National Cyclone Risk Mitigation Project (NCRMP)

National Disaster Management Authority (NDMA)

Consulting Services for Hazard, Risk and Vulnerability Assessment for 13 states and UT's in India

Hazard Assessment Report for Andhra Pradesh and Odisha

November 2015

Submitted by

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Acknowledgements

We appreciate the effort put by the Project Management Office NCRMP, Mr. B. Pradhan, Joint-Secretary, Ms. Mamta Kundra, Project Director, Mr. S.S Jain Deputy Project Director, Mr. P.E. Narayanan, Project Manager, Dr. S. Asta Lakshmi, Environmental Specialist, NCRMP, NDMA in contacting the State Nodal officers and some of the key national organizations like Forest Survey of India (FSI), Survey of India (SOI), and National Hydrographic Office (NHO), Dehradun; India Meteorological Department (IMD) and Census of India, New Delhi; National Remote Sensing Centre (NRSC) and Indian National Centre for Ocean Information System (INCOIS), Hyderabad. We would also like to thank all the State Nodal Officers and other national organizations for providing required support and data for this assignment.

We extend our special thanks to Mr. Saurabh Dani, Senior DRM Specialist, the World Bank, Washington DC, and Mr. Deepak Singh, Senior DRM Specialist, the World Bank, New Delhi for their kind help in providing official RDNA reports of Cyclone Hudhud and Phailin and useful discussions at different stages of this project.

Executive Summary

The Indian coast is highly vulnerable to natural hazards, particularly to severe cyclones and cyclone induced heavy rain and flooding. To reduce the vulnerability of the coastal areas, the Ministry of Home Affairs (MHA), Government of India (GOI) has undertaken the pioneering project "The National Cyclone Risk Mitigation Project (NCRMP)" that is being implemented through NDMA with the financial assistance from the World Bank. The aim of NCRMP is to create suitable physical infrastructure to mitigate/reduce the adverse effects of cyclones.

The present study is a part of the NCRMP project and aims to carry out Hazard, Exposure, Vulnerability and Risk Assessment associated to cyclone, storm surge, and rainfall induced flooding associated with cyclones for the 13 coastal States/UTs of India applying a deterministic approach. Specifically, the study area for this study is the coastal area of these states and UTs, which lies up to 10 m elevation (with reference to Mean Sea Level along the coastline). The study also aims at developing a standardized spatial database, maps, and a web-based Risk Atlas to help decision makers in the States/UTs and Central Government to make informed decisions regarding mitigation measures to protect the people and assets in these coastal regions.

The present report, 'Hazard Assessment Report for Andhra Pradesh and Odisha', is the fourth deliverable of this assignment which showcases the hazard data development and hazard assessment carried out by RMSI for two pilot states – Andhra Pradesh (AP) and Odisha. The report also includes a section on the progress of the web atlas development and testing.

Historical Review, and Hazard Data Collection and Processing

As a first step, the team carried out a thorough review of historical cyclones and cyclone induced flood events. A historical cyclone event catalog was created using four different sources as shown in the table below. All the events were classified as per the IMD storm classification scheme.

Sl. No.	Thematic data	Data source	Data availability
1	Storm Track Atlas	IMD	Cyclone track data for 1891-2007 is available in CD version (2008 ed.)
2	Historical cyclone track data	IMD	Cyclone track data for 1990-2014 is available at IMD website (www.imd.gov.in)
3	Historical cyclone track data	IBTrACS	Cyclonic database is available on public domain at six hourly intervals from 1842-2014
4	Historical cyclones maximum winds, Surge height, extent of inundation and flood depths along with associated loss information	SMRC report (1998), and published literature	IMD reports, SMRC report (1998), and published literature and research publications are available in public domain

A frequency and severity analysis of the historical cyclone catalog from 1877 to 2014 revealed that the Indian coastline can be divided into 5 severity zones varying from very high to low severity zones. Accordingly, the coasts of West Bengal and Odisha come under the very-high severity zone (Zone 1), that of Andhra Pradesh under the high severity zone (Zone

2), while the coasts of Tamil Nadu, Karnataka, Maharashtra, and Gujarat (Zone 3 and 4)come under the moderate severity zone, and Kerala comes under the low severity zone (Zone 5).

Historical data analysis shows that 202 cyclonic events made landfall in Zone 1 on coastal West Bengal and Odisha, an average of less than 2 cyclones per year and 103 cyclonic events crossed Zone 2 on Andhra Pradesh out of 176 cyclonic disturbances, an average of 1 cyclone per year. Out of these, 55 and 47 very severe cyclonic storms hit the Zone-1 and Zone-2 respectively during the period of 138 years.

Cyclone is a complex natural phenomenon that needs several parameters to model accurately. In order to model cyclone winds and surge, and cyclone rainfall induced flooding, the team collected Bathymetry (GEBCO and NHO), Topography (SRTM and NRSC DEMs) data, Meteorological rainfall (IMD) data, Hydrological flow (CWC) data, Land Use Land Cover (), and Soil (FAO) data. Data cleaning was performed by a series of quality control (QC) checks to identify missing values and to flag suspected values. Two types of data validations were carried out, namely, replacement of erroneous values and supplementing missing values using standard and internationally accepted processes.

Cyclone and storm surge modeling

All the historical cyclones that had made landfall in Zone 1 and Zone 2 were considered for identification of deterministic scenarios. The depressions and deep depressions were grouped in representative groups and two to three events from each group were selected. All the other category cyclones, i.e., Cyclone Storms, Severe Cyclonic Storms, Very Severe Cyclonic Storms, and Super Cyclonic Storms were included in the deterministic scenario list for analysis. This gave a total of 350 events in Zone 1 for Odisha and 160 events in Zone 2 for Andhra Pradesh.

Surface winds associated with a tropical cyclone are derived using a dynamic storm model. A variable pressure deficit, forward speed, and radius of maximum winds have been used in the storm model for computing wind fields at model grid points over the study area.

Storm surge hazard modeling was performed using the ADCIRC-2DDI model. The ADCIRC model requires wind forcing which was taken from the wind field derived using the dynamic storm model. Water levels along the open boundary were obtained from global tidal information from FES2004 database. ADCIRC provides surge amplitudes and associated inland inundation and flow velocity over the model domain.

Both the models were validated and calibrated against key historical cyclones using the observed data associated to those historical events. The calibrated models were used to generate the estimates of wind speeds and surge heights associated to every historical event at model grid points over the study area. The Gumbel's extreme value probability distribution was applied to modeled wind speeds and surge inundation depths to derive additional deterministic scenarios of maximum wind speeds for key return periods (2, 5, 10, 25, 50, and 100 years). These were summarized using GIS techniques to create return period scenario maps at village level.

Cyclone Induced Rainfall Flood Modeling

The study area continues to experience, as in the past, severe flooding not only due to storm surge but also flooding of rivers caused by heavy precipitation associated with tropical cyclones and monsoon depressions.

The objective of flood modeling is to assess the flood hazard associated with rainfall generated by cyclones for the study area in Odisha and Andhra Pradesh. Flood hazard has been assessed for major river systems across the study area (Subarnarekha, Brahmani Baitarani, Mahanadi, Godavari, Krishna, and Pennar river basins) to estimate the potential inundation from cyclone induced rainfall. A deterministic approach has been used to combine the information on (1) the scenarios of flooding, (2) the spatial extent of floods for different severity levels, and (3) the consequences of these floods (e.g. inundated area and flood depth).

As a first step, cyclone generated rainfall/flows events have been extracted by reviewing rainfall/flow information associated to the cyclone. Based on this review 92 events in Odisha and 86 events in Andhra Pradesh have been catalogued and have been used for historical flood events simulation and estimation of deterministic scenarios. For all rainfall-based events, hydrologic modeling was performed to generate flows followed by hydraulic modeling whereas for all flow based events directly hydraulic modeling was done.

A hydrological model establishes the flow behavior of the watershed or basin by converting the rainfall into runoff. The team used the open source hydrological model HEC-HMS. It transforms digital terrain information like drainage paths and watershed boundaries into a hydrologic data structure that represents the watershed response to precipitation, thus estimating the flows at various locations along the path of the river. The model was calibrated and validated using observed flow data by generating the flow hydrographs at various gauge stations and comparing the peak flows from multiple historical events.

Finally, two dimensional (2-D) hydraulic model development was undertaken to route the flows from one location to another, while estimating the water surface elevations and profiles for various scenarios. The 2D hydraulic model developed by the USACE HEC-RAS has been used for prediction and understanding of the floodplain inundation process. The model was calibrated and validated using observed water level data at various gauge stations from multiple historical flood events.

Using the river discharges during the various cyclonic events, the boundaries of the flood plains have been determined by using HEC-RAS 2D to provide flood extent maps that integrate model results with elevation data.

Observed cyclonic peak flows and simulated cyclonic peak flows were used for deterministic events generation for key return periods (2, 5, 10, 25, 50, and 100 years) for the gauge stations of various rivers. The key return period values of cyclonic peak flows were estimated using multi-variate extreme value distribution analysis using the Gumbel's Generalized Extreme Value Distribution. The estimated key return period flows have been used as an input to the hydraulic model for flood plain delineation. The flood hazard maps have been generated for the historic and deterministic events for key return periods (2, 5, 10, 25, 50, and 100 years).

Major Findings for cyclone, storm surge, and cyclone induced

- Analysis of historical cyclonic events in across all five Zones indicates that the frequency of Very Severe Cyclonic Storms is higher than the Severe Cyclonic Storms. This is contrary to the normal behavior of hazards as per which the stronger events are rarer. This suggests that the potential for more frequent larger losses in India is higher.
- Comparing severity of Zone-1 and Zone-2, one observes that the total number of cyclones that have hit Zone 1 is much higher than Zone 2 indicating that the risk is much higher in Zone 1 than in Zone 2. However, another interesting finding is that 13 severe cyclonic storms struck the Zone-2 whereas Zone-1, which comes in very-high severity zone, has been affected by only 8 severe cyclonic storms. This suggests that the potential for more frequent moderate losses is high in Zone-2 as compared to Zone-1.
- It is observed for the modeling of the cyclone-induced rainfall that it is the translational speed of the cyclone that plays an important role in flooding. Slower moving cyclone cause more flooding irrespective of their strength.
- In case of both Odisha and Andhra Pradesh, the modeling of flood events reflects specific discharge thresholds beyond which flooding is sure to happen. The trigger discharge values for various rivers at various gauge locations are given below.

River	Gauge	Discharge, cumec
Mahanadi	Tikarpara	10,000
Brahmani	Jenapur	3,000
Baitarani	Anandpur	1,500
Subernarekha	Ghatsila	2,000

River	Gauge	Discharge, cumec
Pennar	Nellore	1,500
Godavari	Polavarm	12,000
Krishna	Vijaywada	9,000
Vamsadhara	Kashinagar	1,500
Nagavali	Srikakulam	1,500

Findings for Andhra Pradesh

- In Andhra Pradesh Guntur, Krishna, and Srikakulam could experience winds of about 128-136 km/h under a 100-year return period scenario. The most vulnerable low-lying areas of Guntur and Krishna are prone to high water levels due to storm surge flooding.
- In Andhra Pradesh the cyclones induced flooding is mainly due to flooding in the small east flooding rivers, as the discharge carrying capacity of these rivers is comparatively low.
- In Andhra Pradesh, a coastal region of East Godavari district and the delta region of the Krishna and Guntur districts are highly affected due cyclone induced flooding. However, the Prakasham and Nellore districts get flooded due to Pennar and others small flowing rivers.

Findings for Odisha

- In Odisha, the delta region of Mahanadi and Brahmani-Baitarani rivers and in Andhra Pradesh the delta region of Krishna and Godavari rivers is highly vulnerable due to cyclone-induced flood.
- The Jagatsinghpur, Kendrapara, and Ganjam districts of Odisha are more vulnerable due to cyclonic wind hazard with Jagatsinghpur is most vulnerable to strong winds of about 144 km/h. Northern Odisha is more prone to cyclone surge with average flood depth for 100-year return period event varying between 0.5 to 5.6 m. The Puri and Ganjam districts are less prone to storm surge with an average flood depths ranging around 0.5 to 4.0 m for a 100-year scenario.
- In Odisha, Kendrapara, Bhadrak, Baleswar and Jajpur districts are the most affected due to cyclone induced flooding. This region gets heavily flooded even due to marginal increase in river flows. However, Puri and Jagatsinghpur districts are less affected due to cyclone induced flooding except few village pockets.

Progress update on Web Based Risk Atlas

This section provides the overall progress in the Web Risk Atlas development and should be read in conjunction with the progress report that was part of the Exposure and Vulnerability Assessment report submitted as the previous deliverable. During the period, some changes have been made to the user interface of the Home Page of the Web Risk Atlas to provide a more user-friendly interface that allows faster and easier comprehension of the cyclone hazard. Besides this, the other major accomplishment during the period was the import and integration of exposure data for Andhra Pradesh into the database.

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Abbreviations

Abbreviation	Expanded Form
ADCIRC	ADvanced CIRCulation
CCHE	Centre for Computational Hydroscience and Engineering
CR	Consistency Ratio
CWC	Central Water Commission
DAD	Development Assistance Database
DEM	Digital Elevation Model
DRM	Disaster Risk Management
DSS	Decision Support System
DTM	Digital Terrain Model
FARL	Flood Attenuation by Reservoirs and Lakes
FD	Finite Difference
FE	Finite Element
FIT	Flood Information Tool
GFDRR	Global Facility for Disaster Reduction and Recovery
GIS	Geographic Information System
GOI	Government of India
HEC	Hydrological Engineering Centre
HEC-RAS	Hydrologic Engineering Centre – River Analysis System
HMS	Hydrological Modeling System
HTTP	Hyper Text Transfer Protocol
HVRA	Hazard Vulnerability and Risk Assessment
IBTrACS	International Best Track Archive for Climate Stewardship
ICMAM	Integrated Coastal and Marine Area Management
ICZMP	Integrated Coastal Zone Management Project
IDRN	India Disaster Resource Network
IE	Internet Explorer
IITD	Indian Institute of Technology Delhi
IMD	Indian Meteorological Department
INCOIS	Indian National Centre for Ocean Information System
IPET	Interagency Performance Evaluation Task
JTWC	Joint Typhoon Warning Center
LULC	Land Use Land Cover
MEOW	Maximum Envelopes of Water
MHA	Ministry of Home Affairs
MoEF	Ministry of Environment and Forest
MSL	Mean Sea Level
NBSS&LUP	National Bureau of Soil Survey and Land Use Planning
NCRMP	National Cyclone Risk Mitigation Project
NDMA	National Disaster Management Authority
NED	National Elevation Dataset
NGDC	National Geophysical Data Centre
NHC	National Hurricane Centre
NHO	National Hydrographic Office
NIOT	National Institute of Ocean Technology
NOAA	National Oceanic and Atmospheric Administration
NOI	National Oceanographic Institute
NRSC	National Remote Sensing Centre
NUIS	National Urban Information System
NWP	Numeric Weather Prediction
PacRIS	Pacific Risk Information System
PCA	Principle Component Analysis
PCRAFI	Pacific Catastrophe Risk Assessment and Financing Initiative

Abbreviation	Expanded Form
PDC	Pacific Disaster Centre
PMU	Project Management Unit
POM	Princeton Ocean Model
PWD	Public Work department
QC	Quality Control
Q-Q	Quantile-Quantile
RAS	River Analysis System
SDI	Spatial Data Infrastructures
SICOM	Society of Integrated Coastal Management
SLOSH	Sea, Lake, and Overland Surges from Hurricanes
SOA	Service Oriented Architecture
SOI	Survey of India
SRS	System requirement Specification
SRTM	Shuttle Radar Topography Mission
STWAVE	Steady-State Spectral Wave Model
SWAN	Simulating WAves Nearshore
USACE	U.S. Army Corps of Engineers
UH	Unit Hydrograph
UNDP	United Nations Development Programme
UN ISDR	United Nations International Strategy for Disaster Reduction
UNESCO	United Nations Educational, Scientific and Cultural Organization
USA	Unite State of America
USACE	US Army Corps of Engineers
WMO	World Meteorological Organization
WMS	Web Mapping Services

1 Introduction

1.1 Project Background

The Indian coast is highly vulnerable particularly to severe cyclone and cyclone induced heavy rain and flooding. An estimated 40% of the total population of the country lives within 100 km of the coast. Keeping these in mind, the National Disaster Management Agency (NDMA) has taken initiatives to develop a proactive approach for integrating disaster risk reduction in development planning.

The National Cyclone Risk Mitigation Project (NCRMP) is a pioneer project of the Ministry of Home Affairs (MHA), Government of India (GOI) and is being implemented through NDMA with the financial support of the World Bank. The aim of NCRMP is to create suitable physical infrastructure to mitigate/reduce the adverse effects of cyclones. Part of this innovative project involves setting up of a web-based Cyclone Risk Atlas that will provide a risk management framework for decision makers in the States/UTs and the Central Government to take mitigation steps to protect the people and assets of the country.

This report, the *'Hazard Assessment Report',* for the pilot states of Andhra Pradesh (AP) and Odisha has been prepared at the end of hazard data development phase.

1.2 Objectives of the Study

The objective of the study is to provide a robust scientific and practical basis for assessing the risks from the cyclone hazard for the 13 coastal States/UTs of India. The main objectives of the study include:

- Developing standardized spatial databases, maps and a decision support framework for assessing the cyclone and related hydro-meteorological hazards, exposure, and vulnerability.
- Identification of critical *'hot-spot'* high vulnerability coastal areas for communities' at-risk and detailed development of planning/mitigation and emergency response decision support mechanisms in 10 of the top identified "hot- spot" areas (enable support for land use planning, shelter locations, evacuation routing, and emergency and contingency planning within these hotspot communities).
- Developing a platform for dynamic risk assessment modeling functionalities that will be taken up subsequently under Phase II of the NCRMP Project. (Deterministic hazard and vulnerability data to risk modeling is being done for phase-I, Dynamic and Probabilistic risk modeling shall be done for phase-II).

1.3 Study Area and Scope of this Report

1.3.1 STUDY AREA

The study area includes the coastal stretches that lie up to 10 m Mean Sea Level (MSL) in the districts of the 13 States/UTs, which could be vulnerable to cyclone winds, surge and cyclone induced flooding. For the convenience of data access and subsequent project activities, we have considered all the talukas/mandals falling within the 10m contours from MSL. Even if only a portion of a taluka/ mandal lies within the 10 m MSL limit, the entire Taluka has been considered. By this method, the total number of talukas/mandals, having geographical extent up to the 10 m MSL limit, is 617 and the names of these selected talukas are provided in Table 6.1 in Annexure 1 and are shown in Figure 1-1. The total geographical area covered by these talukas/ mandals is around 2,55,000 sq km.

These 13 States/UTs are further classified into two categories, based upon the frequency of cyclone occurrence, size of population and the existing institutional mechanisms for disaster management. The categories are as follows:

Category I: Higher vulnerability coastal States/UTs, i.e., Andhra Pradesh, Gujarat, Odisha, Tamil Nadu, and West Bengal

Category II: Lower vulnerability coastal States/UTs, i.e., Maharashtra, Goa, Karnataka, Kerala, Daman & Diu, Puducherry, Lakshadweep, and Andaman & Nicobar Islands.

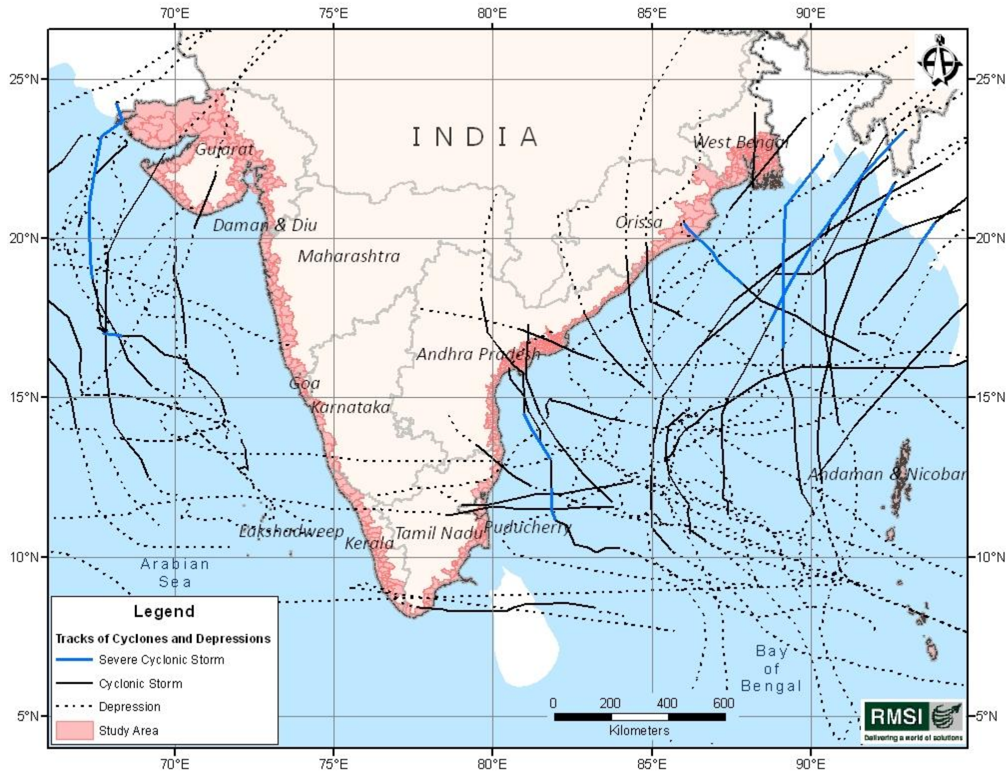

Figure 1-1: States'/UTs' Coastal Talukas/Mandals of the 13 states/UTs with land area falling up to the 10m MSL limit along with major cyclone tracks

1.3.2 SCOPE OF THIS REPORT

The scope of this report includes:

- Data collection and development of hazard database for Andhra Pradesh and Odisha
- Hazard mapping and analysis for Andhra Pradesh and Odisha
- Progress on the web atlas development and testing

1.4 Organization of this Report

This 'Hazard Assessment Report' covers the following aspects of the project:

- Historical review, data collection/development and data quality assessment
- Technical details on the modeling approach for cyclonic winds, storm surge and cyclone induced flooding
- Reporting progress on web atlas development and testing

This report has been organized into five chapters as follows:

- Chapter 1: Provides an overview of the project, and its scope and objectives and introduction to this report.
- Chapter 2: Details historical review, data collection/development, and data quality assessment for this project.

- Chapter 3: Describes the methodology used for assessment of cyclonic wind, associated storm surge, and cyclone-induced flooding hazards. It also addresses hazard mapping and analyses for cyclonic wind hazard, associated storm surge, and cyclone-induced flooding for both the pilot states, i.e., Andhra Pradesh and Odisha.
- Chapter 4: Key findings for hazard assessment
- Chapter 5: Reports the progress on web atlas development

2 Historical Review, Hazard Data Collection/ Development and Data Quality Assessment

The entire Indian coast is affected by tropical cyclones with varying frequency and intensity. Historical records reveal that thirteen coastal states and Union Territories (UTs) in the country are affected by tropical cyclones. Four states (Tamil Nadu, Andhra Pradesh, Odisha and West Bengal) and one UT (Puducherry) on the east coast and one state (Gujarat) on the west coast are more vulnerable to the cyclone hazard. Although the North Indian Ocean (the Bay of Bengal and Arabian Sea) generates only 7% of the world's cyclones (5 to 6 per year), their impact is comparatively high and devastating, especially when they strike the coasts bordering the North Bay of Bengal.

2.1 Hazard Data Collection and Development

Cyclones are a complex natural phenomenon and several parameters are needed to model them. In order to achieve greater confidence in numerical wind and surge estimates associated to cyclones in the Indian seas, one requires good quality data as input parameters in the model. These parameters include oceanographic, hydrographic, meteorological parameters (including the satellite derived storm characteristics), hydrological parameters, basin characteristics and coastal geometry, wind stress and seabed friction, and information about astronomical tides. These input parameters strongly influence wind and surge development along the coastal regions.

Tropical cyclones affect the study area in two seasons annually, namely, pre-monsoon (April-May) and post-monsoon (October-December). Compared to the pre-monsoon season, the months of October and November are known for severe cyclonic storms. For the present study, the historical cyclone catalog was available for the period 1842 – 2014. However, it is complete only for the period 1877 - 2014 having information on cyclone track positions, central pressure, wind speed and bearing at every 6-hourly time-steps. The catalog is compiled by RMSI based on data and information published by India Meteorological Department (IMD), JTWC and other international sources. The compilation process involves sourcing, cleaning and filling the gaps by informed judgment. IMD is the nodal government agency that provides weather services related to cyclones in India. The cyclones are given a Category based on wind speeds provided by the IMD given in Table 2-1.

The sources and vintage of historical cyclone data collected for storm surge modeling are given in Table 2-2.

Table 2-1: Classification of cyclonic disturbances according to IMD

Sl. No.	Storm category (Intensity)	Wind speed in knot	Wind speed in km/h
1.	Low Pressure Area (L)	Less than 17	<31
2.	Depression (D)	17-27	31-49
3.	Deep Depression (DD)	28-33	50-61
4.	Cyclonic Storm (CS)	34-47	62-88
5.	Severe Cyclonic Storm (SCS)	48-63	89-118
6.	Very Severe Cyclonic Storm (VSCS)	64-119	119-221

Sl. No.	Storm category (Intensity)	Wind speed in knot	Wind speed in km/h
7.	Super Cyclonic Storm (Sup. CS)	120 or more	222 or more

As far as historical cyclone tracks database is concerned, a variety of databases with more than a century of records for the Indian region has been used for this study. Initially, available cyclone tracks and their intensity information along with the surge reports were collected for the study area from IMD's database, SAARC Meteorological Research Center[1] (SMRC, 1998), International Best Track Archive for Climate Stewardship (IBTrACS), and from several research publications. The IBTrACS project combines information from numerous tropical cyclone datasets. It contains the most complete global set of historical tropical cyclones[2],[3] The SMRC (1998) report contains historical records dating back to a few centuries of cyclones, which formed over the North Indian Ocean and made landfall over the Indian coasts. The other available sources like SMRC (1998) and several research publications were also considered in preparing a master database of cyclonic tracks and their intensity information for the study area. The basic data collected from different sources was integrated into a GIS database that provided the framework for further analysis.

The storm tracks of past events from 1877 to 2014 for Odisha and Andhra Pradesh are given in Table 8-1 and Table 8-2 of Annexure 2: Cyclone and Storm Surge Hazard.

Table 2-2: Cyclone data availability for storm surge modeling

Sl. No.	Thematic data	Data source	Data availability
1	Storm Track Atlas	IMD	Cyclone track data for 1891-2007 is available in CD version (2008 ed.)
2	Historical cyclone track data	IMD	Cyclone track data for 1990-2014 is available at IMD website (www.imd.gov.in)
3	Historical cyclone track data	IBTrACS	Cyclonic database is available on public domain at six hourly intervals from 1842-2014
4	Historical cyclones maximum winds, Surge height, extent of inundation and flood depths along with associated loss information	SMRC report (1998), and published literature	IMD reports, SMRC report (1998), and published literature and research publications are available in public domain

2.1.1 Bathymetry Data

The amplitude of surge wave is dependent on water depth and varies from deep water to shallow water. Various researchers studied the variations in wave amplitude and wavelength

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[1] SMRC (1998). The impact of tropical cyclones on the coastal regions of SAARC countries and their influence in the region, SMRC-No.1, SAARC Meteorological Research Centre, Dhaka, Bangladesh, October 1998, 329 pp.

[2] http://www.ncdc.noaa.gov/ibtracs/index.php?name=ibtracs-data-access

[3] Knapp, K.R., M.C. Kruk, D.H. Levinson, H.J. Diamond, and C.J. Neumann (2010). The International Best Track Archive for Climate Stewardship (IBTrACS): Unifying tropical cyclone best track data. *Bulletin of the American Meteorological Society*, **91**, 363-376. doi:10.1175/2009BAMS2755.1

in relation to water depths. Their analysis clearly indicates that surge wave gets amplified starting from shelf depths ~200m. Hence, the model warrants high-resolution bathymetry information within the shelf area and coarse resolution data beyond the shelf limit.

High-resolution elevation and bathymetry data along the Indian coastline, as required by the ADvanced CIRCulation model (ADCIRC), are not readily available from a single source. Hence, data on land topography of the areas adjacent to the coastline and the bathymetry of the near shore areas, which are of critical importance for accurate prediction by the model, were collected from different sources as follows.

2.1.1.1 GEBCO Data

General Bathymetric Chart for Oceans (GEBCO) with spatial resolution of 30 arc seconds was used for the analysis area (Figure 2-1). It is a continuous terrain model for ocean and land. GEBCO traditionally concentrated upon the interpretation of bathymetry in deep water. As a general practice, standard contours have been fixed at intervals of 500 m with a 200 m and 100 m contour in shallow zones. GEBCO data is in cylindrical equidistant projection. The horizontal datum is WGS-84 and the vertical datum is the Mean sea level. The horizontal resolution is 30 arc seconds (~ 1 km) of latitude and longitude and the vertical resolution is 1 m. The bathymetric data set has been downloaded from the GEBCO website[4].

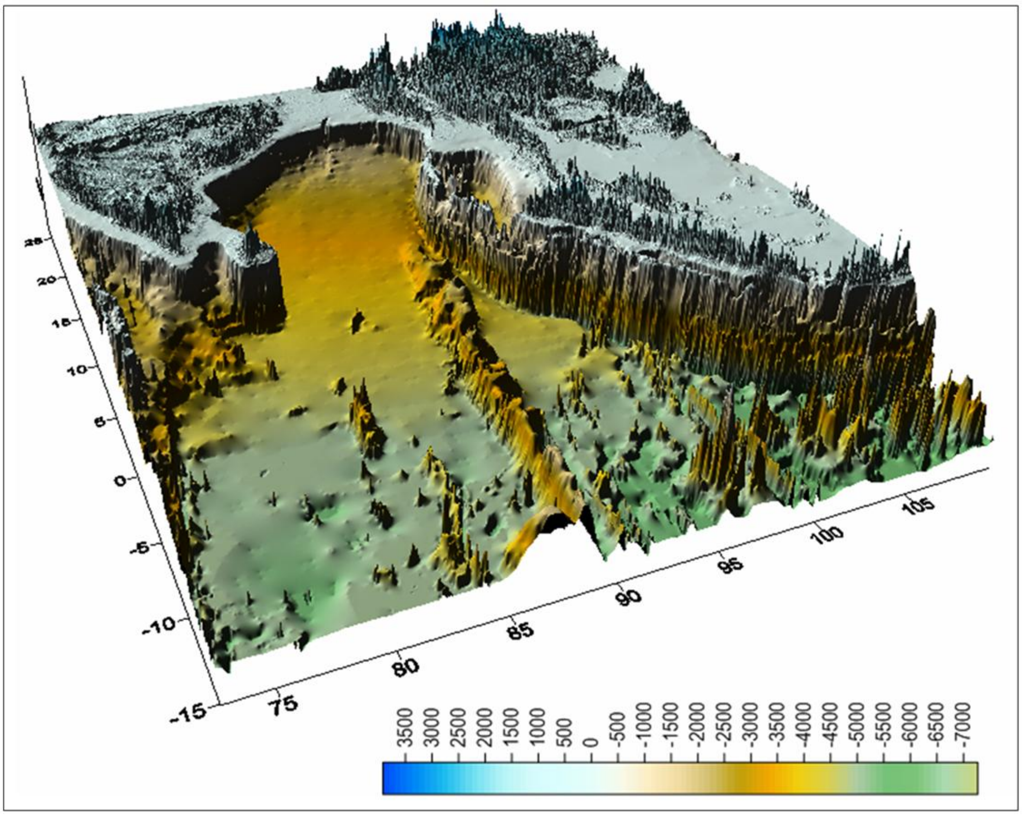


Figure 2-1: General Bathymetric Chart for Ocean (GEBCO) (spatial resolution of 30 arc seconds)

[4] http://www.bodc.ac.uk/products/bodc_products/gebco/

2.1.1.2 NHO Data

The coastal bathymetric spot data was obtained from National Hydrographic Office (NHO), Dehradun as scanned copies of the bathymetry charts and covers the entire coastline of India including Andaman and Nicobar Islands. The extent of this data from coastline to offshore distances was ranging between 75 km to 200 km. These charts were available in 3 CDs containing 176 PDF files at 3 different resolutions. The charts were digitized at RMSI. The details of charts are given in Table 2-3. The seamless bathymetry data is prepared by merging digitized bathymetric charts of resolution 300K with high-resolution charts (resolution 12.5 - 60K) covering ports using GIS analysis. Several digitized bathymetric charts of resolution 150K are used to fill the gaps where bathymetry in charts of 300K was not available. The merged NHO bathymetry along the coast covering West Bengal, Odisha, and Andhra Pradesh is presented in Figure 2-2.

Table 2-3: Details of bathymetric charts received from NHO, Dehradun

Location	300 K	150 K	12.5-60 K
West Coast of India	11	24	77
East Coast of India	7	6	19
Andaman & Nicobar Islands	10	-	23
Total no. of Charts	28	30	119

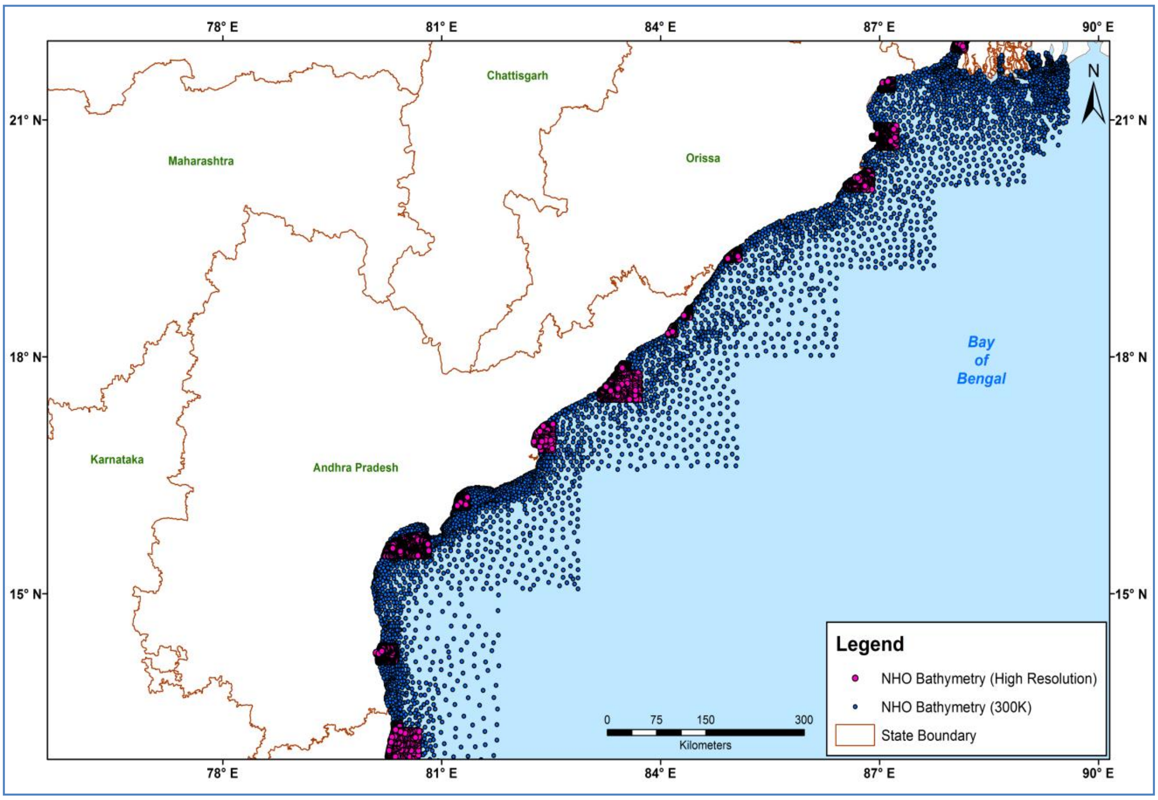


Figure 2-2: Merged Spot depths at different resolutions obtained from NHO used for the study area

In the absence of bathymetric data for off-shore areas, GEBCO gridded bathymetry data is used in the numerical model. Surface Water Modeling System (SMS) was used to interpolate merged bathymetric dataset to the required model resolution of about 90m (near coastline). With this procedure, realistic bathymetry is prepared for shallow waters, which is crucial in determining surge heights along the coastal regions of study area.

2.1.2 TOPOGRAPHIC DATA

High-resolution topographic data is required for mesh generation in hydraulic modeling, while the low-resolution topographic data is good enough for demarcating the catchment boundaries. SRTM DEM having 90-m resolution has been used for catchment delineation.

High-resolution elevation data illustrated in below subsections have been used for mesh generation in hydraulic modeling and floodplain inundation mapping.

2.1.2.1 NRSC Data

The National Disaster Management Authority (NDMA) acquired the high-resolution digital elevation data from NRSC with 10-m spatial resolution for hazard modeling. This data is available for the coastal area up to 10-m elevation form MSL. This data has various issues (source of errors). Major issues include reverse flow of water (hydrologically incorrect elevation values), negative elevation values, sudden disappearance of a river, process errors such as triangulation errors, data gaps (no values) and abrupt changes in elevations. In addition, this DEM was not available for several places of the study area (coastal area up to 10-m elevation form MSL).

2.1.2.2 SRTM Data

Because of various issues in NRSC 10-m data, the recently launched SRTM 30-m spatial resolution with 1-m vertical accuracy DEM has been used in this study. RMSI team first re-sampled the 30 m SRTM DEM to 10 m in order to bring both the data sets at the same level. Then 10 m NRSC DTM was overlaid with re-sampled 10 m SRTM. The areas (at pixel level) that have difference of (+or -) one meter elevation variation in the 10 m NRSC DTM have been picked up and replaced in re-sampled 10 m SRTM DEM.

This modified DTM for Andhra Pradesh, Odisha States having about 100 km buffer North of Odisha and South of Andhra Pradesh were further subjected to various checks, and corrections to develop a contiguous DTM data, which could be effectively used in the project for both cyclone/storm surge and hydrologic (flood) models. This modified DTM also covers entire study area. Figure 2-3 shows the elevation map for the study area.

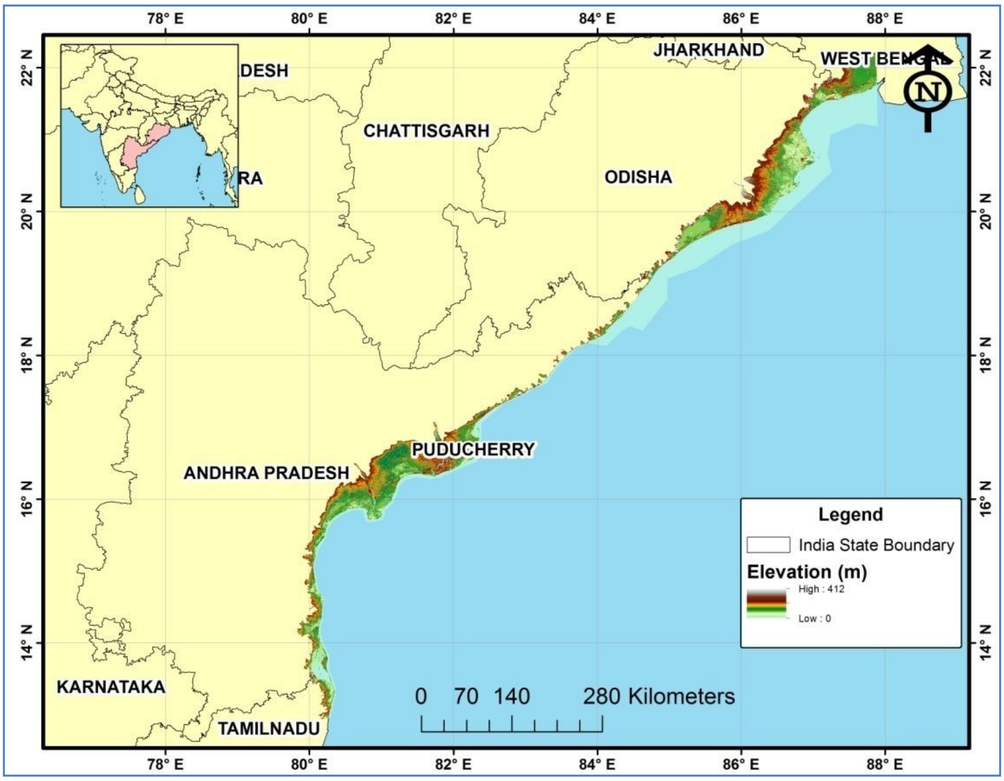


Figure 2-3: DEM data of Andhra Pradesh and Odisha

2.1.3 METEOROLOGICAL DATA

One-degree gridded rainfall data from IMD has been used for hydrological modeling of the basins. Rainfall data is available for 107 years from 1901 to 2007 for entire India. The locations and spatial distribution of rain gauges are shown in Figure 2-4. Figure 2-4 also shows the major river basin India.

Rainfall data is used in the hydrological model for developing rainfall-runoff relationships for cyclone-induced rainfall.

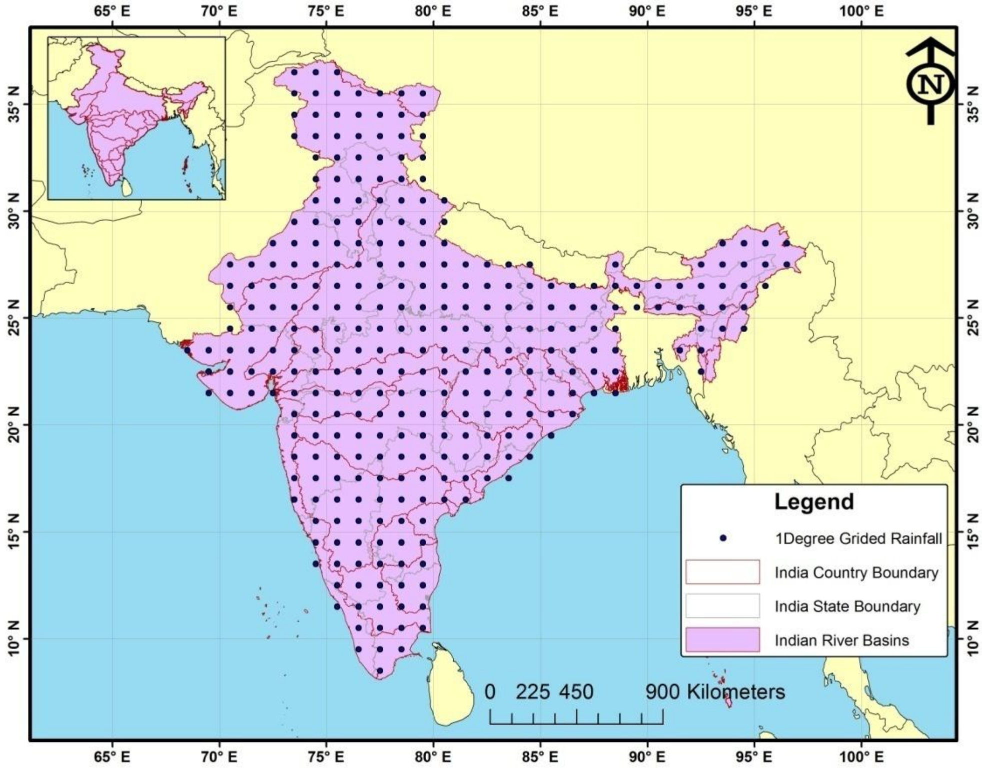


Figure 2-4: 1-degree gridded rainfall of India

2.1.4 HYDROLOGICAL DATA

Flow data has been collected from the Central Water Commission (CWC), India. CWC has a network of flow gauge stations across all rivers in India. River flow datasets for these flow gauge stations are freely available from the CWC Water Resource Information System (WRIS). These datasets are available for different durations for all the rivers.

Table 2-4 provides details of stations along with the durations of available flow data and upstream catchment areas. Flow data is used for inundation modeling of cyclone induced rainfall generated flows in the rivers of Andhra Pradesh and Odisha. The table shows that data is available from 1964 for a number of stations, while data is available only for recent years for a few of the stations. The locations and the spatial distribution of flow gauges are shown Figure 2-5.

In addition to the above flow data, the cyclonic rainfall induced peak flows for the major rivers has also been collected from various other sources like the State Disaster Management Departments of Andhra Pradesh and Odisha states.

Apart from using flow data in the inundation modeling, this data is also used for the calibration and validation of hydrological models.

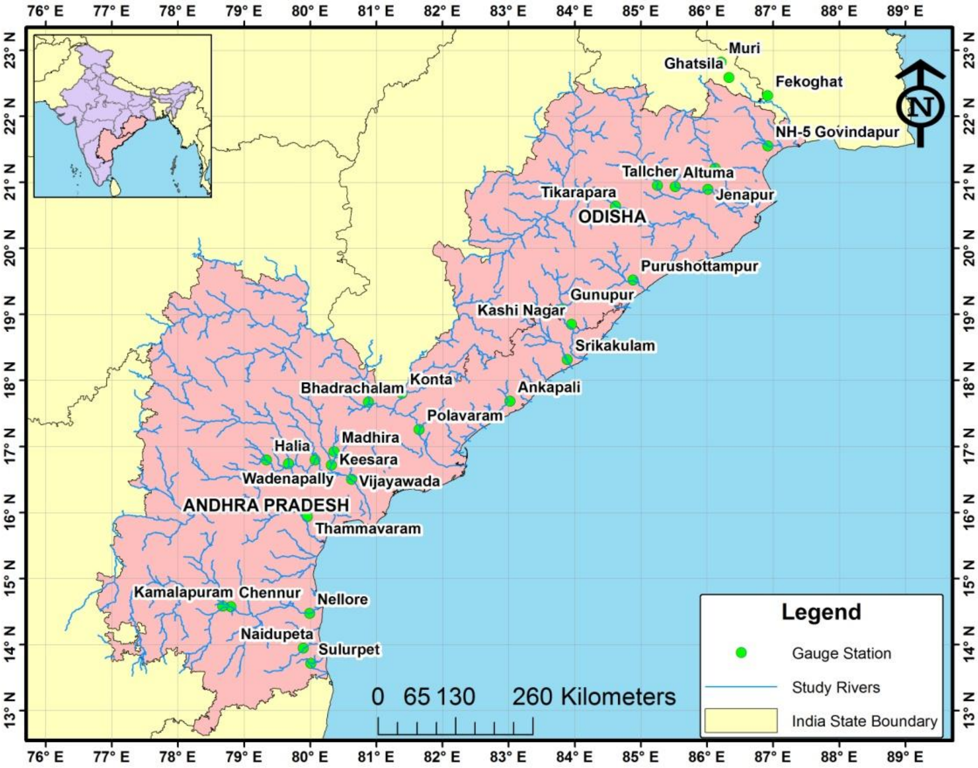


Figure 2-5: Flow gauge locations in Andhra Pradesh and Odisha

Table 2-4: Availability of discharge gauge datasets in Andhra Pradesh and Odisha

Sr. No.	Gauge Name	River Name	Latitude (Degree Decimal)	Longitude (Degree Decimal)	Upstream Area, sq. km.	Data Length
1	Bhadrachalam	Godavari	17.67	80.88	280,505	2007-2012
2	Konta	Godavari	17.80	81.39	19,550	1964-2012
3	Polavaram	Godavari	17.25	81.65	307,800	1965-2012
4	Dameracherla	Krishna	16.74	79.67	11,501	1968-2012
5	Halia	Krishna	16.79	79.34	3,100	1984-2012
6	Keesara	Krishna	16.71	80.32	9,854	1965-2010
7	Madhira	Krishna	16.92	80.36	1,850	1984-2012
8	Vijayawada	Krishna	16.50	80.63	251,360	1965-2012
9	Wadenapally	Krishna	16.79	80.07	235,544	1965-2010
10	Chennur	Pennar and other east flowing rivers	14.57	78.80	37,981	1989-2012
12	Naidupeta	Pennar and other east flowing rivers	13.95	79.90	2,650	1977-2011
13	Nellore	Pennar and other east flowing rivers	14.47	79.99	50,800	1987-2012
14	Sulurpet	Pennar and other east flowing rivers	13.71	80.01	5,927	1988-2012
15	Thammavaram	Pennar and other east	15.93	79.95	7,889	1977-2012

Sr. No.	Gauge Name	River Name	Latitude (Degree Decimal)	Longitude (Degree Decimal)	Upstream Area, sq. km.	Data Length
		flowing rivers				
16	Altuma	Brahmani	20.93	85.52	830	1990-2012
17	Jenapur	Brahmani	20.89	86.01	33,955	1979-2012
18	Tallcher	Brahmani	20.95	85.25	29,750	1985-1996
19	Tikarapara	Mahanadi	20.63	84.62	124,450	1971-2012
20	Ankapali	Rushikulya, Vamsadhara, Sarada & Nagavali	17.68	83.02	2,090	1989-2013
21	Gunupur	Rushikulya, Vamsadhara, Sarada & Nagavali	19.08	83.82	6,740	1978-2013
22	Kashi Nagar	Rushikulya, Vamsadhara, Sarada & Nagavali	18.85	83.95	7,820	1971-2013
23	Purushottampur	Rushikulya, Vamsadhara, Sarada & Nagavali	19.52	84.88	7,112	1978-2013
24	Srikakulam	Rushikulya, Vamsadhara, Sarada & Nagavali	18.31	83.89	9,500	1988-2013
25	Anandpur	Subarnarekha, Budhabalanga and Baitarani	21.21	86.12	8,570	1972-2012
26	Fekoghat	Subarnarekha, Budhabalanga and Baitarani	22.31	86.92	700	1987-2013
27	Ghatsila	Subarnarekha, Budhabalanga and Baitarani	22.58	86.33	14,176	1971-2013
28	Muri	Subarnarekha, Budhabalanga and Baitarani	22.82	86.21	1,330	1988-2013
29	NH-5 Govindapur	Subarnarekha, Budhabalanga and Baitarani	21.55	86.92	4,495	1978-2013

2.1.5 LAND USE LAND COVER DATA

Land Use Land Cover (LULC) data is an essential dataset that is used in hydrological modeling of a basin for determination of catchment response characteristics. It affects the patterns of overland flow within the basin boundaries. In the present study, LULC data is used in hydrological modeling as well as two-dimensional inundation modeling.

