnaur stretch of NH 5 has seen multiple landslides in the past, with Urni village being one of the most risk prone locations. Kinnaur frequently remains disconnected in the monsoon season owing to landslides and soil subsidence. • Non-climate parameters, such as slope instability and seismic activity also affect Highways in the hills. • Slope instability is very high in this stretch of NH 5. One of the key reasons is development activities for the numerous hydropower plants and their impacts. • Mr Dwivedi suggested that HP State Action Plan on Climate Change (SAPCC), Hazard Risk and Vulnerability Assessment (HRVA), and Environmental Vulnerability Assessment (EVA) exercises conducted by the Department of Environment, Science and Technology, Government of Himachal Pradesh, may be referred for the purpose of the study. Though Highways/ National Highways were not the focus of these studies, they have taken other sectors, viz. livelihood, agriculture, tourism, etc., into consideration. The same were taken into consideration while conducting the VA for NH 5.
3	Mr A K Kohli	Chief Engineer State Public Works Department, Himachal Pradesh	• Discussions were held with Mr Kohli regarding risks and hazards related to National Highways. Key highlights of discussions are summarized as follows: • Landslides are one of the key risks faced by highways and roads in the hills. Two key factors affecting this are drainage and geology. Improper drainage and soft sandy soils increase vulnerability to landslides. Blasting for construction of hydropower plants has also increased the vulnerability of highways in the region. • Other climate-related risks in mountainous regions, such as Himachal Pradesh, include avalanches and flash floods as a result of cloudbursts and lake bursts. These have been experienced in the upper reaches of the state in the past and impact populations and livelihoods as a result of disruption of connectivity. • Frequency and intensity of above mentioned climate risks is typically high in monsoon season. • Some key adaptation measures could be the use of retaining wall and structures, geosynthetics and regular maintenance practices. • Although certain degree of awareness on these good practices and safety measures is already present with NHAI, state PWDs, these are typically not implemented due to lack of funds and regulations/ implementation mechanisms. • Prioritizing risk prone areas would be the optimal way forward.
4	Mr Venkata Ramana	Project Implementation Unit, Asst. Executive Engineer, MoRTH, Kakinada, Andhra Pradesh	• Discussions were held with Mr Ramana regarding National Highway 216 of coastal stretch study. Key highlights of discussions are summarized as follows: • NH 216 is being upgraded from 2 lanes to 4 lanes of which phase 1/stretch 1 from Kathipudi to Kakinada (27.4 km) is under implementation stage and phase 2/ stretch from Kakinada to Amalapuram is under survey stage.

			• During the upgradation from 2 lanes to 4 lanes, wherever widening of roads was not possible due to the location of dense settlements, by pass roads were constructed. • Retaining walls have been used at locations where River Godavari is in proximity to the Highway. • 7,000 trees are to be replanted for stretch 1 and 3,000 trees for stretch 2. • In Kakinada, infrastructure, such as trunk water supply lines, sewerage lines are maintained by the Municipality and not by MoRTH/NHAI. • The highway stretch closest to the coast is located about 2 km from the coast. • Spun concrete electric poles are used instead of the normal electric poles in order to better withstand extreme winds.
5	Dr T R Kiran Chand	SE forestry and ecology group, National Remote Sensing Centre, Hyderabad	• Dr Kiran Chand highlighted the influence of highways on forest vice versa, which are: • There is a higher probability of forest fires when there is a highway nearby due to increased anthropogenic activities. • Highways act as quick escape routes during forest fires. • Forests and tree cover along the roadside of hilly terrain help in reducing the risk of landslides.
6	Mr G V Rao	Project Implementation Unit, Team leader for Kathipudi to Kakinada stretch, NH 216, Andhra Pradesh	• In response to Questionnaire (Annexure 1) he responded with the following answers: • There exists no evacuation route or disaster relief and recovery plan for the NH 216 stretch. • During high temperatures, i.e. an average of 50° C in summer, highways are subject to cracking, rutting, and shoving of pavements. • Heat stress also affects the traffic operation. • The Highway faces erosion and subsidence during heavy rainfall/ precipitation/ flooding due to lack of maintenance and capacity of drainage system. • Temperature thresholds are considered for designing the pavement but rainfall thresholds are usually not considered in pavement design. • IRC 50 and IRC 42 are used as guidelines for the design of stormwater drainage. Both these codes have climatic parameters taken into consideration. In the case of rainfall data, it is taken from flood estimation report. • The materials used for highway construction are granular sub-base (GSB), wet mix macdam (WMM), stone aggregate, cement, bitumen and concrete, and steel. • Measures for maintenance of the highway assets include: • Regular cleaning of storm water drainage • Monthly maintenance and attending to repair of street lights • Cleaning and watering of roadside vegetation • Daily checking, cleaning of safety barriers