In inundation modeling, LULC data is used for generation of the spatially varied Manning roughness coefficient layer for the main channel as well as for the floodplain.

RMSI has in-house updated and validated high-resolution (25-m) LULC data, which has been used in this study. This data has been developed using LISS IV high-resolution (23.5-

m) satellite imageries. Figure 2-6 shows the LULC map of Andhra Pradesh and Odisha. The land use is predominantly agriculture/fallow and forest classes in both the states.

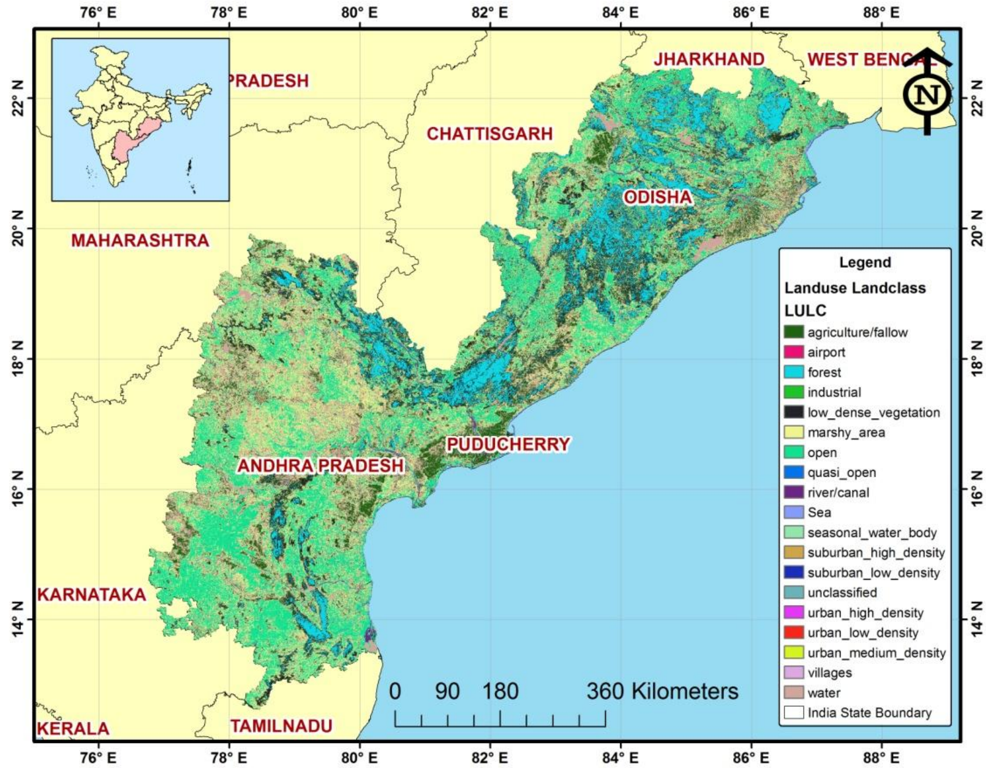


Figure 2-6: Land Use Land Cover classes in Andhra Pradesh and Odisha

2.1.6 SOIL DATA

Soil data is an essential parameter used to estimate the hydrological response characteristics of a river basin. The dataset is required for all the basins. The project team reviewed available data sets from project documents and in-house datasets. Since a single soil database was not available for all the basins, soil data included in the Food and Agriculture Organization's (FAO) Harmonized World Soil Database was used. Figure 2-7 shows the soil texture classes in Andhra Pradesh and Odisha.

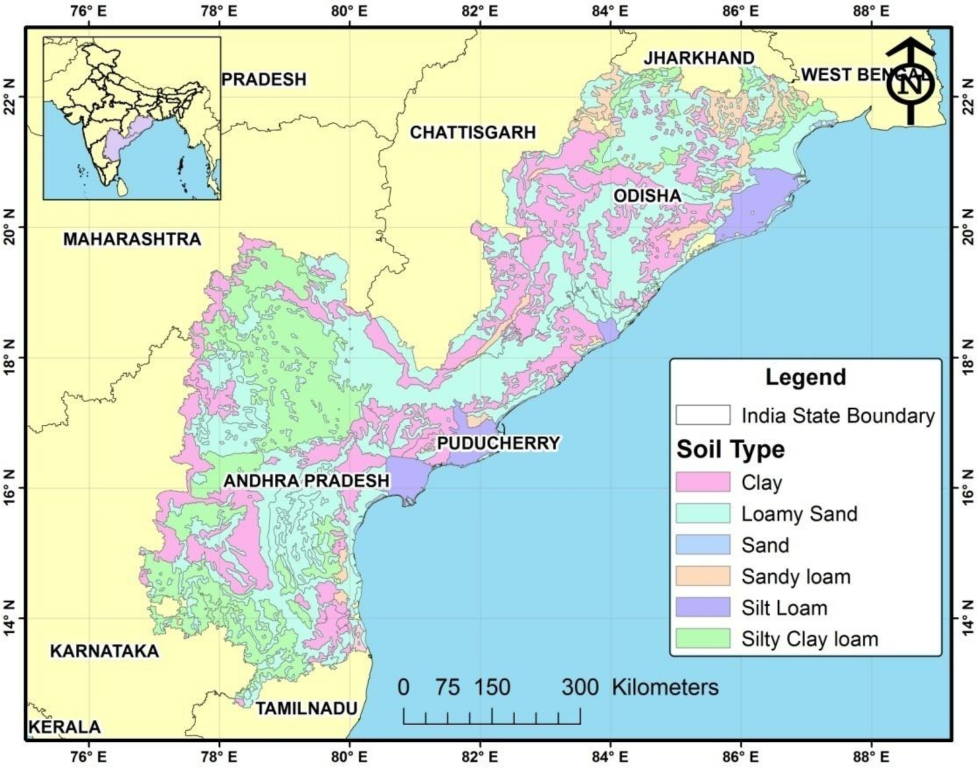


Figure 2-7: Soil textural classes in Andhra Pradesh and Odisha

This soil data is provided as a set of land units, each with a unique ID number. This unique ID number is used to match the textural properties and other parameters of soils. Based on the soil textural class, a hydrological soil group is assigned to each land unit within the basin.

The soil is predominant Clay and Loamy Sand in Odisha, while the Mahanadi and Brahmani-Baitarani delta regions of the state are predominated with Silt Loam soil. In Andhra Pradesh, the major soil classes are Clay, Loamy Sand, and Silty Clay Loam, while the Krishna-Godavari delta region is dominantly Silt Loam soil.

2.2 Review of Historical Cyclone and Cyclone Induced Flood Events

North Indian Ocean is one of the most prominent hot spots of cyclogenesis in the world. Statistics show that about 15% of the global tropical cyclones form over the Bay of Bengal and the Arabian Sea, and on an average, 5 to 6 storms form in this region every year, out of which 2 to 3 may be severe. The massive destruction and loss of human life associated with tropical cyclones can be attributed mainly to the cyclonic winds, sudden inundation and flooding of the coastal areas produced by storm surges and floods caused by cyclone induced rainfall.

2.2.1 Major Cyclonic events for Andhra Pradesh and Odisha

Extremely violent winds, heavy rains causing floods and storm tides (combination of storm surge and astronomical tides) causing coastal inundation are the destructive factors associated with tropical cyclones. Historical records state that the deadliest super cyclones of October 1999 and May 1990 severely affected coastal regions of Odisha and Andhra Pradesh, respectively. The November 1977 Andhra cyclone crossed the Andhra coast near Nizampatnam and devastated parts of the eastern coast of India, killing about 10,000 people and 27,000 cattle heads. Damage to the crops and other property was estimated to be around INR 350 crores (SMRC, 1998). The 1990 cyclone crossed 40 Km southwest of Machilipatnam and had severe impact on coastal Andhra Pradesh with over 967 people reported to have been killed, 7.8 million people and 5160 villages were affected. Over 3.6 million livestock perished in the cyclone with the total cost of damages to crops and properties estimated at over 2,248 crores rupees (SMRC, 1998). The Orissa super cyclone of 25-31 October 1999, which struck the coast near Paradip on 29th October carried in its core winds of nearly 260 km/h and generated storm surge, which was nearly 6m above sea level. The massive destruction caused by winds, surge and torrential rains eventually resulted in collapse of nearly 4 Lakh houses, affected more than 25 Lakh people, took a toll of nearly 10,000 human lives, and left nearly 7,500 persons injured. The storm surge alone was responsible for nearly 7000 lives lost (Kalsi, 2003). The extensive destruction caused by the Orissa super cyclone has brought into focus the damage potential of tropical cyclones and associated storm surge. Odisha and Andhra Pradesh witnessed several storms ranging from tropical depressions (31 – 61 km/h) to very severe cyclonic storms (88-221 km/h). Table 8-3, Table 8-4, and Table 8-5 in Annexure 2: Cyclone and Storm Surge Hazard shows the list of extreme historical cyclones and flooding that hit Odisha and Andhra Pradesh along with the damage details.

From the review of historical data it emerges that the entire coastline of India witnessed several storms ranging from Tropical Depressions (31 – 61 km/h) to very severe cyclonic storms (88-221 km/h). Considering the frequencies of total cyclones, total severe cyclones, landfalling cyclonic events and associated actual maximum wind from the period of 1877 to 2014 Indian coastline has been divided into 5 severity zones varying from very high to low severity zone. The areas struck with higher number of landfalling cyclonic events including super cyclones and Probable Maximum Storm Surge (PMSS) has been assigned a very-high severity zone prone to cyclone hazard, which includes coastal West Bengal and Odisha. Kerala, the maritime state having low intensity and frequency of cyclonic events, has been put into the category of low cyclone severity zone (Figure 2-8). Zone wise distribution of cyclonic events of various categories is provided in Figure 2-9.

A total number of 588 cyclonic disturbances hit Zone-1 from 1877 and 2014 (Figure 2-10). Out of these, 202 cyclonic events made landfall on coastal West Bengal and Odisha, an average of less than 2 cyclones per year. Figure 2-11 shows the tracks of 103 cyclonic events that crossed Zone-2. Out of 176 cyclonic disturbances, an average of one cyclone crossed per year. Historical data also revealed that 55 and 40 very severe cyclonic storms hit the Zone-1 and Zone-2 respectively during the period of 138 years. It is to be noted that 13 severe cyclonic storms struck the Zone-2 whereas Zone-1 that comes in very-high severity zone has been affected by 8 severe cyclonic storms only.

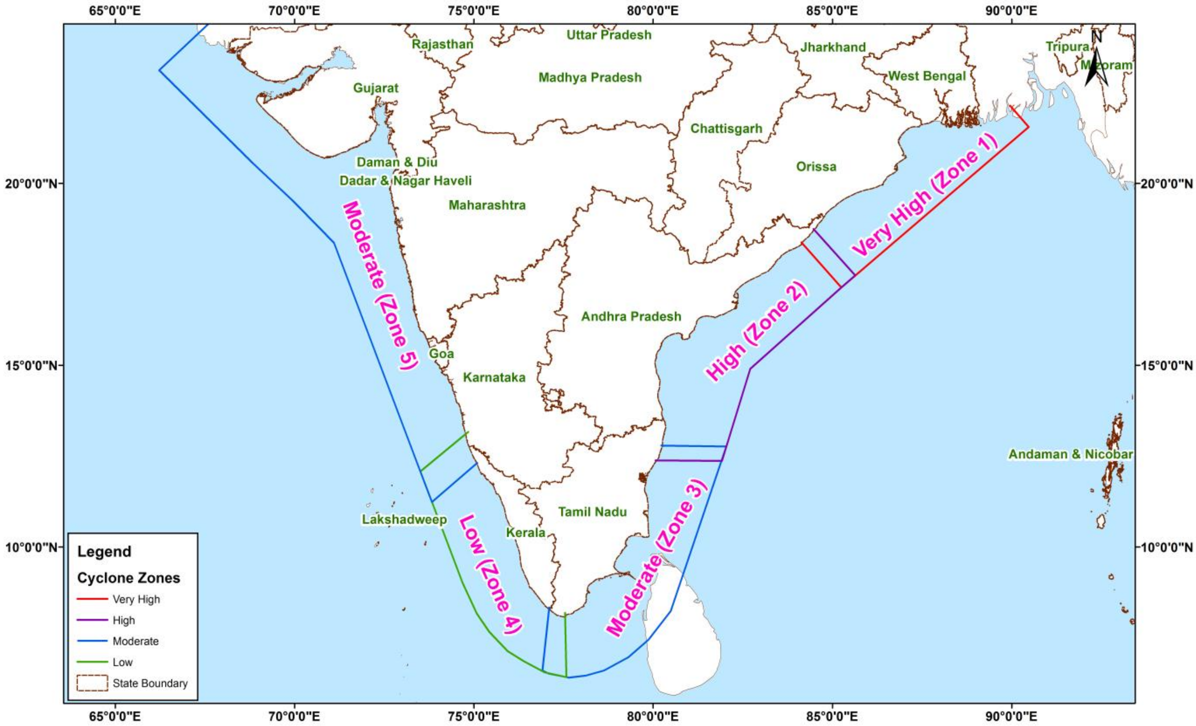


Figure 2-8: Cyclone-severity zones along the Indian coastline based on frequency and intensity of various categories of historical cyclones

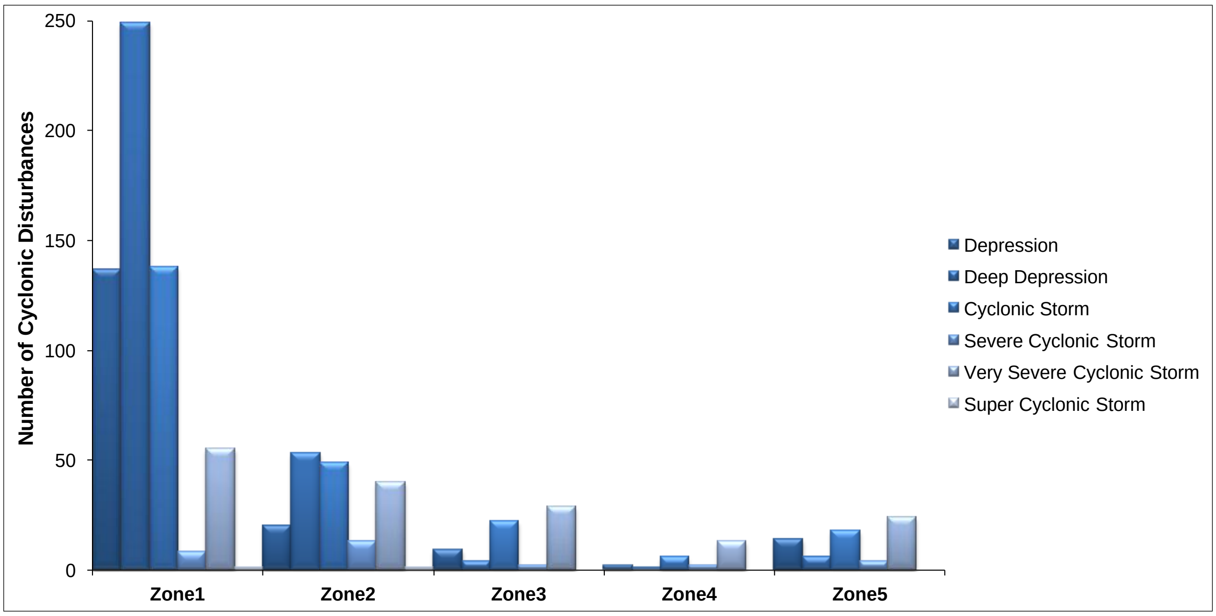
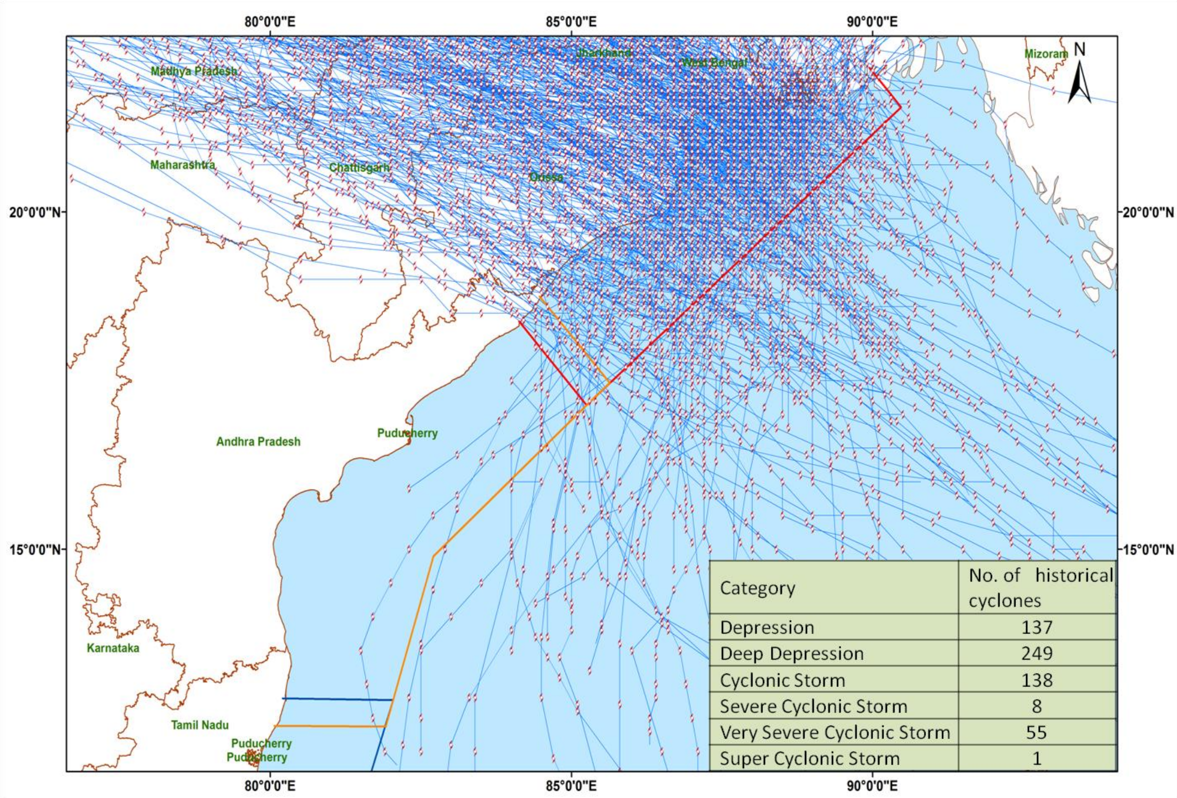
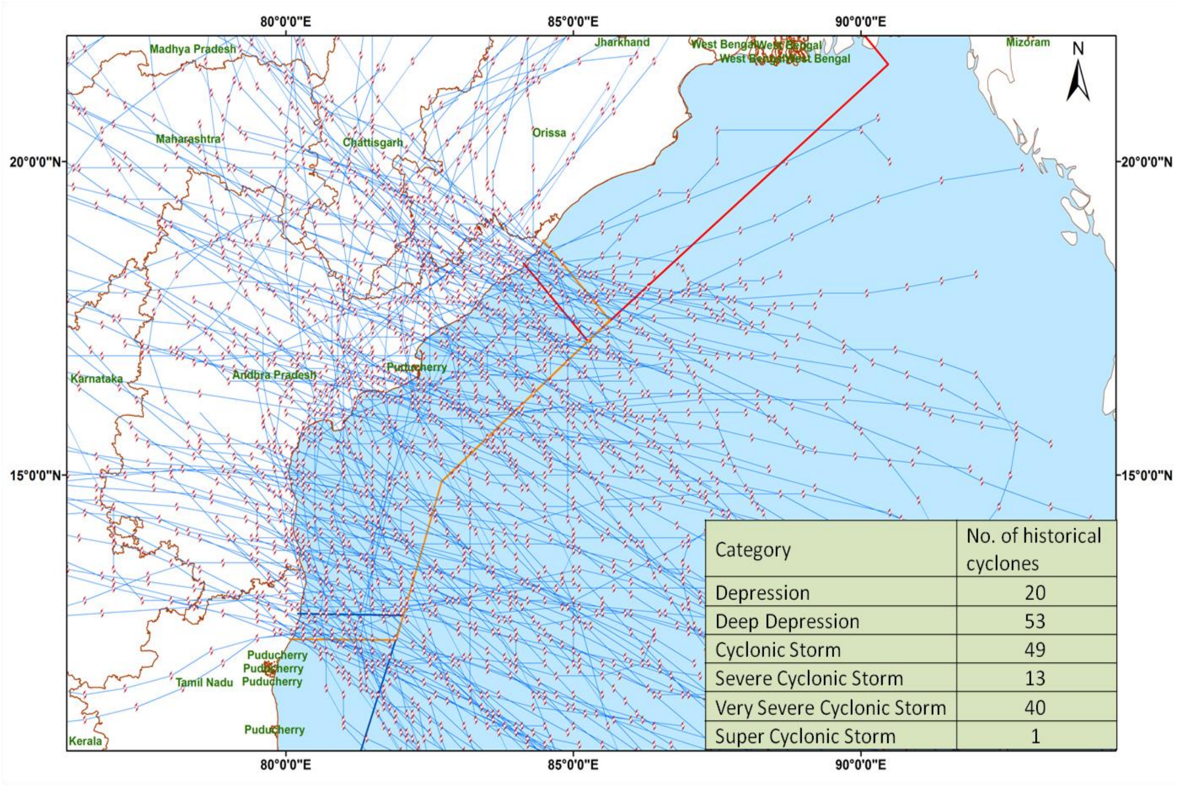


Figure 2-9: Zone wise distribution of cyclonic events of various categories



Category	No. of historical cyclones
Depression	137
Deep Depression	249
Cyclonic Storm	138
Severe Cyclonic Storm	8
Very Severe Cyclonic Storm	55
Super Cyclonic Storm	1

Figure 2-10: Tracks of landfalling cyclonic disturbances on Zone-1 during 1877-2014



Category	No. of historical cyclones
Depression	20
Deep Depression	53
Cyclonic Storm	49
Severe Cyclonic Storm	13
Very Severe Cyclonic Storm	40
Super Cyclonic Storm	1

Figure 2-11: Tracks of landfalling cyclonic disturbances on Zone-2 during 1877-2014

North Indian Ocean is one of the most prominent hot spots of cyclogenesis in the world. Statistics show that about 15% of the global tropical cyclones form over the Bay of Bengal and the Arabian Sea, and on an average, 5 to 6 storms form in this region every year, out of which 2 to 3 may be severe. The massive destruction and loss of human life associated with tropical cyclones can be attributed mainly to the cyclonic winds, sudden inundation and flooding of the coastal areas produced by storm surges and floods caused by cyclone induced rainfall.

2.2.2 FLOOD HISTORY

Odisha is most frequently affected state by cyclone and flooding. Most of the districts of the state are prone to these two hazards. Odisha has a coastal stretch of 480 km. In addition to this, Mahanadi, Brahmani-Baitarani, Rushikulya, Birupa, Budhabalanga and Subarnarekha, and their tributaries pass through Odisha, making the state prone to flooding. Since 1804 to 2010, floods in general have occurred in 126 out of 206 years. The frequency of floods has increased many times in the last few decades. During the last decade (2001 to 2010) the state was affected by flood for nine consecutive years.

Andhra Pradesh is exposed to cyclones, storm surges, floods, and droughts. A moderate to severe intensity cyclone can be expected to make landfall every two to three years. Once cyclones make landfall, they often cause heavy rains that translate into floods, as was the case with the damaging cyclone-induced floods in the Godavari delta in August 1986. In general, the flooding problem in Andhra Pradesh is due to the spilling of small rivers. Many of the major east flowing rivers of India pass through Andhra Pradesh. These major rivers, along with their smaller tributaries bring a large silt load from their upstream reaches and deposit it in the river mouth area. This subsequently increases the drainage problems in the delta area. Out of 59 major flood events occurred in Andhra Pradesh during the period 1977-2010, about 50% (29 events) have occurred due to heavy rainfall only.

The delta areas are affected by storm surge and cyclone induced rainfall simultaneously, which increase the severity of flooding problems. Figure 2-12, Figure 2-13, and Figure 2-14 show the 2005 and 2006 flooding in Andhra Pradesh and 2005 flooding in Odisha respectively.

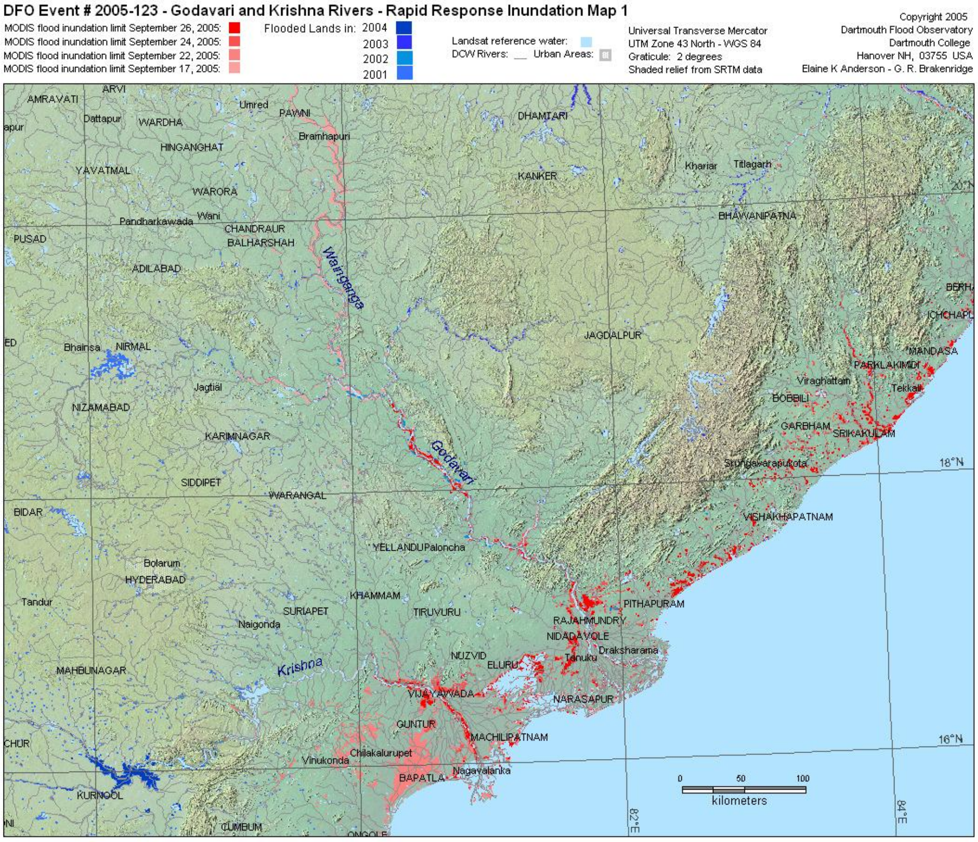


Figure 2-12: 2005 flood map of Andhra Pradesh (Dartmouth Flood Observatory)

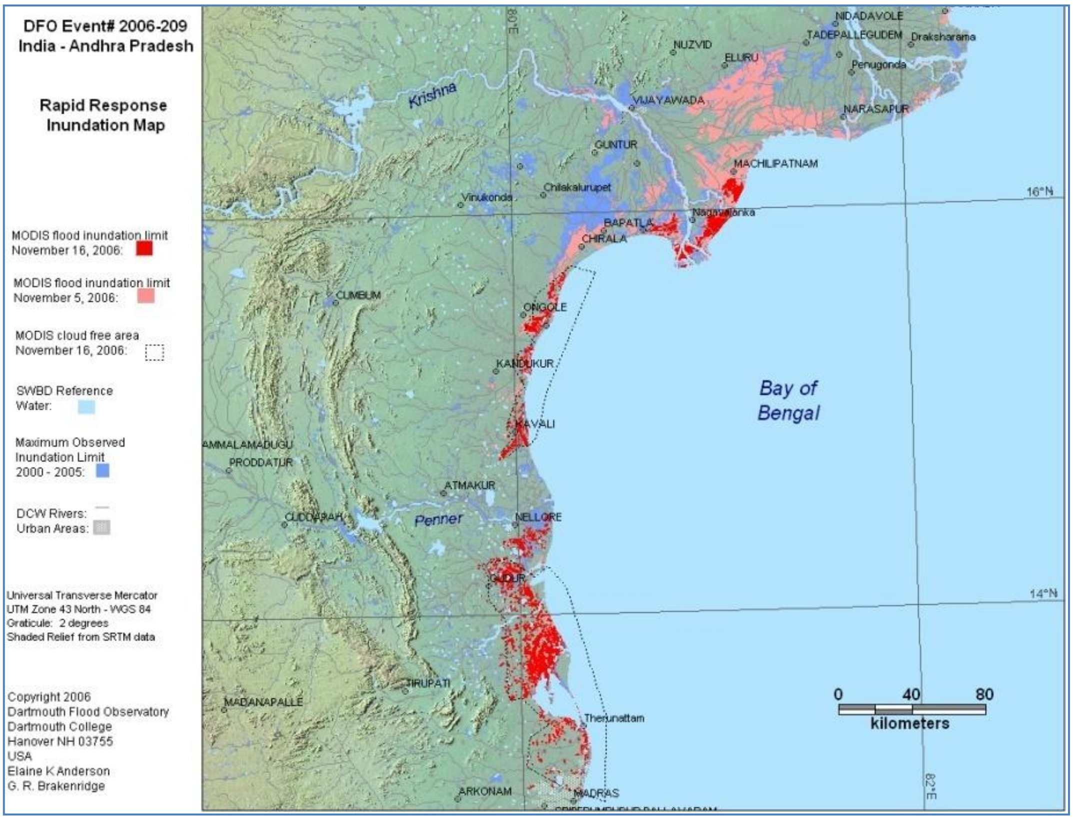


Figure 2-13: 2006 flood map of Andhra Pradesh (Dartmouth Flood Observatory)

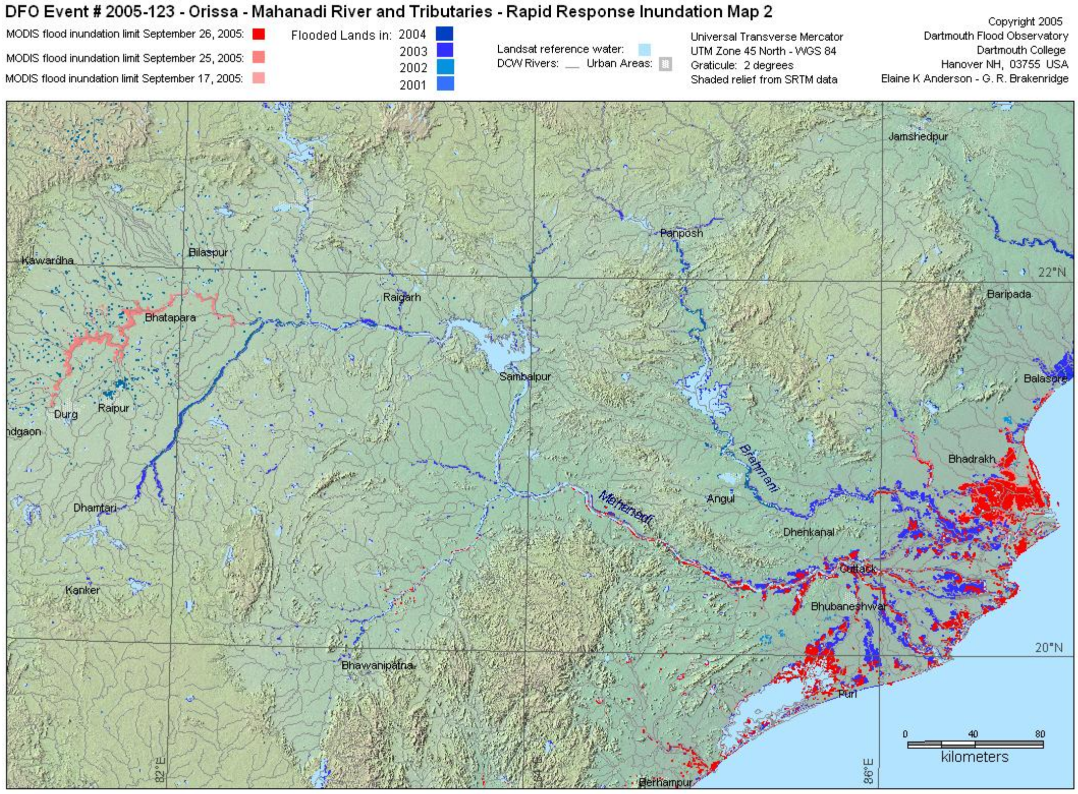


Figure 2-14: 2005 flood map of Odisha (Dartmouth Flood Observatory)

2.3 Data Quality Assessment

The 'raw' data obtained from different agencies often contain missing and erroneous values. There can be discontinuities due to non-climatic factors such as station relocations, changes in the surroundings, etc.

Data cleaning was performed by a series of quality control (QC) checks to identify missing values and to flag suspected values. Two types of data validation were carried out, namely, replacement of erroneous values and missing values. For interpolating a missing value, data from a number of stations surrounding a target station (spatial interpolation) and interpolation between observations over time (temporal interpolation) were used. For enhancing the data, the potential dates of discontinuity due to changes in the station location were identified from the station history.

The projection and datum of bathymetry/topography data obtained from various data sources was different and needed corrections before they were used in the numerical model (Figure 2-15). In addition, the resolution of data is dependent on the source and geographical location. For example, GEBCO data is gridded with resolution of 30 arc sec, whereas bathymetric spot data (NHO, Dehradun) is not gridded. Hence, the data is gridded to 90 m resolution using kriging interpolation, which is a method of interpolation that predicts unknown values from data observed at known locations. This method uses a variogram to express the spatial variation and it minimizes the error of predicted values, which are estimated by spatial distribution of the predicted values (Oliver and Webster, 1990). Hence, the corrected and re-projected datasets comprising of data from NRSC DEM, SRTM 30 m, NHO bathymetry from field surveys, and GEBCO have been merged to create seamless data sets.

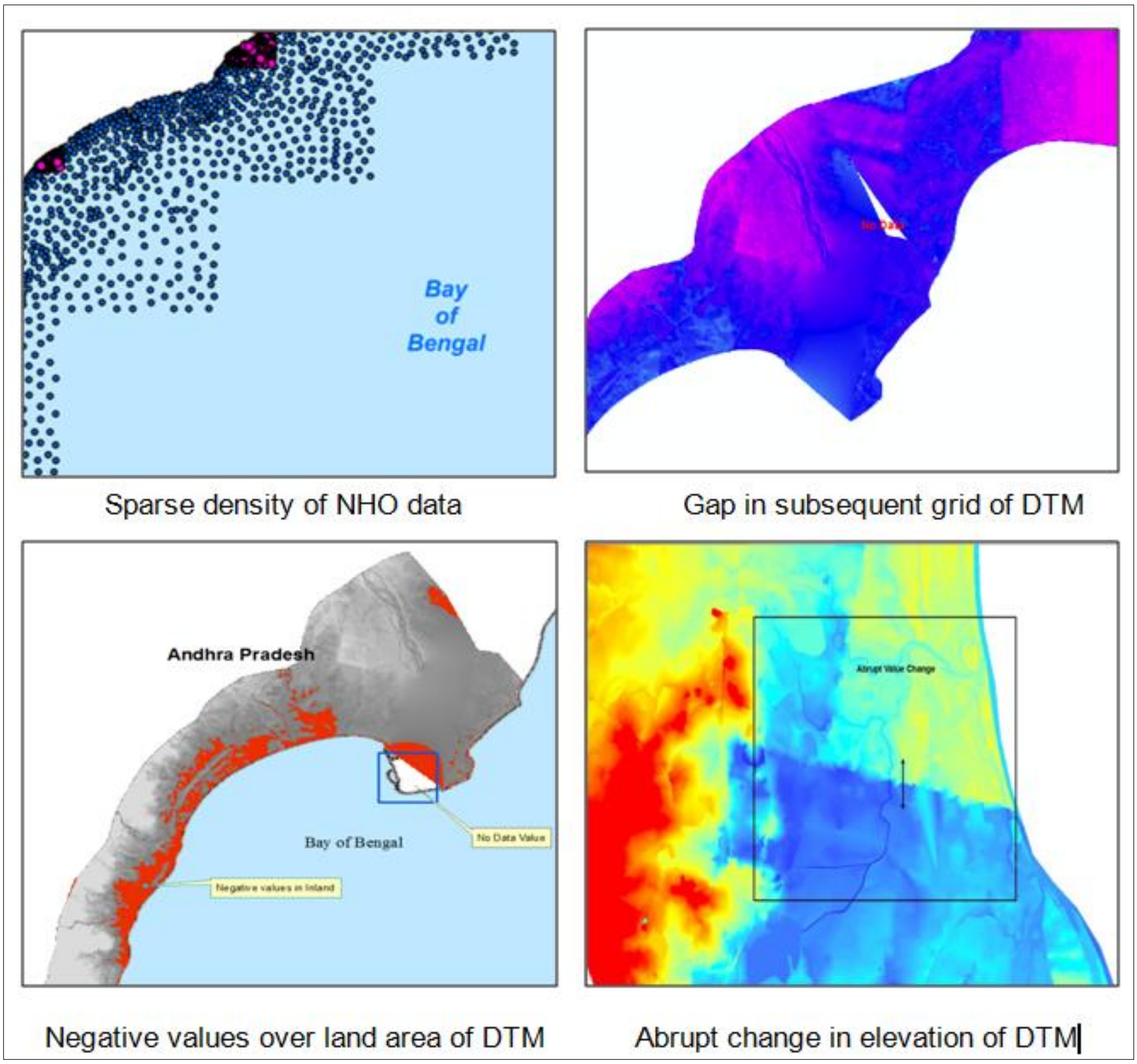


Figure 2-15: Data anomalies in different sources of bathymetry and topography

3 Cyclonic Wind, Storm Surge and Cyclone Induced Flooding Hazard

3.1 Introduction

Tropical cyclones are intense low pressure areas of the earth atmosphere coupled system and are extreme weather events of the tropics. Hazards associated with tropical cyclones are long duration rotatory high velocity winds, very heavy rain, and storm tide (the combined effect of storm-surge and astronomical tide). Out of these, storm surge is the most loss-causing hazard associated with cyclone, which can cause massive damage to assets in the coastal region and bring misery to the coastal human and livestock population. The focus of hazard assessment is to assess the impact of cyclonic wind, storm surge, and inland flooding induced by cyclones along the 13 coastal states/union territories of India covering area up to 10 m elevation with reference to mean sea level along the coastline. This section discusses the approach to cyclone modeling and its application to the coastal areas of the pilot states of Andhra Pradesh and Odisha.

A scenario based cyclone hazards assessment approach has been applied using high-resolution numerical storm surge, hydrologic and hydraulic models. The models are used for simulating the impacts of historical storms using their characteristics. The complex cyclone model comprises of three separate, but related, sub-models: 1) Wind model, 2) Storm surge model, and 3) cyclone rainfall induced flood model. Each of the three models has produced a hazard estimate that was viewed separately from others. However, their combined effect is a subject matter of the risk assessment and will be discussed in the Risk Assessment Report.

- Cyclonic wind hazard assessment identifies and demarcates areas, which are exposed to strong winds associated with tropical cyclones. It provides information on the extent and wind speed throughout cyclone prone areas for a range of wind magnitudes.
- Storm surge hazard assessment identifies and demarcates areas, which are exposed to surges. It provides information on the extent and depth of flooding for a range of events, which is the result of hazard assessment.
- The flood hazard assessment demarcates the flood-prone area (extent), and assesses its intensity and magnitude for cyclone rainfall induced historic and deterministic flood events.

This information is very useful to identify coastal stretches vulnerable to the impact of surge inundation. The methodology used for cyclone hazard modeling (cyclonic wind, storm surge, and cyclone rainfall induced flood) is presented in Figure 3-1 below and is described in details in the subsequent sections.

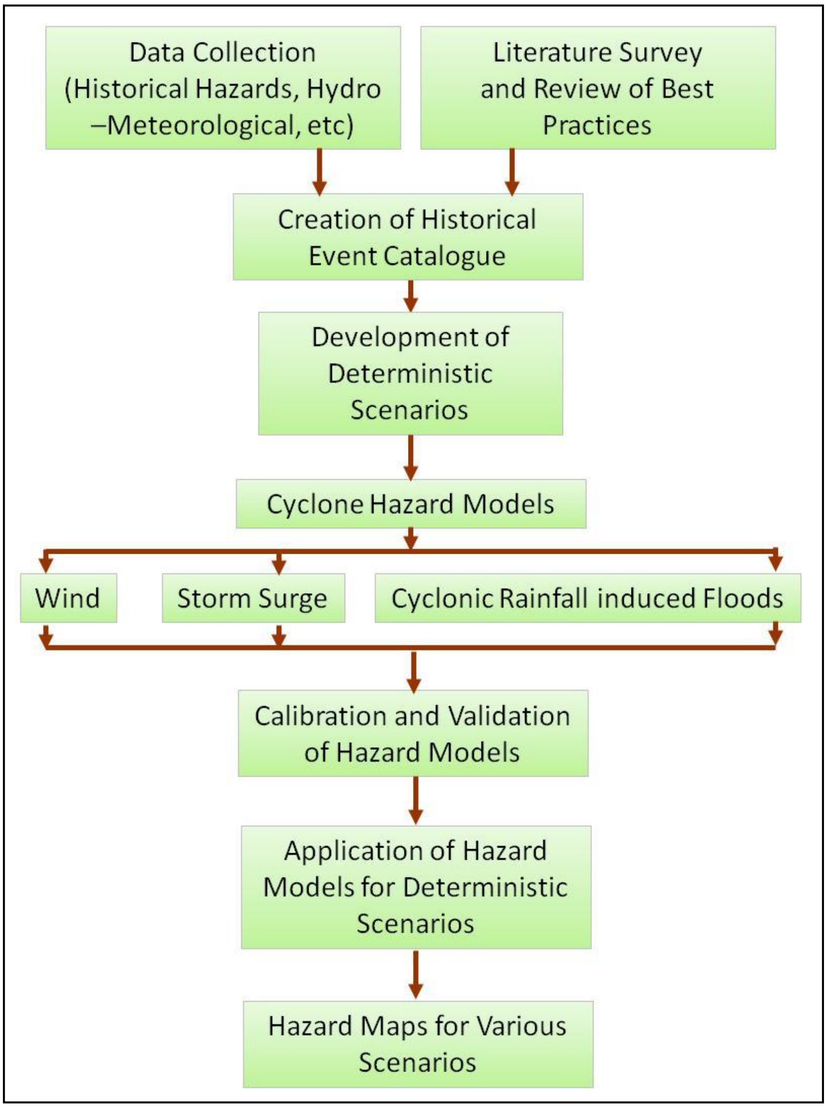


Figure 3-1: Flowchart showing approach for Hazard Assessment

3.2 Cyclone and Storm Surge Hazard Modeling

All the historical cyclones that had made landfall in Zone-1 and Zone-2 were considered for identification of deterministic scenarios. The depressions and deep depressions were grouped in representative groups and two to three events from each group were selected. All the other category cyclones, i.e., Cyclone Storms, Severe Cyclonic Storms, Very Severe Cyclonic Storms and Super Cyclonic Storms were included in the deterministic scenario list for analysis. This gave a total of 350 events in Zone-1 for Odisha and 160 events in Zone-2 for Andhra Pradesh. These deterministic scenarios of cyclonic wind speed and associated inland inundation and cyclone induced flooding were estimated using three different models. The following sections detail the procedure of setup and usage of these models for the present study.

3.2.1 Wind Hazard Model

Cyclonic wind hazard assessment identifies and demarcates areas, which are exposed to strong winds associated with tropical cyclones. It provides information on the extent and wind speed to the cyclone prone areas for a range of wind magnitudes. The wind hazard assessment framework adopted for this study is depicted in Figure 3-2. Deterministic events have been developed based on the catalogue of historical cyclonic events for the periods of 1877-2014. Based on this catalogue, following approach has been adopted.

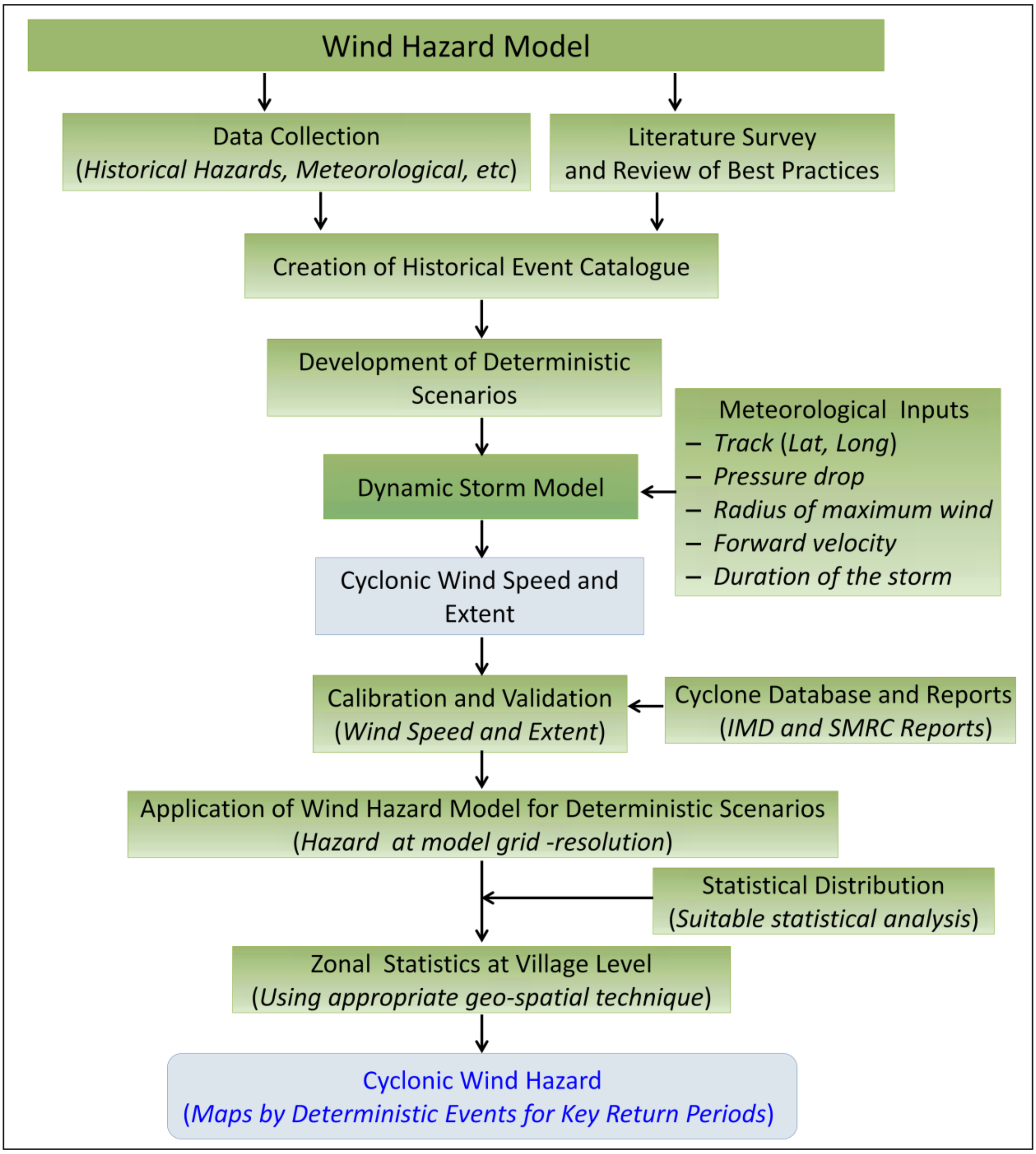


Figure 3-2: Flowchart showing approach for wind Hazard Assessment

- Identification, acquisition, compilation, and review of all relevant historical cyclone tracks and associated meteorological parameters. These parameters include positions of the cyclone, pressure drop, and radii of maximum winds at any fixed interval of times, which form the input for the storm model.
- Wind hazard modeling performed using dynamic storm model to estimate maximum wind fields and its extent for various historical cyclonic events.
- Calibration and validation of the modeled wind fields against observed wind speeds
- Application of the calibrated model for selected historical cyclonic events.
- Computation of maximum wind speed for key return periods using suitable statistical analysis

- Wind hazard mapping using modeled wind speeds and ArcGIS to show wind extent and winds magnitude for a range of events, which is the result of hazard assessment.

Dynamic Storm Model: Surface winds associated with a tropical cyclone are derived using a 2-D dynamic storm model (Jelesnianski and Taylor, 1973). Meteorological inputs used for this model include positions of the cyclone, pressure drop, and radii of maximum winds at any fixed interval of times.The main component of the storm model is a trajectory model and a wind speed profile approximation scheme. The trajectory model represents a balance among pressure gradient, and centrifugal, Coriolis, and surface frictional forces for a stationary storm. A variable pressure deficit, forward speed, and radius of maximum winds have been used in the location-specific storm model for computation of wind fields at model grid points. The storm strength is reduced after the cyclone crosses the coast. As a cyclone makes landfall, its strength reduces relative to Land use Land cover (LULC) of the areas which manifests modification in recorded meteorological parameters associated to the cyclone. This kind of data is used as input parameters for the storm model for computation of wind distribution associated with cyclonic event. The LULC aspect is accounted in the wind hazard model while computing pressure field and wind distribution based on meteorological parameters.

The cyclonic wind hazard modeling estimates wind magnitudes and provides associated area of influence affected due to strong winds at any time during cyclonic events. This process has been repeated for each model time step along the track and the maximum wind at each location throughout the life of the storm has been computed. Figure 3-3 explains the step-by-step process implemented for the computation of winds associated to any event. The model computed wind fields have been validated with available observed wind data related to important historical cyclones.

The calibrated storm model was used for the computation of wind fields associated with all selected landfalling historical cyclonic events. The Gumbel's[5] extreme value probability distribution was applied to the modeled wind speeds at each grid point of the model domain and maximum wind speeds for key return periods (2, 5, 10, 25, 50, and 100 years) were estimated.

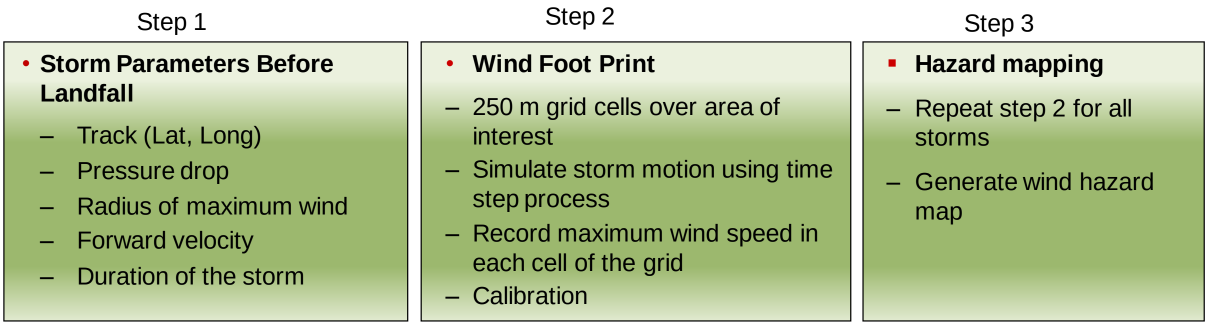


Figure 3-3 : Steps for wind hazard assessment

A zonal statistics (geo-spatial technique) was applied on peak gust wind speeds to get an aggregated value at village level. Finally, wind hazard maps at village level have been prepared for key return period events to identify the strong wind prone extent delineation.

[5] Gumbel, EJ (1954) Statistics of extremes. Nat. Bureau of Stand. App. Math. Series. 33, Washington D.C.

3.2.2 STORM SURGE HAZARD MODELING

Storm surge hazard modeling was performed using the ADCIRC-2DDI model. A detailed description of the finite-element based hydrodynamic model ADCIRC-2DDI is available in Luettich et al (1992)[6]. The governing model equations comprise of the depth-integrated equations for mass and momentum conservation, subject to incompressibility, and Boussinesq, and hydrostatic pressure approximations. These equations are discretized in space using linear finite elements and in time by a finite-difference scheme. Water levels along the open boundary were obtained from global tidal information and were represented by the six major constituents (M2, S2, N2, K1, O1 and P1) from Le Provost et al. (1995)[7] FES2004 database. This database was developed using a global tidal model and has been found to perform very well in deep waters.

The ADCIRC model requires wind forcing as an essential input parameter. For this purpose, the wind fields computed using the dynamic storm model of Jelesnianski and Taylor (1973)[8] were used. The details of the storm model are provided in the above section. Further, the wind model provides the wind-fields and pressure gradient to the ADCIRC model. The conversion of pressure gradient to equivalent water column height was obtained through the transformation $P/\rho_w g$ proposed by Blain et al. (1994)[9]. Finally, the wind stress and equivalent water column heights were linearly interpolated at each computational node of the finite element mesh used in the model.

The finite-element mesh for the study area was constructed using the software package Surface Modeling System (SMS) (Westerink et al. 1994)[10]. The program generated a grid with a low resolution in the deeper region, and high-resolution when approaching near the coast. The node spacing was set to 100 m near the coast and about 20 km in the open ocean. The model mesh with variable grid resolution for Odisha is shown in Figure 3-4 and the mesh in zoomed area of the study area is depicted in Figure 3-5. The mesh generated for Andhra Pradesh is depicted in Figure 3-6. The bathymetry and topography in study area, is shown in Figure 3-7 and Figure 3-8 for Odisha and Andhra Pradesh respectively. The landward boundary of the model is fixed from the coast based on 11m topo contour, presuming that the surge would never exceed 11m in this region. An explicit scheme is used in time discretization with a time step of 3 Sec.

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[6] Luettich RA Jr., Westerink JJ and Scheffner NW (1992) ADCIRC: an advanced three dimensional circulation model for shelves coasts and estuaries, report 1: theory and methodology of ADCIRC-2DDI and ADCIRC-3DL. Dredging Research Program Technical Report DRP-92-6, U.S. Army Engineers Waterways Experiment Station, Vicksburg, MS, 137 pp.
[7] Le Provost, C, Bennett, AF and Cartwright, DE (1995) Ocean tides for and from TOPEX/Poseidon, Science, 267, 639-642.
[8] Jelesnianski CP and Taylor AD (1973) NOAA Technical Memorandum. ERL, WMPO-3, 33 pp.
[9] Blain, CA, Westerink JJ, and Luettich RA (1994) Domain and grid sensitivity studies for hurricane storm surge predictions. Computational Methods in Water Resources X, A. Peters et al., [eds], Heidelberg, July 1994.
[10] Westerink JJ, Blain CA, Luettich RA, and Scheffner NW (1994) ADCIRC: an advanced three dimensional circulation model for shelves coasts and estuaries, report 2: Users manual for ADCIRC-2DDI. Dredging Research Program Technical Report DRP-92-6, U.S. Army Engineers Waterways Experiment Station, Vicksburg, MS., 156 pp.

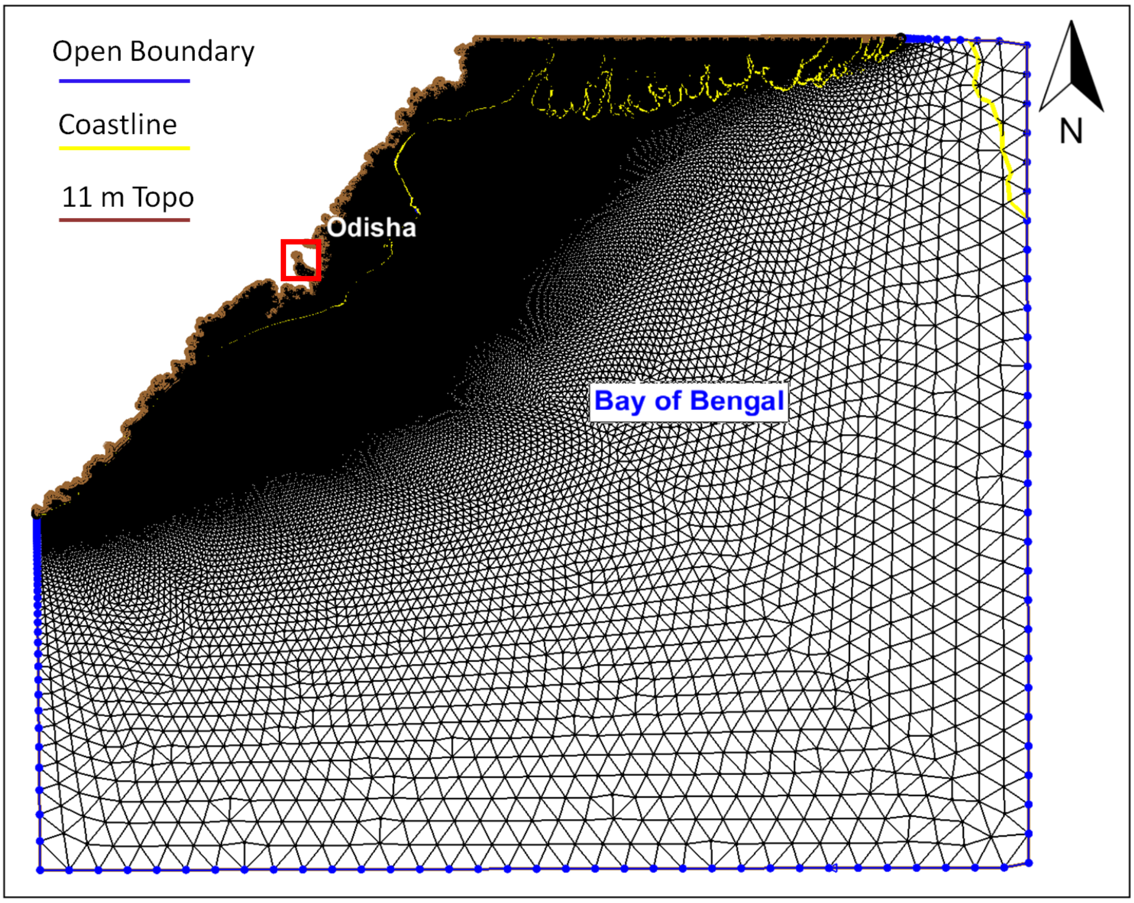

Figure 3-4: ADCIRC finite-element grid of the model domain for Odisha

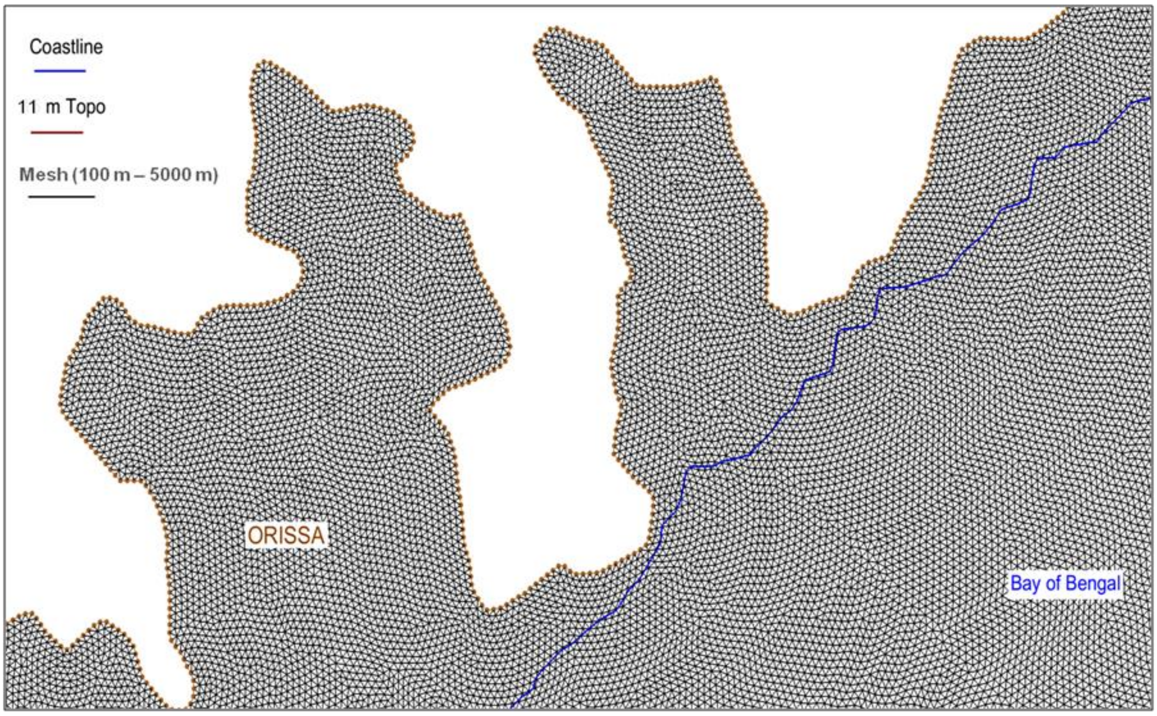

Figure 3-5: Zoomed portion of the ADCIRC finite-element grid of the model domain

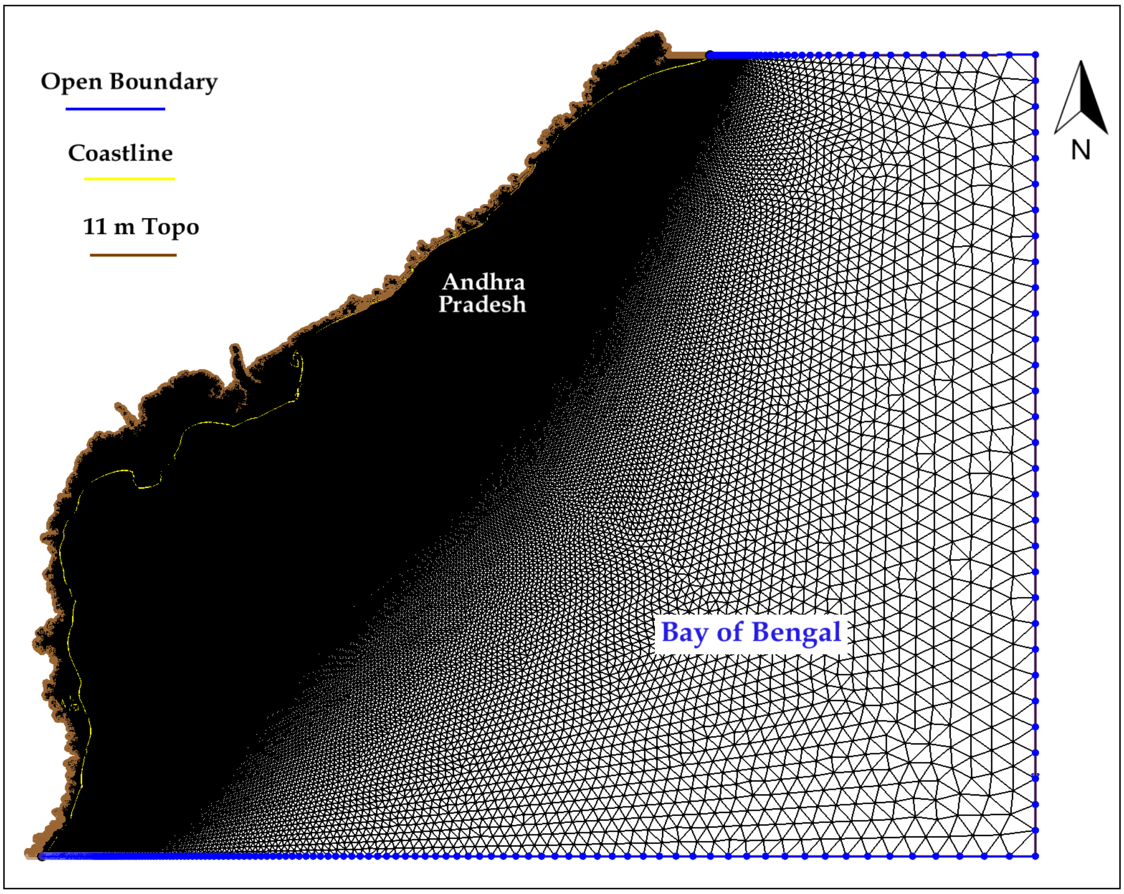

Figure 3-6: ADCIRC finite-element grid of the model domain for Andhra Pradesh

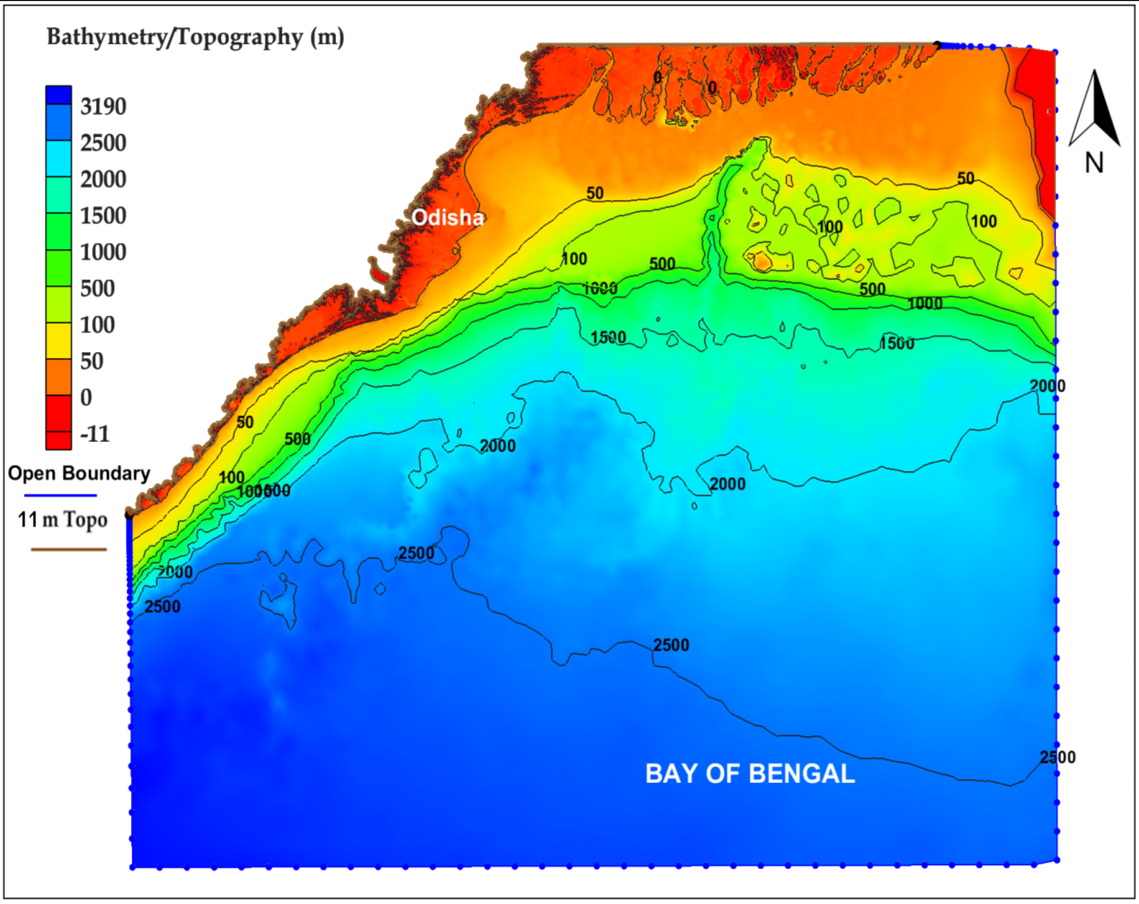

Figure 3-7: Bathymetry/Topography (m) of the model domain for Odisha

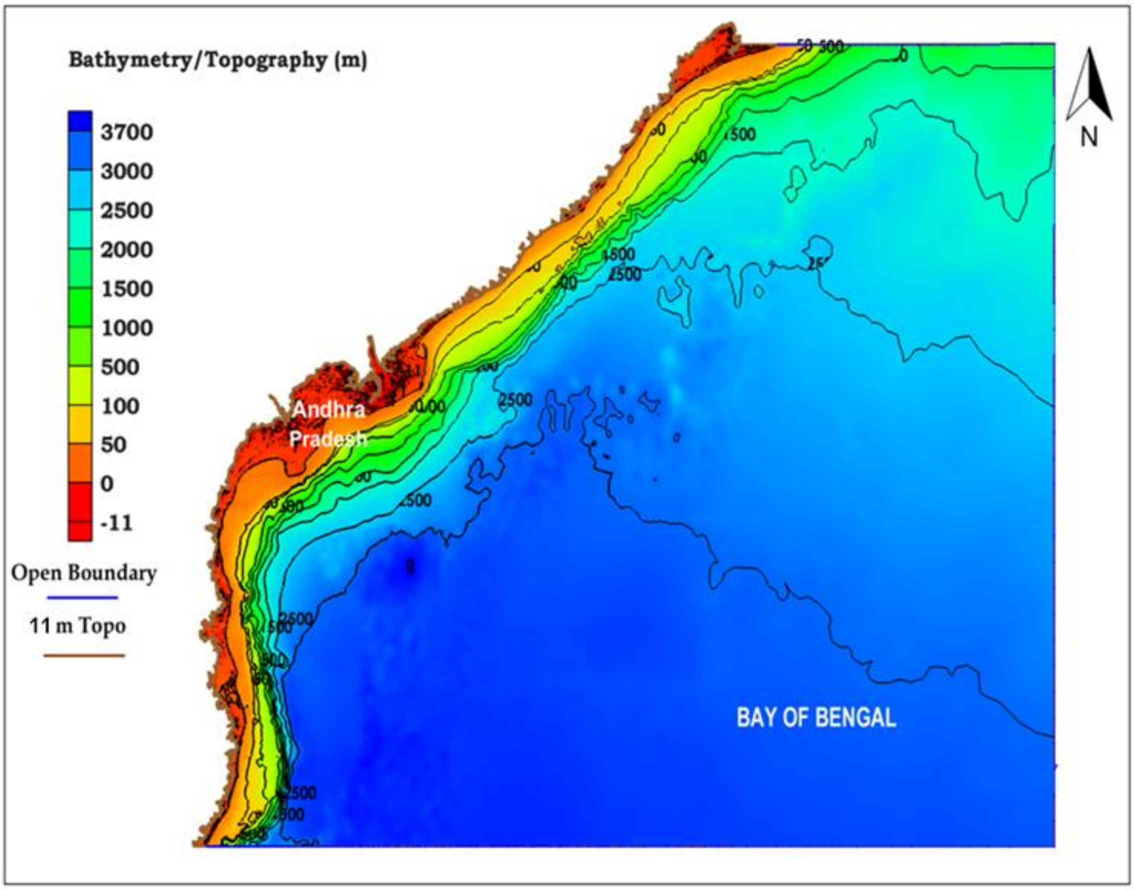

Figure 3-8: Bathymetry/Topography (m) of the model domain for Andhra Pradesh

The storm surge hazard assessment framework adopted for this study for Odisha and Andhra is presented in Figure 3-9, which comprises of the following:

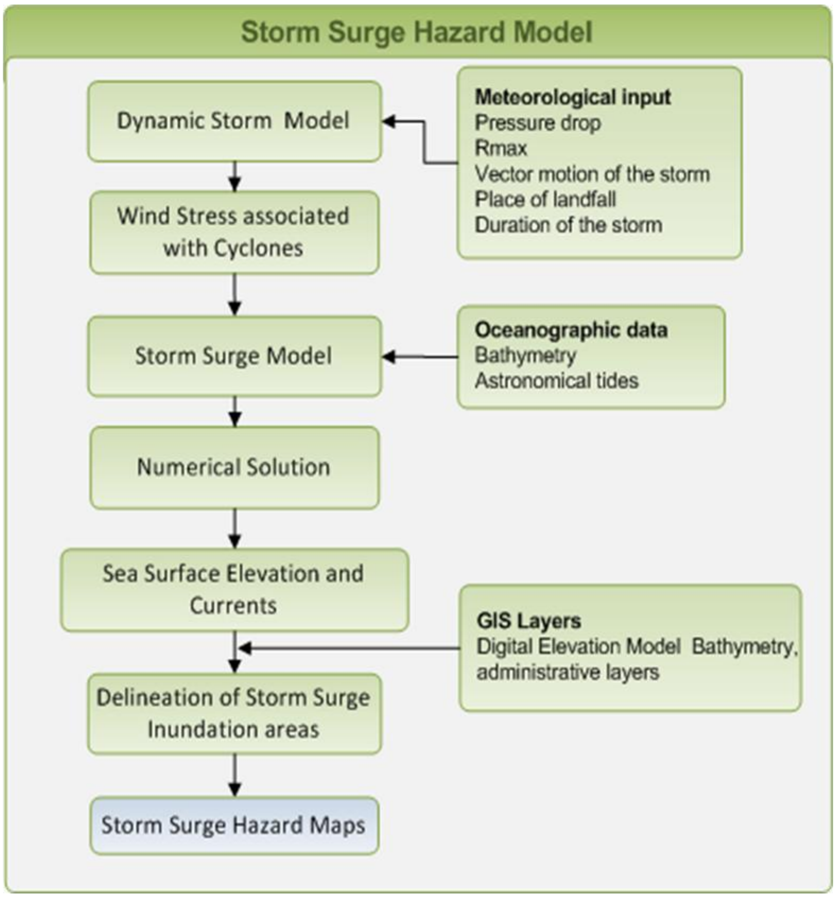

Figure 3-9: Storm surge hazard assessment framework

Using the landfalling historical tracks, pressure drop, radius of maximum wind, storm motion, and bathymetry/topography, dynamical simulation of storm surges have been carried out by making use of the location specific ADCIRC model. The maximum surge height computed with the model is calibrated/validated against the observed surge heights. The calibrated storm surge model was applied for landfalling historical cyclonic events and associated surge amplitude was computed at the coast.

The Probable Maximum Storm Surge amplitude (PMSS) at each coastal grid point of the numerical model has been calculated by making use of tidal amplitudes, wind wave setup and maximum surge amplitudes due to cyclonic winds along the coast. The Gumbel's extreme value probability distribution to the PMSS values was applied and maximum surge heights for key return periods (2, 5, 10, 25, 50 and 100 years) were calculated. Finally, scenarios of storm surge flooding due to probable maximum surge amplitude have been prepared for all the return period events for the selected villages to identify the flood-prone extent delineation.

3.2.2.1 Derivation of Inundation Extent Maps

Flood extent maps were prepared by integrating model outputs (maximum probable surge amplitude) with GIS elevation data to produce maps with varying flood depths depicted in different colors. The corresponding flood extent maps were generated for all the key return periods (2, 5, 10, 25, 50 and 100) for further use in loss assessment and risk modeling. GIS technologies were used to demarcate the areas that are prone to storm surge flooding and to estimate the flood depth in the inundated areas with the help of 10 m DEM.

3.2.3 Cyclone and Storm Surge Hazard Analysis

3.2.3.1 Calibration and Validation of Cyclone and Surge Models

The calibration and validation process is intended to ensure that the model parameters are well set to reflect the physical nature of each cyclone. A good fit in this case indicates a robust simulation, which can be used with reasonable confidence. A poor fit, on the other hand, indicates low confidence. Model calibration consists of changing values of model input parameters in an attempt to match field conditions within some acceptable criteria. This requires that field conditions at a site be properly characterized.

An independent sample of events has been used to calibrate and validate the cyclone model in terms of pressure drop, which plays a fundamental role over the wind speed for the episode, and surge height and extent of inundation in the coastal areas, an important factor owing to the high flow velocities. The performance of the model components (wind speed, surge height, and flood depth) simulations has been checked by means of the relative error of observed components, expressed as percentage (%ERR):

$$\%ERR = \frac{(Vs - Vo)}{Vo} * 100$$

where Vo and Vs are the observed and simulated surge heights (wind speed, flood depth), respectively. Therefore, %EV > 0 and %EV < 0 indicates an over- and underestimation of the heights by the model, respectively.

3.2.3.1.1 Calibration and validation of the wind hazard model

The performance of the cyclone and ADCIRC model was assessed against many historical events wherever observed values were available for wind speed and storm surge. The validation of wind speeds for 5 famous historical events -1999 cyclone of Odisha, 2013 VSCS Phailin, 1977 and 1990 Andhra Pradesh and VSVS Hudhud is given in Table 3-1 and Table 3-2 respectively. The modeled peak gust wind speeds for these events are shown in Figure 3-10 to Figure 3-14. The error in between the observed and computed wind speeds varies between 0%-4%. The computed maximum wind fields are found in good agreement with the available observations.

Table 3-1: Validation of wind speeds for Odisha cyclones

Cyclone name and year	Observed peak gust (km/h)	Modeled peak gust (km/h)	Error in % between observed and modeled peak gust
1999 Odisha cyclone	260	267	2.7
2013 Phailin cyclone	213	219	2.8

Table 3-2: Validation of wind speeds for Andhra Pradesh cyclones

Cyclone name and year	Observed peak gust (km/h)	Modeled peak gust (km/h)	Error in % between observed and modeled peak gust
1977 Andhra cyclone	204	209	2.5
1990 Andhra cyclone	235	241	2.6
2014 Hudhud	185	191	3.2

3.2.3.1.2 Calibration and Validation of the storm surge model

Damage from tropical cyclones is caused not only by their strong winds but also by accompanying storm surges and torrential rains. The severity of the storm surge at any location of interest is a consequence not only of the strength of the storm but also of the complex interaction of the storm's track, pressure and wind fields with the bathymetry (water depth offshore) near the coast. Storm surge simulations resulting from the application of wind, surface pressure and tidal constituents of K1, O1, P1, M2, S2, and N2 along the open ocean boundary, were consistent with the observations.

The validation of peak surge heights for 5 severe events namely, October 1999 Paradip cyclone, October 2013 Phailin cyclone, November 1977 Andhra cyclone, May 1990 Andhra cyclone and Hudhud cyclone are given in Table 3-3 and Table 3-4 respectively. The observed number in bracket is taken for error estimation. Simulation of surge heights is found in good agreement with the available observations. The error in between the observed and computed surge heights varies between 0%-14%.

Table 3-3: Validation of surge heights for Odisha cyclones

Cyclone name and year	Observed surge height (m)	Modeled surge height (m)	Error in % between observed and modeled surge height
1999 Odisha cyclone	6-7 (7)	6.8	2.8
2013 Phailin cyclone	2-3 (3)	3.0	0.0

Table 3-4: Validation of surge heights for Andhra Pradesh cyclones

Cyclone name and year	Observed peak gust (km/h)	Modeled peak gust (km/h)	Error in % between observed and modeled surge height
1977 Andhra cyclone	5	5.3	6
1990 Andhra cyclone	4-5 (5)	4.3	14
2014 Hudhud	2.0	2.1	5

The model results reported in this study are in good agreement with the available maximum wind and peak surge observations/estimates. The results emphasize the suitability of a fine resolution location specific model for a reasonable simulation of winds and surges along the Odisha and Andhra Pradesh coasts.

3.2.3.2 Mapping of historical and deterministic events for wind and storm surge hazards

3.2.3.2.1 Wind extent mapping for historical events

The dynamic storm model was used for the computation of wind fields associated with the landfalling historical cyclonic events. Model calculated maximum wind speeds at each grid point of the model domain. This model has been calibrated and validated using available observed data related to important historical cyclones. Wind hazard extent maps for historical events have been prepared by integrating model results with various GIS themes to produce maps with varying wind magnitudes and are depicted in different colors (Figure 3-10 to Figure 3-14).

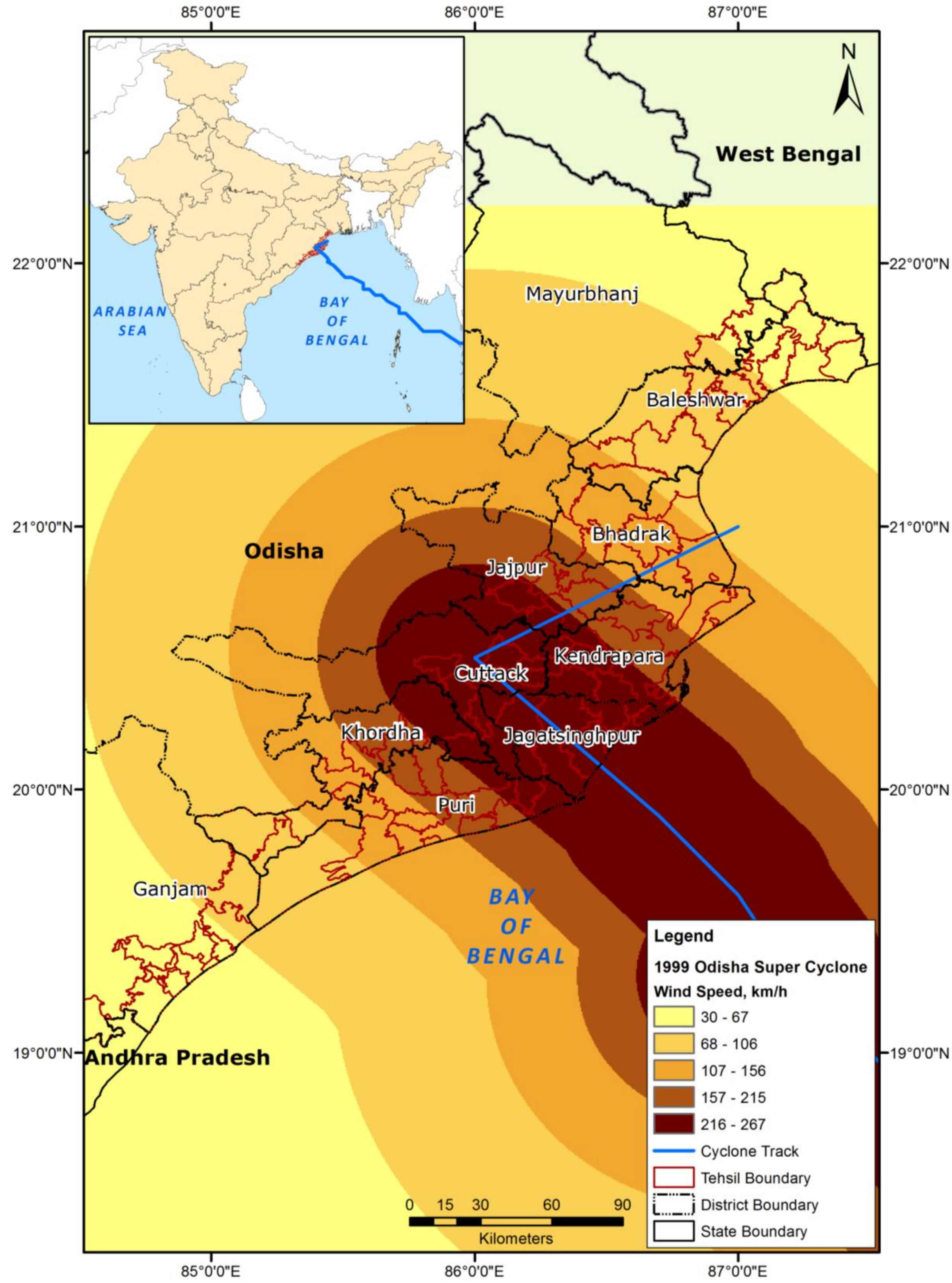

Figure 3-10: Modeled wind field of 1999 Odisha cyclone

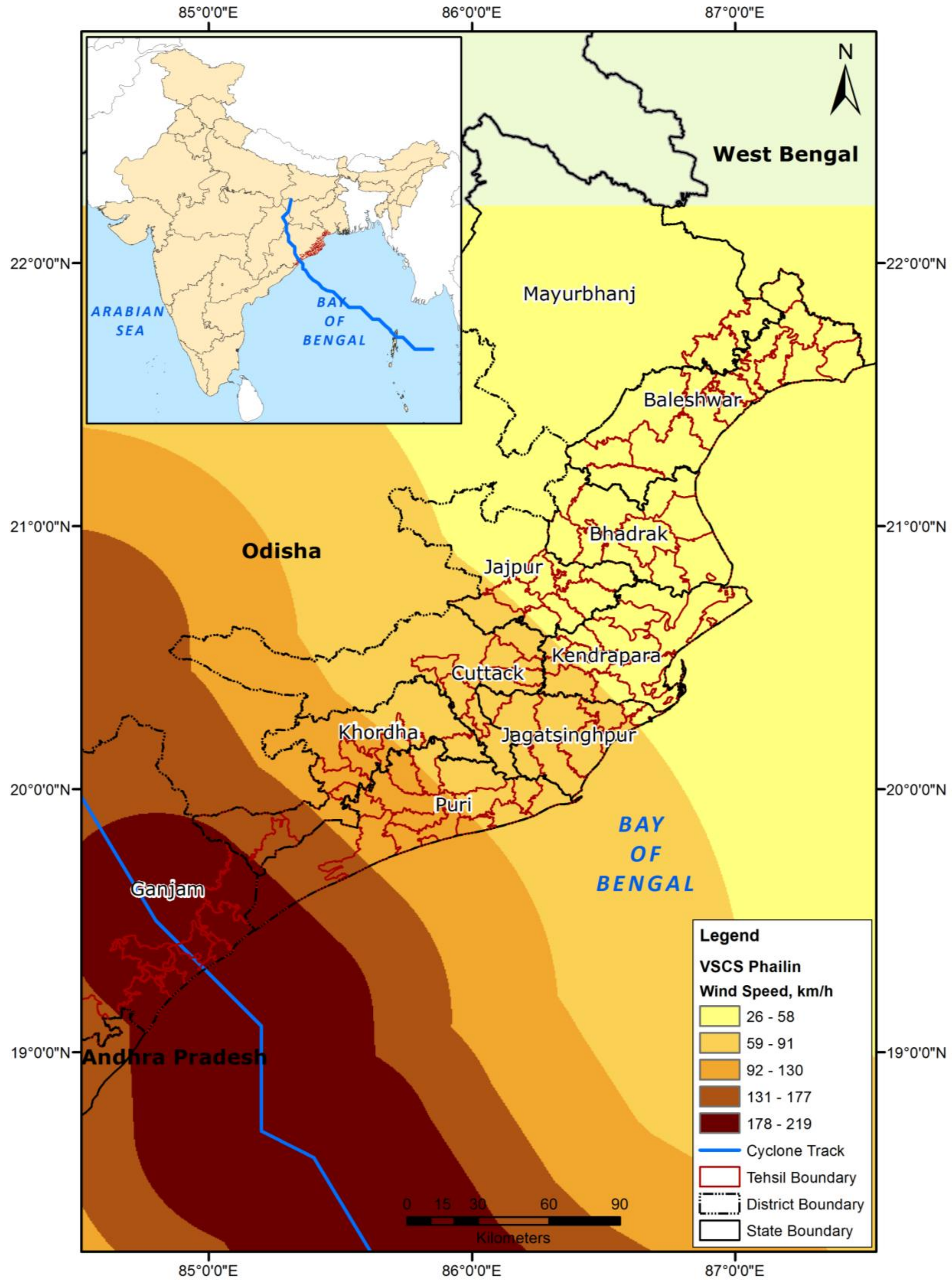

Figure 3-11: Modeled wind field of 2013 VSCS Phailin

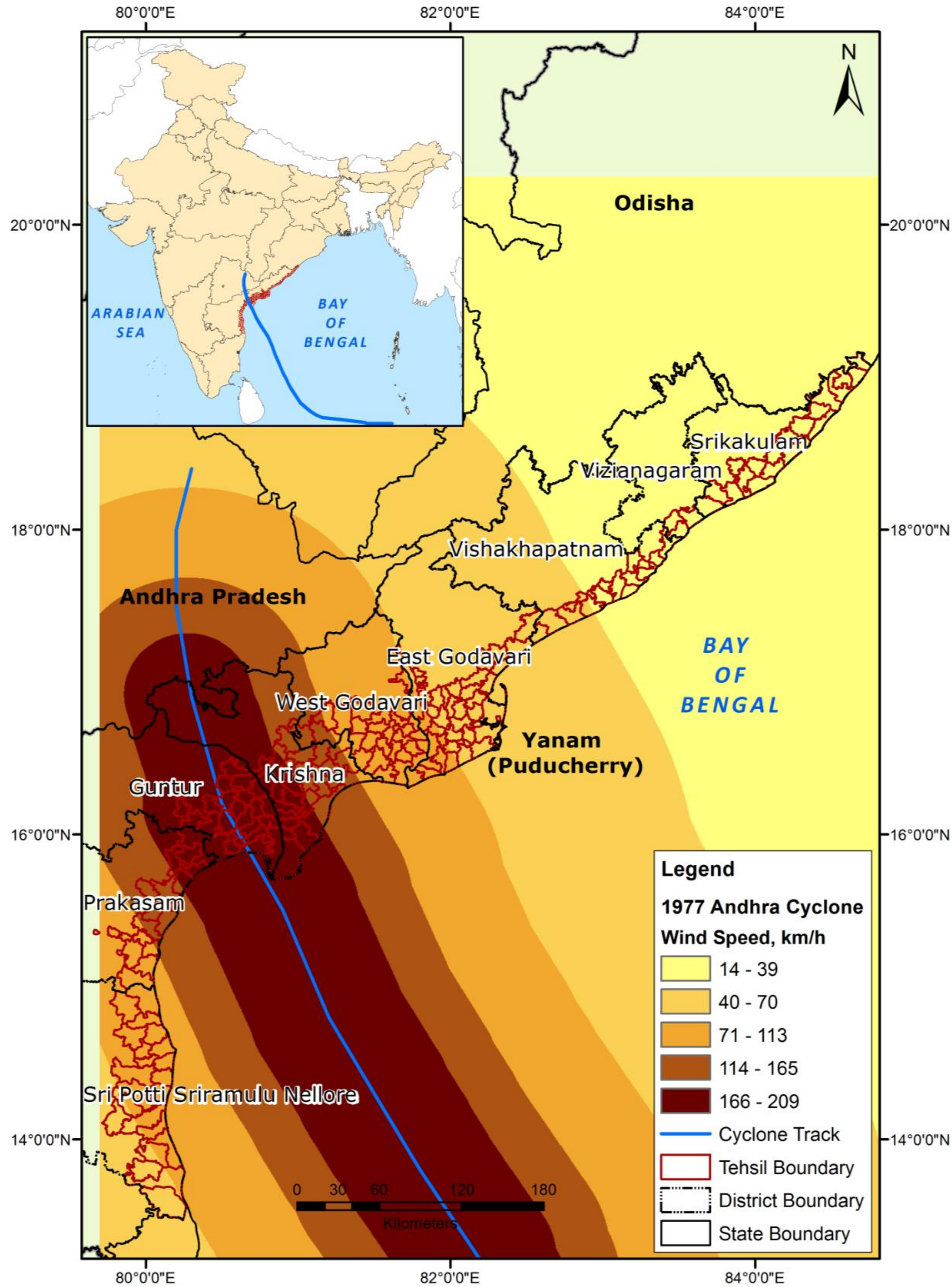

Figure 3-12: Modeled wind field of 1977 Andhra Pradesh cyclone

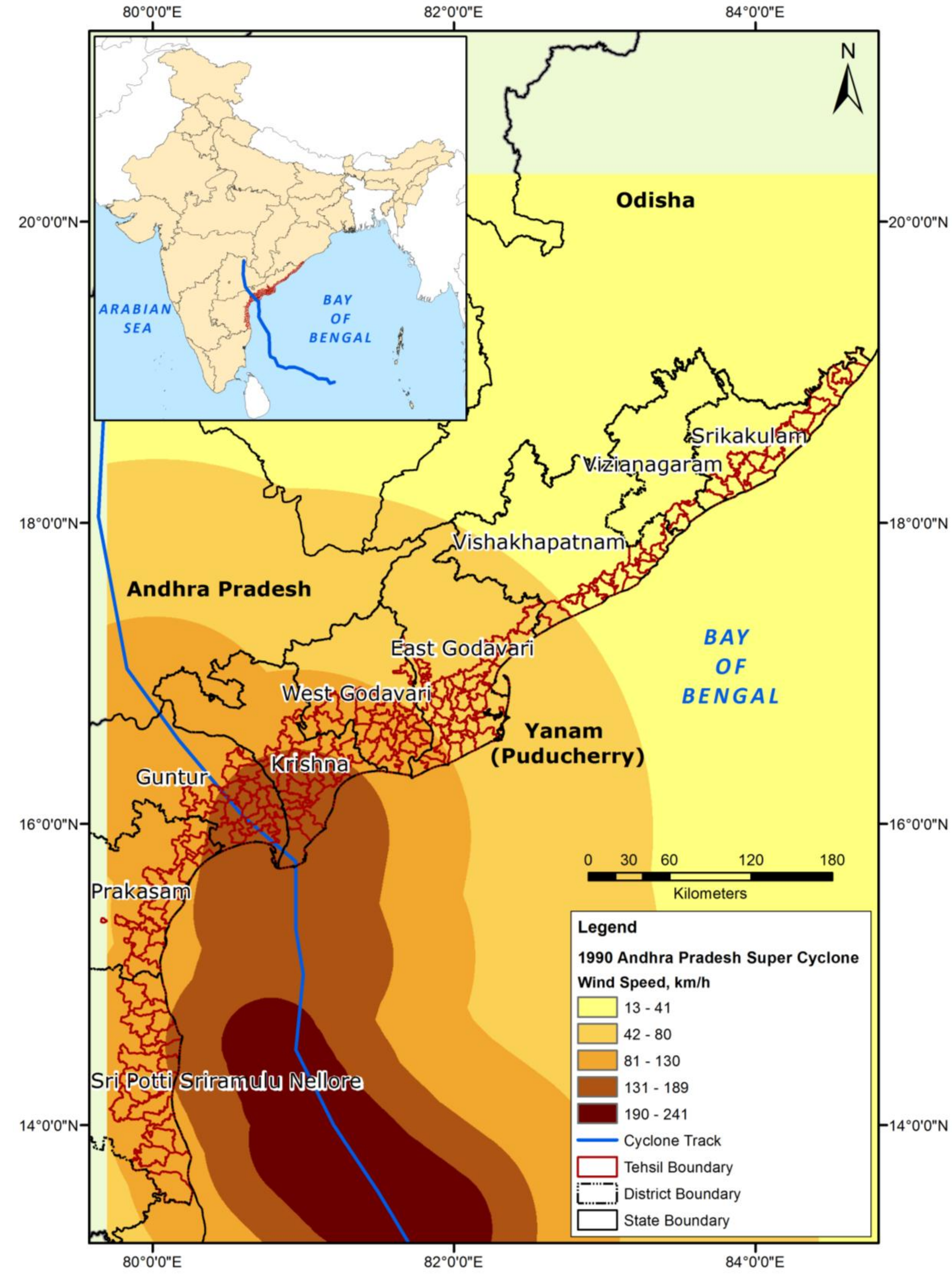

Figure 3-13: Modeled wind field of 1990 Andhra Pradesh cyclone

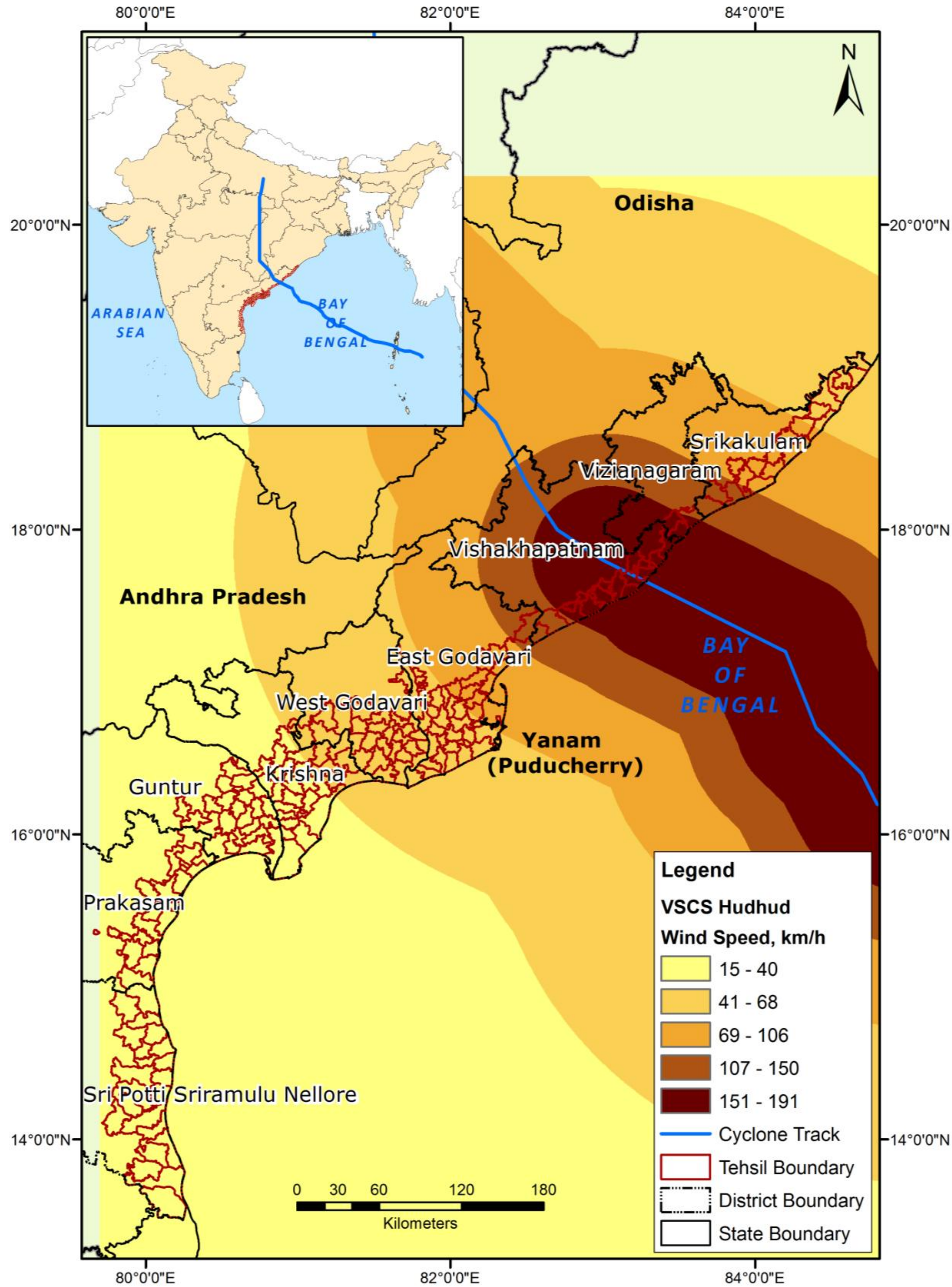

Figure 3-14: Modeled wind field of 2013 VSCS Hudhud

3.2.3.2.2 Wind extent mapping for deterministic events

Based on the key return periods wind speeds, wind hazard extent at village level was determined with the help of GIS techniques. Wind hazard extent maps were prepared by integrating model results with various GIS themes to produce maps with varying wind magnitudes and are depicted in different colors. The wind hazard maps show the wind extent and wind magnitude for various return periods. These return periods are 2, 5, 10, 25, 50, and 100 years. The highest return period indicates the worst case of wind hazard. Each of the wind hazard maps shows town locations, tehsil boundary, district boundary, and state boundary and wind extent and wind magnitudes. The cyclone wind hazard maps of Odisha and Andhra Pradesh for 100-year return period are shown in Figure 3-15 and Figure 3-16 respectively. Wind hazard maps for other return periods are given in Annexure 2: Cyclone and Storm Surge Hazard.