7	Mr G V P S Reddy	Project Implementation Unit, Team leader for Kakinada to Amalapuram, NH 216, Andhra Pradesh	• In response to the questionnaire (Annexure 1), he responded with the following answers: • This stretch, (part of NH 216) falls under four districts, East Godavari being one of them with a population of 51,51,549 (2011 Census) and density of 477 per sq. km. This stretch is currently being upgraded to 4 lanes in East Godavari. • Annual Average Daily Traffic (AADT) in Passenger Car Unit (PCUs) is 875 and May is the peak traffic period of the year. • There are 1,339 trees along the NH in the Kakinada to Amalapuram stretch (Stretch 2). • Stretch 2 is a part of disaster relief and recovery plan. • NH16 is used as the alternative when there is a traffic disruption on NH 216 • It is observed stretch 2 of the Highway segment faces erosion and subsidence, damage of pavement due to percolation of rainwater under the pavement, flooding due to lack of maintenance and capacity of drainage system and accidents and tree damage. • Temperature in the stretch usually rises up to an average of 46° C during summers. • IS codes and IRC, which consider temperature thresholds, rainfall/ precipitation thresholds are used while designing the pavement and storm water drainage. • The highway stretch from Kakinada to Amalapuram stretch receives monthly rainfall of upto 267.5 mm.
8	Mr Ashutosh Pathak	Expertise: Member of Central Engineering Services Group "A", served CPWD & Ministry of Transport, Government of India (1968–2008)	• Discussions with Mr Pathak centred on soil stability and its relation to National Highways. • He gave insights on the different soil types, such as types of soil-clayey, clay-skeletal, loamy and sandy and their relevance on soil stability. • From his experiences, he stated that loamy soil and sandy soil when combined with water are most vulnerable to landslides. • Clay soil is mostly stable when compared to other types of soil. • Landslides are caused depending not only on the soil type, but also on the combined parameters of water action, slope, degradation of soil, and sometimes human interventions.
9	Mr K Srineevas	Soil expert National Remote Sensing Centre, Hyderabad	• Discussions were held with Mr K Srineevas regarding NH 216 of coastal stretch study. Key highlights of discussions are summarized as follows: • NRSC developed the soil erosion map based on a combination of various parameters such as soil deformation, soil type, soil of the terrain, natural vegetation, mass landslide movements, water erosion, temporal satellite data for recording the changes in soil cover, gully and ravines deformation.