The colors designated for the specific wind speed ranges are shown in the legend of each map. The wind speeds are shown with brown color indicating higher wind speeds and light yellow indicating lower wind speeds. The cyclone hazard maps for different return period events were overlaid over the tehsil boundaries for analyzing detailed susceptibility in specific regions. By taking into consideration the resolution of LULC data used for modeling, the team carried out the analysis at village level as the lowest possible unit and accordingly the analytical results were developed.

From the maps, it can be seen that for lower return periods (2 to 25 years) lower wind speed ranging between 66 to 117 km/h are covering the entire coastal Odisha. While in the case of 100-year return period (Figure 3-15), the relatively higher wind speeds of about 128-144 km/h cover a large extent of the districts such as Jagatsinghpur, Kendrapara, and Ganjam. As per IMD Guidelines, wind speed associated with tropical cyclones of 50-61 km/h may cause minor damage to loose and unsecured structures. Whereas, wind speeds associated with cyclonic storms (62- 87 km/h) or storms of higher categories, can cause extensive damage to thatched roofs and huts, minor damage to power and communication lines due to uprooting of large avenue trees, etc. Hence, in the higher return periods (>25 Years) under most severe scenario, wind magnitude and extent start increasing and cover many areas of the coastal Odisha.

The maps showing wind speed and their extent for the key return periods of Andhra Pradesh clearly indicate that for lower return period events (2-50 years) variation in wind magnitudes varies between 26-118 km/h. On the other hand, for 100-years return period events (Figure 3-16), higher winds of about 128-136 km/h covering many coastal districts including Guntur, Krishna, and Srikakulam are observed.

These maps will help to identify the high vulnerability zones for Odisha and Andhra Pradesh. Assessment of cyclone risk and vulnerability at village level will be useful to evolve a sustainable local-level development action plan for preparedness and mitigation. List of villages prone to higher wind speed of about 144 km/h and more than 135 km/h for Odisha and Andhra Pradesh are given in Table 3-5 and Table 3-6 respectively.

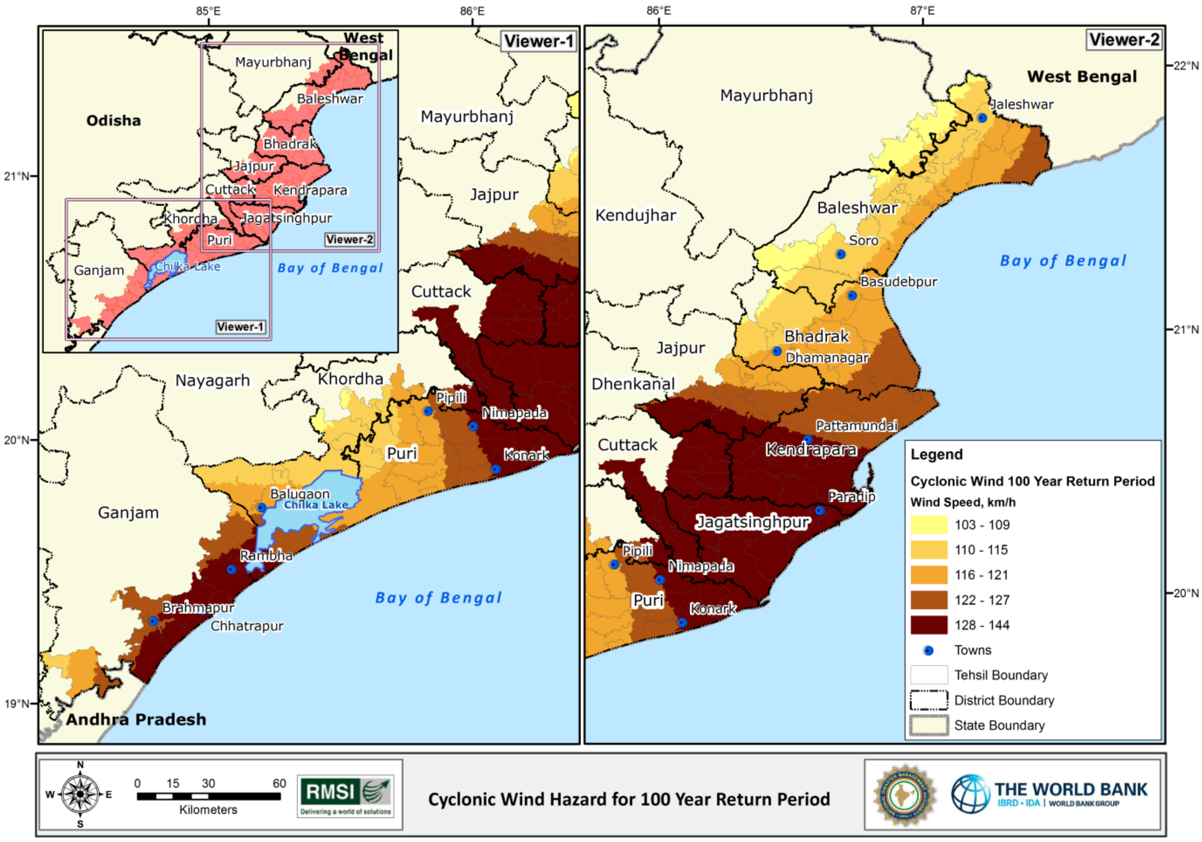

Figure 3-15: Cyclone hazard map of Odisha for 100-year return period

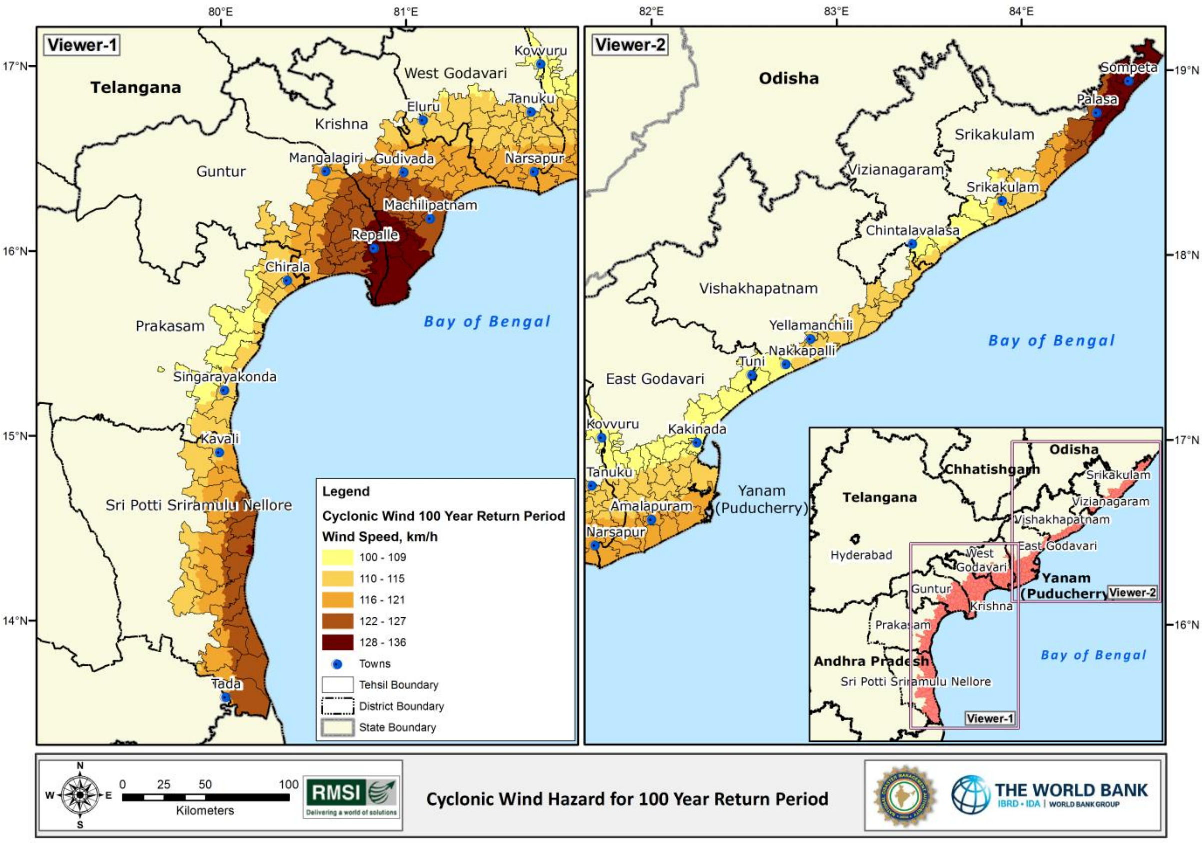

Figure 3-16: Cyclone hazard map of Andhra Pradesh for 100-year return period

Table 3-5: List of villages of district Jagatsinghpur (Odisha) prone to higher wind speed of 144 km/h

S. No.	Tehsil	Village
1	Abhyachandpur	Chauliapalanda
2		Forest
3		Nuagan
4		Panigadiakandha
5		Gobindapur
6		Dhinkia
7		Kansaripatia
8		Trilochanpur
9		Abhayachandapur
10		Bagadia
11	Kujang	Bamadeipur
12		Barunakandha
13		Jalapadakandha
14		Chhatarakandha
15		Pratappur
16		Fatepur
17		Kokakhandha
18		Kankardia
19		Banapatakandha
20		Kuatarakandha
21		Sunadiakandha
22		Baulanga
23		Kharigotha
24		Gandakipur
25		Ghodamara
26		Panpalli
27	Paradeep Luck	Jhimani
28	Paradip	Paradip (m)

Table 3-6: List of villages of district Srikakulam (Andhra Pradesh) prone to higher wind speed of 135-136 km/h

S. No.	Tehsil	Village
1	Ichchapuram	Burjapadu
2		Ichchapuram (M)
3		Kesapuram
4		Edupuram
5		Kotari
6		Purnatakam
7		Tulasigam
8		Dharmapuram

S. No.	Tehsil	Village
9	Kanchili	Kokkiliputtuga
10		Kuttuma
11		Talatampara
12		Makarampuram
13	Kaviti	Putiyadala
14		Kaviti
15		Nelavanka
16		Kapasakuddi
17		Borivanka
18		Bejjiputtuga
19		Chandiputtuga
20		Deppili Gonapaputtuga
21		Bhyripuram
22		Manikyapuram
23		Balliputtuga
24		Kusumpuram
25		Varakha
26		Jagathi
27		Rajapuram
28		Raghunadhapuram
29		Vinjagiri
30		Silagam
31	Sompeta	Rushikudda
32		Gollagandi
33		Baruva
34		Baruvapeta

3.2.3.2.3 Storm surge flood extents mapping for historical events

The modeled flood depth and flood extents associated with computed peak surge height for 1999 Paradip cyclone and November 1977 Andhra cyclone are shown in Figure 3-17 and Figure 3-18 respectively. (Figure 3-17) shows the model computed flood depth and flood extent associated with October 1999 Paradip cyclone. Model simulates maximum surge height of about 6.8 m. As per post-storm survey reports, storm surges of more than 6 m above the astronomical tide level affected the region to the right of the track of the cyclone near Paradip (IMD report, 1999)[11]. After performing the validation for this case study, the model was further used to simulate the surge amplitude and extent of inland inundation for each identified deterministic events. Each deterministic event has been assigned a probability of occurrence.

[11] IMD Report: 1999, Report on cyclonic disturbances over North Indian Ocean during 1998. Abridged report for circulation during the meeting of WMO/ESCAP panel on Tropical cyclones. RSMC Tropical cyclones, New Delhi. 71 pp.

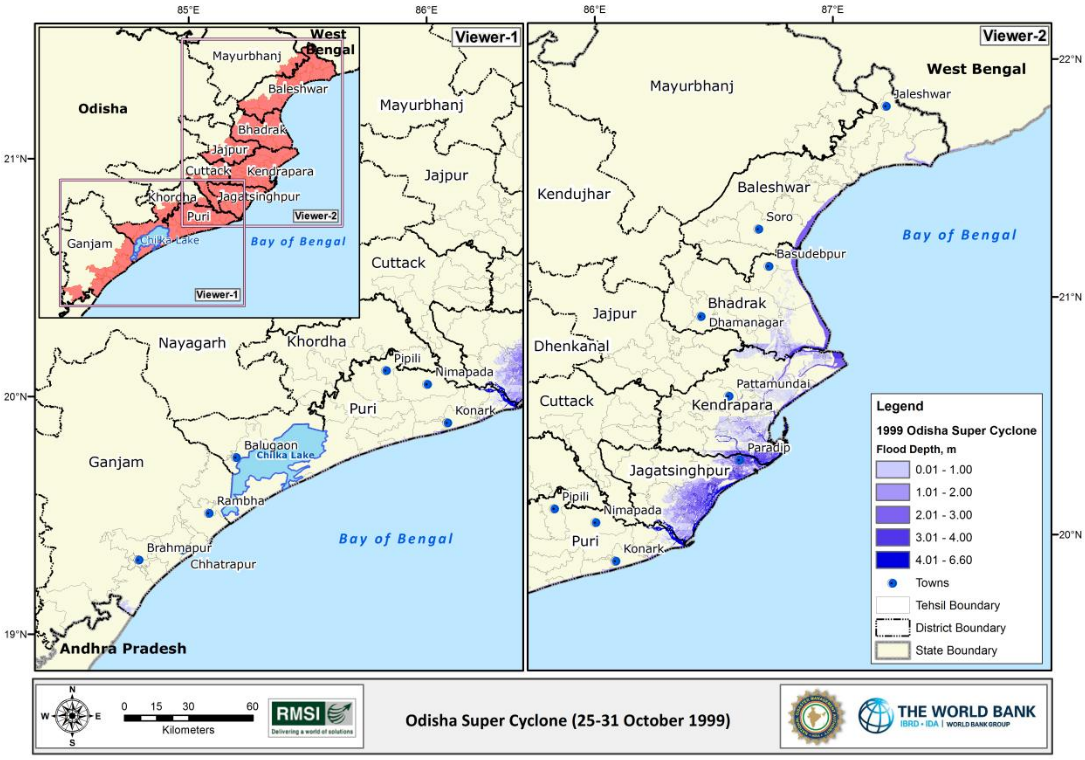

Figure 3-17: Storm surge flood hazard map associated with October 1999 Paradip cyclone

The ADCIRC model was applied for the study area selected for Andhra Pradesh. The model is validated with two severe cyclones that struck Machlipatnam coast of Andhra Pradesh in 1977 and 1990, respectively. Figure 3-18 shows flooded region along the Andhra coast associated with the November 1977 Andhra cyclone. The flooded extent can be clearly seen from Divi to Machilipatnam. Tehsils Vakadu and Sullurpeta of Nellore district were affected with inland inundation of about 10-12 km. Model simulates maximum surge of about 5.3 meters at a grid point close to Divi Island. This is in good agreement with the post storm survey estimates of about 5 meters surge in that region.

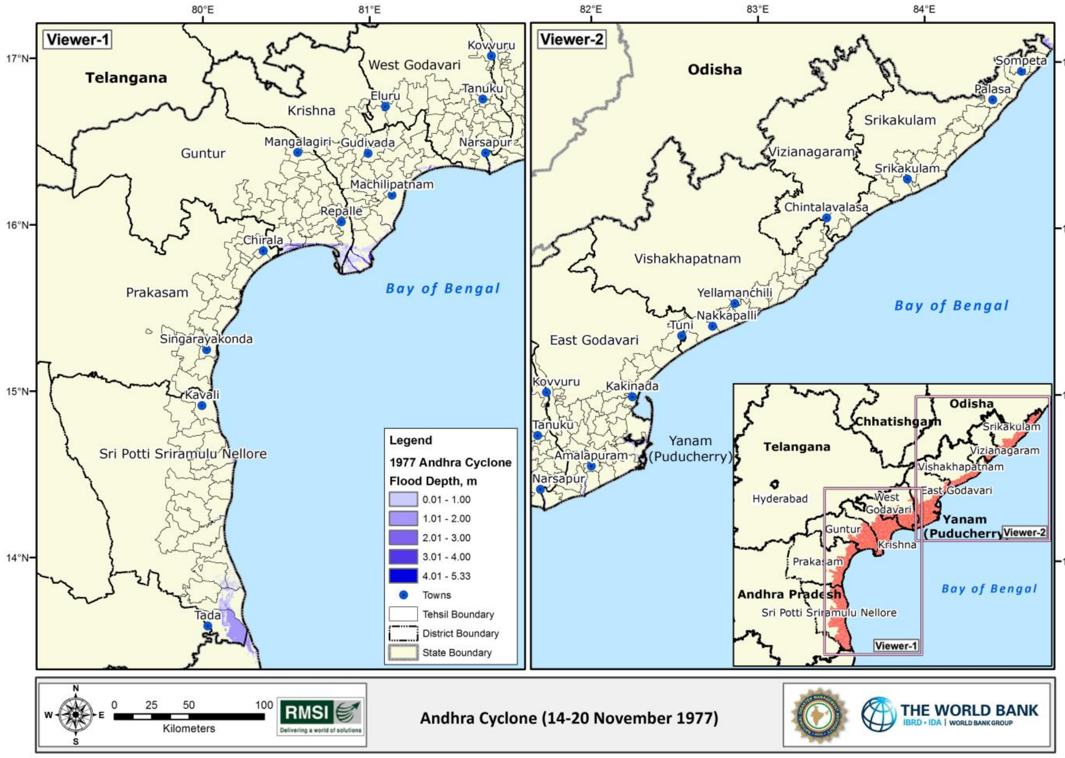

Figure 3-18: Storm surge flood hazard map associated with November 1977 Andhra Pradesh cyclone

3.2.3.2.4 Storm surge flood extents mapping for deterministic events

The maximum probable storm surge heights for key return periods were projected onto the coastal land using GIS techniques and intersected with DEM to demarcate the horizontal extent of inundation and flood depths due to storm surge. As the surge heights are generated above the mean sea level, the flood depths are deduced by subtracting local topographic heights from the surge heights. The storm surge hazard maps have been developed for flood depth and associated extent of inundation with varying levels depicted in different colors. The maps show the inundation extents and flood water depths for key return periods. In descriptive terms, highest probable storm surge heights indicate surge heights corresponding to 100-year return period event. Each storm surge hazard map depicts town location, tehsil boundaries, district boundary, river, surge flooding extent and depths. The storm surge hazard maps of 100 years return period events for Odisha and Andhra Pradesh are shown in Figure 3-19 and Figure 3-20. Storm surge hazard maps for other return periods are given in Annexure 2: Cyclone and Storm Surge Hazard.

Storm surge flood depths are shown in blue color ramp with dark blue indicating higher flood depth and light blue indicating lower flood depths. From the maps, it can be seen that inland inundation extents are limited to areas near the coast. In the higher return period maps (most severe cases) flood depths and extents are still limited to the coastal areas. The 100-year return period event (Figure 3-19) could generate maximum flood depth for Odisha coast of about 5.7 m and associated extents of inland inundation from the coastline is about 15 km. The analysis of the model output indicates that Jagatsinghpur, Kendrapara, Bhadrak and Baleshwar are the most affected districts of Odisha in terms of higher flooded extent and flood depth. However, several tehsil of district Jagatsinghpur such as Paradip, Abhyachandpur, and Ersama are affected by flood depths of more than 4 m and associated maximum flood extents varies between 8 -12 km inland from the coast. Moreover, it is to be noted that tehsil Bansada, and Naikanidihi of Bhadrak district and Mahakalpada of district Kendrapara were also severely affected due to this super cyclone. It was also observed that surge penetrates upstream into the river Hamada up to distances of about 25-30 km for 100-year return period event.

As shown in Figure 3-19 for 100-year return period, the maximum water levels for Odisha vary from about 2.5 m to 5.7 m. These are the highest water levels from the mean sea level that could occur along the coast as a response to any cyclone crossing the region. The high tides together with shallow depths of the region and high-intensity cyclones make this coast prone to high surges. In the southern part of Odisha, the surges are small compared to those of the northern part (almost 50% smaller). The lowest and highest values of the surge are about 4 m and 5.7 m, respectively. This difference is due to the near shore topography and orientation of the coastline with reference to the storm tracks. Shallow water and flat slopes close to the shoreline result in larger surges than deeper water and steeper near shore slopes.

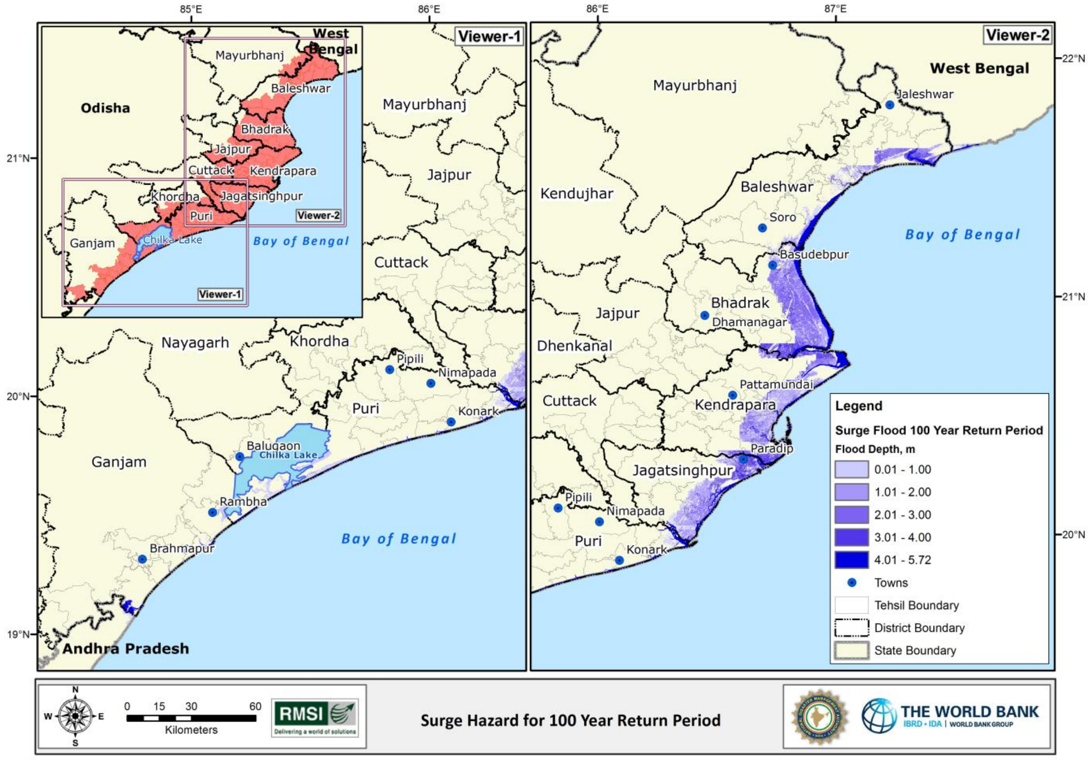

Figure 3-19: Storm surge flood hazard map of Odisha for 100-year return period

The computed maximum flood depth for 100-year return period for Andhra Pradesh coast (Figure 3-20) is about 3.9 m. The most vulnerable low-lying areas of Krishna and Guntur are prone to high water levels of 3.9 m. As a result, associated inland inundation extents in these areas vary between 5 km to 12 km. As expected, these regions are more prone to storm surge hazard compared to any other region.

Three coastal districts namely Nellore, Krishna and Guntur are most vulnerable to storm surge hazard. Tehsils Vakadu and Sullurpeta of Nellore district was affected with maximum flood depth of 3 m and associated inland inundation varies between 5-10 km, Nizampatnam tehsil of Guntur district is affected with flood extents of about 3 km. It is to be noted that Nagayalanka and Koduru tehsils of Krishna district are flooded with about 10 km and 3.5 km respectively with 100-year return period event.

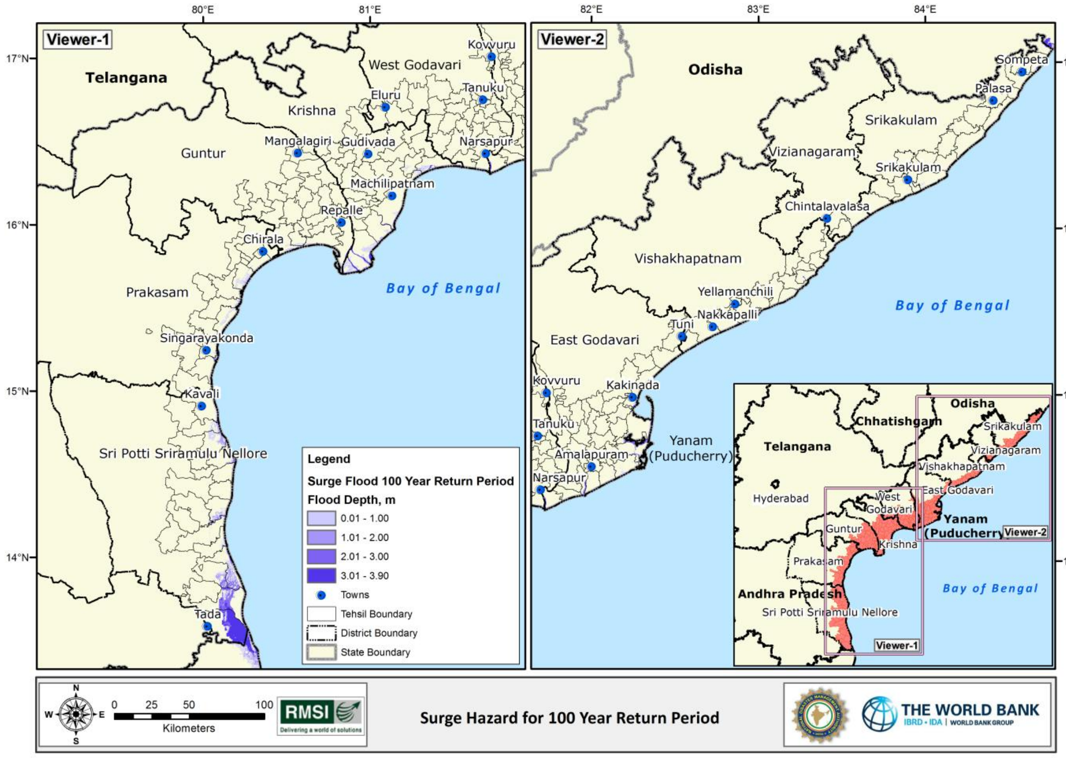

Figure 3-20: Storm surge flood hazard map of Andhra Pradesh for 100-year return period

3.3 Cyclone Induced Rainfall Flood Modeling

The coastal districts of India have experienced severe flooding in the past not only due to storm surges originating in the Bay of Bengal and the Arabian Sea, but also flooding in the rivers caused by heavy precipitation associated with tropical cyclones and monsoon depressions. The detailed methodology for flood hazard assessment due to cyclone-induced rainfall is presented in brief in the subsequent sub-sections.

The objective of this task is to assess the flood hazard associated with rainfall generated by cyclones for the study area (area up to 10 m elevation with reference to MSL along the coastline). A review of historical flooding has been done to identify the worst and most widespread flood events and to understand the nature of flooding (fluvial, coastal, monsoon influenced, cyclone or depression influenced).

The outcome of the flood hazard assessment is to demarcate the flood-prone area (extent), and assess its intensity and magnitude. Flood-prone areas are those areas subjected to inundation with regular frequency. The outlets of the major perennial rivers of India draining into the Bay of Bengal and the Arabian Sea lie in the study area. In order to capture the impact of the upstream conditions of the river basin, it is important to take into account the precipitation that is happening upstream. To handle this situation, the hydrological unit (river basin) approach has been used in the study. The hydrological unit approach has been discussed in the section 3.3.3.

To conduct the flood modeling, the study area is divided into two parts: 1) prototype states, and 2) other states. The prototype states include Andhra Pradesh and Odisha. The major river basins in the prototype states include Subarnarekha, Brahmani Baitarani, Mahanadi, Godavari, Krishna and Pennar.

The outputs from this task will be flood depth maps at grid and village level for various events that will be used in the vulnerability and risk assessment associated with cyclone induced rainfall flooding.

3.3.1 DETERMINISTIC EVENTS SCENARIO GENERATION

Flood hazard has been assessed for major river systems across the study area to estimate the potential inundation from cyclone induced rainfall. A deterministic approach has been used to combine the information on (1) the scenarios of flooding, (2) the spatial extent of floods for different severity levels, and (3) the consequences of these floods (e.g. inundated area and flood depth). Flood hazard modeling methodology is presented in the flowchart below (Figure 3-21).

Deterministic events have been developed based on the catalogue of cyclone-induced rainfall/flows. Based on data availability, following step-by-step approach has been adopted.

1. Consider the historical cyclone events used for the cyclone wind and surge analysis
2. If the event is after 1965 then check for the availability of flow data for that event as flow data at various gauge locations was available from 1965 onwards. In case of availability of flow data for the event in consideration, flows at important gauge stations (upstream of the rivers in study area) have been extracted. So, for the period of 1965 onwards, cyclonic peak flows for the gauge stations of various rivers were directly used from observed flow data. Every cyclonic event has been selected and then modeled only the ones that generated flood.
3. In case of unavailability of flow data (1901-1965), a rainfall-based approach has been used to estimate the flows for cyclonic events. Rainfall events associated to a cyclone were identified and the hydrological model (HEC-HMS) was used to establish a rainfall runoff relationship. The model is calibrated and validated using observed flow data. The hydrological modeling is performed for the various cyclonic events occurred before 1965, and the corresponding simulated cyclonic peak flows have been estimated for the gauge stations of various rivers. These rainfall events were identified on the basis peak rainfall, average rainfall and number of stations recording the rainfall greater than a particular threshold value. The threshold value of 100 mm rainfall at any station in a basin has been used for identification of rainfall events during the cyclone duration.
4. All the historical inland flood producing cyclonic events have been simulated using the hydraulic model for floodplain delineation.
5. Observed cyclonic peak flows and simulated cyclonic peak flows were used for deterministic events generation for key return periods (2, 5, 10, 25, 50, and 100 years) for the gauge stations of various rivers.
6. The key return period values of cyclonic peak flows were estimated using multi-variate extreme value distribution analysis. The multi-variate extreme value distributions are popularly used to model rainfall/flows. The advantage of this approach is the consideration of a dependence structure among the stations, which will not be the case when the individual stations are analyzed. Gumbel's Generalized Extreme Value Distribution was found to be the best marginal distribution for peak rainfall/flows of various durations.
7. The estimated key return period flows have been used as an input to the hydraulic model for flood plain delineation.
8. The flood hazard maps have been generated for the historic and deterministic events for key return periods (2, 5, 10, 25, 50, and 100 years).

Process flow chart of the various steps included in modeling is shown in the Figure 3-21 and discussed in detail in the following sections.

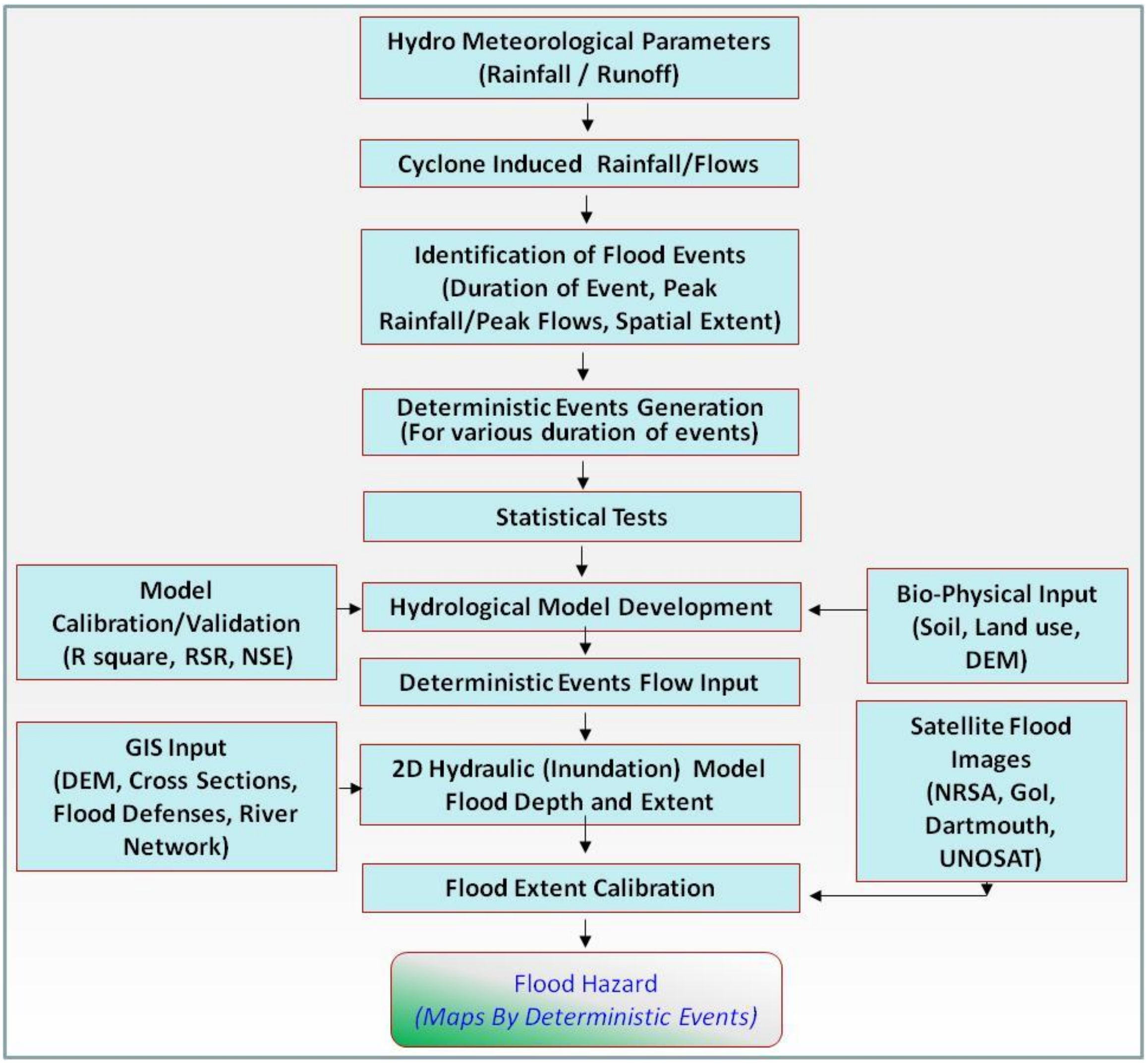

Figure 3-21: Cyclone induced rainfall flood modeling approach

3.3.2 EXTRACTION OF HISTORICAL CYCLONE GENERATED RAINFALL/FLOWS

Cyclone generated rainfall/flows have been extracted by using historical cyclones and rainfall/flow information. The historical rainfall/flow discharge data has been studied and analyzed along with the history of cyclones in the region to demarcate rainfall/flows generated from the cyclones. Historical cyclone information has been used from the historical cyclone catalog created as described in the earlier section. Rainfall data has been used from IMD's high-resolution gridded rainfall data. This data is available for the period 1901-2009 at 1-Degree grid resolution.

All the historical cyclonic events that were analyzed for cyclone wind and surge estimation were reviewed for cyclone induced inland flood analysis. From this review, synoptic situations of major cyclones, meteorological causes of heavy rainfall, and the general climatology of an area of interest were assessed. By using historical cyclone information, dates of all cyclones, which made landfall, have been extracted. This helped in compiling a catalogue of cyclones affecting various parts of India.

The rainfall/flow data corresponding to dates of cyclones have been derived from available flow/rainfall information. The rainfall/flow data have been extracted for three days prior and seven days after the date of landfall of the cyclones for entire peninsular India. In case of longer duration of cyclonic events, flow/rainfall has been extracted even up to ten day after the landfall of cyclone. This has helped in compiling the catalogue of cyclone-generated rainfall/flows for characterization of floods. Flow/discharge information was used wherever flow/discharge data was available. In case of unavailability of flow data, rainfall data has been used and subsequently flows are estimated. Using the catalogue of cyclone-generated rainfall/flows, deterministic events have been developed by using the approach described in the next sub section.

To extract the cyclone-generated rainfall/flow, all cyclones have been studied to assess their impacts on the various basins lying in two states. The major basins lying in the Odisha are Mahanadi, Brahmani-Baitarani, and Subarnarekha. The major basins lying in the Andhra Pradesh are Krishna, Godavari, Pennar and Vamsadhara. Based on the synoptic situations of cyclonic events, meteorological causes of heavy rainfall, and the general climatology of the basins, the rainfall/flow events have been catalogued in three cyclones induced flooding zones. The details of these zones and the corresponding rivers considered in each zone has been given in Table 3-7

The flooding zone wise number of cyclone generated rainfall/flow events for Andhra Pradesh and Odisha are given in the Table 3-7.

Overall, there are 94 events in Odisha and 92 events in Andhra Pradesh have been catalogued. These events have been used for historical flood events simulation and estimation of deterministic scenarios.

Table 3-7: Cyclone generated rainfall events in basins lying in Odisha and Andhra Pradesh

Sr. No.	River Basin Name	No. of cyclone generated rainfall/flow events
1	Subarnarekha, Budhabalanga, Brahmani-Baitarani, Mahanadi, and Rushikulya rivers	94
2	Vamsadhara, Nagavali, Sarada, Godavari, Krishna, and other small east flowing rivers between Mahanadi and Godavari	52
3	Pennar and other small east flowing rivers	55

3.3.3 Hydrological Model Development

A hydrological model establishes the flow behavior of the watershed or basin by converting the rainfall into runoff. They often represent the spatial variability of the atmosphere and land surface characteristics that control the rainfall-runoff process. The hydrological model, prior to being employed into flood risk studies, needs to be developed, calibrated, and validated for the study area. The outputs of the hydrological model are flow hydrographs at various locations in the basin.

The observed flow data was available at various flow gauge locations for basins in Andhra Pradesh and Odisha after 1965 only. The cyclone generated flows for the cyclones occurred after 1965 have been directly used as an input to the hydraulic models. The cyclone generated flows for the events occurred prior to 1965 have been estimated using the hydrological model which, have been developed for the major river basins in Andhra Pradesh and Odisha for developing a rainfall-runoff relation.

The major river basin in Andhra Pradesh and Odisha are:

- Pennar Basin (AP)
- Krishna Basin (AP)
- Godavari Basin (AP)
- Vamsadhra Basin (AP)
- Mahanadi Basin (Odisha)
- Brahmani-Baitarani Basin (Odisha)

- Subarnarekha Basin (Odisha)

The open source hydrological model HEC-HMS has been used for hydrological modeling. The USACE's Hydrologic Engineering Center (HEC) developed the Hydrologic Modeling System (HMS) model. This model is widely used for hydrologic modeling and is publicly available from USACE. The HEC-HMS model is a generalized modeling system capable of representing many different watersheds. HEC-HMS is designed to simulate the precipitation-runoff processes of dendritic watershed systems. It is applicable across a wide range of geographic areas for addressing a variety of project goals. Applications include large river basin water supply and flood hydrology, as well as supporting small urban or natural watershed runoff modeling.

HEC-HMS is primarily a lumped modeling system in which spatial variations in the physical processes are averaged over the watersheds or sub basins. Most of the models included in HEC-HMS are event based and deterministic (USACE, 2000). The model can also be applied for the continuous, long-term simulation of rainfall-run-off.

The HEC-HMS model includes a number of assumptions (USACE, 1994), including: (1) excess precipitation - and losses can be treated as basin-average (lumped) quantities; (2) the ordinates of a direct run-off hydrograph corresponding to precipitation excess of a given duration are directly proportional to the volume of excess (assumption of linearity); and (3) the direct run-off hydrograph resulting from a given increment of precipitation excess is independent of the time of occurrence of the excess (assumption of time invariance).

To apply the model for a specific purpose and location, a model of the watershed is constructed by dividing the hydrologic cycle into manageable pieces, by constructing boundaries around the watershed of interest, and establishing appropriate geographic and other parameters in the model. The model provides a completely integrated work environment, including a database, data entry utilities, computation engine, and reporting tools, with a graphical user interface. Additional information on the model is available at: http://www.hec.usace.army.mil/software/hec-hms/.

The core elements of the HEC-HMS model are the basin model, meteorological model, control specifications, and time-series data manager. To develop the model for a particular use and location, the following steps are generally implemented:

- Basin Delineation (using HEC–GeoHMS)
- Creation of Basin Model (including all elements such as sub-basins, channels and reservoirs)
- Estimation of Physical Loss, Routing and Transformation Parameters (for each sub-basin element)
- Addition of Time-Series Data (for various meteorological parameters)
- Setting Control Specifications (for running the model)
- Calibration and Validation
- Interpretation of Flows at Critical Locations

HEC-HMS allows the user to select from a number of methods to represent catchment characteristics for Rainfall Loss and Infiltration, Rainfall-Runoff Transformation, Stream Flow Routing, Base flow Methods, and input of meteorological data. The flowchart in Figure 3-22 explains the step-by-step approach adopted for hydrological modeling.

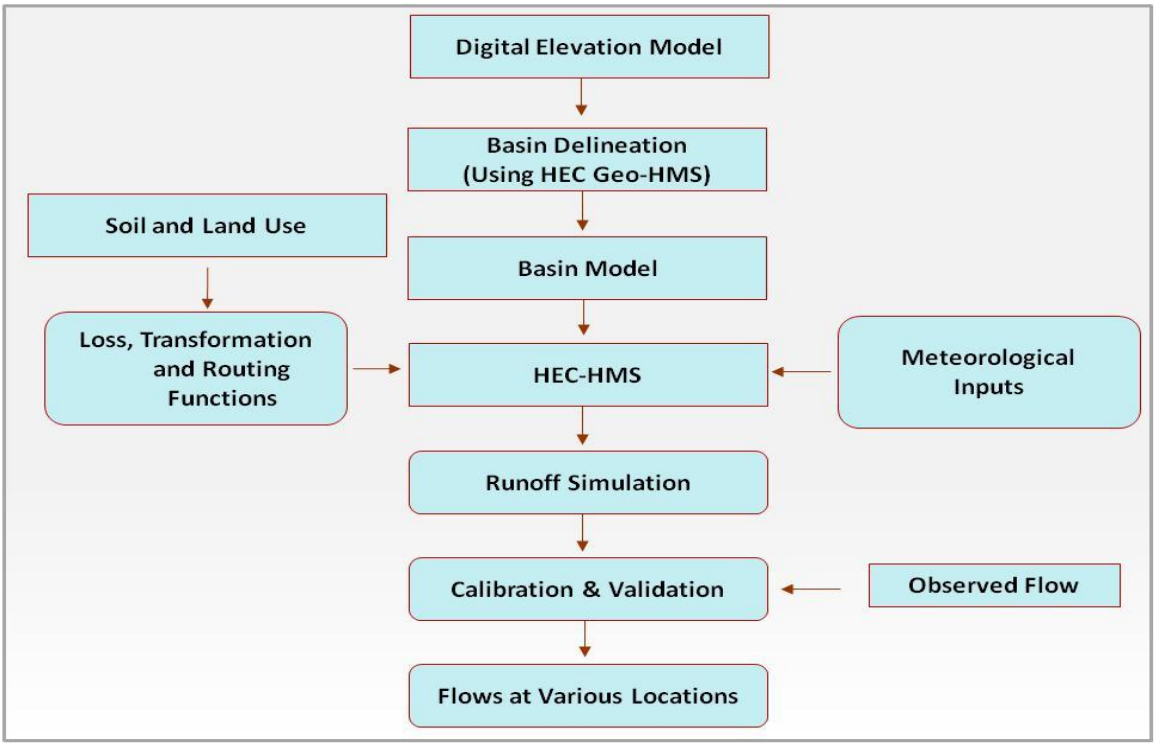

Figure 3-22: Flowchart for hydrological modeling

3.3.3.1 Basin Delineation using the HEC GEO-HMS

A number of hydrologic modeling inputs were developed using the Geospatial Hydrologic Modeling Extension (HEC- GeoHMS) tool (USACE 2009).

HEC-GeoHMS works within a Geographic Information System (GIS) interface. HEC-GeoHMS transforms digital terrain information like drainage paths and watershed boundaries into a hydrologic data structure that represents the watershed response to precipitation. The following sections detail the steps taken to develop the HEC-HMS model.

Using HEC Geo-HMS, the river network and sub basins were delineated using a systematic approach. The approach creates raster grids for catchment delineation using the DEM as input. Activities to complete the model include filling sinks, creating flow directions and flow accumulation grids, processing catchment grid, and processing drainage line. Filling sinks is the process of numerically correcting the DEM, where large sinks (abnormal depressions) or voids are present. The delineated river network using the model has been overlaid and verified with the river network map available at WRIS system.

Physical representation of the basin incorporates various hydrologic elements (sub basins, river reaches, junctions, and reservoirs), which are connected in a dendritic network to simulate the rainfall-runoff process. Figure 3-23 shows the map of delineated sub basins of the Mahanadi Basin.

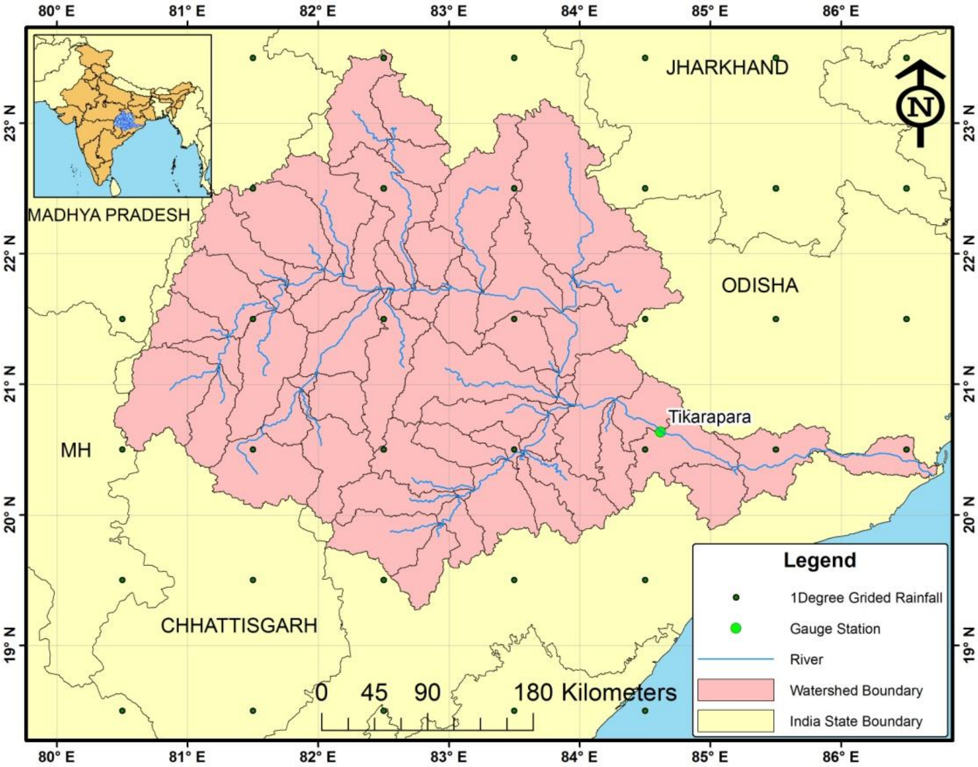

Figure 3-23: Catchment delineation of Mahanadi Basin

3.3.3.2 Model Development

The river profile was checked and used to merge several sub basins at locations with smooth slopes. Physical characteristics of streams and sub-basins were extracted by calculating River Length, River Slope, Basin Slope, Longest Flow Path, Basin Centroid, and Centroidal Flow Path. Hydrologic parameters such as SCS (Soil Conservation Service) curve number (CN), time of concentration (Tc), channel routing coefficients, etc. were developed based on the physical properties of the sub-basins.

Hydrologic elements such as nodes, links, and junctions were created using HEC-GeoHMS to define the hydrologic model that was exported into HEC-HMS. The basin model comprises of hydrologic elements and their connectivity to characterize the movement of water through the drainage system.

For each sub-basin, the overland flow length (L) and average basin slope (S) were determined. This information was used to calculate the initial Tc for each sub-basin, based on the TR-55 methodology developed by the United States Department of Agriculture (USDA). Initial base flow estimates have also been given as inputs into the model to compensate for the subsurface flow contribution.

HEC-HMS allows the user to select from a number of methods to represent catchment characteristics. The available methods for reach and sub-basin elements are shown in Table 3-8.

Table 3-8: Methods available in the subbasin and reach hydrological elements

Hydrologic Element	Calculation Type	Method
Subbasin	Canopy	Dynamic Simple (also gridded)
	Surface	Simple (also gridded)
	Loss Rate	Deficit and constant (also gridded) Exponential Green and Ampt (also gridded) Initial and constant SCS curve number (also gridded) Smith Parlange Soil moisture accounting (also gridded)
	Transform	Clark unit hydrograph Kinematic wave ModClark SCS unit hydrograph Snyder unit hydrograph User-specified s-graph User-specified unit hydrograph
	Baseflow	Bounded recession Constant monthly Linear reservoir Nonlinear Boussinesq Recession
Reach	Routing	Kinematic wave Lag Modified Puls Muskingum Muskingum-Cunge Straddle stagger
	Gain/Loss	Constant Percolation

The methods used for hydrological modeling in this study include:

Basin Model:

- Rainfall Loss and Infiltration: SCS Curve Number
- Rainfall-Runoff Transformation: SCS Unit Hydrograph
- Stream Flow Routing: Muskingum Method

Meteorological Model:

- Precipitation: Gauge Weights

Rainfall Loss and Infiltration: SCS Curve Number

The Curve Number (CN) method of the U.S. Dept. of Agriculture, Natural Resources Conservation Service (NRCS) (formerly Soil Conservation Service, SCS) known as SCS CN was used to predict the runoff properties of the surface based on the hydrologic soil group and ground cover (US SCS, 1986).

The SCS curve numbers were assigned based on the USDA soil classification and land use data for the basin. The soil and land use information was merged using Arc GIS Spatial Analyst and HEC-GeoHMS. A Curve Number (CN) grid that includes soil and land use information for the basin was developed. The CN is an index that combines hydrologic soil group and land use factors to estimate the amount of rainfall that becomes runoff. Table 3-9 shows the CN used for the present analysis.

Hydrologic Soil Group A comprises sand, loamy sand or sandy loam types of soils. They have low runoff potential and high infiltration rates even when thoroughly wetted. It consists chiefly of deep, well to excessively drained sands or gravels and has a high rate of water transmission.

Group B comprises of silt loam or loam. They have a moderate infiltration rate when thoroughly wetted and consists chiefly or moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures.

Group C soils are sandy clay loam. They have low infiltration rates when thoroughly wetted and consist chiefly of soils with a layer that impedes downward movement of water and soils with moderately fine to fine structure.

Group D consists of soils such as clay loam, silty clay loam, sandy clay, silty clay, or clay. This HSG has the highest runoff potential. They have very low infiltration rates when thoroughly wetted and consist chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface and shallow soils over nearly impervious material.

Table 3-9: Curve numbers used for analysis

Available Land use class	USDA classification	A	B	C	D
Water	Water	100	100	100	100
Settlement	Medium Residential	57	72	81	86
Coconut Forest	Forest	30	58	71	78
Secondary Forest					
Banana	Agricultural	67	77	83	87
Cassava					
Coconut Crops					
Cultivated Land					
Open Land / Grassland					
Rice					
Unknown Crops					

(http://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=17757.wba)

Rainfall-Runoff Transformation: SCS Unit Hydrograph

The transformation of excess precipitation into surface run-off was accomplished using the U.S. Soil Conservation Service (SCS) Unit Hydrograph Transform Method. This method requires lag time as an input. The lag time was taken to be 60% of the time of concentration (USACE, 2005). The time of concentration represents the time required for a drop of water to travel from the most hydrologically remote point in the sub catchment to the outlet. The time of concentration (Tc) is calculated using the Kirpich formula (Kirpich, 1940), which requires the maximum length of the flow path and the average slope of the watershed as inputs:

Tc (min) = 0.0078 L0.77 S-0.385 - (1)

where L = flowpath length (m) and S = average slope (m/m).

Stream Flow Routing: Muskingum Method

The Muskingum Method (McCarthy, 1938) has been widely adopted for hydrologic flow routing and was used for flow routing through the streams. This method uses a simple conservation of mass approach to route flow through each stream. This method represents a river reach as a linear time-invariant system with its inflow I, outflow Q, and storage w, related as:

w = K [X I + (I – X) Q] - - - - -- -- - - - - - - - - - - - - - - - - - (2)

Where K and X are Muskingum parameters.

Muskingum method assumes that water surface in the reach is a uniform unbroken surface profile between upstream and downstream ends of the section. It also assumes that K and X are constant through the range of flows (Veissmann and Lewis, 2003). The Muskingum parameters (K and X) are best derived from stream flow measurements and are not easily related to channel characteristics. The Muskingum method is limited to slow-rising hydrographs when routed along mild sloping channels. In small catchments, where measured inflow and outflow hydrographs are not available, or where significant uncertainty and errors are reported for the outflow data, modeling the flow using this method is quite a source of errors, and the Muskingum method fails to simulate the flow hydrograph using this type of data. In addition to this, the method ignores backwater effects, such as, when there is a dam downstream, and constriction, bridges, and tidal influences. It may also give negative flows in the initial portion of the hydrograph.

For the model input, the Muskingum parameters K and X were calculated based on stream length and upstream and downstream elevations for routing of flows in streams. Upstream and downstream elevations and stream lengths were based on the SRTM data. These parameters were later refined and adjusted during the calibration of the model.

Meteorological Model: Gauge Weights

The meteorological model calculates the precipitation input required by a subbasin element. The meteorological models can utilize both point and gridded precipitation. A brief description of the methods available for calculating basin average precipitation is shown in Table 3-10.

Table 3-10: Precipitation methods available for describing meteorology of the basin

Precipitation Methods	Description
Frequency storm	Used to develop a precipitation event where depths for various durations within the storm have a consistent exceedance probability.
Gage weights	User specified weights applied to precipitation gages.
Gridded precipitation	Allows the use of gridded precipitation products, such as NEXRAD radar.
Inverse distance	Calculates subbasin average precipitation by applying an inverse distance squared weighting with gages.
SCS storm	Applies a user specified SCS time distribution to a 24-hour total storm depth.
Specified hyetograph	Applies a user defined hyetograph to a specified subbasin element.
Standard project storm	Uses a time distribution to an index precipitation depth.

The Gauge Weight Method (also known as Thiessen Polygon Method) has been used for the areal distribution of rainfall from rain gauge stations across a range of different sub basins. Thiessen Polygons are straight-edged areas whose boundaries define the area that is closest to a specified point (in this case, a rain gauge) relative to all other points (other rain gauges). This polygon method subdivides a drainage basin into multiple polygons, each containing a rain gauge. The process takes care of spatial averaging of rainfall over the catchment. When constructing runoff predictions, nonlinearity inherent in the catchment hydrological response should not be neglected. The classical definition of nonlinearity from systems theory refers to the case where input-output linearity via proportionality and superposition does not hold. The other definition of nonlinearity considers the dependence of a catchment hydrological statistic (e.g. mean annual runoff) on the area of the catchment. Catchment response for different types of rainfall events has been considered linear. Linear models have been widely used in rainfall-runoff studies.

The Thiessen Polygon is globally accepted method by hydrologists for basin average rainfall estimation. The limitation of the Thiessen method is its inflexibility, a new Thiessen diagram being required every time there is a change in the gauge network. In addition, the method does not allow for orographic influences or where rain gauges are predominantly located at lower elevations of the basin. It simply assumes linear variation of precipitation between stations and assigns each segment of area to the nearest station. Altitude weighted polygons (including altitude as well as areal effects) have been devised but are not widely used.

First, the rain gauges are plotted on a base map. These rain gauge points are then connected by drawing straight lines between them. The lines are bisected by perpendiculars, which meet to form the polygons. The areas of the polygons are then calculated and expressed as fractions or weights of the total area of each sub basin. The daily level precipitation data for each station is given in the time series data, which is stored in DSS file format. A weighted approach has been used to calculate the rainfall in a basin. This is achieved by multiplying each fraction of the area by the precipitation recorded by the rain gauge in that polygon and then summing up the weighted precipitations to represent the total precipitation over the sub basin (catchment area).

Model Parameter Estimation for Hydrological Methods

Parameters for the hydrological methods were estimated based on soil textural classes, land use data, and GIS derived sub basins and streams. The length of the streams and areas of each sub basin were adopted from the HEC Geo-HMS delineation steps described previously. SCS curve number, Initial Abstraction (mm), and percent imperviousness were calculated from the soil and land use data to arrive at precipitation loss. For rainfall run-off transformation, a time of concentration was calculated using the Kirpich formula (Kirpich, 1940). The calculated time of concentration was used to estimate the sub basin lag time. The Muskingum parameters K and X were calculated based on stream length and upstream and downstream elevations for routing of flows in streams. Upstream and downstream elevations and stream lengths were based on the DEM data. These parameters were later refined and adjusted during the calibration of the model.

HEC-HMS model schematics for the Godavari and Mahanadi River Basins are shown in Figure 3-24 and Figure 3-25 respectively.

HEC-HMS model schematics for the Krishna, Baitarani, Pennar, and Vamsadhara River Basins are shown in Figure 12-2 to Figure 12-4 respectively (Annexure 3: Cyclone Induced flooding).

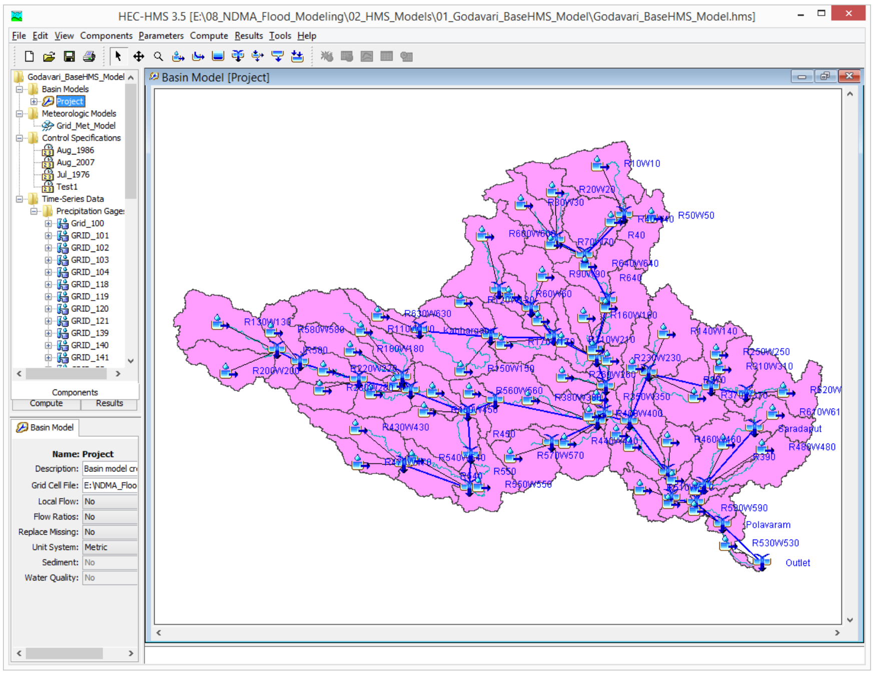

Figure 3-24: HEC-HMS model schematic for the Godavari Basin

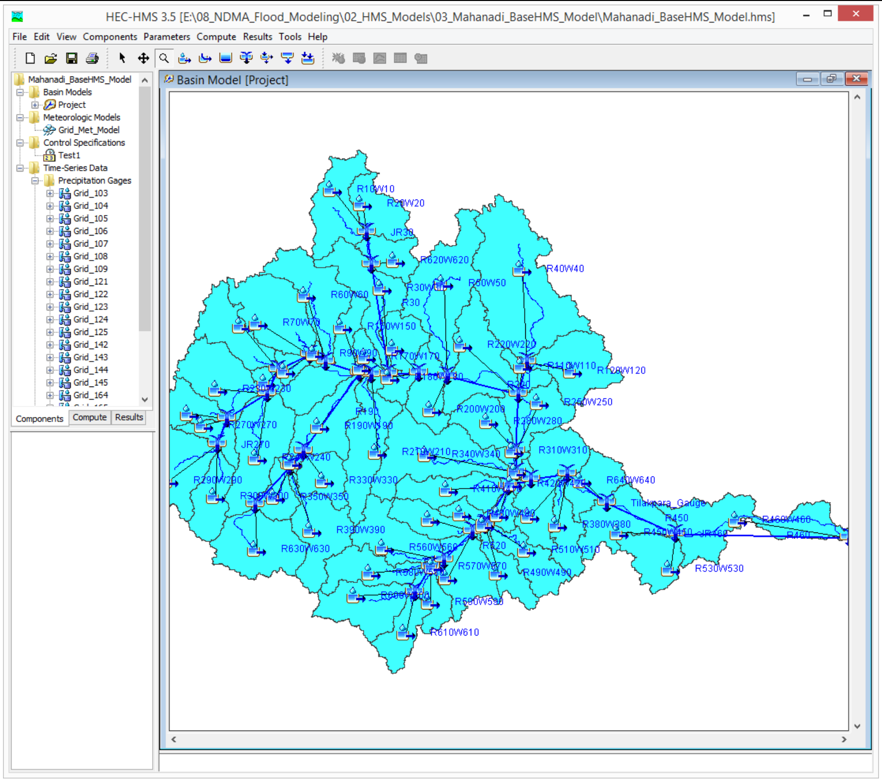

Figure 3-25: HEC-HMS model schematic for the Mahanadi Basin

3.3.3.3 Calibration and Validation of hydrological models

In HEC-HMS model calibration, simulation runs were carried out for a number of historical events for which both rainfall and stream flow records were available. To calibrate the model, historical and modeled flows were compared. Model parameters, as discussed above, were reviewed to obtain reasonable agreement between the observed and modeled flow hydrographs. In flood risk studies, emphasis is placed on emulating the peak flow of water contained in the hydrograph. Ideally, a number of flood events can be fitted adequately with only small parameter variations. The calibration process is usually manual, using engineering judgment to iteratively adjust hydrologic parameters and evaluate the fit between the computed and observed hydrographs.

The model calibration process was initiated at the most upstream flow gauge. It next considered the flow gauges in the centre of the basin and finally, at the end, the most downstream flow gauge. Various sub basin parameters such as lag time, initial abstraction, and SCS curve number were manually adjusted to improve the match between observed and modeled flows during the calibration process. For streams, parameters such as K and X were manually adjusted to match observed and modeled flows.

Model Performance

The statistics used to evaluate the performance of the models included the Nash-Sutcliffe measure of efficiency (NSE), the ratio of the root mean square to the standard deviation of the observed data (RSR) (Moriasi and others, 2007) and coefficient of determination (R^2). In the present study, the coefficient of determination (R^2) is used for evaluation of hydrological model performance.

The R^2 value is an indicator of the strength of relationship between the observed and simulated values. It indicates how well the plot of the observed versus the simulated values fits the 1:1 line. If the R^2 values are less than or very close to zero, the model prediction is considered unacceptable. If the values approach 1, the model predictions are considered perfect

Three historical cyclone events were considered for calibrating flows at most downstream flow gauge stations in each basin. Table 3-11 give a list of events along with gauge name and simulation duration used for the calibration process for various basins in Odisha and Andhra Pradesh.

Table 3-11: Details of calibration events for various basins in Odisha and Andhra Pradesh

Sr. No.	Basin	Gauge	Events / Simulation duration		
			Calibration 01	Calibration 02	Calibration 03
1	Brahmani-Baitarani	Jenapur	22 Jul 1985 - 30 Oct 1985	18 Aug 1991 - 16 Sep 1991	20 Aug 2003- 24 Sep 2003
2	Mahanadi	Tikarapara	03 Jul 1973 - 13 Jul 1973	05 Jul 1976 - 10 Oct 1976	18 Jul 1979 - 05 Sep 1979
3	Pennar	Nellore	01 Nov 1987 - 07 Nov 1987	12 Oct 2001 - 22 Oct 2001	31 Oct 1994 - 07 Nov 1994
4	Krishna	Vijayawada	14 Sep 1970 - 30 Sep 1970	16 Oct 1975 - 22 Nov 1975	28 Sep 1983 - 21 Oct 1983
5	Godavari	Polavaram	16 Jul 1970 - 17 Oct 1970	01 Jul 1983 - 31 Oct 1983	01 Jun 2000 - 31 Oct 2000
6	Vamsadhara	Kashinagar	05 Oct 1992 - 17 Oct 1992	12 Jun 1974 - 22 Jun 1974	01 Nov 1990 - 11 Nov 1990

The validation process is intended to ensure that the model parameters are well set to reflect the physical nature of each basin. Validation runs have been made with the selected "best fit" parameters without further parameter changes. A good fit in this case indicates a robust model, which can be used with reasonable confidence. A poor fit, on the other hand, indicates low confidence. The validation process uses events that were not included in the calibration to evaluate the reliability of the model for other historical events. The average values from the three calibration events for each model parameter were given as inputs for sub basins and streams above the respective flow gauge stations in validation runs.

The hydrological model for each basin was run for the validation events (one event for each river basin). Table 3-12 give a list of events along with gauge name and simulation duration used for the validation process for various basins in Odisha and Andhra Pradesh.

Table 3-12: Details of validation events for various basins in Odisha and Andhra Pradesh

Sr. No.	Basin	Gauge	Events / Simulation duration
			Validation events
1	Mahanadi	Tikarapara	27 Jul 1974 - 15 Sep 1974
2	Brahmani-Baitarani	Jenapur	01 Sep 2008 - 30 Oct 2008
3	Pennar	Nellore	20 Aug 2000 - 03 Sep 2000
4	Krishna	Vijayawada	15 Sep 1991 - 10 Oct 1991
5	Godavari	Polavaram	01 Jul 1968 - 19 Oct 1968
6	Vamsadhara	Kashinagar	22 Oct 1995 - 28 Nov 1995

From the plots, it can be seen that the simulated flows are in close agreement with the observed flows. The results show that the model is adequately calibrated.

Following section gives the details of the calibration and validation events of Brahmani-Baitarani, Mahanadi, Vamsadhara, Godavari, Krishna, and Pennar river basins.

Brahmani-Baitarani Basin

The hydrological model of Brahmani-Baitarani Basin was calibrated for three cyclonic events and validated for one cyclonic event. The historical flow data at Jenapur discharge gauge station was used in the calibration and validation process.

Comparison between observed and simulated flow hydrographs at the Jenapur station for three calibration events (1985, 1991, and 2003) and one validation event (2008) are shown in Figure 3-26. The cyclone date, duration of simulation run, comparison between simulated and observed peak flows along with the R^2 performance statistics are given in Table 3-13.

The performance statistics R^2 for the calibration events are in the range of 0.63 to 0.70 while same for validation event is 0.83. From these tables and plots, it can be observed that the simulated flows are in close agreement with observed flows. The results show that the hydrological model of Brahmani-Baitarani Basin is adequately calibrated and can be used for simulation of other historical cyclone events.

Table 3-13: Comparison of simulated and observed peak flows for calibration and validation events of Brahmani-Baitarani Basin with computed R^2-statistics

Flow gauge station	Cyclone date	Simulation duration	Simulated peak flow, cumecs	Observed peak flow, cumecs	Computed R^2
Calibration Events					
Jenapur	15-Oct-1985	22 Jul 1985 - 30 Oct 1985	7,095	7,485	0.63
Jenapur	22-Aug-1991	18 Aug 1991 - 16 Sep 1991	4,200	5,538	0.70
Jenapur	27-Aug-2003	20 Aug 2003 24 Sep 2003	4,300	3,747	0.64
Validation Event					
Jenapur	16-Sep-2008	01 Sep 2008 - 30 Oct 2008	7,012	7,489	0.83

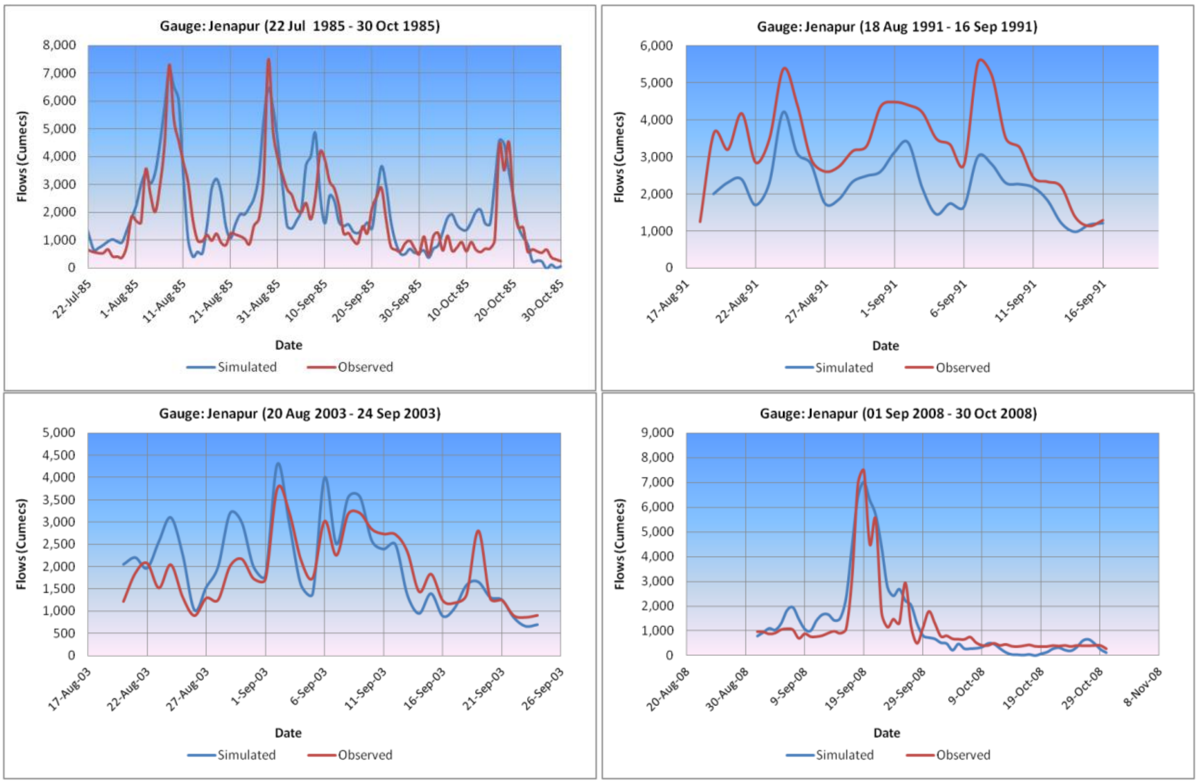

Figure 3-26: Comparison of observed and simulated hydrographs for Jenapur flow gauge station in Brahmani-Baitarani Basin for various cyclonic events

Mahanadi Basin

The hydrological model of Mahanadi Basin was calibrated for three cyclonic events and validated for one cyclonic event. The historical flow data at Tikarpara discharge gauge station was used in the calibration and validation process.

Comparison between observed and simulated flow hydrographs at the Tikarpara station for three calibration events (1973, 1976, and 1989) and one validation event (1974) are shown in Figure 3-27. The cyclone date, duration of simulation run, comparison between simulated and observed peak flows along with the R^2 performance statistics are given in Table 3-14

The performance statistics R^2 for the calibration events are in the range of 0.61 to 0.78 while same for validation event is 0.65. From these tables and plots, it can be observed that the simulated flows are in close agreement with observed flows. The results show that the hydrological model of Mahanadi Basin is adequately calibrated and can be used for simulation of other historical cyclone events.

Table 3-14: Comparison of simulated and observed peak flows for calibration and validation events of Mahanadi Basin with computed R^2-statistics

Flow gauge station	Cyclone date	Simulation duration	Simulated peak flow, cumecs	Observed peak flow, cumecs	Computed R^2
Calibration Events					
Tikarpara	12-Jul-1973	03 Jul 1973 - 13 Jul 1973	19,120	20,725	0.61
Tikarpara	12-Aug-1976	05 Jul 1976 - 10 Oct 1976	26,597	26,324	0.64
Tikarpara	06-Aug-1979	18 Jul 1979 - 05 Sep 1979	14,319	14,257	0.78
Validation Event					
Tikarpara	13-Aug-1974	27 Jul 1974 - 15 Sep 1974	17,563	17,400	0.65

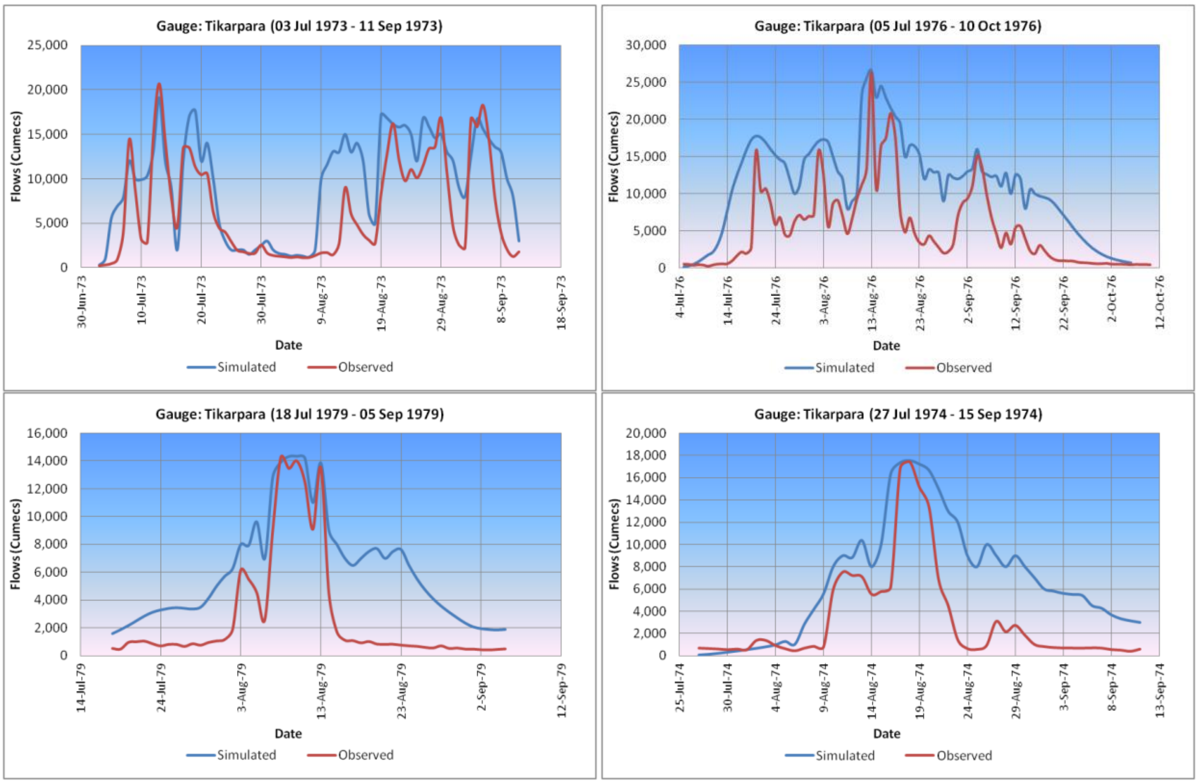

Figure 3-27: Comparison of observed and simulated hydrographs for Tikarpara flow gauge station in Mahanadi Basin for various cyclonic events

Vamsadhara Basin

The hydrological model of Vamsadhara Basin was calibrated for three cyclonic events and validated for one cyclonic event. The historical flow data at Kashinagar discharge gauge station was used in the calibration and validation process.

Comparison between observed and simulated flow hydrographs at the Kashinagar station for three calibration events (1974, 1990, and 1992) and one validation event (1995) are shown in Figure 3-28. The cyclone date, duration of simulation run, comparison between simulated and observed peak flows along with the R^2 performance statistics are given in Table 3-15.

The performance statistics R^2 for the calibration events are in the range of 0.60 to 0.81 while same for validation event is 0.67. From these tables and plots, it can be observed that the simulated flows are in close agreement with observed flows. The results show that the hydrological model of Vamsadhara Basin is adequately calibrated and can be used for simulation of other historical cyclone events.

Table 3-15: Comparison of simulated and observed peak flows for calibration and validation events of Vamsadhara Basin with computed R^2-statistics

Flow gauge station	Cyclone date	Simulation duration	Simulated peak flow, cumecs	Observed peak flow, cumecs	Computed R^2
Calibration Events					
Kashinagar	15-Jun-1974	12 Jun 1974 - 22 Jun 1974	1,092	1,081	0.81
Kashinagar	03-Nov-1990	01 Nov 1990 - 11 Nov 1990	2,252	2,240	0.60
Kashinagar	08-Oct-1992	05 Oct 1992 - 17 Oct 1992	1,195	1,185	0.68
Validation Event					
Kashinagar	09-Nov-1995	22 Oct 1995 - 28 Nov 1995	1,388	1,306	0.67

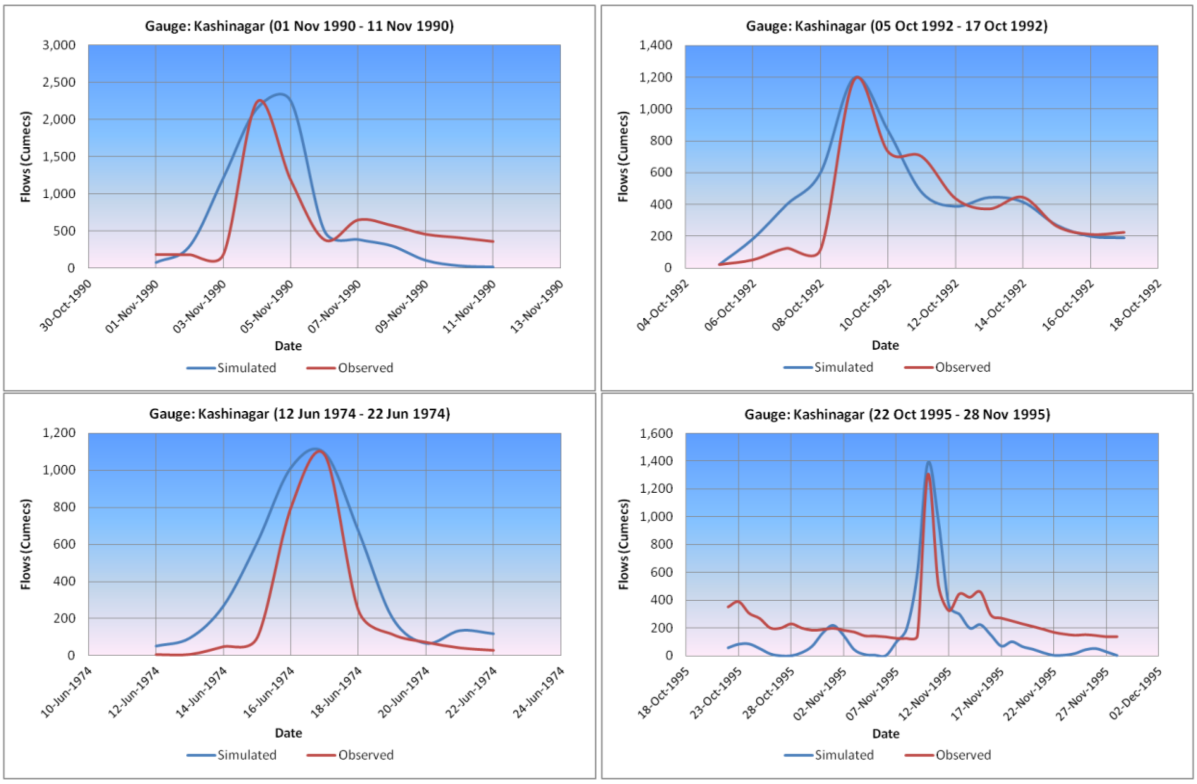

Figure 3-28: Comparison of observed and simulated hydrographs for Kashinagar flow gauge station in Vamsadhara Basin for various cyclonic events

Godavari Basin

The hydrological model of Godavari Basin was calibrated for three cyclonic events and validated for one cyclonic event. The historical flow data at Polavaram discharge gauge station was used in the calibration and validation process.

Comparison between observed and simulated flow hydrographs at the Polavaram station for three calibration events (1970, 1983, and 2000) and one validation event (1968) are shown in Figure 3-29. The cyclone date, duration of simulation run, comparison between simulated and observed peak flows along with the R^2 performance statistics are given in Table 3-16.

The performance statistics R^2 for the calibration events are in the range of 0.64 to 0.65 while same for validation event is 0.45. From these tables and plots, it can be observed that the simulated flows are in close agreement with observed flows. The results show that the hydrological model of Godavari Basin is reasonably calibrated and can be used for simulation of other historical cyclone events.

Table 3-16: Comparison of simulated and observed peak flows for calibration and validation events of Godavari Basin with computed R^2-statistics

Flow gauge station	Cyclone date	Simulation duration	Simulated peak flow, cumecs	Observed peak flow, cumecs	Computed R^2
Calibration Events					
Polavaram	20-Sep-1970	16 Jul 1970 - 17 Oct 1970	37,228	38,701	0.65
Polavaram	01-Oct-1983	01 Jul 1983 - 31 Oct 1983	41,104	40,716	0.65
Polavaram	23-Aug-2000	01 Jun 2000 - 31 Oct 2000	35,320	35,217	0.64
Validation Event					
Polavaram	28-Sep-1968	01 Jul 1968 - 19 Oct 1968	25,338	26,189	0.45

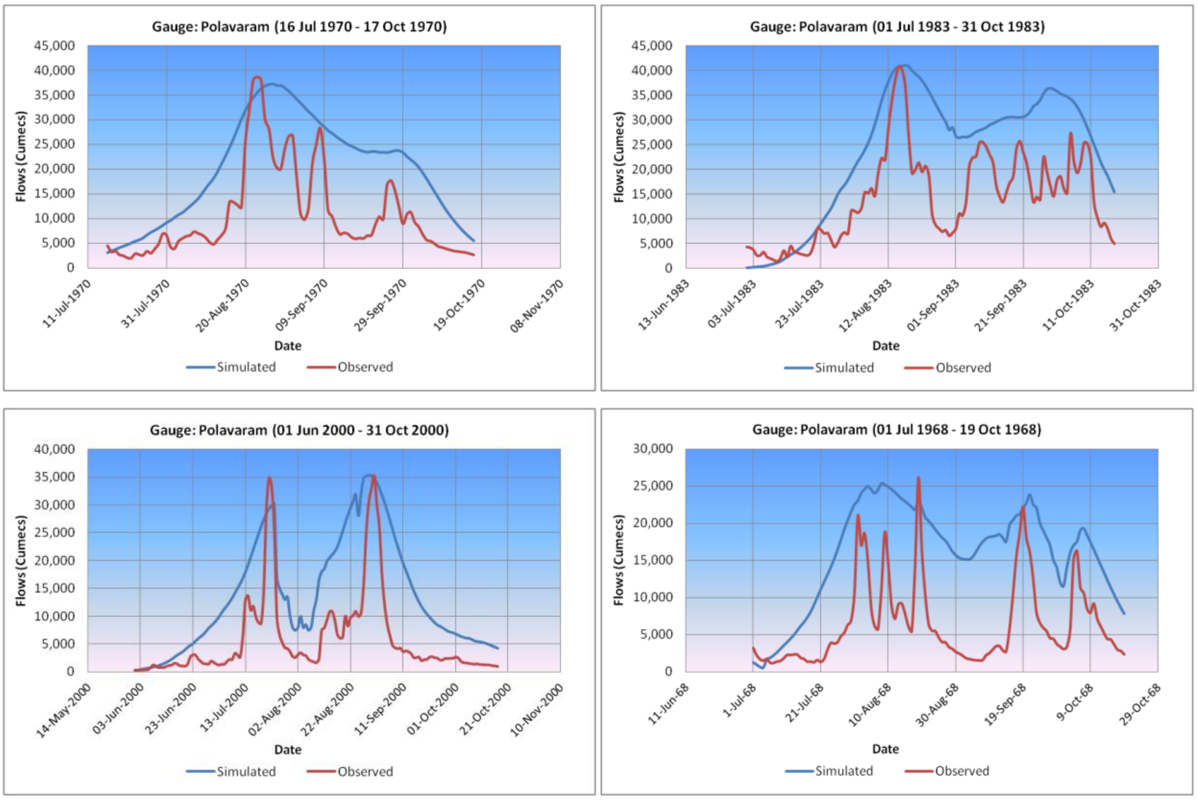

Figure 3-29: Comparison of observed and simulated hydrographs for Polavaram flow gauge station in Godavari Basin for various cyclonic events

Krishna Basin

The hydrological model of Krishna Basin was calibrated for three cyclonic events and validated for one cyclonic event. The historical flow data at Vijayawada discharge gauge station was used in the calibration and validation process.

Comparison between observed and simulated flow hydrographs at the Vijayawada station for three calibration events (1970, 1975, and 1983) and one validation event (1991) are shown in Figure 3-30. The cyclone date, duration of simulation run, comparison between simulated and observed peak flows along with the R^2 performance statistics are given in Table 3-17.

The performance statistics R^2 for the calibration events are in the range of 0.60 to 0.66 while same for validation event is 0.71. From these tables and plots, it can be observed that the simulated flows are in close agreement with observed flows. The results show that the hydrological model of Krishna Basin is adequately calibrated and can be used for simulation of other historical cyclone events.

Table 3-17: Comparison of simulated and observed peak flows for calibration and validation events of Krishna Basin with computed R^2-statistics

Flow gauge station	Cyclone date	Simulation duration	Simulated peak flow, cumecs	Observed peak flow, cumecs	Computed R^2
Calibration Events					
Vijayawada	20-Sep-1970	14 Sep 1970 - 30 Sep 1970	14,368	14,193	0.64
Vijayawada	17-Oct-1975	16 Oct 1975 - 22 Nov 1975	15,423	15,211	0.60
Vijayawada	01-Oct-1983	28 Sep 1983 - 21 Oct 1983	22,000	20,712	0.66
Validation Event					
Vijayawada	21-Sep-1991	15 Sep 1991 - 10 Oct 1991	15,000	12,000	0.71

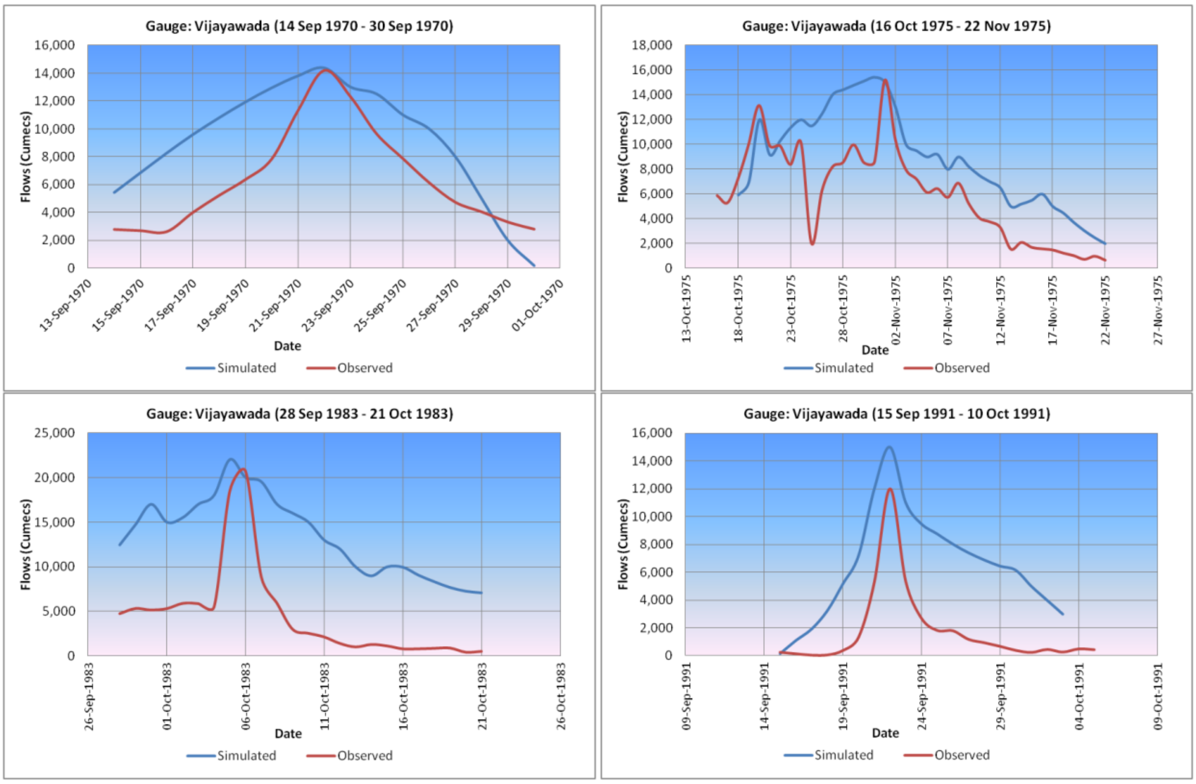

Figure 3-30: Comparison of observed and simulated hydrographs for Vijayawada flow gauge station in Krishna Basin for various cyclonic events

Pennar Basin

The hydrological model of Pennar Basin was calibrated for three cyclonic events and validated for one cyclonic event. The historical flow data at Nellore discharge gauge station was used in the calibration and validation process.

Comparison between observed and simulated flow hydrographs at the Nellore station for three calibration events (1987, 1994, and 2001) and one validation event (2000) are shown in Figure 3-31. The cyclone date, duration of simulation run, comparison between simulated and observed peak flows along with the R^2 performance statistics are given in Table 3-18.

The performance statistics R^2 for the calibration events are in the range of 0.81 to 0.96 while same for validation event is 0.70. From these tables and plots, it can be observed that the simulated flows are in close agreement with observed flows. The results show that the hydrological model of Pennar Basin is adequately calibrated and can be used for simulation of other historical cyclone events.

Table 3-18: Comparison of simulated and observed peak flows for calibration and validation events of Pennar Basin with computed R^2-statistics

Flow gauge station	Cyclone date	Simulation duration	Simulated peak flow, cumecs	Observed peak flow, cumecs	Computed R^2
Calibration Events					
Nellore	30-Oct-1987	01 Nov 1987 - 07 Nov 1987	1,055	1,004	0.96
Nellore	31-Oct-1994	31 Oct 1994 - 07 Nov 1994	1,722	1,762	0.86
Nellore	15-Oct-2001	12 Oct 2001 - 22 Oct 2001	5,210	5,196	0.81
Validation Event					
Nellore	23-Aug-2000	20 Aug 2000 - 03 Sep 2000	3,843	4,589	0.70

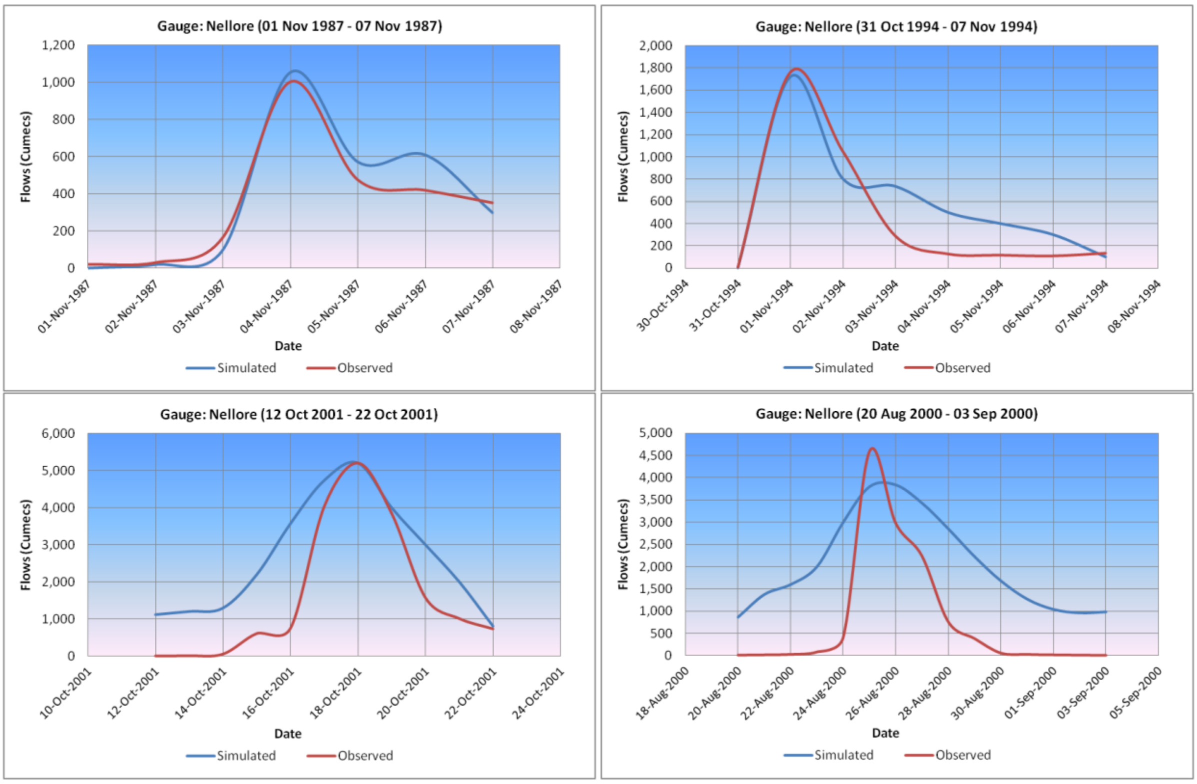

Figure 3-31: Comparison of observed and simulated hydrographs for Nellore flow gauge station in Pennar Basin for various cyclonic events

The results of the calibration and validation of the hydrological models of various basins discussed above shows that the models are adequately calibrated and validated. After the calibration and validation, these models are used for the simulation of other historical cyclonic events.

3.3.3.4 Deterministic scenario flows

Deterministic flows for the flow gauge stations on various rivers were estimated using the methodology discussed in the section 3.3.1 for 2, 5, 10, 25, 50, and 100 year return period are given in Table 3-19 and Table 3-20

Table 3-19: Deterministic scenario flows for gauge stations on various rivers of Odisha

Flow Gauge Station	River Basin	Return period wise peak flows , cumecs					
		2	5	10	25	50	100
Purushttampur	Rushikulya	1,441	2,342	2,938	3,692	4,251	4,805
Tikarpara	Mahanadi	16,106	2,3604	28,568	34,840	39,493	44,111
Jenapur	Brahmani	3,529	5,680	7,104	8,903	10,238	11,563
Anandpur	Baitarani	1,698	3,941	5,426	7,303	8,695	10,076
Govindpur	Budhabalanga	571	1,154	1,540	2,027	2,389	2,748
Ghatsila	Subarnarekha	2,055	4,559	6,216	8,310	9,864	11,406

Table 3-20: Deterministic scenario flows for gauge stations on various rivers of Andhra Pradesh

Flow Gauge Station	River Basin	Return period wise peak flows , cumecs					
		2	5	10	25	50	100
Sulurpet	Pennar	305	611	814	1,070	1,261	1,449
Naidupet	Pennar	195	832	1,254	1,787	2,183	2,575
Nellore	Pennar	2,257	4,014	5,177	6,647	7,738	8,820
Thammavaram	Pennar	464	1,173	1,642	2,234	2,674	3,111
Polavarm	Godavari	12,748	23,670	30,900	40,036	46,814	53,542
Vijaywada	Krishna	8,482	15,209	19,663	25,291	29,467	33,611
Anakapally	Sarada	356	667	873	1,133	1,326	1,517
srikakulam	Nagavali	1,753	3,184	4,132	5,329	6,218	7,099
Kashinagar	Vamsadhara	1,951	3,695	4,850	6,309	7,391	8,465

The outputs of hydrological models are the flood hydrograph at outlet of the basin. The flood hydrograph are then used as an input to the hydraulic models (HEC-RAS 2D).

Apart from the major rivers, many small east flowing rivers cause flooding in the Odisha and Andhra Pradesh. The catchment areas of these rivers are very small in comparison to the major rivers. All these rivers are ungauged, so an alternate approach is needed to model them.

It is important to estimate flood magnitude for these small rivers for hydraulic modeling. The transposition approach of un-gauge site flow estimation was applied for these river segments.

$$Q_u = Q_g \left\{\frac{A_u}{A_g}\right\}^m$$

Here Q_g is the flood estimate at the gauged site and contributing catchment area is A_g; Q_u is the flood estimate at the ungauged site where contributing catchment area is A_u; and m is an exponent less than unity.

The exponent m was determined from the data at multiple gauged sites within the same basin or a neighboring hydrological homogeneous region. While estimating this exponent, a number of factors were considered. These factors include spatial variations in storm rainfall, antecedent rainfall, catchment surface characteristics including soil and vegetation, topography, and hydrogeology. Along with these factors and relative locations of tributaries, a typical exponent based on area adjustment was estimated and used appropriately for modeling the extreme events in this study.

3.3.4 Two Dimensional (2-D) Hydraulic Model Development

The main purpose of hydraulic modeling is to route the flows from one location to another, while estimating the water surface elevations and profiles for various scenarios. Generally, the flows or water surface elevations observed at a particular location are given as inputs to the model along with the channel characteristics such as cross-section, slope, and roughness. Alternatively, flows estimated in the hydrologic modeling provide input to the hydraulic modeling. Detailed hydraulic modeling requires an inventory of drainage conveyance structures, surveyed cross-sections of streams and rivers, and topographic mapping of flood plain areas. In addition, site and aerial photographs, historical high water marks from past events, and anecdotal flood observations all serve to guide a detailed hydraulic model development.