			• Each of the above said parameters are classified into different vulnerability ranges, for example soil deformation is classified into four classes on the basis of soil tonnes per ha per year, i.e. • <10 tonnes/ha/year as slight deformation. • 10 to 20 tonnes/ha/year as moderate deformation. • 20 to 50 tonnes/ha/year as high deformation. • >50 tonnes/ha/year as very severe deformation. • He suggested that the map prepared by NRSC through satellite imagery does not solely depict landslides or soil stability but also soil erosion as a whole. Hence, it will not be appropriate to analyse the vulnerability zones for Highways using this map, as Highways are more vulnerable to extreme events and not to slow onset of change. • He also mentioned that NRSC is now presently working on landslides and the prediction of their occurrence, in India .
10	Mr D. Roychowdhury	Superintending Engineer, Central Public Works Department, New Delhi	• Discussions were held with Mr D Roychowdhury regarding cost implications for resilient National Highways. Key highlights of discussions are summarized as follows: • He mentioned that incorporating disaster resilient features in any infrastructure project would incur significant costs. For instance, the resilience considerations for greenfield and brownfield projects will be different, hence its cost implications. • He recommended engineering measures and preventive technologies, which included erosion protection, soil nailing, rock anchors, etc. He also mentioned they are costly alternatives and thus are rarely used. • He proposed that the DPRs must clearly indicate the cost implications for building resilient roads. The documents should be prepared based on available benchmarking documents, such as IRC codes, MoRTH specifications, MoRTH Databook, etc. • He suggested technology vendor registration for important technologies on the same lines as empanelment of manufacturers of bearings for bridges should be considered.
11.	Mr K V V Satyanarayan	Retd. Structural Engineer, (Road and Building division, National Highway Authority of India)	• Discussions were held with Mr Satyanarayan regarding NH 216. Key highlights of discussions are summarized as follows: • NH 216 is subject to waterlogging due to blockage of natural drains during the rainy seasons. • Local panchayat and municipal authorities are responsible for operation and maintenance of drains. • Annual and periodic maintenance are the responsibility of the road and buildings division of NHAI. • No research studies have been conducted related to vulnerability assessment of roads. • The inundation of Highways is mainly due to choking of drains, as a result of urbanization of the adjacent settlements.

12	Ms Mini Korulla (VP) and Ms Anunsha Nandavaram (Engineer)	Maccaferri Environmental Solutions Pvt. Ltd	• Discussions were held with Ms Mini and Ms Anusha regarding the engineering interventions that have been recommended as part of the Study. Key highlights of the interaction are summarized as follows: • The list of region-wise engineering interventions was vetted by them. • Proof of concepts for the several engineering interventions were provided by Maceferri • A list of the IRC codes which already talk about the engineering interventions recommended as part of the study was made with assistance from Maccaferri.
13	Rahul Gupta, Executive Director and Adil Singh, General Manager (Tech.)	National Highways and Infrastructure Development Corporation Limited	Discussions were held with Mr Rahul Gupta and Mr Adil Singh to understand if any good practices are being implemented in North East region of India, while constructing NHs to enhance the climate resilience of the highways. In this regard they indicated the engineering interventions that are implemented are in line with the IRC guidelines and manuals. As the projects undertaken by NHIDCL are largely through EPC contracts, the contractors generally do not deploy new technologies for highway construction as the contractors have to bear the risk.

Annexure 4 –Proof of concept for Engineering Interventions

i. Laying of geo-grid for subgrade stabilization, Gharni-Nitur-Nilanga Road SH-167, Taluka-Nilanga, District- Latur, Maharashtra.

Source (Techfab India)

ii. Use of glass grids in Cochin International Airport, Kerala

Source (Techfab India)

iii. Use of glass grids on NH24 Lucknow–Sitapur , Uttar Pradesh

Source (Techfab India)

iv. NDMC roads are maintained for crack sealing and maintenance

Source (INCKAH Infrastructure technologies for road operation and maintenance)

v. Pot hole, after its repair at Sukhdev Vihar road,New Delhi

Source (Central Road Research Institute, 2009-2010)

vi. Geotextiles in Road Construction and Prevention of Soil Erosion for Sub grade Stabilization at Jejuri - Morgon Road MDR-65, Taluka-Purandhar, District-Pune, Maharashtra

Source (Techfab India)

vii. Geotextile for separation, filtration and drainage (as per IRC: SP: 59-2002 & MORTH Clause-700) at Link Road between Paithan Road to Nagar Road (CH 0/000 to 4/041 including Bridge at CH 3/270 to 3/340) Taluka/District-Aurangabad, Maharashtra

Source (Techfab India)

viii. Usage of mono oriented reinforced steel wire mesh, rhomboidal cable wire rope panels, dynamic rock fall barriers, anchors , Mumbai –Pune Expressway

Source (Singh, 2016)

ix. Planting of shrubs and trees in a phased manner for erosion control

Source Anil, Rakesh, and Kiran, 2001

x. Construction of beach protection bund and groyne using geotextile tubes Kochi, Kerala, India

Source (Maccaferri India, 2015)

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