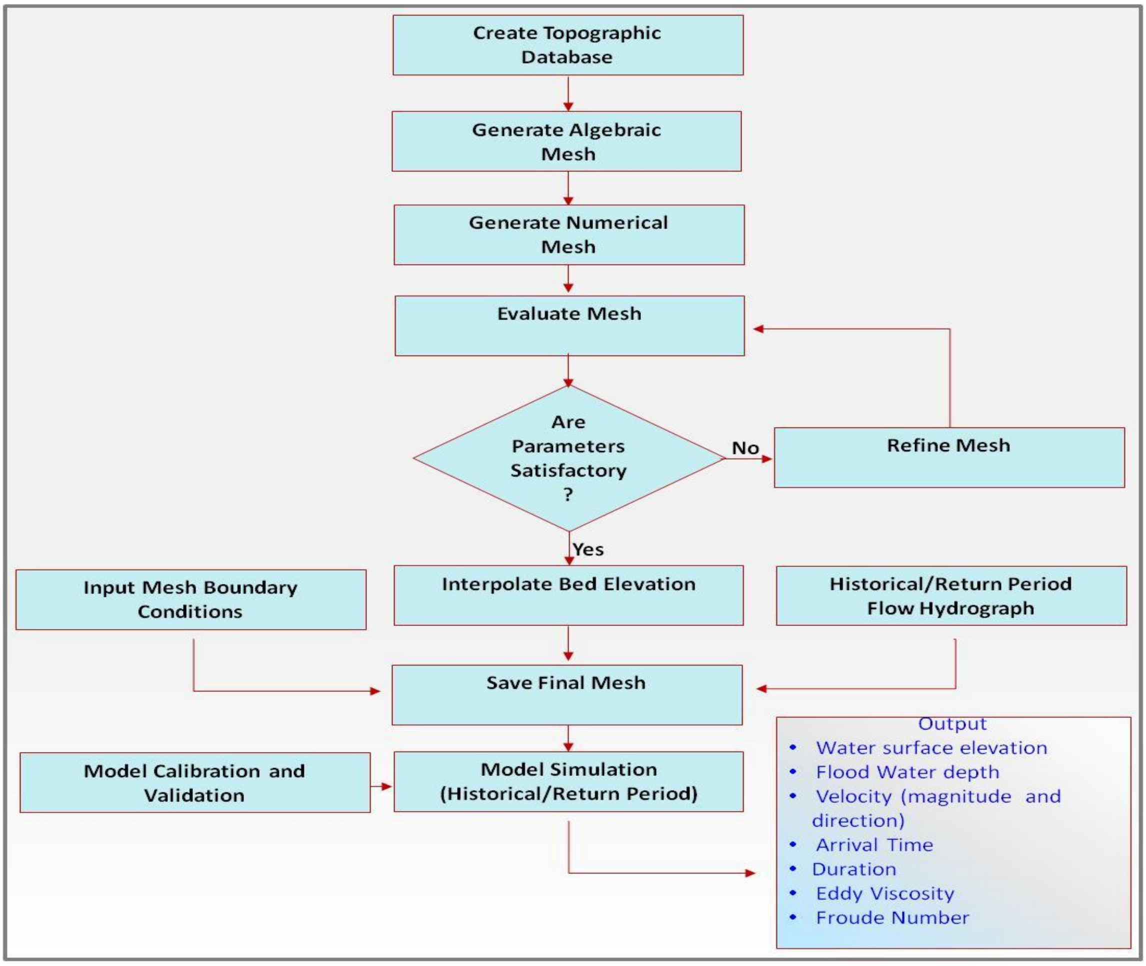

Figure 3-32: Flowchart for two-dimensional hydraulic modeling

3.3.4.1 Model Setup

A 2D hydraulic model developed by the USACE (Hydrologic Engineering Centre's River Analysis System) has been used for prediction and understanding of the floodplain inundation process. HEC-RAS is an integrated system of software. The system is comprised of a graphical user interface (GUI), separate hydraulic analysis components, data storage and management capabilities, graphics, mapping (HEC-RAS Mapper) and reporting facilities.

The HEC-RAS system contains four hydraulic analysis components for: (1) steady flow water surface profile computations; (2) 1D and 2D unsteady flow simulations; (3) movable boundary sediment transport computations (cohesive and non-cohesive sediments); and (4) water temperature and constituent transport modeling. A key element is that all four components use a common geometric data representation and common geometric and hydraulic computation routines. In addition to the four hydraulic analysis components, the system contains several hydraulic design features that can be invoked once the basic water surface profiles are computed. The software also contains tools for performing inundation mapping directly inside the software. (USACE-2015)

Figure 3-32 shows the flowchart for methodology adopted for hydraulic modeling. The broader outline of the process can be given as follows.

- Generate or acquire Digital Elevation Model (DEM) of area of interest
- Convert the DEM in to floating point raster grid for mesh generation
- Create the river and floodplain terrain model using the raster grid/grids
- Create a spatially varied Manning's roughness layers using land use dataset (optional)
- Associate the terrain model and Manning's Roughness layers with the geometry data
- Define the river and floodplain 2D flow area boundaries
- Generate the 2D mesh area using the appropriate cell size for river and floodplain
- Refine the generated mesh for any ambiguity and shape
- Define the upstream and downstream boundary conditions along with other parameters
- Simulation of the cyclone generated flows
- Calibrate the model using the historical high flood water levels and flood extent maps
- Visualize and interpret results

The HEC-RAS model simulation can be started after setting up parameters like initial flow conditions, flow parameters, and upstream/downstream boundary conditions. The initial conditions include initial water surface, bed roughness, and reservoir level. The upstream boundary condition can be given in the form of total/ maximum discharge or discharge hydrograph at upstream section and outlet boundary can be open boundary condition, rating curve, normal depth or stage hydrograph. A set of simulation parameters like simulation time, time step, mapping output interval, and detailed output intervals are given while running the model for any cyclonic event. The typical output from the model can be evaluated for water surface elevation, floodwater depth, and velocity.

To carry out the inundation modeling of cyclone-generated flows, rivers of Andhra Pradesh and Odisha were divided into smaller inundation modeling units consisting of all major rivers. Three inundation models were developed for these rivers system. These river systems include the Mahanadi and Brahmani-Baitarani rivers including Subarnarekha, Rushikulya, and Budhabalanga Rivers; the Krishna and Godavari rivers including Sarada, Nagavali and Vamsadhara Rivers; and Pennar and other east flowing rivers. Figure 3-33 shows the 2D model schematic of the Mahanadi and Brahmani-Baitarani rivers system.

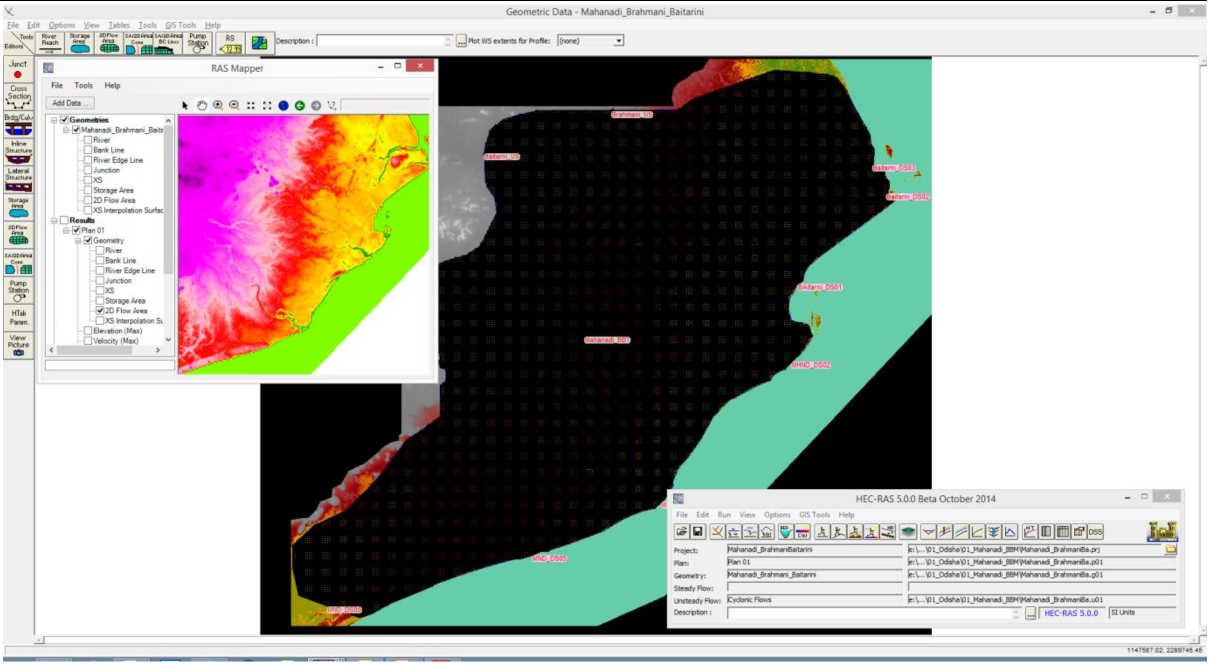

Figure 3-33: 2D model schematic for Mahanadi and Brahmani-Baitarani Rivers

Mesh Generation

Mesh generation is an important process in discretizing the area of interest into smaller units of regular geometric shape.

The HEC-RAS 2D modeling capability uses a Finite-Volume solution scheme. This algorithm was developed to allow the use of a structured or unstructured computational mesh. This means that the computational mesh can be a mixture of 3-sided, 4-sided, 5-sided, etc. computational cells (HEC-RAS has a maximum of eight sides in a computational cell). However, a nominal grid resolution (e.g. 300 x 300 m or 500 x 500 m cells) were used for the mesh generation in the present study. After initial mesh generation, the mesh was refined for consistency using the Mesh Editor.

Figure 3-34 shows the 2D mesh for the Mahanadi and Brahmani-Baitarani rivers including Subernarekha, Rushikulya, and Budhabalanga rivers.

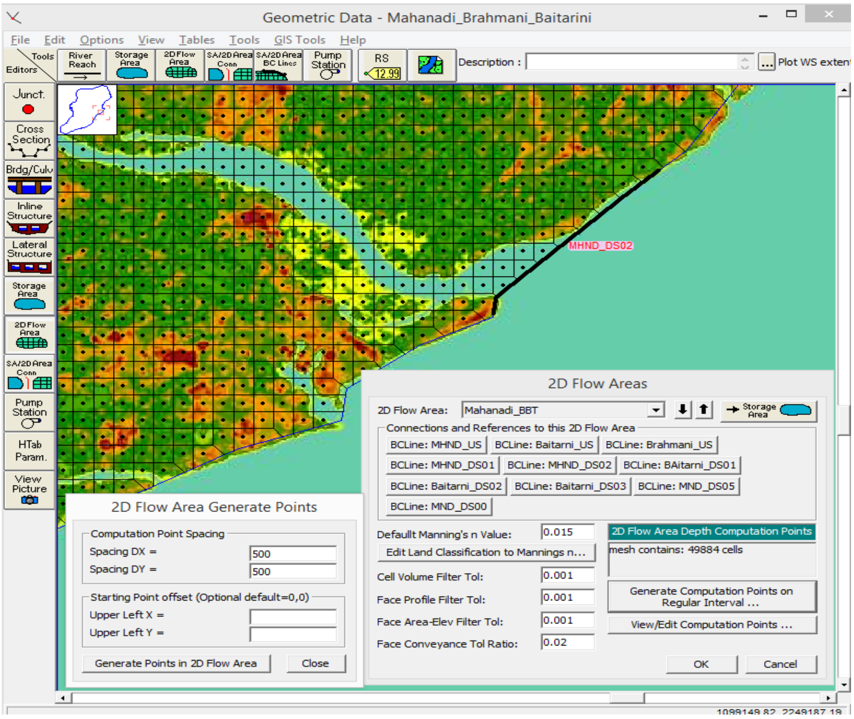

Figure 3-34: 2D Mesh Generation for Mahanadi and Brahmani-Baitarani Rivers

Hydraulic Parameters of River (Roughness and Other Channel Properties)

The hydraulic properties of the channel like the Manning's roughness were estimated using the land use land cover datasets of Odisha and Andhra Pradesh. In normal case of riverine flooding, a single roughness value is used. However, in the case of coastal flooding where the floodplains are very wide, variable roughness coefficient are used.

The land use data was given as input in the model and the Manning's n values were given as input for each land use type using the HEC-RAS Hydraulic reference Manual (2010). This creates a Spatially Varying Manning's Roughness layer. Once the model was simulated for any historical event, the Manning's values were adjusted for model calibration using historical water level.

Figure 3-35 shows the Spatially Varied Manning's Roughness layer for Odisha along the coastline. Figure 3-36 shows the base Manning's Roughness values assigned to the various land use classes. These values are used as base estimates and have been adjusted during the calibration and validation for each model.

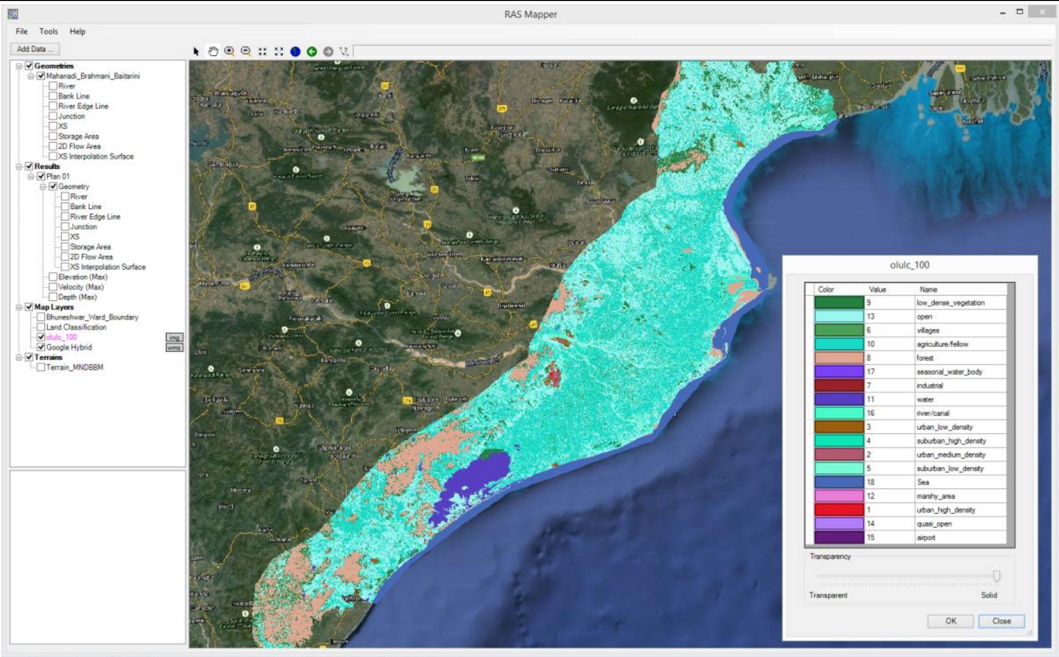

Figure 3-35: Spatially varied Manning's roughness layer for Odisha

Land Classification to Manning's n (2D Flow Areas only in Beta)

Edit Manning's n for each Name (blank for default 2D Value)

	Land Classification Name	Base Mann n
1	agriculture/fellow	0.03
2	airport	0.016
3	forest	0.08
4	industrial	0.013
5	low_dense_vegetation	0.025
6	marshy_area	0.035
7	open	0.02
8	quasi_open	0.02
9	river/canal	0.032
10	Sea	0.034
11	seasonal_water_body	0.015
12	suburban_high_density	0.011
13	suburban_low_density	0.013
14	urban_high_density	0.012
15	urban_low_density	0.012
16	urban_medium_density	0.011
17	villages	0.02
18	water	0.03

Associated Layer: e:\...\03_Statewise_RAS2D_Models\08_AP_LULC\ap_LandClass.tif

OK Cancel

Figure 3-36: Spatially varied Manning's roughness values

3.3.4.2 Calibration and validation of 2D-hydraulic models

The development of hydraulic models across a large floodplain requires a rigorous calibration process to ensure that the hydraulic model accurately reproduces the observed flood behavior. The calibration process consists of systematically comparing observed flood behavior within the study area against the hydraulic model's reproduction of that behavior. This process generally incorporates comparisons between simulated flood levels and observed flood levels. This can also be done by comparing the areas of inundation from historical event with simulated flood extents from the model. (http://www.wcma.vic.gov.au/index2.php?option=com_docman&task=doc_view&gid=385&Itemid=50).

The first approach requires detailed data about the flood levels over time (temporal distribution) at discrete points of interest within and along the river, such as important bridges, levees, and embankments. The water level data available from CWC WRIS were used for the comparison.

The water levels data for Mahanadi River were available at Naraj, Nimpara, Punsbansa, and Marshnghai gauge stations for variable duration. Table 3-21 gives the comparison of observed and simulated water levels for these gauge stations during the various cyclonic events.

Table 3-21: Comparison of observed and simulated water level (m) for gauge stations used in Mahanadi River during various cyclonic events

Cyclone Date	Naraj		Nimpara		Punsbansa		Marshnghai	
	Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated
08-Oct-1990	25.7	27.7	10.8	11.3	-	-	-	-
22-Aug-1991	25.3	27.2	9.9	11.1	-	-	-	-
26-Jul-1992	26.6	29.1	10.9	11.5	-	-	-	-
05-Aug-1997	26.2	28.2	10.4	11.3	-	-	-	-
20-Aug-1997	25.8	27.8	10.3	11.3	-	-	-	-
27-Aug-2003	27.1	28.5	10.9	11.5	12.4	12.4	5.7	5.6
30-Jul-2005	26.1	27.8	10.0	11.2	11.3	12.1	4.6	5.6
12-Sep-2005	25.6	27.1	-	-	10.6	11.7	4.3	4.9
19-Sep-2005	25.9	27.1	9.2	11.1	10.8	11.7	4.6	4.9
02-Jul-2006	26.2	27.5	-	-	10.9	11.8	4.5	4.8
02-Aug-2006	25.2	26.8	-	-	9.9	11.4	3.7	5.0
29-Aug-2006	26.4	28.9	-	-	10.4	11.8	4.6	5.0
06-Aug-2007	25.8	26.8	4.5	0.2	10.0	11.4	4.1	4.8
16-Sep-2008	27.2	28.0	-	-	13.0	12.5	6.0	5.7
20-Jul-2009	26.1	27.7	9.9	11.3	10.7	12.1	4.5	5.5

The water levels data for Brahmani-Baitarani River were available at Akhupada gauge station. Table 3-22 gives the comparison of observed and simulated water levels for Akhupada gauge station during the various cyclonic events.

Table 3-22: Comparison of observed and simulated water level (m) for gauge station used in Brahmani-Baitarani River during various cyclonic events

Cyclone Date	Akhupada	
	Observed	Simulated
06-Aug-1979	19.8	19.7
15-Oct-1985	21.2	20.3
22-Aug-1991	18.3	18.9
15-May-1995	17.7	18.7
17-Sep-1995	17.6	18.8
05-Aug-1997	19.5	19.9

Cyclone Date	Akhupada	
	Observed	Simulated
20-Aug-1997	17.8	18.6
06-Aug-1999	18.4	19.8
17-Oct-1999	18.1	19.2
29-Oct-1999	18.5	19.9
27-Jun-2005	18.8	19.5
30-Jul-2005	18.7	19.1
02-Aug-2006	18.0	18.9
16-Aug-2006	18.1	18.6
04-Sep-2006	18.2	18.6
16-Jun-2008	19.5	20.0
16-Sep-2008	18.7	19.5

The water levels data for Subarnarekha River were available at Rajghat gauge station. Table 3-23 gives the comparison of observed and simulated water levels for Rajghat gauge station during the various cyclonic events.

Table 3-23: Comparison of observed and simulated water level (m) for gauge station used in Subarnarekha River during various cyclonic events

Cyclone Date	Rajghat	
	Observed	Simulated
12-Aug-1976	17.2	17.9
08-Oct-1990	18.4	18.0
17-Sep-1995	13.1	12.0
09-Nov-1995	13.1	11.6
26-Jun-1997	12.8	12.6
06-Aug-1999	12.9	12.3
17-Oct-1999	13.0	12.1
02-Aug-2006	12.3	12.2
05-Sep-2009	12.1	12.1

The water levels data for Godavari River were available at Dowlaiswaram gauge station. Table 3-24 gives the comparison of observed and simulated water levels for Dowlaiswaram gauge station during the various cyclonic events

The comparison of water levels at various gauge stations for historical cyclonic events show that simulated and observed water level are fairly matching.

Table 3-24: Comparison of observed and simulated water level (m) for gauge stations used in Godavari River during various cyclonic events

Cyclone Date	Dowlaiswaram	
	Observed	Simulated
01-Oct-1983	0.945	1.51
23-Aug-2000	5.430	5.11
19-Sep-2005	5.910	5.74
29-Sep-2006	2.800	3.34
08-Oct-1985	1.036	1.26
17-Jun-1999	2.220	2.75

The second approach requires flood extent and/or depth measurements (spatial distribution) for particular events. Global mapping agencies, such as the Dartmouth Flood Observatory (DFO), and government agencies record the behavior of historical flood events and provide footprints of recent floods.

The 16 Sept. 2008 cyclonic flooding due to deep-depression in the Odisha was simulated using the 2D HEC-RAS models and output flood extent was prepared in ArcGIS. A comparison of simulated flood extent and DFO flood extent map is shown in Figure 3-37. Flood extent comparison shows that simulated and observed flood extent are fairly matching.

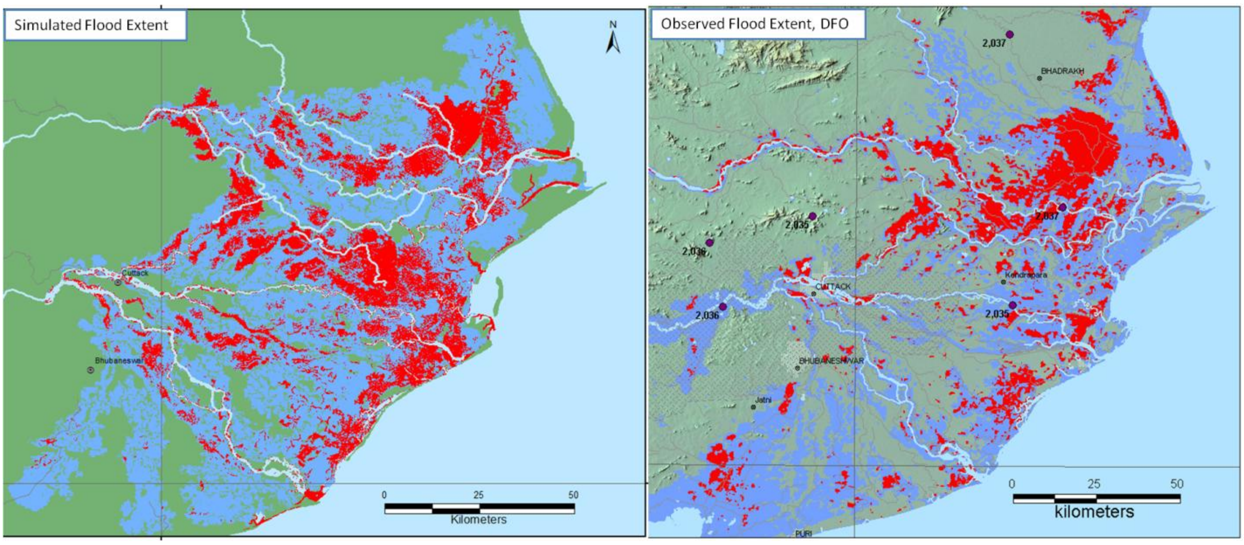

Figure 3-37: Comparison of simulated flood extent v/s Dartmouth observed flood extent map of 16 Sep. 2008 Cyclone events

The results of the calibration and validation of the 2D-hydraulic models using the both the approaches discussed above show that the models are adequately calibrated and can be used for simulation of other historic and deterministic events.

3.3.5 Simulation of Flood Extent Maps

3.3.5.1 Flood Extent maps for historical cyclones

As mentioned in the methodology above based on the river discharges during the various cyclonic events, the boundaries of the flood plains have been determined by using two-dimensional hydraulic model HEC-RAS 2D. Flood extent maps have been prepared by integrating model results with elevation data to produce a map with varying flood depths using GIS tools.

As discussed earlier, from year 1901 to 2013 around 94 historical cyclone induced flood events have been simulated for Odisha. For Andhra Pradesh around 94 cyclone induced flood events have been simulated. The flood extents of all these flood events were simulated using HECRAS 2D model.

The cyclone induced flood hazards maps for three major historical cyclones affecting Odisha are shown in Figure 3-38, Figure 3-39, and Figure 3-40 respectively.

The cyclone induced flood hazards maps for three major historical cyclones affecting Andhra Pradesh are shown in Figure 3-41, Figure 3-42, and Figure 3-43 respectively

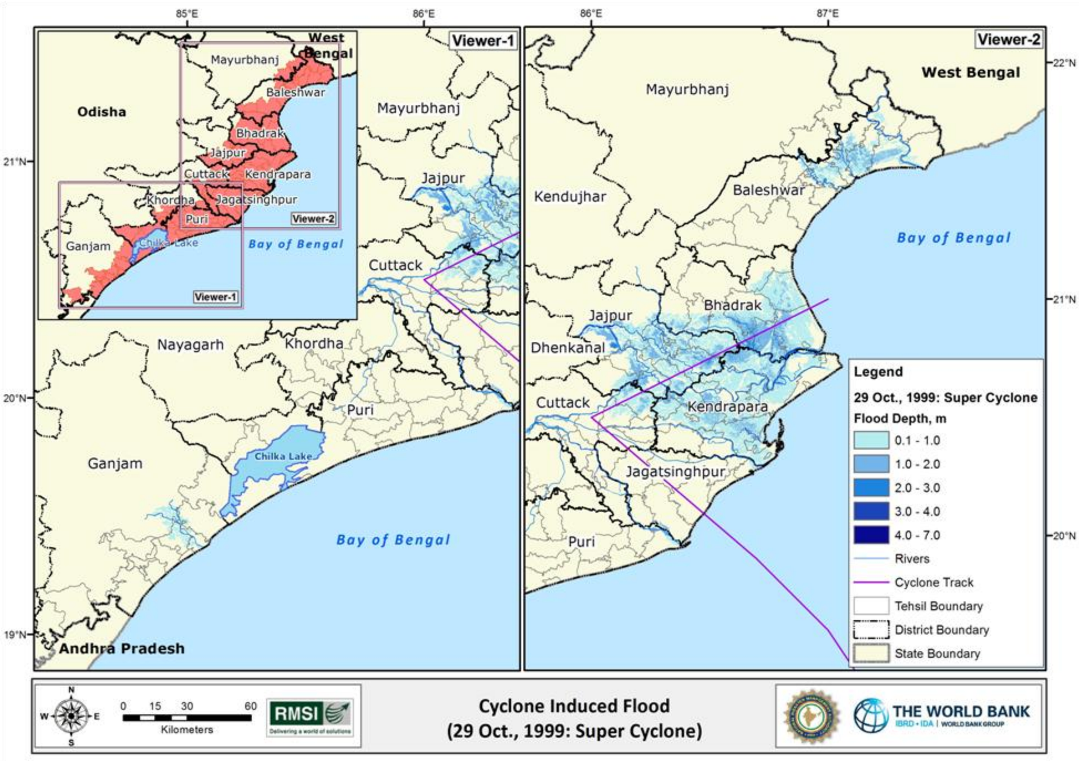

Figure 3-38: Cyclone induced flood map for 29 Oct. 1999 Super Cyclone

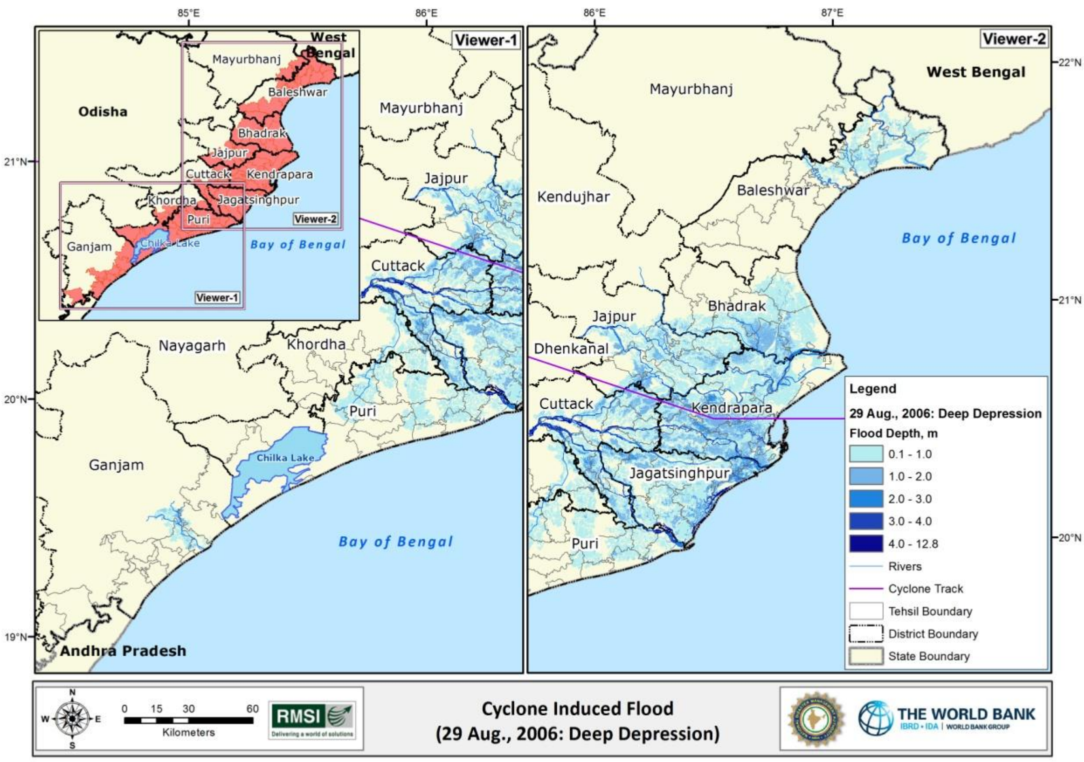

Figure 3-39: Cyclone induced flood map for 29 Aug. 2006 deep depression

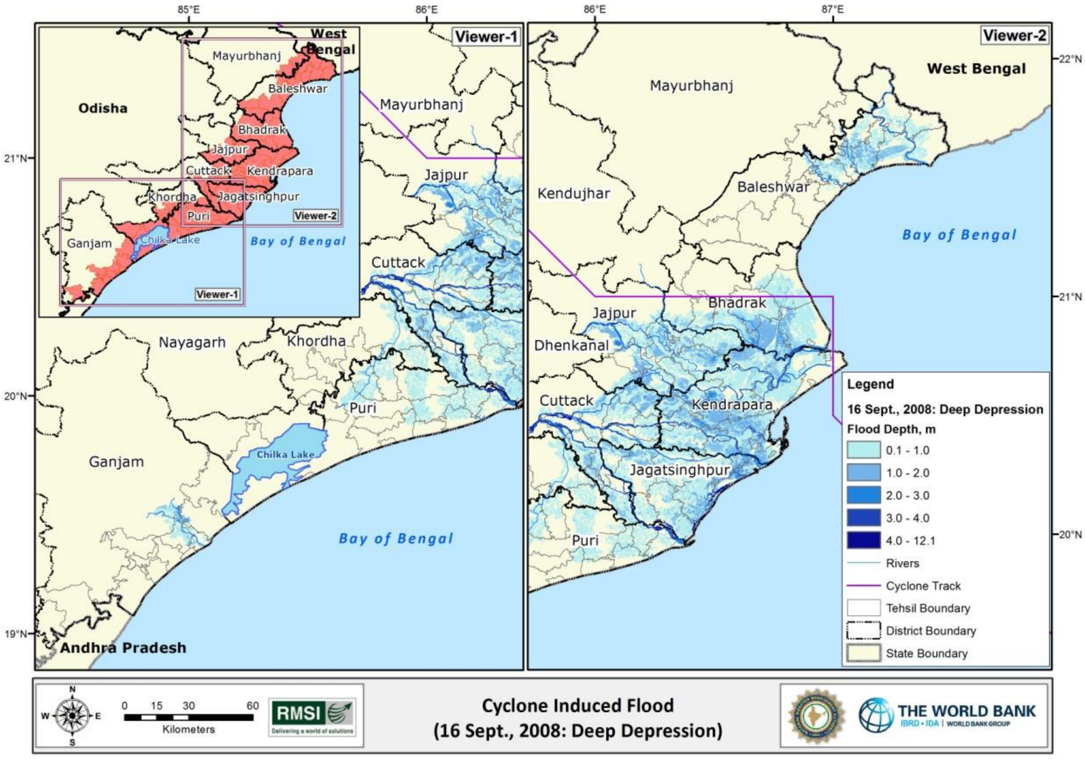

Figure 3-40: Cyclone induced flood map for 16 Sept. 2008 deep depression

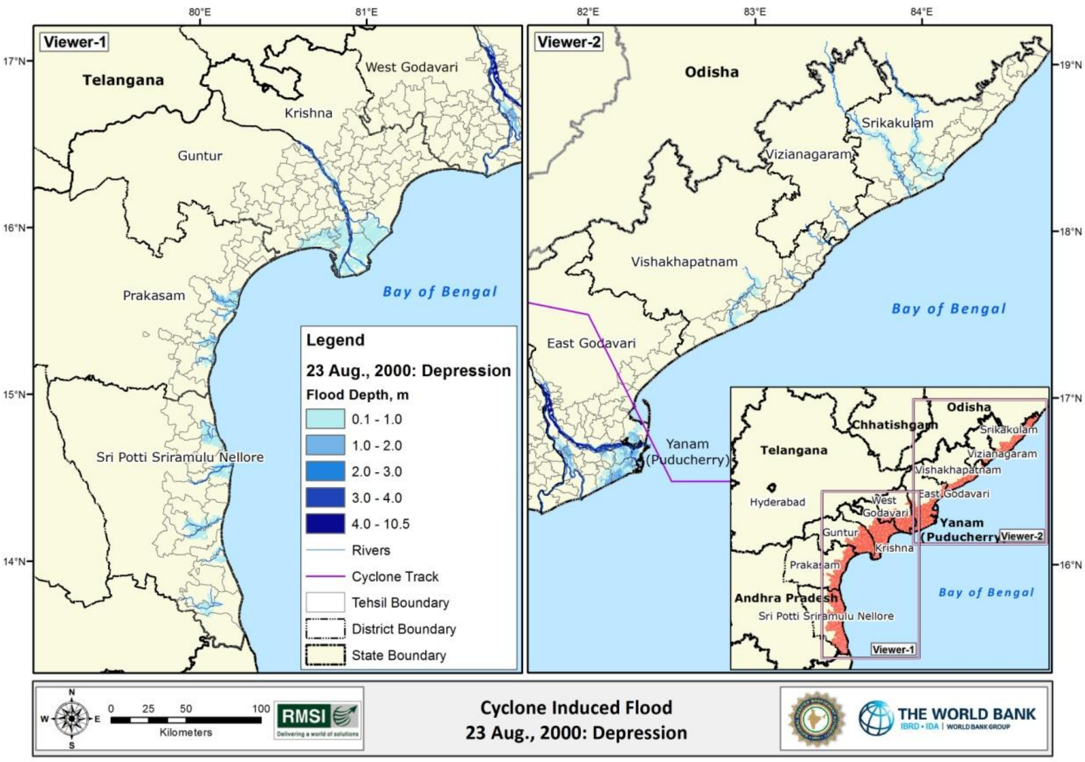

Figure 3-41: Cyclone induced flood map for 23 Aug. 2000 depression

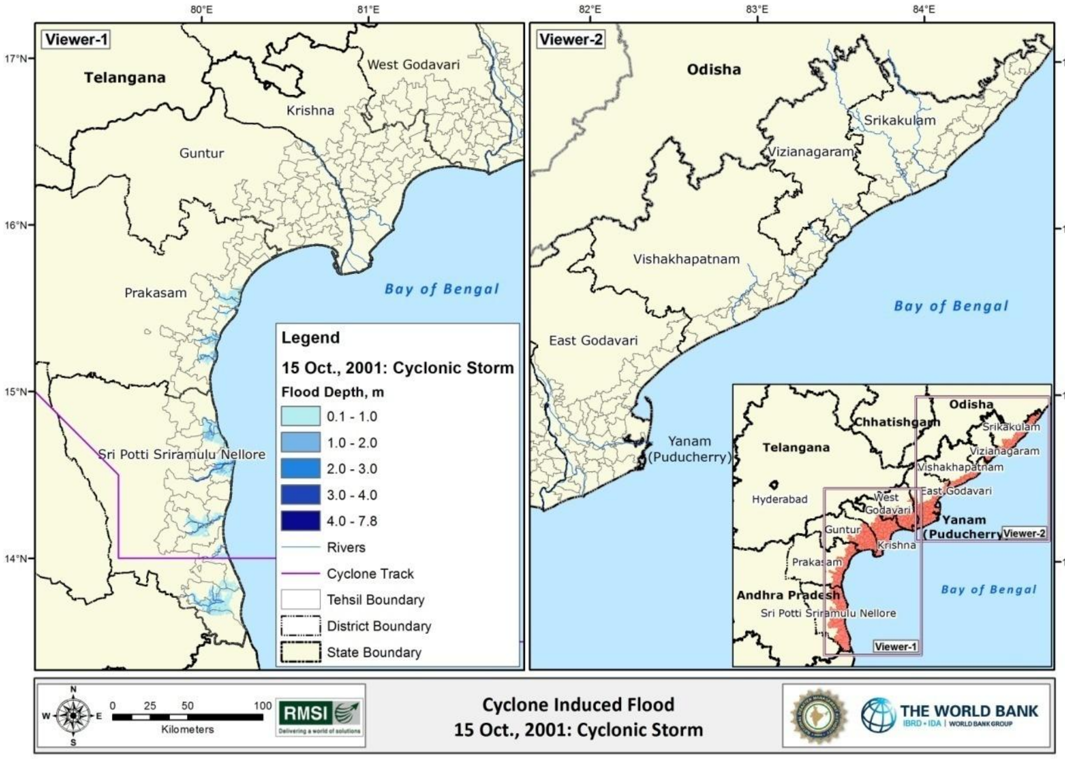

Figure 3-42: Cyclone induced flood map for 15 Oct. 2001 cyclonic storm

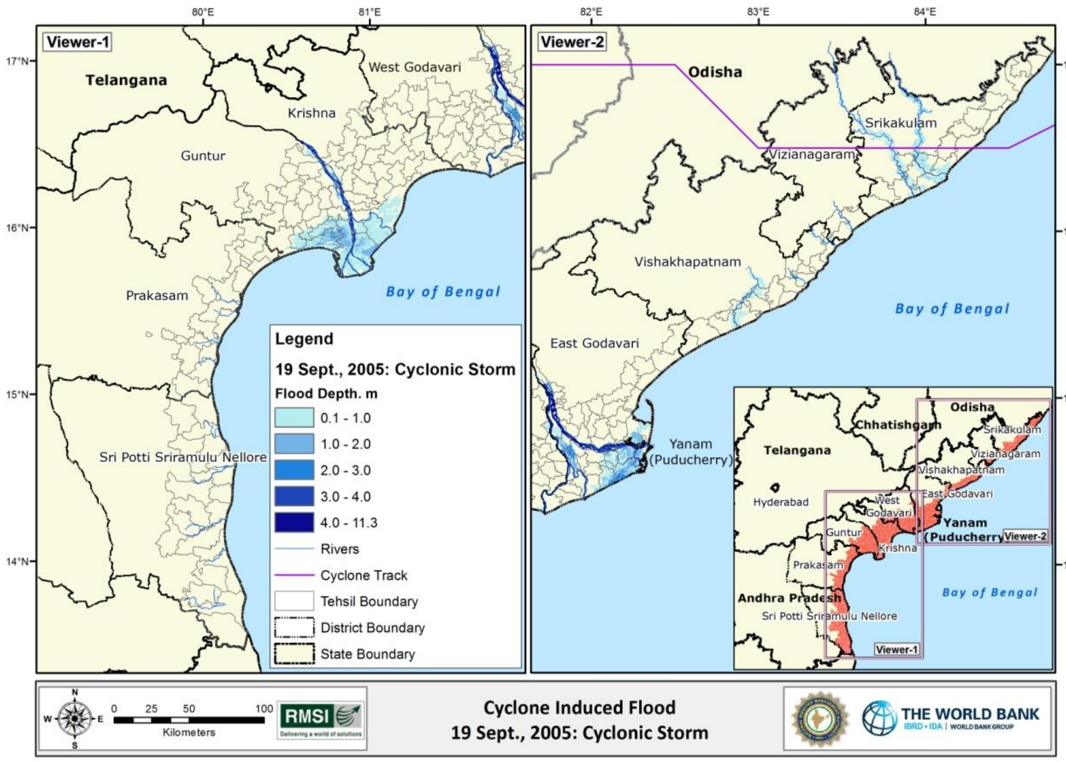

Figure 3-43: Cyclone induced flood map for 19 Sept. 2005 cyclonic storm

3.3.5.2 Flood Extent maps for deterministic events

After simulating the historical cyclone induced flood events for both the states of Odisha and Andhra Pradesh, the 2, 5, 10, 25, 50, and 100 year deterministic events were simulated using the HECRAS 2D model.

The flood hazard maps for 100 year return period events for Odisha and Andhra Pradesh shown in Figure 3-44 and Figure 3-45 respectively.

The flood hazard maps for 2, 5, 10, 25, and 50-year return period events for Odisha are shown in Figure 12-5 to Figure 12-9 of Annexure 3: Cyclone Induced flooding respectively. Similarly, the flood hazard maps for 2, 5, 10, 25, and 50-year return period events for Andhra Pradesh are shown in Figure 12-10 to Figure 12-14 of Annexure 3: Cyclone Induced flooding respectively.

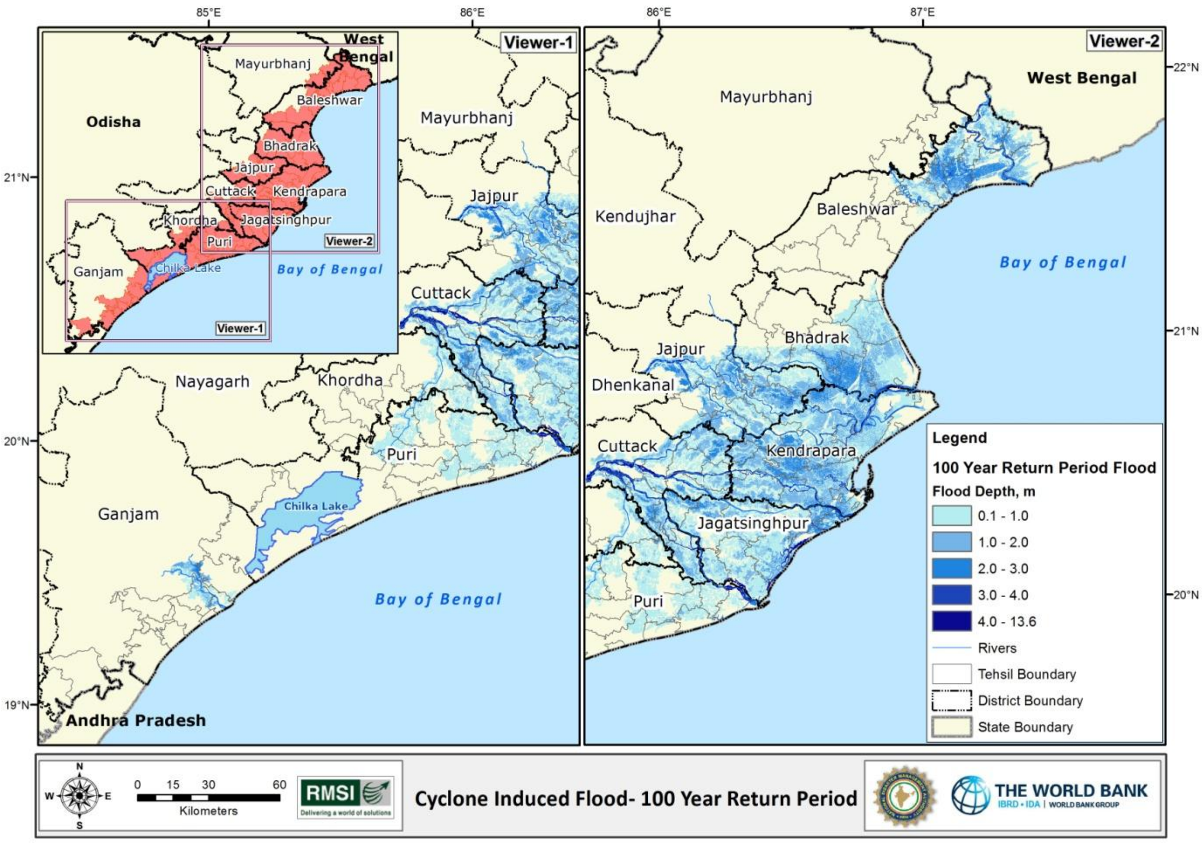

Figure 3-44: Cyclone induced flood map of Odisha for 100-year return period

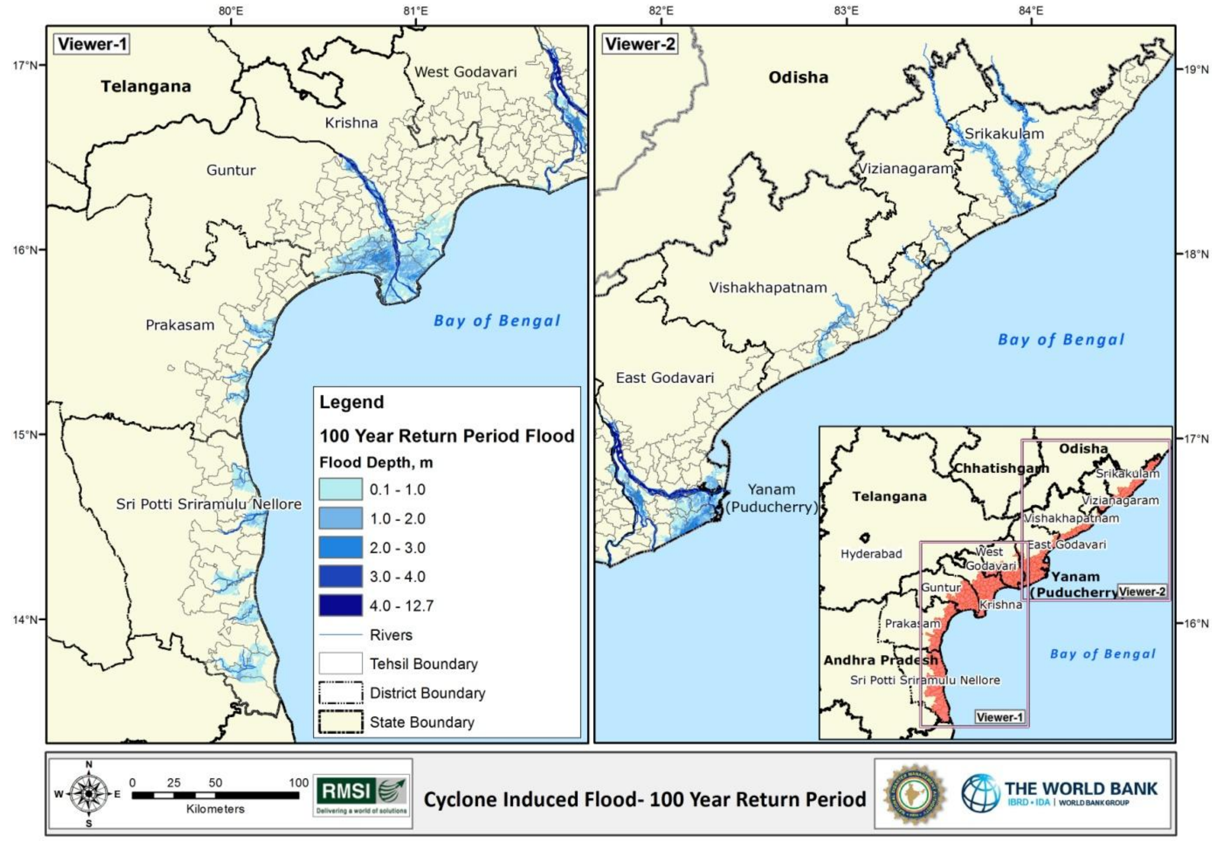

Figure 3-45: Cyclone induced flood map of Andhra Pradesh for 100-year return period

4 Key Findings

4.1 Cyclone and Storm surge hazard

This section discusses the key findings from the cyclonic wind and associated storm surge flood hazard assessment of Odisha and Andhra Pradesh. The key findings have been derived by the analysis of the frequency and severity of various return period scenarios over the coastal areas of the two states. The following are the major findings of the hazard assessment:

- The model reaffirms the common knowledge that Odisha is more prone in terms of high intensity and frequency of cyclones as compared to Andhra Pradesh.
- Analysis of historical cyclonic events in across all five Zones indicates that the frequency of Very Severe Cyclonic Storms is higher than the Severe Cyclonic Storms. This is contrary to the normal behavior of hazards as per which the stronger events are rarer. This suggests that the potential for more frequent larger losses in India is higher.
- Comparing severity of Zone-1 and Zone-2, one observes that the total number of cyclones that have hit Zone 1 is much higher than Zone 2 indicating that the risk is much higher in Zone 1 than in Zone 2. However, another interesting finding is that 13 severe cyclonic storms struck the Zone-2 whereas Zone-1 that comes in very-high severity zone has been affected by only eight severe cyclonic storms. This suggests that the potential for more frequent larger losses is high in Zone-2.
- The Jagatsinghpur, Kendrapara, and Ganjam districts of Odisha are more vulnerable due to cyclonic wind hazard for 100-year return period event where higher wind speeds of about 128-144 km/h cover a large extent of these districts. Among these districts, Jagatsinghpur is most vulnerable to strong winds of about 144 km/h.
- Extent of flooding due to storm surge is more in northern Odisha for 100-year return period event. The average flood depth for 100-year return period event in Odisha varies between 0.5 to 5.6 m. Many villages in the Bhadrak and Kendrapara districts show higher flood depth of about 5.7 m and flood extent 15 km.
- The Puri and Ganjam districts are less affected due to storm surge flooding. The average flood depths in these districts are around 0.5 to 4.0 m.
- 100-years return period event could generate higher winds of about 128-136 km/h covering many coastal districts of Andhra Pradesh including Guntur, Krishna, and Srikakulam. Among these districts, Srikakulam is most vulnerable to strong winds of about 136 km/h.
- In Andhra Pradesh, the most vulnerable low-lying areas of Guntur and Krishna are prone to high water levels due to storm surge flooding for a 100-year return period event.

4.2 Cyclone Induced Flooding

This section discusses the key findings from the cyclonic rainfall induced flood hazard assessment of Odisha and Andhra Pradesh. The key findings have been derived by the analysis of the frequency and severity of various return period scenarios over the coastal areas of the two states. The following are the major findings of the hazard assessment:

- It is observed during the modeling of the cyclone-induced rainfall that it is the translational speed of the cyclone that plays an important role in flooding. Slower moving cyclones cause more flooding irrespective of their strength. Generally it is observed that the depressions and deep depressions have a lower translational speed in comparison to the very severe cyclonic storms and severe cyclonic storms, they stay for longer durations over the basin areas. This causes depressions and deep depressions to cause long duration rainfall in the basins and subsequent flooding.

- The analysis shows that in Odisha, the flooding events are triggered above a particular thresholds discharge at various gauge locations. The trigger discharge values for various rivers at various gauge locations are given in Table 4-1.

Table 4-1: Average threshold discharges for various rivers in Odisha

River	Gauge	Discharge, cumec
Mahanadi	Tikarpara	10,000
Brahmani	Jenapur	3,000
Baitarani	Anandpur	1,500
Subernarekha	Ghatsila	2,000

- Similarly, for Andhra Pradesh, the analysis shows that, the flooding events are triggered above a particular threshold discharge at various gauge locations. The trigger discharge values for various rivers at various gauge locations are given in Table 4-2.

Table 4-2: Average threshold discharges for various rivers in Andhra Pradesh

River	Gauge	Discharge, cumec
Pennar	Nellore	1,500
Godavari	Polavarm	12,000
Krishna	Vijaywada	9,000
Vamsadhara	Kashinagar	1,500
Nagavali	Srikakulam	1,500

- The model outputs reaffirm the common belief that Odisha is more severely affected due to cyclone induced flooding as compared to Andhra Pradesh because cyclone occurrence frequency is very high in Odisha.
- In Odisha, the delta region of Mahanadi and Brahmani-Baitarani rivers is highly vulnerable due to cyclone-induced flood.
- Similarly, in Andhra Pradesh the delta region of Krishna and Godavari rivers is highly vulnerable due to cyclone-induced flood.
- In Andhra Pradesh the cyclones induced flooding is mainly due to flooding in the small east flooding rivers, as the discharge carrying capacity of these rivers is comparatively low.
- In Odisha, Kendrapara, Bhadrak, and Jajpur districts are the most affected due to cyclone induced flooding. This region gets heavily flooded even due to marginal increase in river flows. The average flood depth due to 100 year flood in the region is around 1.5 to 2.0 m. A few villages pockets in the Bhadrak and Kendrapara districts, show higher flood depth in tune of 2.0 to 3.0 m
- The Puri and Jagatsinghpur districts are less affected due to cyclone induced flooding except few village pockets. The average flood depths in these districts are around 0.5 to 1.0 m.
- The Baleswar district is severely affected due to flooding in Subarnarekha and Budhabalanga rivers. Most the village in the district shows the average flood depth in the range of 2.0 to 2.5 m.
- The villages on both sides of Rushikulya River in Ganjam districts are affected due to cyclone induced flooding. The average flood depth in the region is around 1.5 m.

- In Andhra Pradesh, a coastal region of East Godavari district is affected due cyclone induced flooding. The average flood depth in the region is around 1.0 to 1.5 m.
- The delta region of the Krishna and Guntur districts are severely affected due to cyclone induced flooding. The average depth flooding is around 1.5 to 2.0 m.
- Prakasham and Nellore districts get flooded due to Pennar and others small flowing rivers.

5 Progress on the Web Atlas Development

5.1 Introduction

Web-based Risk Atlas is under development on Geo Node platform for developing geospatial information systems (GIS) and for deploying spatial data infrastructures (SDI). The goal of this application is to help estimate the impacts of cyclone, surge, and cyclone-induced flood on 13 coastal states/UTs.

This section provides the overall progress in the Web Risk Atlas development and should be read in conjunction with the progress report that was part of the Exposure and Vulnerability Assessment report submitted as the previous deliverable.

5.2 Functionality

Based on the requirements for the web risk atlas, the major functionalities that are to be developed include:

1. View and Query Risk Atlas

To view and query the Risk Atlas, the application will provide the user with a navigation pane and search by attribute pane respectively. Navigation pane will help the user in performing basic GIS operations such as:

- Pan
- Zoom in
- Zoom out
- Previous view
- Next view
- Attribute information tool

The Select by Attributes functionality will provide users the facility to map or highlight an active layer based on the attributes of the layer.

2. Manage Exposure

This functionality will allow the user to update exposure values of aggregated and site-specific details. This functionality will allow the user to modify the base values corresponding to the various occupancy types. With this functionality, the user will be able to modify the population, crop, building, and infrastructure exposures.

There will be three separate interfaces for updating aggregated exposure, site-specific exposure and building structural distribution exposure. These details will be updated at village level. Aggregated exposure interface will help in updating the occupancy details whereas with site-specific interface will help in modifying infrastructure and other details. User will be able to update structural distribution exposure of the various structural type values.

3. Risk Analysis

Risk analysis functionality will provide the user to work on both base and user-defined exposure values. The various hazards for which analysis can be performed are:

- Cyclone
- Flood
- Surge

These analyses will be performed at scenario level for various exposure types, viz., occupancy, essential facilities, public buildings, utilities, transportation etc.

As soon as the analysis is performed, requested analysis job is added in the queue in asynchronous mode. An option will be given to the user to view the status of the submitted analysis job from where the user can generate a report once the analysis is complete. The generated report will display tables and graphs showing the losses in monetary terms and their distribution over a region based on the choices the user has made.

4. Manage vulnerability

Vulnerability updates will be session specific. Changes in vulnerability will not affect the base table. The user will be provided with two interfaces. One will be to update the aggregated vulnerability functions and the other one will be to update site-specific vulnerability. Through aggregate vulnerability, the user will be able to update structural type distribution details and through the site-specific interface, the user will be able to edit the vulnerability functions corresponding to various types of infrastructure, transport, and utilities.

5. Hot-spot Analysis

Based on the hot spot areas identified in various districts, the user will be able to perform hot spot analysis for areas falling under the state assigned. For the selected hot spot user will be able to modify the hot-spot exposure (building, infrastructure, essential facilities etc) and can then run the hot-spot analysis. The user will be able to modify the exposure for current scenario only. After the analysis is run, the changed exposure values are not reflected the next time analysis is performed.

Once the analysis is performed, a report will be generated showing the risk maps that will help the user in disaster risk management functions. It will also help the user in evacuation and shelter planning.

6. **Manage user account**

This functionality is specifically for the administrator to maintain user accounts. This will include adding, modifying, or deleting user account information from the Atlas.

1. Add new user: The administrator will have the right to add a new user to the atlas. The new user will be able to login to the system with the username, password, and the role assigned to him/her by the administrator.
2. Modify the user: This will allow the administrator to edit the existing rights/ role assigned to the user.
3. Delete the user: This will allow the administrator to delete a user from the Atlas, in case the user needs to be excluded from accessing the Risk Atlas or when the user log in is no longer required to be used.

5.3 Web atlas status update

In continuation with the previous project status report submitted, the summary table below provides details on the development status of various functionalities that have been completed and/or are in progress. The section below explains the changes that have been made in the existing implemented functionality and the development that has been done after the last submitted status report.

Table 5-1: Progress in development of Risk Atlas components

Functionality	Sub Functionality		Status*
Design	Database design	Database structure	Done
		Relationship between tables	Done

Functionality	Sub Functionality		Status*
	Interface design	Login page	Done
		Manage Aggregate Exposure	Done
		Manage Site specific exposure	Done
		Building structural distribution	Done
		Aggregate vulnerability	Done
		Site specific vulnerability	Done
		Risk Analysis	Done
		Viewing Analysis status	Done
		Hot spot exposure	In Process
		Hot spot analysis	In Process
Login Page	Login to application		Done
	Register to application		In Process
Homepage	Risk Summary of state		Done
	Map Applications		Done
	View Detailed Risk of state		Done
	View Detailed Map Applications		Done
GIS Functionalities	Pan Map		Done
	Zoom in		Done
	Zoom out		Done
	Measure distance		Done
	Measure Area		Done
	Get attribute information		Done
Manage Risk Atlas	Manage Risk Map		Done
	Manage Risk Analysis Map		In process

Functionality	Sub Functionality		Status*
	Manage Hotspot Map		In process
Manage Exposure	Manage Aggregated Exposure		Done
	Manage Site-specific Exposure		Done
	Manage Crop exposure		In process
	Manage Population		In process
	Manage Hotspot Exposure		In process
Exposure Data integration	Admin boundaries	Andhra Pradesh	Done
		Odisha	In process
	Aggregated data	Andhra Pradesh	Done
		Odisha	In process
	Site specific data	Andhra Pradesh	Done
		Odisha	In process
Hazard Data integration	Historical Cyclone catalogue - Soil maps - Bathymetry data	Andhra Pradesh	In process
		Odisha	
	Historical Cyclone event hazard maps	Wind	In process
		Surge	
		Flood	
	Return period scenarios	Wind	In process
		Surge	
		Flood	
Manage Vulnerability	Manage Aggregated Vulnerability		Done
	Manage Site-specific vulnerability		Done
	Manage crop vulnerability		In process
	Manage population vulnerability		In process
	Manage hotspot vulnerability		In process
Risk Analysis	Submit Analysis		Done
	Create Analysis Scheduler		Done
	Write Risk Assessment functions in database		In process
	Design and implementation of Risk analysis		In process

Functionality	Sub Functionality	Status*
	report	
Hotspot Analysis	Submit Hotspot Analysis	In process
	Create Hotspot Analysis Scheduler	In process
	Write hotspot analysis functions in database	In process
	Design and implementation of Hotspot analysis report	In process
Upload	Upload Layers	Done
	Upload Document	Done
User based Accessibility	Admin accessibility	Done
	Registered user accessibility	In process

*The functionality corresponding to green highlighted column is done and the orange highlighted columns indicate that the implementation on the same has been started and is underway.

5.3.1 ACCESS TO LOGIN

The Web risk atlas comprises of three different kinds of users each having access to different kind of functionalities. The three different users are:

a. **Administrator**: The administrator would have access to all the rights in the system.
b. **Registered user**: Each registered user will be assigned one state. User will be able to perform the various functions for their respective states only.
c. **Guest user**: The guest user can only use the application once he is registered. Guest user has to follow a registration process where user will be asked to provide his/her name, company name, contact details, state etc to access the system. To register, user is given with the Register link at the bottom right of the Login button as shown in below figure.

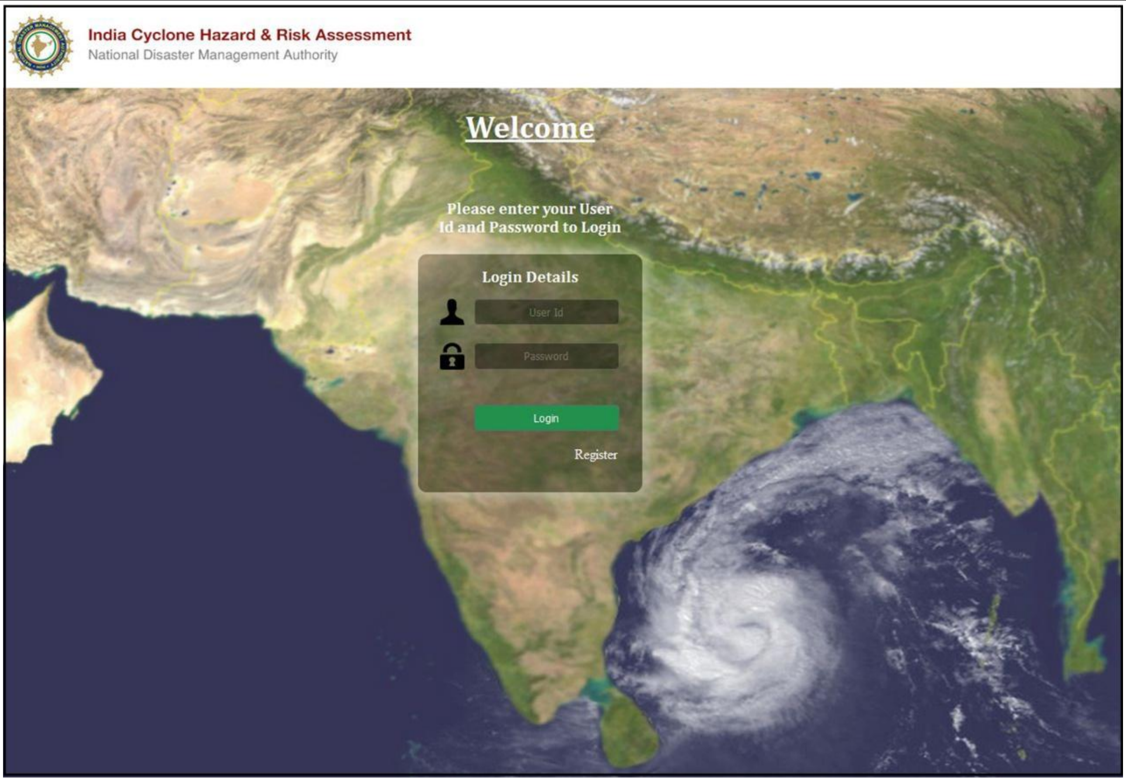

Figure 5-1: Login page

5.3.2 RISK ATLAS HOME PAGE

Based on the type of user and the state assigned, the user will be navigated to the homepage of the application with the respective state zoomed in. In order to help disaster management specialists and other users to deal with challenges of mitigating losses from cyclones, RMSI provides a quick glance of information on the homepage that would help users in taking effective decisions. To provide a user-friendly interface that allows faster and easier comprehension of the cyclone hazard, some modifications have been done in the representation of the homepage interface.

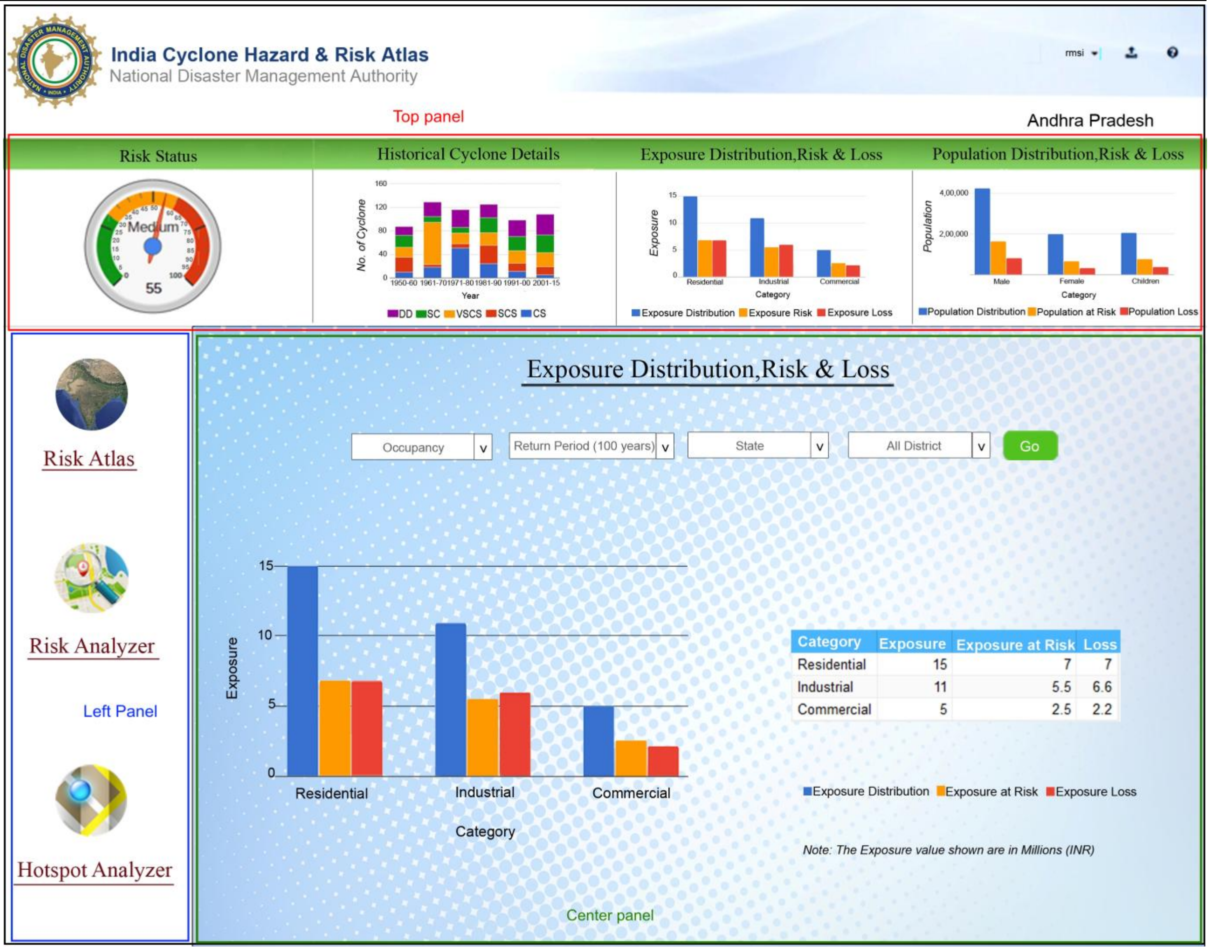

Figure 5-2: Home page

The homepage has been divided into three different panels:

a. **Left panel** – It provides users with access to three functionalities, namely:

  i. **Risk Atlas**: To visualize the risks from cyclone, surge and cyclone induced rainfall in a state. The detailed explanation of it is given in sections further below.

  ii. **Risk Analyzer**: To visualize the risk associated with a state with respect to the analysis performed by updating the exposure values.

  iii. **Hot- spot Analyzer**: To visualize the hot-spot locations in a state

b. **Top panel** – The top panel provides risk information associated to a state in the form of charts and graphs that will help decision-makers in DRR planning and taking necessary actions to reduce the adverse affects of cyclones.

  i. **Cyclone risk status**: A Risk Meter has been added in the application that provides the status of the cyclone risk associated to a state, i.e., whether the state is in the Low, medium, or high-risk zone.

  ii. **Historical Cyclone Details**: It gives year-level counts of cyclones that have occurred in a state with respect to their intensity, i.e. whether they were severe cyclones, super cyclones etc.

  iii. **Exposure distribution, risk, and loss**: It gives the exposure distribution, risk and loss details for various categories such as residential, industrial, and commercial in the form of a bar graph.

iv. **Population distribution, risk, and loss:** It gives the population distribution details, the associated risks, and loss details of the state with respect to cyclones.

c. **Center panel** – This panel will give a map view of the state. As the user clicks on the various bar graphs displayed in the top panel, the corresponding detailed information is displayed in the form of charts and graphs.

The table below shows the various sub-functionalities of the homepage and their development status.

Functionality	Description	Status
Risk Charts	It displays the cyclone risk status, exposure distribution, population distribution details etc.	Done
Map Applications	All three map application will display at right panel Risk Map Risk Analysis Hotspot map	Done
View Detailed Map Applications	By click on header of Maps in left panel Details map will display in center panel	Done
View Detailed Risk Charts	By Click on header of charts in top panel detailed chart will be displayed in the center panel	In process

The sub functionalities of the left panel are described below:

i. Risk Atlas

The Risk Atlas provides users with the functionality to view various layers such as administrative boundaries, base layers, transportation layer etc. These layers can be used in conjunction with one another. As the user clicks on a checkbox corresponding to the layer, its map is displayed in the Map window. Users can also see the full view of the risk atlas by clicking the Full View link given at the top right side of the Risk Atlas window.

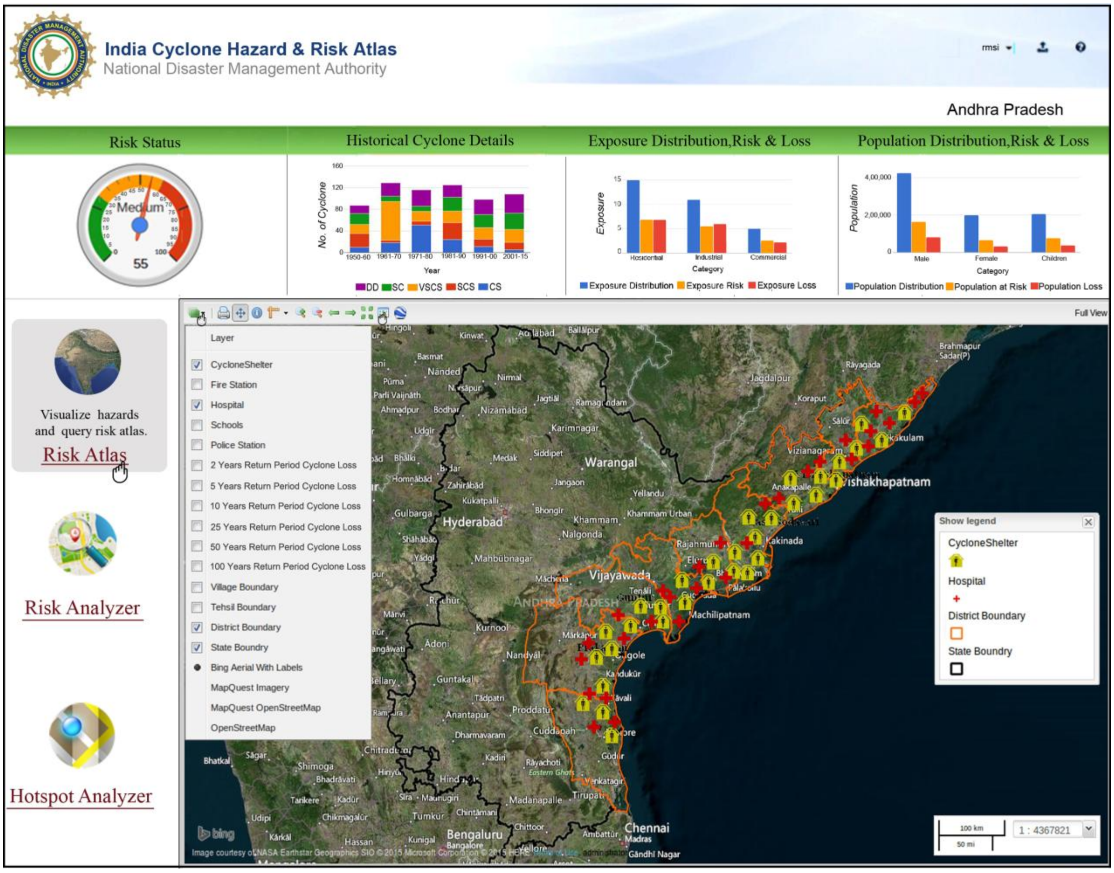

Figure 5-3: Risk Atlas view

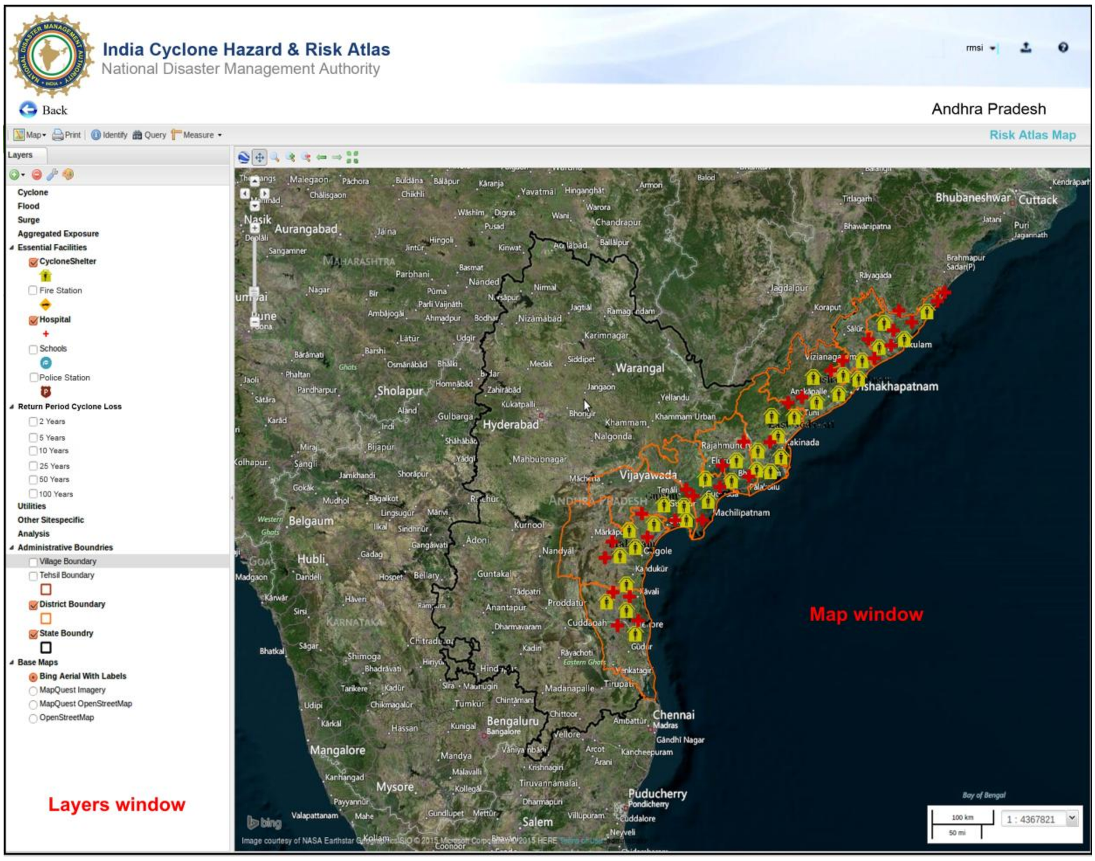

Figure 5-4: Full view of the Risk Atlas

ii. Risk Analyzer

This helps the user in managing the exposure and vulnerability values and the capability to perform a risk analysis based on user-defined values. To manage the exposure and vulnerability values, a user is given three tools in the toolbar that are:

- Exposure: This allows the user to update the aggregated and site-specific exposure values.
- Vulnerability: This allows the user to update the aggregated and site-specific vulnerability data.
- Risk Analysis: This allows the user to perform a risk analysis at base or at user-defined data. The user can also view the status of various analyses jobs submitted.

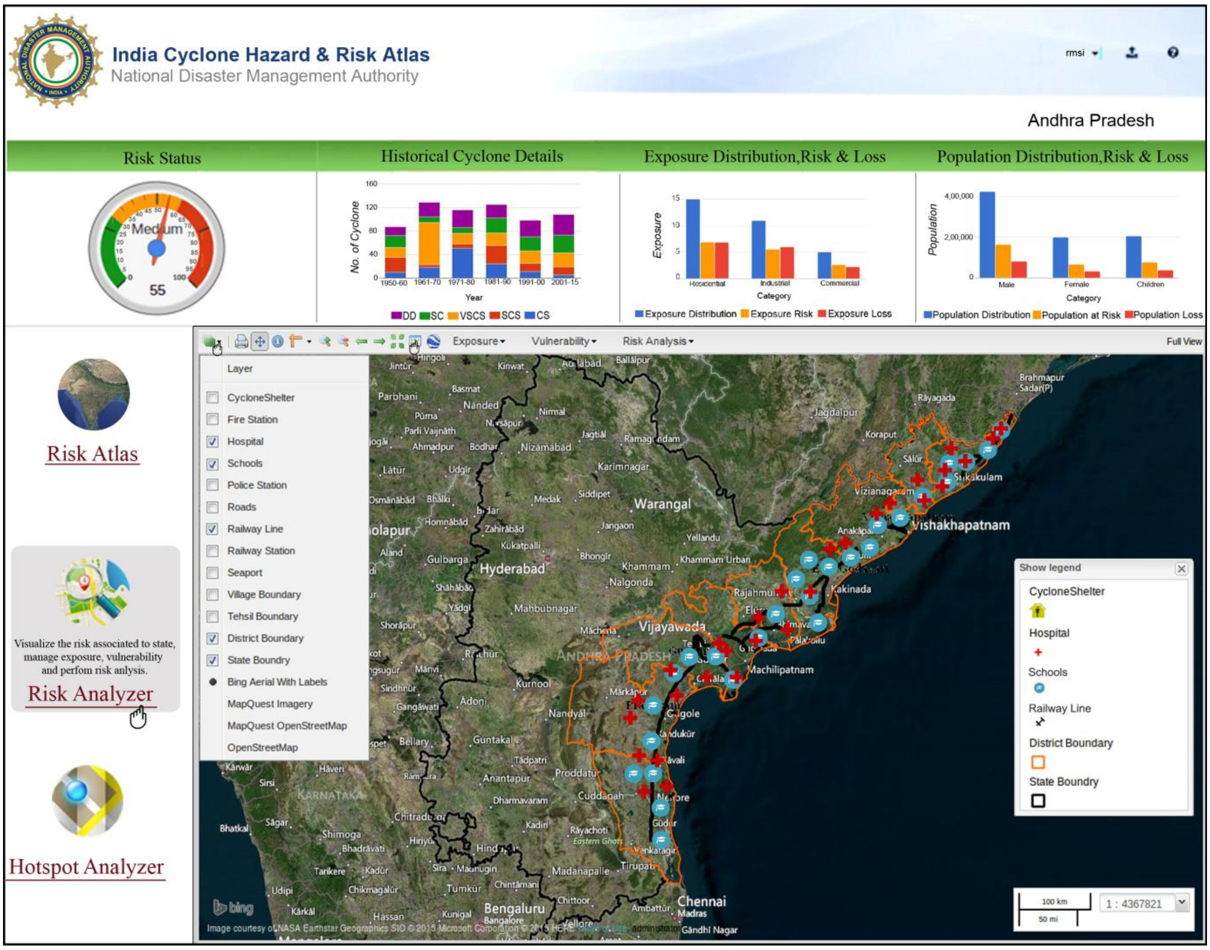

Figure 5-5: Risk Analyzer

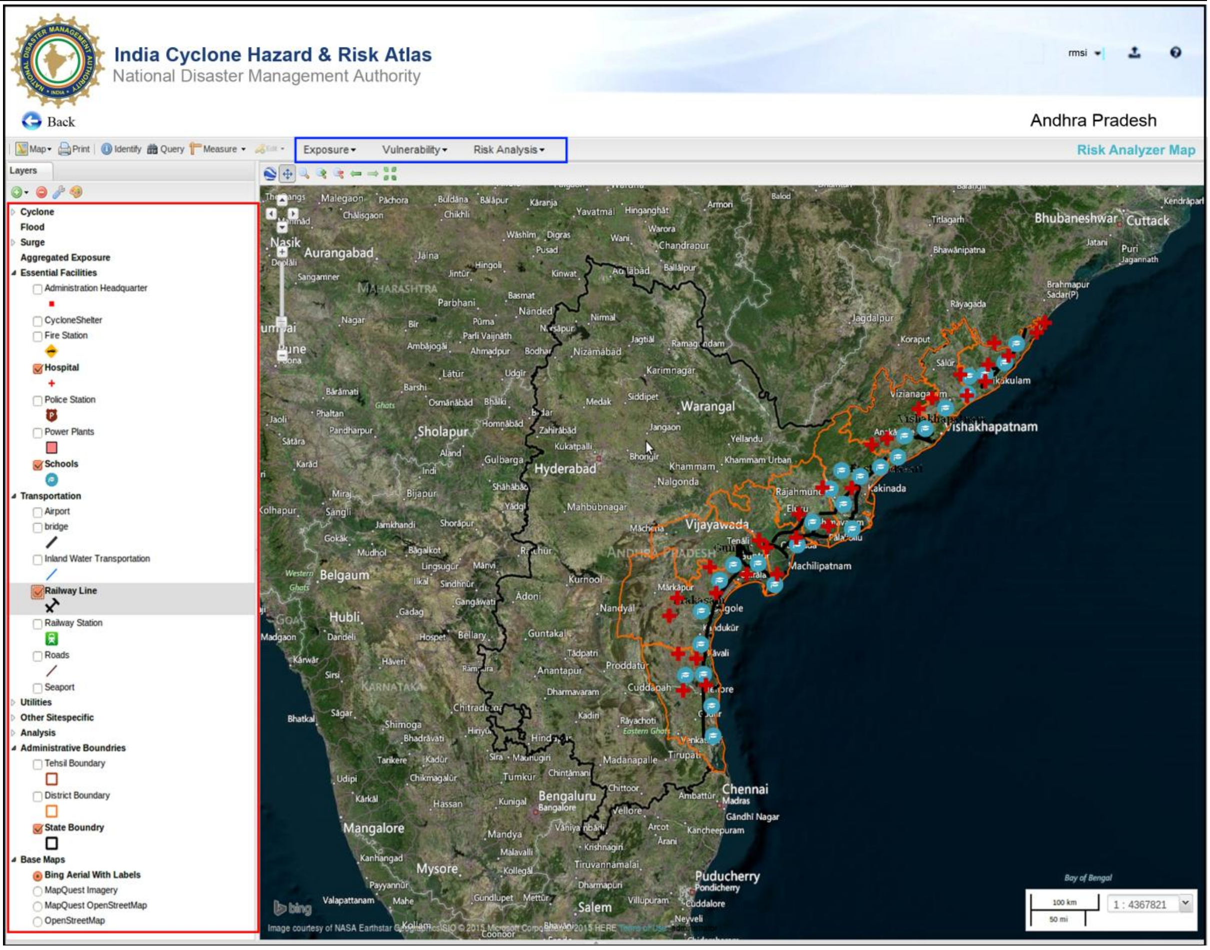

Figure 5-6: Full view of risk analyzer

iii. Hotspot Analyzer

Based on the hot spot areas identified in various districts, the user will be able to perform hot spot analysis for areas falling under the state assigned. For the selected hot spot, the user will be able to modify the hot-spot exposure (buildings, infrastructure, essential facilities etc.) and can then run the hot-spot analysis. The full view of the same is shown in the next figure.

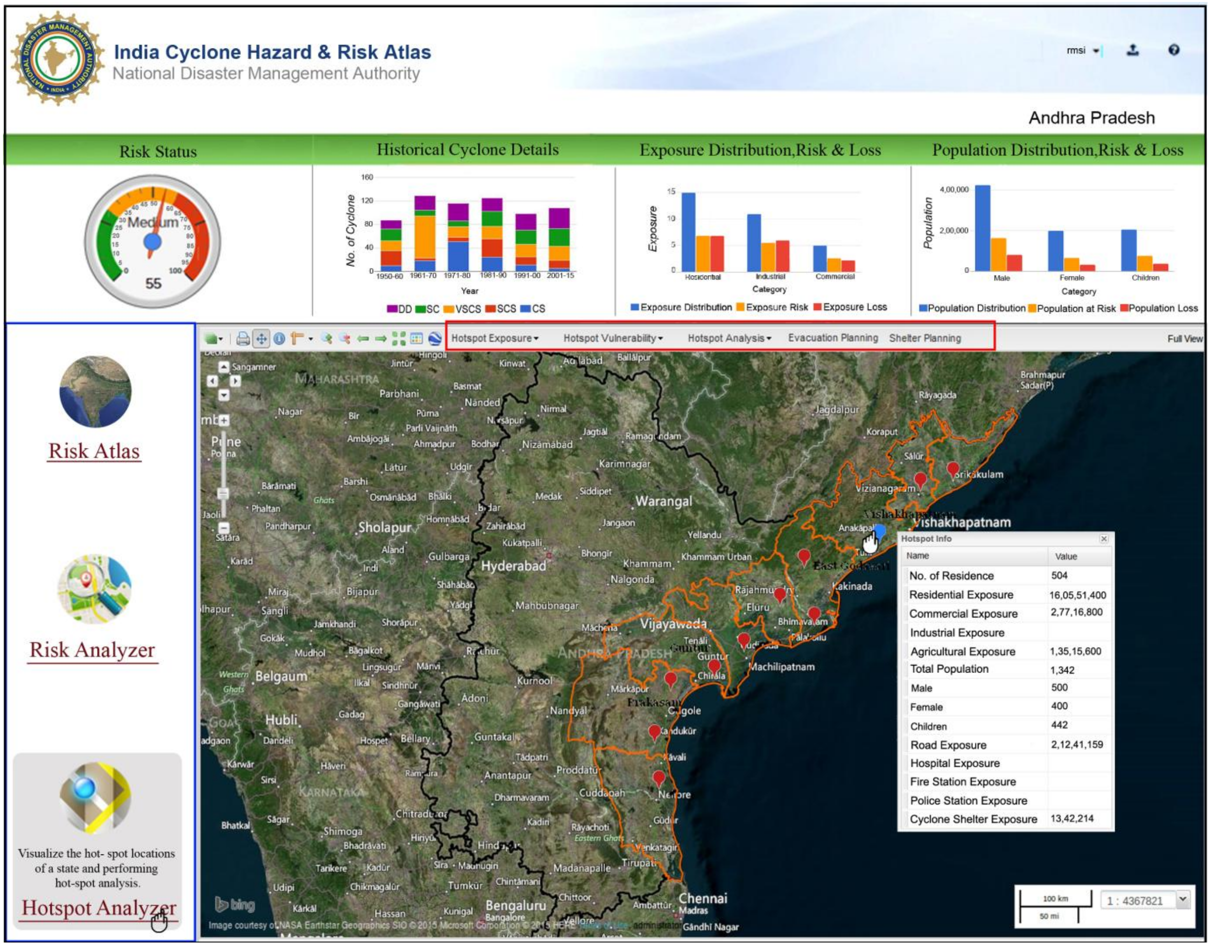

Figure 5-7: Hotspot analyzer

5.3.3 Exposure Data Integration

At present, the application allows users to view exposure data for Andhra Pradesh. The data that has been imported into the application is shown in the table below.

Table 5-2: Table showing import of exposure data

S. No.	Category	Sub category
1.	Admin boundary	Tehsil
		District
		State
2.	Aggregated data	Age details – (year 2011 and year 2014)
		Disabled Population – (year 2011 and year 2014)
		Population – (year 2011 and year 2014)
		Population density
		Acreage

S. No.	Category	Sub category
1.	Admin boundary	Tehsil
		District
		State
3.	Site- specific data	Administrative headquarter
		Bridges
		Cultural heritage
		Cyclone shelters
		Electricity line
		Embankment
		Hospitals
		Mangrove
		Oil and Gas pipelines
		Police stations
		Power plants
		Railway line
		Railway stations
		Religious places
		Roads
		Schools

The imported data can be seen in the form of layers as shown below.

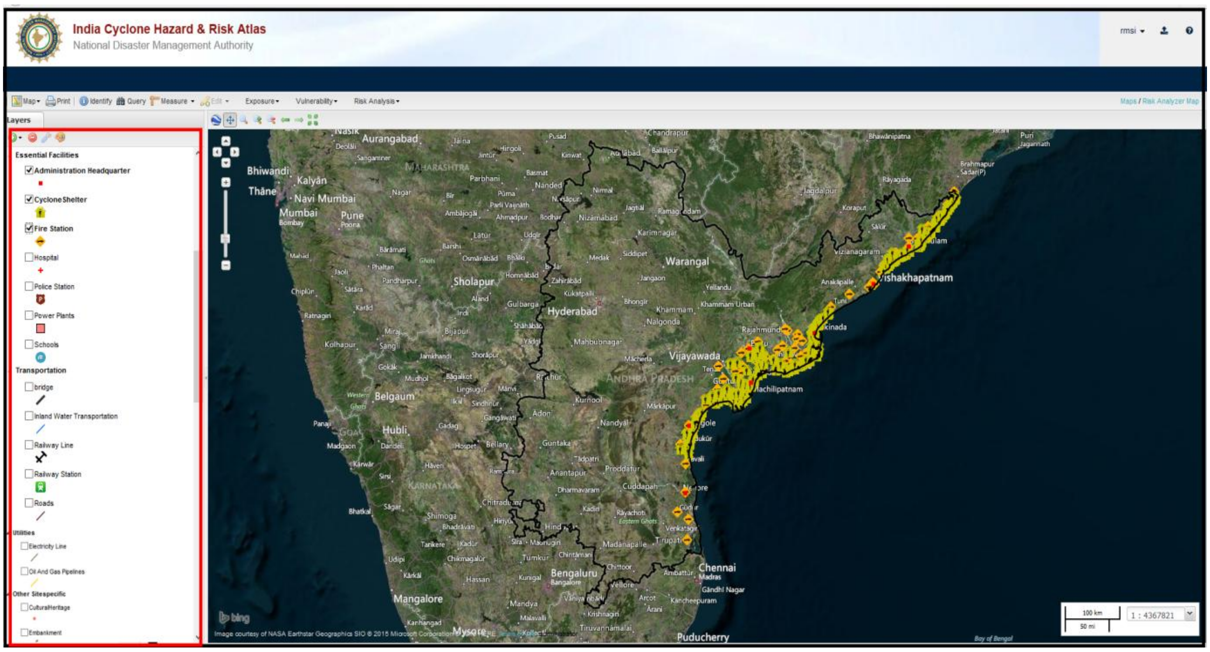

Figure 5-8: Layer view of the imported data

5.3.4 Hazard Data Integration

The integration of hazard data is in progress. The various data and hazard maps that are to be included in the Atlas are summarized in the following table.

Table 5-3: Hazard data details

S. No.	Category	Sub category
	Hazard data	Historical cyclone catalogue
		Soil maps
		Bathymetry data
1.	Historical cyclone event hazard maps	Wind
		Surge
		Flood
2.	Return period scenarios	Wind
		Surge
		Flood

Remarks:

The progress on the Web Risk Atlas corresponding to the tasks that are in progress and the functionalities corresponding to risk assessment will be shared as part of the next status report appended to the next deliverable in the project.

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7 Annexure 1: Study Area Details

Table 7-1: Details of Talukas/Mandals, which are considered for the study

State	District	Subdivision	Talukas/Tehsil	Area (Sq Km)	Remarks
Andaman & Nicobar	South Andaman		Ferargunj	1185	
	South Andaman		Port Blair	480	
	South Andaman		Little Andaman	692	
	North & Middle Nicobar		Rangat	1190	
	North & Middle Nicobar		Mayabundar	757	
	North & Middle Nicobar		Diglipur	1339	
	Nicobar		Carnicobar	129	
	Nicobar		Noncowry	473	
	Nicobar		Campbellbay	1147	
Andhra Pradesh	Vizianagaram	Bhogapuram		111	
	Chittoor	Varadayyapalem		328	Either Discrepancy In Tehsil Boundary Or Shape
	East Godavari	Ainavalli		95	
	East Godavari	Alamurui		77	
	East Godavari	Ambajipeta		70	
	East Godavari	Anaparthi		57	
	East Godavari	Atreyapuram		259	Either Discrepancy In Tehsil Boundary Or Shape
	East Godavari	Allavaram		106	
	East Godavari	Amalapuram		61	
	East Godavari	Bikkavolu		99	
	East Godavari	Gollaprolu		125	
	East Godavari	Ravulapalem		93	
	East Godavari	Rayavaram		75	
	East Godavari	Razole		85	
	East Godavari	Tuni		211	
	East Godavari	Uppalaguptam		117	

State	District	Subdivision	Talukas/Tehsil	Area (Sq Km)	Remarks
	East Godavari	I Polavaram		198	
	East Godavari	Kottapeta		84	
	East Godavari	Katrenikona		166	
	East Godavari	Tallarevu		288	Either Discrepancy In Tehsil Boundary Or Shape
	East Godavari	Kadiam		64	
	East Godavari	Kajuluru		112	
	East Godavari	Kakinada		109	
	East Godavari	Kapileswarapu ram		116	
	East Godavari	Karapa		102	
	East Godavari	Malikipuram		92	
	East Godavari	Kottapalle		105	
	East Godavari	Mamidikuduru		98	
	East Godavari	Pedda Gannavaram		112	
	East Godavari	Mandapeta		107	
	East Godavari	Mummidivara m		97	
	East Godavari	Pamarru		124	
	East Godavari	Peddapudi		103	
	East Godavari	Sakhinetipalle		118	
	East Godavari	Samalkot		143	
	East Godavari	Pithapuram		122	
	East Godavari	Rajahmundry Rural		69	
	East Godavari	Rajahmundry Urban		31	
	East Godavari	Ramachandra puram		105	
	East Godavari	Tondangi		169	
	Guntur	Amrutaluru		122	
	Guntur	Bhattiprolu		94	
	Guntur	Bapatla		261	
	Guntur	Chebrolu		128	
	Guntur	Cherukupalli		95	
	Guntur	Duggirala		143	
	Guntur	Chunduru		103	

State	District	Subdivision	Talukas/Tehsil	Area (Sq Km)	Remarks
	Guntur	Edlapadu		106	
	Guntur	Repalle		262	
	Guntur	Tadepalle		72	
	Guntur	Kakumanu		176	
	Guntur	Karlapalem		103	
	Guntur	Kollipara		109	
	Guntur	Kolluru		116	
	Guntur	Mangalagiri		138	
	Guntur	Nagaram		140	
	Guntur	Nizampatnam		183	
	Guntur	Peda Kakani		95	
	Guntur	Pedda Nandipadu		138	
	Guntur	Ponnuru		169	
	Guntur	Pittalavaripalem		70	
	Guntur	Tenali		18	
	Guntur	Vatticherukuru		114	
	Guntur	Vemuru		100	
	Krishna	Avanigadda		73	Either Discrepancy In Tehsil Boundary Or Shape
	Krishna	Bapulapadu		218	
	Krishna	Bantummilli		124	
	Krishna	Challapalle		91	
	Krishna	Gudivada		106	
	Krishna	Mopidevi		83	Either Discrepancy In Tehsil Boundary Or Shape
	Krishna	Movva		139	
	Krishna	Mudinepalle		172	
	Krishna	Unguturu		145	
	Krishna	Ghantasala		115	
	Krishna	Gudlavalleru		123	
	Krishna	Guduru		125	
	Krishna	Kankipadu		94	
	Krishna	Kaikalur		159	
	Krishna	Kalidindi		174	

State	District	Subdivision	Talukas/Tehsil	Area (Sq Km)	Remarks
	Krishna	Koduru		212	
	Krishna	Kruttivennu		181	
	Krishna	Machilipatnam		398	
	Krishna	Mandavalli		13	
	Krishna	Mandavalli		160	
	Krishna	Nagayalanka		410	Either Discrepancy In Tehsil Boundary Or Shape
	Krishna	Nandivada		150	
	Krishna	Pamarru		119	
	Krishna	Pamidimukkal a		117	
	Krishna	Pedana		138	
	Krishna	Peddaparupud i		8	
	Krishna	Peddaparupud i		89	
	Krishna	Totlavalluru		16	
	Krishna	Totlavalluru		105	
	Krishna	Vuyyuru		84	
	Nellore	Allur		186	
	Nellore	Bogole		180	
	Nellore	Chillakur		331	
	Nellore	Chittamur		264	
	Nellore	Dagadarti		248	
	Nellore	Doravarisatra m		275	
	Nellore	Sullurpeta		263	
	Nellore	Tada		477	
	Nellore	Vakadu		239	
	Nellore	Gudur		246	
	Nellore	Indukurupeta		140	
	Nellore	Jaladanki		302	
	Nellore	Kavali		323	
	Nellore	Kodavalur		109	
	Nellore	Kota		184	
	Nellore	Kovur		86	
	Nellore	Muttukuru		178	

State	District	Subdivision	Talukas/Tehsil	Area (Sq Km)	Remarks
	Nellore	Manubolu		220	
	Nellore	Nellore		350	
	Nellore	Venkatachalam		299	
	Nellore	Totapalligudur		154	
	Nellore	Vidavalur		164	
	Nellore			156	
	Prakasam	Chinna Ganjam		168	
	Prakasam	Chirala		103	
	Prakasam	Ulavapadu		184	
	Prakasam	Gudulur		244	
	Prakasam	Inkollu		142	
	Prakasam	Kottapatnam		163	
	Prakasam	Kandukur		218	
	Prakasam	Karamchedu		159	
	Prakasam	Maddipadu		164	
	Prakasam	Paruchuru		218	
	Prakasam	Nagulaupalapadu		252	
	Prakasam	Ongole		200	
	Prakasam	Singarayakonda		109	
	Prakasam	Zarugumalli		181	
	Prakasam	Tangutur		198	
	Prakasam	Vetapalem		90	
	Srikakulam	Amudalavalasa		102	
	Srikakulam	Echcherla		154	
	Srikakulam	Sompeta		119	Either Discrepancy In Tehsil Boundary Or Shape
	Srikakulam	Vajrapukotturu		131	
	Srikakulam	Srikakulam		153	
	Srikakulam	Gara		158	
	Srikakulam	Ichchapuram		102	
	Srikakulam	Kaviti		111	Either Discrepancy In Tehsil Boundary Or Shape

State	District	Subdivision	Talukas/Tehsil	Area (Sq Km)	Remarks
	Srikakulam	Kanchili		165	Either Discrepancy In Tehsil Boundary Or Shape
	Srikakulam	Kotabommali		146	
	Srikakulam	Kusumala		220	Either Discrepancy In Tehsil Boundary Or Shape
	Srikakulam	Laveru		168	
	Srikakulam	Nandigam		180	
	Srikakulam	Narasannapet a		116	
	Srikakulam	Palasa		146	
	Srikakulam	Tekkal		128	
	Srikakulam	Santbommali		187	
	Srikakulam	Polaki		135	
	Srikakulam	Ranasthal		182	
	Vishakhapatnam	Achchutapura m		137	
	Vishakhapatnam	Bhimunipatna m		127	
	Vishakhapatnam	Elamanchili		120	
	Vishakhapatnam	Gajuvaka		108	
	Vishakhapatnam	Munagapaka		78	
	Vishakhapatnam	Nakkapalli		221	
	Vishakhapatnam	Paravada		142	
	Vishakhapatnam	Payakaraopet a		108	
	Vishakhapatnam	Pedda Gantyada		77	
	Vishakhapatnam	Pendurti		108	
	Vishakhapatnam	Rambilli		147	
	Vishakhapatnam	Sarvasiddhi Rayavaram		162	
	Vishakhapatnam	Visakhapatna m Rural		128	Either Discrepancy In Tehsil Boundary Or Shape
	Vishakhapatnam	Visakhapatna m Urban		95	Either Discrepancy In Tehsil Boundary Or Shape
	Vizianagaram	Denkada		123	
	Vizianagaram	Pusapatirega		161	

State	District	Subdivision	Talukas/Tehsil	Area (Sq Km)	Remarks
	West Godavari	Achanta		66	
	West Godavari	Attili		83	
	West Godavari	Akividu		108	
	West Godavari	Bhimadolu		210	
	West Godavari	Bhimavaram		183	
	West Godavari	Denduluru		181	
	West Godavari	Elamanchili		80	
	West Godavari	Undi		127	
	West Godavari	Ganapavaram		4	
	West Godavari	Ganapavaram		98	
	West Godavari	Mogalturru		136	
	West Godavari	Eluru		229	
	West Godavari	Iragavaram		78	
	West Godavari	Unguturu		197	
	West Godavari	Kalla		7	
	West Godavari	Kalla		154	
	West Godavari	Kovvuru		96	
	West Godavari	Kovvuru		3	
	West Godavari	Nidamarru		9	
	West Godavari	Narasapur		154	
	West Godavari	Nidamarru		113	
	West Godavari	Palakoderu		86	
	West Godavari	Palakollu		84	
	West Godavari	Peddapadu		167	
	West Godavari	Pentapadu		111	
	West Godavari	Penumantra		80	
	West Godavari	Penugonda		66	
	West Godavari	Peravalli		77	
	West Godavari	Poduru		89	
	West Godavari	Tanuku		75	
	West Godavari	Viravasaram		4	
	West Godavari	Viravasaram		95	
Daman & Diu	Diu	Diu		25	
Goa	South Goa	Mormugao		104	
	South Goa	Mormugao		104	

State	District	Subdivision	Talukas/Tehsil	Area (Sq Km)	Remarks
	North Goa	Ponda		259	
	North Goa	Dicholi		240	
	North Goa	Pernem		239	
	South Goa	Sasashti		290	
	South Goa	Kankon		353	
	South Goa	Quepem		317	
	North Goa	Tiswadi		201	
	North Goa	Bardez		254	
Gujarat	Ahmadabad		Barwala	479	
	Ahmadabad		Bavla	767	
	Ahmadabad		Dhandhuka	1775	
	Ahmadabad		Dholka	924	
	Ahmadabad		Sanand	770	
	Ahmadabad		Viramgam	790	
	Amreli		Rajula	633	
	Amreli		Jafrabad	1	
	Amreli		Khambha	581	
	Anand		Anklav	176	
	Anand		Borsad	405	
	Anand		Khambhat	1068	
	Anand		Tarapur	322	
	Banaskantha		Vav	1694	
	Bharuch		Amod	430	
	Bharuch		Anklesvar	436	
	Bharuch		Bharuch	607	
	Bharuch		Hansot	534	
	Bharuch		Jambusar	1382	
	Bharuch		Jhagadia	775	
	Bharuch		Vagra	1574	
	Bhavnagar		Ghogha Mahal	654	
	Bhavnagar		Umrala	400	
	Bhavnagar		Sihor	692	
	Bhavnagar		Talaja	911	
	Bhavnagar		Valabhipur Mahal	588	
	Bhavnagar		Mahuva	1236	

State	District	Subdivision	Talukas/Tehsil	Area (Sq Km)	Remarks
	Jamnagar		Jamnagar	3025	Either Discrepancy In Tehsil Boundary Or Shape
	Jamnagar		Kalyanpur	1415	
	Jamnagar		Khambhaliya	1263	
	Jamnagar		Lalpur	1073	
	Jamnagar		Okha Mandal	653	
	Junagarh		Malia	506	
	Junagarh		Keshod	545	
	Junagarh		Kodinar	517	
	Junagarh		Manavadar	574	
	Junagarh		Sutrapada	315	
	Junagarh		Una	1511	
	Junagarh		Veraval	352	
	Junagarh		Mangrol	570	
	Kachchh		Abdasa	2162	
	Kachchh		Anjar	1149	
	Kachchh		Bhachau	1756	
	Kachchh		Bhuj	5227	
	Kachchh		Gandhidham	191	
	Kachchh		Lakhpat	1924	
	Kachchh		Rapar	2841	
	Kachchh		Mundra	855	
	Kachchh		Nakhatrana	1878	
	Kachchh		Mandvi	1384	
	Kachchh			20695	
	Khera		Matar	371	
	Navsari		Gandevi	282	
	Navsari		Jalalpore	475	
	Navsari		Navsari	242	
	Patan		Radhanpur	578	
	Patan		Sami	1529	
	Patan		Santalpur	1274	
	Porbandar		Kutiyana	564	
	Porbandar		Porbandar	1101	
	Porbandar		Ranavav	562	

State	District	Subdivision	Talukas/Tehsil	Area (Sq Km)	Remarks
	Rajkot		Maliya	728	
	Surat		Chorasi	444	
	Surat		Palsana	192	
	Surat		Olpas	661	
	Surat		Suratcity	150	
	Surendranagar		Dhrangadhra	1326	
	Surendranagar		Dasada	1495	
	Surendranagar		Halvad	1206	
	Surendranagar		Lakhtar	729	
	Surendranagar		Limbdi	1124	
	Vadodara		Padra	515	
	Valsad		Pardi	414	
	Valsad		Umargam	346	
	Valsad		Valsad	495	
Karnataka	Uttar Kannada		Ankola	917	
	Udupi		Udupi	933	
	Uttar Kannada		Bhatkal	347	
	Dakshin Khand		Buntwal	759	
	Uttar Kannada		Karwar	733	
	Uttar Kannada		Honavar	745	
	Uttar Kannada		Kumta	581	
	Udupi		Kundapura	1556	
	Dakshin Khand		Mangalore	861	
	Alappuzha		Ambalappuzha	184	
	Alappuzha		Chengannur	149	
	Alappuzha		Chertala	332	
	Alappuzha		Kartikappalli	235	
	Alappuzha		Kuttanad	313	
	Alappuzha		Mavelikkara	236	
	Ernakulam		Aluva	550	
	Ernakulam		Kochchi	139	
	Ernakulam		Kanayannur	321	
	Ernakulam		Kunnattunad	477	
	Ernakulam		Muvattupuzha	449	
	Ernakulam		Paravur	194	
	Kannur		Kannur	352	Either Discrepancy

State	District	Subdivision	Talukas/Tehsil	Area (Sq Km)	Remarks
					In Tehsil Boundary Or Shape
	Kannur		Talasseri	1214	Either Discrepancy In Tehsil Boundary Or Shape
	Kannur		Talipparamba	1399	
	Kasargod		Kasargod	995	
	Kasargod		Hosdurg	984	
	Kollam		Kottarakkara	370	
	Kollam		Pathanapuram	1472	Either Discrepancy In Tehsil Boundary Or Shape
	Kollam		Karunagappally	178	
	Kollam		Kollam	389	
	Kollam		Kunnattur	144	
	Kottayam		Kottayam	515	
	Kottayam		Minachil	693	
	Kottayam		Vaikom	323	
	Kottyam		Changanasseri	268	
	Kozikode		Vadakara	579	
	Kozikode		Koilandi	742	
	Kozikode		Kozhikkod	1032	
	Malappuram		Eranad	816	
	Malappuram		Ponnani	203	
	Malappuram		Tirur	417	
	Malappuram		Tirurangadi	259	
	Palakkad		Ottappalam	854	
	Pathanamthitta		Adoor	336	
	Pathanamthitta		Kozhenchery	922	
	Pathanamthitta		Mallappally	161	
	Pathanamthitta		Thiruvalla	168	
	Thiruvananthpuram		Neyyattinkara	584	
	Thiruvananthpuram		Chirayinkeezhu	383	
	Thiruvananthpuram		Thiruvananthapuram	315	
	Thrissur		Chavakkad	246	
	Thrissur		Kodungallur	149	

State	District	Subdivision	Talukas/Tehsil	Area (Sq Km)	Remarks
	Thrissur		Mukundapuram	1323	
	Thrissur		Talappilly	689	
Lakshadweep	Kavaratti			5	
	Kavaratti			0	
	Kavaratti			2	
	Lakshadweep			30	
Maharashtra	Greater Mumbai			62	
	Raigarh	Alibag		485	
	Raigarh	Mhasla		1106	
	Raigarh	Mangaon		906	
	Raigarh	Murud		237	
	Raigarh	Panvel		586	
	Raigarh	Pen		486	
	Raigarh	Roha		620	
	Raigarh	Srivardhan		233	
	Raigarh	Uran		293	
	Raigarh			5	
	Ratnagiri	Chiplun		1089	
	Ratnagiri	Dapoli		854	
	Ratnagiri			8	
	Ratnagiri	Guhagar		623	
	Ratnagiri	Khed		1011	
	Ratnagiri	Mandangarh		419	
	Ratnagiri	Lanja		739	
	Ratnagiri	Rajapur		1181	
	Ratnagiri	Ratnagiri		922	
	Ratnagiri	Sangameshwar		1238	
	Ratnagiri			0	
	Sindhudurg	Devgarh		766	
	Sindhudurg	Kudal		890	
	Sindhudurg	Malvan		612	
	Sindhudurg	Savantwadi		1336	Either Discrepancy In Tehsil Boundary Or Shape
	Sindhudurg	Vengurla		208	
	Suburban			420	

State	District	Subdivision	Talukas/Tehsil	Area (Sq Km)	Remarks
	Mumbai				
	Thane	Bhiwandi		672	
	Thane	Dahanu		982	
	Thane	Kalyan		301	
	Thane	Thane		385	
	Thane	Palghar		1064	
	Thane	Talsari		257	
	Thane	Vasai		523	
Odisha	Baleswar		Basta	351	Either Discrepancy In Tehsil Boundary Or Shape
	Baleswar		Baleshwar	603	Either Discrepancy In Tehsil Boundary Or Shape
	Baleswar		Jaleswar	705	Either Discrepancy In Tehsil Boundary Or Shape
	Baleswar		Baliapal	320	Either Discrepancy In Tehsil Boundary Or Shape
	Baleswar		Soro	750	Either Discrepancy In Tehsil Boundary Or Shape
	Baleswar		Similia	277	
	Bhadrak	Bhadrak	Chandabali	2429	Either Discrepancy In Tehsil Boundary Or Shape
	Cuttack	Cuttack	Cuttack	1732	Either Discrepancy In Tehsil Boundary Or Shape
	Ganjam		Khallikote	613	Either Discrepancy In Tehsil Boundary Or Shape
	Ganjam		Purusottampur	364	Either Discrepancy In Tehsil Boundary Or Shape
	Ganjam		Patrapur	492	Either Discrepancy In Tehsil Boundary Or Shape
	Ganjam		Berhampur	327	Either Discrepancy In Tehsil Boundary Or Shape
	Ganjam		Chatrapur	303	
	Ganjam		Kanishi	288	Either Discrepancy

State	District	Subdivision	Talukas/Tehsil	Area (Sq Km)	Remarks
					In Tehsil Boundary Or Shape
	Jagatsinghpur	Jagatsinghpur	Jagatsinghpur	1673	Either Discrepancy In Tehsil Boundary Or Shape
	Jajpur	Jajpur	Jajpur	2793	Either Discrepancy In Tehsil Boundary Or Shape
	Kendrapara	Kendraparha	Kendraparha	2472	Either Discrepancy In Tehsil Boundary Or Shape
	Khordha	Khordha	Khordha	1862	Either Discrepancy In Tehsil Boundary Or Shape
	Khordha	Bhubaneswar	Bhubaneswar	929	Either Discrepancy In Tehsil Boundary Or Shape
	Mayurbhanj	Baripada	Baripada	3999	Either Discrepancy In Tehsil Boundary Or Shape
	Puri	Puri	Krushnaprasad	3379	Either Discrepancy In Tehsil Boundary Or Shape
Pondicherry	Puducherry			35	Either Discrepancy In Tehsil Boundary Or Shape
	Puducherry			67	Either Discrepancy In Tehsil Boundary Or Shape
	Puducherry			66	Either Discrepancy In Tehsil Boundary Or Shape
	Puducherry			20	Either Discrepancy In Tehsil Boundary Or Shape
	Puducherry			25	Either Discrepancy In Tehsil Boundary Or Shape
	Puducherry			55	Either Discrepancy In Tehsil Boundary Or Shape
	Puducherry			30	Either Discrepancy In Tehsil Boundary Or Shape
	Karaikal			24	Either Discrepancy In Tehsil Boundary Or Shape

State	District	Subdivision	Talukas/Tehsil	Area (Sq Km)	Remarks
	Karaikal			26	Either Discrepancy In Tehsil Boundary Or Shape
	Karaikal			43	Either Discrepancy In Tehsil Boundary Or Shape
	Karaikal			27	Either Discrepancy In Tehsil Boundary Or Shape
	Karaikal			21	Either Discrepancy In Tehsil Boundary Or Shape
	Karaikal			22	Either Discrepancy In Tehsil Boundary Or Shape
Tamil Nadu	Chennai		Mylapore Tiruvallikkeni	33	
	Chennai		Fort Tondiarpet	26	
	Chennai		Mambalam Guindy	42	
	Chennai		Perambur Purasavakkam	33	
	Chennai		Egmore Nungambakkam	31	
	Cuddalore		Chidambaram	603	
	Cuddalore		Cuddalore	532	
	Cuddalore		Kattumannarkoil	458	
	Kanchipuram		Tambaram	237	
	Kanchipuram		Chengalpattu	781	
	Kanchipuram		Cheyyur	612	
	Kanchipuram		Tirukkalukkunra m	360	
	Kanyakumari		Agasthiswaram	287	
	Kanyakumari		Kalkulam	654	
	Kanyakumari		Vilavancode	408	
	Nagapattinam		Nagapattinam	313	
	Nagapattinam		Kilvelur	283	
	Nagapattinam		Vedaranyam	675	
	Nagapattinam		Mayiladuturai	422	
	Nagapattinam		Sirkazhi	464	
	Nagapattinam		Tarangambadi	294	

State	District	Subdivision	Talukas/Tehsil	Area (Sq Km)	Remarks
	Nagapattinam		Thirukkuvalai	146	
	Pudukkottai		Arantangi	492	
	Pudukkottai		Avadiyarkovil	426	
	Pudukkottai		Manamelkudi	218	
	Ramanathapuram		Kadaladi	630	
	Ramanathapuram		Paramakkudi	768	
	Ramanathapuram		Ramanathapuram	885	
	Ramanathapuram		Tiruvadanai	980	
	Thanjavur		Pattukkottai	731	
	Thanjavur		Peravurani	289	
	Thiruvarur		Mannar Gudi	537	
	Thiruvarur		Nidamangalam	249	
	Thiruvarur		Nannilam	238	
	Thiruvarur		Thiruvarur	149	
	Thiruvarur		Kudavasal	325	
	Thiruvarur		Tirutturaipundi	439	
	Tirunelveli		Radhapuram	901	
	Tiruvallur		Ambattur	289	
	Tiruvallur		Ponneri	696	
	Tiruvallur		Gummidipundi	423	
	Tuticorin		Ottapidaram	770	
	Tuticorin		Sattankulam	378	
	Tuticorin		Srivaikuntam	618	
	Tuticorin		Tuticorin	372	
	Tuticorin		Vilattikulam	889	
	Tuticorin		Tiruchendur	493	
	Villupuram		Tindivanam	999	
	Villupuram		Vanur	468	Either Discrepancy In Tehsil Boundary Or Shape
	Villupuram		Villupuram	898	Either Discrepancy In Tehsil Boundary Or Shape
West Bengal	Bardaman		Kalna - Ii	168	
	Delta		Delta	1	

State	District	Subdivision	Talukas/Tehsil	Area (Sq Km)	Remarks
	Eastmednipur		Egra	920	Either Discrepancy In Tehsil Boundary Or Shape
	Eastmednipur		Kanthi	1195	Either Discrepancy In Tehsil Boundary Or Shape
	Eastmednipur		Haldia	648	Either Discrepancy In Tehsil Boundary Or Shape
	Eastmednipur		Tamluk	1052	Either Discrepancy In Tehsil Boundary Or Shape
	Haora		Shyampur 1	119	
	Haora		Udaynarayanpur	107	
	Haora		Domjur	93	
	Haora		Uluberia 2	101	
	Haora		Bally Jagachha	86	
	Haora		Uluberia 1	96	
	Haora		Sankrail	61	
	Haora		Panchla	68	
	Haora		Bagnan 1	74	
	Haora		Amta 1	116	
	Haora		Jagat Ballavpur	124	
	Haora		Bagnan 2	74	
	Haora		Shyampur 2	92	
	Haora		Amta 2	132	
	Hugli		Haripal	177	
	Hugli		Pursura	98	
	Hugli		Arambag	298	
	Hugli		Singur	193	
	Hugli		Jangipara	157	
	Hugli		Tarakeswar	115	
	Hugli		Chanditala I	90	
	Hugli		Goghat I	177	
	Hugli		Khanakul I	167	
	Hugli		Khanakul Ii	119	
	Hugli		Chanditala Ii	66	
	Hugli		Chinsurah Magra	91	
	Hugli		Balagarh	190	

State	District	Subdivision	Talukas/Tehsil	Area (Sq Km)	Remarks
	Hugli		Dhaniakhali	265	
	Hugli		Pandua	271	
	Hugli		Polba Dadpur	277	
	Hugli		Serampur Uttarpara	83	
	Nadia			151	
	Nadia			0	
	Nadia			3	
	Nadia			275	
	Nadia			340	
	Nadia			315	
	Nadia			0	
	Nadia			2	
	Nadia			1	
	Nadia			2	
	Nadia			2	
	Nadia			0	
	North Pragana		Swarupnagar	201	
	North Pragana		Baduria	205	
	North Pragana		Haora	155	
	North Pragana		Deganga	209	
	North Pragana		Barrackpur -I	168	
	North Pragana		Sandeshkhali -Ii	187	
	North Pragana		Hingalganj	269	
	North Pragana		Bongaon	338	
	North Pragana		Gaighata	240	
	North Pragana		Rajarhat	143	
	North Pragana		Sandeshkhali -I	178	
	North Pragana		Minakhan	149	
	North Pragana		Barasat- Ii	117	
	North Pragana		Basirhat -I	120	
	North Pragana		Hasnabad	157	
	North Pragana		Barasat- I	146	
	North Pragana		Amdanga	130	
	North Pragana		Basirhat -Ii	132	
	North Pragana		Barrackpur -Ii	158	

State	District	Subdivision	Talukas/Tehsil	Area (Sq Km)	Remarks
	North Pragana		Habra -Ii	128	
	North Pragana		Habra -I	126	
	North Pragana		Bagda	221	
	Pashchim Medinipur		Mohanpur	128	
	Pashchim Medinipur		Pingla	234	
	Pashchim Medinipur		Dantan -I	247	
	Pashchim Medinipur		Dantan -Ii	170	
	Pashchim Medinipur		Narayangarh	498	
	Pashchim Medinipur		Sabang	284	
	Pashchim Medinipur		Debra	353	
	Pashchim Medinipur		Keshpur	476	
	Pashchim Medinipur		Daspur -I	164	
	Pashchim Medinipur		Daspur -Ii	155	
	Pashchim Medinipur		Chandrakona -I	214	
	Pashchim Medinipur		Ghatal	226	
	Pashchim Medinipur		Chandrakona -Ii	180	
	South 24 Parganas		Gosaba	481	
	South 24 Parganas		Magrahat -Ii	106	
	South 24 Parganas		Diamond Harbour -I	88	
	South 24 Parganas		Canning -Ii	264	
	South 24 Parganas		Budge Budge -I	40	
	South 24 Parganas		Namkhana	221	
	South 24 Parganas		Sagar	279	

State	District	Subdivision	Talukas/Tehsil	Area (Sq Km)	Remarks
	South 24 Parganas		Mathurapur	138	
	South 24 Parganas		Mathurapur -Ii	226	
	South 24 Parganas		Kulpi	227	
	South 24 Parganas		Kakdwip	246	
	South 24 Parganas		Jaynagar -I	154	
	South 24 Parganas		Canning -I	195	
	South 24 Parganas		Patharpratima	548	
	South 24 Parganas		Gosaba	320	
	South 24 Parganas		Magrahat -I	96	
	South 24 Parganas		Mandirbazar	124	
	South 24 Parganas		Falta	140	
	South 24 Parganas		Budge Budge -Ii	98	
	South 24 Parganas		Baruipur	162	
	South 24 Parganas		Diamond Harbour -Ii	102	
	South 24 Parganas		Jaynagar -Ii	123	
	South 24 Parganas		Bishnupur -I	92	
	South 24 Parganas		Sonarpur	195	
	South 24 Parganas		Bhangar -I	176	
	South 24 Parganas		Bhangar -Ii	166	
	South 24 Parganas		Kultali	335	
	South 24 Parganas		Bishnupur -Ii	81	
	South 24 Parganas		Thakurpukur Mahestola	120	

State	District	Subdivision	Talukas/Tehsil	Area (Sq Km)	Remarks
	South 24 Parganas			95	
	South 24 Parganas	Sagar		7	
	South 24 Parganas	Lakshmikantpur		8	
	South 24 Parganas	Lakshmikantpur		30	
	South 24 Parganas	Lakshmikantpur		44	
	South 24 Parganas	Lakshmikantpur		40	
	South 24 Parganas	Lakshmikantpur		61	
	South 24 Parganas	Lakshmikantpur		3	
	South 24 Parganas	Lakshmikantpur		18	
	South 24 Parganas	Lakshmikantpur		20	
	South 24 Parganas	Lakshmikantpur		15	
	South 24 Parganas	Lakshmikantpur		11	
	South 24 Parganas	Lakshmikantpur		62	
	South 24 Parganas	Lakshmikantpur		65	
	South 24 Parganas	Lakshmikantpur		18	
	South 24 Parganas	Lakshmikantpur		92	
	South 24 Parganas	Lakshmikantpur		18	
	South 24 Parganas	Lakshmikantpur		111	
	South 24 Parganas	Lakshmikantpur		16	
	South 24 Parganas	Lakshmikantpur		45	
	South 24 Parganas	Lakshmikantpur		38	
	South 24 Parganas	Lakshmikantpur		225	

State	District	Subdivision	Talukas/Tehsil	Area (Sq Km)	Remarks
	South 24 Parganas	Lakshmikantpur		63	
	South 24 Parganas	Lakshmikantpur		15	
	South 24 Parganas	Lakshmikantpur		35	
	South 24 Parganas	Lakshmikantpur		144	
	South 24 Parganas	Lakshmikantpur		26	
	South 24 Parganas	Lakshmikantpur		33	
	South 24 Parganas	Lakshmikantpur		642	
	South 24 Parganas	Lakshmikantpur		14	
	South 24 Parganas	Lakshmikantpur		52	

8 Annexure 2: Cyclone and Storm Surge Hazard

Table 8-1: List of cyclonic events during (1877-2014) used for Odisha

Sl. No.	Day	Month	Year	Maximum wind speed in km/h	Cyclone category
1	18	7	1882	83	Cyclonic Storm
2	11	7	1882	83	Cyclonic Storm
3	6	9	1882	83	Cyclonic Storm
4	26	9	1882	83	Cyclonic Storm
5	12	10	1882	83	Cyclonic Storm
6	26	6	1883	83	Cyclonic Storm
7	12	7	1883	83	Cyclonic Storm
8	9	7	1884	83	Cyclonic Storm
9	24	10	1884	83	Cyclonic Storm
10	16	6	1885	83	Cyclonic Storm
11	19	9	1885	83	Cyclonic Storm
12	15	6	1886	83	Cyclonic Storm
13	12	8	1886	83	Cyclonic Storm
16	17	7	1887	63	Cyclonic Storm
15	11	6	1887	83	Cyclonic Storm
14	21	5	1887	118	Very Severe Cyclonic Storm
17	21	9	1887	118	Very Severe Cyclonic Storm
18	12	7	1888	83	Cyclonic Storm
19	19	7	1888	83	Cyclonic Storm
20	21	8	1888	83	Cyclonic Storm
22	1	10	1888	83	Cyclonic Storm
21	13	9	1888	118	Very Severe Cyclonic Storm
23	8	6	1889	83	Cyclonic Storm
24	19	7	1889	83	Cyclonic Storm
26	17	9	1889	83	Cyclonic Storm
27	25	10	1889	83	Cyclonic Storm
28	18	11	1889	83	Cyclonic Storm
25	16	8	1889	118	Very Severe Cyclonic Storm
29	23	9	1890	83	Cyclonic Storm
30	20	9	1891	83	Cyclonic Storm
31	1	11	1891	118	Very Severe Cyclonic Storm
33	9	7	1892	83	Cyclonic Storm
34	7	9	1892	83	Cyclonic Storm

Sl. No.	Day	Month	Year	Maximum wind speed in km/h	Cyclone category
32	8	6	1892	118	Very Severe Cyclonic Storm
36	21	9	1893	83	Cyclonic Storm
37	1	9	1893	83	Cyclonic Storm
38	9	9	1893	83	Cyclonic Storm
35	23	5	1893	118	Very Severe Cyclonic Storm
39	21	6	1894	83	Cyclonic Storm
40	11	7	1894	83	Cyclonic Storm
41	16	7	1894	83	Cyclonic Storm
42	30	9	1895	118	Very Severe Cyclonic Storm
44	18	6	1896	83	Cyclonic Storm
45	22	7	1896	83	Cyclonic Storm
47	1	8	1896	83	Cyclonic Storm
48	13	9	1896	83	Cyclonic Storm
43	26	6	1896	118	Very Severe Cyclonic Storm
46	26	7	1896	118	Very Severe Cyclonic Storm
49	13	8	1897	83	Cyclonic Storm
50	2	10	1897	83	Cyclonic Storm
51	13	6	1898	83	Cyclonic Storm
52	9	8	1898	83	Cyclonic Storm
53	11	9	1898	83	Cyclonic Storm
54	8	8	1899	83	Cyclonic Storm
55	12	10	1899	83	Cyclonic Storm
56	11	6	1900	83	Cyclonic Storm
57	29	7	1900	83	Cyclonic Storm
58	15	8	1900	118	Very Severe Cyclonic Storm
59	24	11	1901	118	Very Severe Cyclonic Storm
60	15	7	1902	63	Cyclonic Storm
62	5	10	1903	63	Cyclonic Storm
61	12	7	1903	83	Cyclonic Storm
63	12	8	1904	83	Cyclonic Storm
64	30	6	1905	83	Cyclonic Storm
65	5	7	1905	83	Cyclonic Storm
66	18	6	1906	63	Cyclonic Storm
67	25	7	1906	83	Cyclonic Storm
68	21	7	1906	83	Cyclonic Storm
69	13	6	1907	83	Cyclonic Storm
70	23	6	1907	83	Cyclonic Storm

Sl. No.	Day	Month	Year	Maximum wind speed in km/h	Cyclone category
71	16	6	1908	83	Cyclonic Storm
72	28	8	1908	83	Cyclonic Storm
73	24	10	1909	118	Very Severe Cyclonic Storm
74	15	10	1909	118	Very Severe Cyclonic Storm
76	1	8	1910	83	Cyclonic Storm
75	1	7	1910	118	Very Severe Cyclonic Storm
77	9	6	1911	83	Cyclonic Storm
78	27	7	1912	83	Cyclonic Storm
79	1	8	1912	83	Cyclonic Storm
80	28	10	1912	118	Very Severe Cyclonic Storm
83	16	7	1913	63	Cyclonic Storm
85	13	10	1913	63	Cyclonic Storm
84	30	8	1913	83	Cyclonic Storm
81	30	7	1913	118	Very Severe Cyclonic Storm
82	23	7	1913	118	Very Severe Cyclonic Storm
87	24	6	1914	63	Cyclonic Storm
86	13	5	1914	118	Very Severe Cyclonic Storm
88	1	8	1915	118	Very Severe Cyclonic Storm
89	4	6	1916	83	Cyclonic Storm
91	7	11	1916	83	Cyclonic Storm
90	19	9	1916	118	Very Severe Cyclonic Storm
92	1	5	1917	118	Very Severe Cyclonic Storm
93	28	7	1919	83	Cyclonic Storm
94	23	9	1919	118	Very Severe Cyclonic Storm
95	24	7	1921	83	Cyclonic Storm
96	3	8	1924	83	Cyclonic Storm
97	26	6	1925	83	Cyclonic Storm
98	13	8	1926	83	Cyclonic Storm
99	14	9	1926	83	Cyclonic Storm
101	16	6	1927	83	Cyclonic Storm
102	27	7	1927	83	Cyclonic Storm
100	31	5	1927	118	Very Severe Cyclonic Storm
104	17	7	1928	63	Cyclonic Storm
103	23	7	1928	83	Cyclonic Storm
105	1	10	1928	83	Cyclonic Storm
107	23	8	1929	63	Cyclonic Storm
106	15	7	1929	83	Cyclonic Storm

Sl. No.	Day	Month	Year	Maximum wind speed in km/h	Cyclone category
108	28	6	1930	83	Cyclonic Storm
109	19	8	1931	83	Cyclonic Storm
110	11	10	1931	83	Cyclonic Storm
112	18	9	1932	63	Cyclonic Storm
113	19	10	1932	83	Cyclonic Storm
111	23	5	1932	118	Very Severe Cyclonic Storm
114	14	6	1933	83	Cyclonic Storm
115	2	8	1933	83	Cyclonic Storm
116	17	9	1933	83	Cyclonic Storm
117	17	9	1934	63	Cyclonic Storm
118	8	7	1935	63	Cyclonic Storm
120	11	6	1936	63	Cyclonic Storm
119	23	5	1936	118	Very Severe Cyclonic Storm
121	29	9	1936	118	Very Severe Cyclonic Storm
122	22	7	1937	63	Cyclonic Storm
124	11	10	1937	83	Cyclonic Storm
123	26	9	1937	118	Very Severe Cyclonic Storm
125	6	10	1938	118	Very Severe Cyclonic Storm
126	28	8	1939	83	Cyclonic Storm
128	20	10	1940	83	Cyclonic Storm
127	30	6	1940	118	Very Severe Cyclonic Storm
130	8	8	1941	63	Cyclonic Storm
131	15	8	1941	83	Cyclonic Storm
129	6	7	1941	118	Very Severe Cyclonic Storm
132	2	7	1942	83	Cyclonic Storm
133	14	10	1942	118	Very Severe Cyclonic Storm
134	24	7	1943	63	Cyclonic Storm
135	22	9	1943	83	Cyclonic Storm
137	28	7	1944	63	Cyclonic Storm
136	23	7	1944	83	Cyclonic Storm
138	18	8	1944	83	Cyclonic Storm
139	6	7	1945	65	Cyclonic Storm
140	23	6	1947	65	Cyclonic Storm
141	11	8	1948	65	Cyclonic Storm
142	8	6	1950	65	Cyclonic Storm
143	11	9	1950	65	Cyclonic Storm
144	23	7	1951	65	Cyclonic Storm

Sl. No.	Day	Month	Year	Maximum wind speed in km/h	Cyclone category
145	3	7	1952	65	Cyclonic Storm
146	31	7	1953	65	Cyclonic Storm
147	1	9	1955	65	Cyclonic Storm
148	29	9	1955	65	Cyclonic Storm
149	28	5	1956	120	Very Severe Cyclonic Storm
150	18	8	1957	65	Cyclonic Storm
151	27	6	1959	65	Cyclonic Storm
152	9	7	1959	65	Cyclonic Storm
153	26	9	1959	120	Very Severe Cyclonic Storm
154	26	5	1960	65	Cyclonic Storm
155	10	9	1961	65	Cyclonic Storm
156	19	9	1962	65	Cyclonic Storm
158	23	8	1965	65	Cyclonic Storm
157	9	5	1965	120	Very Severe Cyclonic Storm
159	27	9	1966	120	Very Severe Cyclonic Storm
160	17	11	1966	120	Very Severe Cyclonic Storm
161	7	10	1967	120	Very Severe Cyclonic Storm
163	9	9	1968	65	Cyclonic Storm
162	28	9	1968	120	Very Severe Cyclonic Storm
164	8	11	1968	120	Very Severe Cyclonic Storm
165	8	10	1969	65	Cyclonic Storm
166	6	6	1970	65	Cyclonic Storm
167	17	10	1970	120	Very Severe Cyclonic Storm
168	7	11	1970	120	Very Severe Cyclonic Storm
169	3	6	1971	65	Cyclonic Storm
170	27	9	1971	120	Very Severe Cyclonic Storm
171	26	10	1971	120	Very Severe Cyclonic Storm
172	13	7	1972	65	Cyclonic Storm
174	20	9	1972	130	Very Severe Cyclonic Storm
173	7	9	1972	148	Very Severe Cyclonic Storm
175	19	7	1973	65	Cyclonic Storm
176	6	10	1973	74	Cyclonic Storm
177	3	11	1973	111	Severe Cyclonic Storm
178	5	12	1973	111	Severe Cyclonic Storm
180	26	9	1974	65	Cyclonic Storm
179	13	8	1974	120	Very Severe Cyclonic Storm
181	8	9	1976	74	Cyclonic Storm

Sl. No.	Day	Month	Year	Maximum wind speed in km/h	Cyclone category
182	6	8	1979	120	Very Severe Cyclonic Storm
183	5	12	1981	139	Very Severe Cyclonic Storm
184	30	5	1982	102	Severe Cyclonic Storm
185	10	10	1984	83	Cyclonic Storm
186	15	10	1985	93	Severe Cyclonic Storm
187	9	11	1986	93	Severe Cyclonic Storm
188	17	10	1988	65	Cyclonic Storm
189	21	11	1988	204	Very Severe Cyclonic Storm (H)
190	23	5	1989	102	Severe Cyclonic Storm
191	7	11	1995	143	Very Severe Cyclonic Storm
192	19	11	1998	120	Very Severe Cyclonic Storm
193	15	10	1999	167	Very Severe Cyclonic Storm
194	25	10	1999	259	Super Cyclonic Storm
195	25	10	2000	65	Cyclonic Storm
196	10	11	2002	102	Severe Cyclonic Storm
197	17	9	2005	65	Cyclonic Storm
198	11	11	2007	213	Very Severe Cyclonic Storm (H)
199	25	10	2008	83	Cyclonic Storm
200	23	5	2009	111	Severe Cyclonic Storm
201	16	6	2011	65	Cyclonic Storm
202	8	10	2013	213	Very Severe Cyclonic Storm (H)

Table 8-2: List of cyclonic events during (1877-2014) used for Andhra Pradesh

Sl. No.	Day	Month	Year	Maximum wind speed in km/h	Cyclone category
1	15	5	1877	118	Very Severe Cyclonic Storm
2	20	5	1879	118	Very Severe Cyclonic Storm
3	28	11	1882	83	Cyclonic Storm
4	2	11	1885	83	Cyclonic Storm
5	2	11	1886	118	Very Severe Cyclonic Storm
6	11	6	1887	83	Cyclonic Storm
7	7	10	1887	83	Cyclonic Storm
8	12	7	1888	83	Cyclonic Storm
9	27	10	1888	118	Very Severe Cyclonic Storm
10	17	9	1889	83	Cyclonic Storm
11	15	10	1889	83	Cyclonic Storm
12	18	11	1889	83	Cyclonic Storm

Sl. No.	Day	Month	Year	Maximum wind speed in km/h	Cyclone category
13	23	9	1890	83	Cyclonic Storm
14	18	10	1892	83	Cyclonic Storm
15	12	6	1893	83	Cyclonic Storm
16	4	9	1895	118	Very Severe Cyclonic Storm
17	2	10	1897	83	Cyclonic Storm
18	9	10	1898	83	Cyclonic Storm
19	5	11	1898	118	Very Severe Cyclonic Storm
20	28	10	1903	83	Cyclonic Storm
21	25	5	1904	83	Cyclonic Storm
22	14	10	1904	83	Cyclonic Storm
23	22	9	1905	83	Cyclonic Storm
24	18	6	1906	63	Cyclonic Storm
25	24	9	1908	83	Cyclonic Storm
26	24	10	1909	118	Very Severe Cyclonic Storm
27	20	9	1911	118	Very Severe Cyclonic Storm
28	13	10	1913	63	Cyclonic Storm
30	24	6	1914	63	Cyclonic Storm
29	13	5	1914	118	Very Severe Cyclonic Storm
31	23	6	1915	83	Cyclonic Storm
32	30	9	1915	83	Cyclonic Storm
33	4	11	1915	83	Cyclonic Storm
34	21	10	1916	83	Cyclonic Storm
35	10	11	1918	83	Cyclonic Storm
36	4	10	1921	118	Very Severe Cyclonic Storm
37	4	11	1924	83	Cyclonic Storm
38	12	5	1925	118	Very Severe Cyclonic Storm
39	29	10	1927	118	Very Severe Cyclonic Storm
40	16	11	1930	83	Cyclonic Storm
41	30	10	1931	63	Cyclonic Storm
42	11	10	1931	83	Cyclonic Storm
43	19	10	1932	83	Cyclonic Storm
44	13	10	1933	83	Cyclonic Storm
45	17	10	1935	83	Cyclonic Storm
46	25	10	1936	83	Cyclonic Storm
47	21	11	1938	118	Very Severe Cyclonic Storm
48	18	5	1940	118	Very Severe Cyclonic Storm

Sl. No.	Day	Month	Year	Maximum wind speed in km/h	Cyclone category
49	9	12	1941	83	Cyclonic Storm
51	16	10	1943	83	Cyclonic Storm
52	5	10	1943	83	Cyclonic Storm
50	13	5	1943	118	Very Severe Cyclonic Storm
54	25	10	1944	83	Cyclonic Storm
53	29	2	1944	118	Very Severe Cyclonic Storm
55	14	10	1945	120	Very Severe Cyclonic Storm
56	5	11	1946	65	Cyclonic Storm
58	28	10	1948	65	Cyclonic Storm
57	18	9	1948	120	Very Severe Cyclonic Storm
59	20	10	1949	120	Very Severe Cyclonic Storm
60	25	9	1954	65	Cyclonic Storm
61	5	10	1955	120	Very Severe Cyclonic Storm
62	26	4	1956	65	Cyclonic Storm
63	24	6	1956	65	Cyclonic Storm
64	25	10	1956	120	Very Severe Cyclonic Storm
65	5	10	1958	120	Very Severe Cyclonic Storm
66	17	11	1958	120	Very Severe Cyclonic Storm
67	13	5	1962	65	Cyclonic Storm
68	25	11	1962	120	Very Severe Cyclonic Storm
69	3	11	1964	120	Very Severe Cyclonic Storm
70	30	12	1965	120	Very Severe Cyclonic Storm
71	31	10	1966	120	Very Severe Cyclonic Storm
72	24	11	1966	120	Very Severe Cyclonic Storm
73	17	11	1966	120	Very Severe Cyclonic Storm
74	30	12	1966	120	Very Severe Cyclonic Storm
75	28	9	1968	120	Very Severe Cyclonic Storm
76	13	5	1969	65	Cyclonic Storm
77	20	10	1969	65	Cyclonic Storm
78	3	11	1969	120	Very Severe Cyclonic Storm
80	20	9	1972	130	Very Severe Cyclonic Storm
79	7	9	1972	148	Very Severe Cyclonic Storm
81	15	11	1972	167	Very Severe Cyclonic Storm
84	22	11	1976	65	Cyclonic Storm
82	3	11	1976	120	Very Severe Cyclonic Storm
83	15	11	1976	120	Very Severe Cyclonic Storm

Sl. No.	Day	Month	Year	Maximum wind speed in km/h	Cyclone category
85	27	10	1977	74	Cyclonic Storm
86	14	11	1977	204	Very Severe Cyclonic Storm (H)
88	27	10	1979	65	Cyclonic Storm
87	5	5	1979	157	Very Severe Cyclonic Storm
89	16	10	1980	65	Cyclonic Storm
90	13	10	1982	93	Severe Cyclonic Storm
91	17	10	1982	93	Severe Cyclonic Storm
92	1	10	1983	93	Severe Cyclonic Storm
93	9	11	1984	157	Very Severe Cyclonic Storm
94	8	10	1985	93	Severe Cyclonic Storm
96	9	12	1985	93	Severe Cyclonic Storm
95	13	11	1985	102	Severe Cyclonic Storm
97	14	10	1987	83	Cyclonic Storm
99	8	11	1987	93	Severe Cyclonic Storm
98	30	10	1987	102	Severe Cyclonic Storm
100	4	5	1990	235	Super Cyclonic Storm
101	29	10	1994	111	Severe Cyclonic Storm
102	7	11	1995	143	Very Severe Cyclonic Storm
103	4	11	1996	143	Very Severe Cyclonic Storm
104	13	11	1998	143	Very Severe Cyclonic Storm
105	15	10	1999	167	Very Severe Cyclonic Storm
106	14	10	2001	65	Cyclonic Storm
107	11	12	2003	102	Severe Cyclonic Storm
108	17	9	2005	65	Cyclonic Storm
109	29	10	2006	65	Cyclonic Storm
110	13	11	2008	74	Cyclonic Storm
111	17	5	2010	102	Severe Cyclonic Storm
112	4	11	2010	111	Severe Cyclonic Storm
113	28	10	2012	83	Cyclonic Storm
115	19	11	2013	102	Severe Cyclonic Storm
116	23	11	2013	139	Very Severe Cyclonic Storm
114	8	10	2013	213	Very Severe Cyclonic Storm (H)
117	7	10	2014	185	Very Severe Cyclonic Storm (H)

Table 8-3: Loss details due to cyclone and flood events during (1977-2010) used for Andhra Pradesh

Sr.No	Year of Cyclone/Heavy Rains	Period of Cyclone/Heavy rains	Event	No.of districts affected	Population affected (in lakhs)	Human deaths	Live-stock loss	Houses damaged	Crop area damaged (hects)	Estimated Loss (Rs.in Cr.)
1	Nov-77	28th Oct-1 Nov'1977	Severe Cyclonic Storm	8	34	10000	250000	1014800	1351000	172
2		15-20 Nov' 1977	Severe Cyclonic Storm with core of hurricane							
3	Aug-78	Aug-78		16	0.49	52	1465	22000	951000	150
4	May-79	15-13th May '1979	Heavy Rains /Floods Severe Cyclonic Storm with core of hurricane winds	10	37.4	706		748000		242.65
5		24-25 Nov'1979	Cyclonic Storm							
6	Oct-80	16-18 Oct'1980	Severe Cyclonic Storm with core of hurricane							
7	Oct-82	16-18 Oct'1982	Cyclonic Storm							
8	Aug-83	Aug-83	Heavy Rains /Floods	8	1.58	58	1726	94218	714000	89.56
9	Oct-83	3-5th Oct'1983	Cyclonic Storm							
10	Nov-84	11-15th Nov'1984	Severe Cyclonic Storm with core of hurricane winds	3	19	7	3976	8244	192000	55.53
11	Oct-85	10-11 Oct,1985	Cyclonic Storm							
12	Dec-85	11-13 Dec'1985	Severe Cyclonic Storm	11	11.75	16	4	3196	214000	40.5
13	Aug-86	Aug-86	Heavy Rains/Floods	13	21.15	309	22000	423000	853200	1686.74
14	Oct-87	15-16th Oct'1987	Cyclonic Storm							
15	Nov-87	2-3 Nov'1987	Severe Cyclonic Storm	10	32.04	119		110550	961000	126.48
16		12-13 Nov' 1987	Severe Cyclonic Storm							
17	Jul-88	Jul-88	Heavy Rains /Floods	11	23.43	88	4233	48694	406000	245.4
18	Jul-89	Jul-89	Heavy Rains /Floods	22	89.44	232	10905	227000	593000	913.5
19	Nov-89	3-6 Nov' 1989	Cyclonic Storm							

Sr.No	Year of Cyclone/Heavy Rains	Period of Cyclone/Heavy rains	Event	No.of districts affected	Population affected (in lakhs)	Human deaths	Live-stock loss	Houses damaged	Crop area damaged (hects)	Estimated Loss (Rs.in Cr.)
20	Nov-89	5-8 Nov'1989	Severe Cyclonic Storm with core of hurricane winds							
21	May-90	5-10 May'1990	Severe Cyclonic Storm with core of hurricane winds	14	77.81	817	27625	1439659	563000	2137.27
22	Aug-90	Aug-90	Heavy Rains/Floods	10	12.45	50		76420	173000	179.86
23	Oct&Nov-1991	11-15 Nov'1991	Cyclonic Storm	9	0.18	192		97470	409000	367.32
24	Oct/Nov&Dec-1993	Oct/Nov &Dec1993	Cyclonic Storm	5					37000	70.87
25	July/Aug/Sep-1994	July/Aug/sep-1994	Heavy Rains /Floods	6	2.81	12			52000	130.45
26	Oct&Nov-1994	29-31 Oct'1994	Severe Cyclonic Storm	7	2.86	3		79172	452000	625.93
27	May-95	May-95	Severe Cyclonic Storm with core of hurricane winds	10	2.56	26	3260	43179	320000	471.86
28	Oct&Nov -1995	6th-18th Oct,9-10th Nov 95	Heavy Rains /Floods	19	2.3	229	3663	146525	665000	917
29	Jun-96	12-16 June'1996	Cyclonic Storm	10	0.22	100	1607	21517	15000	129.1
30	Aug&Sep-96	Aug & Sep 96	Heavy Rains /Floods	13	0.21	140	188	12100	134000	159
31	Oct(1-3)1996	Oct(1-3) 1996	Heavy Rains /Floods	14	0.27	61	154	18058	449000	262.53
32	Oct(17-21)1996	Oct(17-21) 1996	Heavy Rains /Floods	11	87.37	338	146621	130731	1128000	843.27
33	Nov 1996 (6-7th)	Nov1996 (6-7th)	Severe Cyclonic Storm with core of hurricane winds	4	80.62	1077	19856	616553	511000	6129.25
34	Dec-96	28 Nov-7 Dec'1996	Severe Cyclonic Storm with core of hurricane winds	3	0.37	27	293	7569	21000	53.59
35	Sep-97	23-26th Sep'1997	Severe Cyclonic Storm	6	9.47	40	93	7725	135000	255.87
36	Sep-Oct 1998	Sep-Oct 1998	Heavy Rains /Floods	22	16.34	260	5126	150196	1405000	2525.2
37	Nov-98	13-15th Nov'1998	Very Severe Cyclone Storm	5	0.68	16	5874	13543	339000	305.99

Sr.No	Year of Cyclone/Heavy Rains	Period of Cyclone/Heavy rains	Event	No.of districts affected	Population affected (in lakhs)	Human deaths	Live-stock loss	Houses damaged	Crop area damaged (hects)	Estimated Loss (Rs.in Cr.)
38	Oct-99	16-17th Oct 1999	Cyclonic Storm	1	1.89	3	388	3425		237.76
39	Aug'2000	22-31st Aug'2000*	Heavy rains / Floods	17	1.98364	207	6156	99800	178000	966.15
40	1-Oct	15-17th Oct-2001	Heavy Rains / Flash Floods	5		119		111340		
41	Dec-2003	15-16th Dec-2003	Cyclonic Storm / Flash Floods	6	42.68	44	102324	17147	265741	765.92
42	Sept-2005	18-19th Sept-2005	Heavy Rains / Flash Floods	10	350	107	14416	118618	551966	2697.97
43	6-Aug	2-5th August-2006	Cyclone Storm / Floods	10	13.84	165	20530	276567	219897	3455.23
44	6-Sep	14-22ne Sept-2006	Heavy Rains	8	0.23	52	4849	29837	219950	188.44
45	Oct-Nov-06	28-4th Nov-2006	Ogni Cyclone	5	13.85	41	350000	95218	384550	7173.25
46	7-Jun	21st Jun to 24th Jun07	Heavy Rains	16	8.35	50	47172	195456	51587	1296.2
47	7-Sep	17th to 22nd sept2007	Heavy Rains/Floods	15	2.4	77	745	33241	62000	
48	7-Oct	5th to 7th Oct-2007	Heavy Rains/Floods	6	0.94	9	3126	9246	16405	1156.11
49	Oct-Nov-07	29th oct to 1st Nov-07	Heavy Rains/Floods	4	27.32	36	0	611907	23000	
50	8-Feb	9th to 13th Feb- 2008	Heavy Rains/Floods	11	0.13	4	3000	122	292854	741.47
51	8-Mar	22nd to 29th March-08	Unseasonal Heavy Rains and Consequent Floods	22	0.014	36	1643	3556	227507	929.88
52	8-Aug	3rd to 11th Aug-08	Heavy Rains/ Floods	15	44.28	130	6692	44364	196038	1116
53	8-Nov	14th to 16th Nov-08	Khaimuk - Cyclone	9	1	0	37	1190	59287	36
54	8-Nov	25th to 30th Nov-08	Nisha - Cyclone	5	1	9	28	8258	220000	80
55	Sept-Oct-09	29th Sept to 4th Oct.2009	Floods due to unprecedented Rains	13	20.72	90	49686	259095	226092	12455.75
56	10-May	17th to 22nd May 2010	Laila - Cyclone	14	17.8	22	2075	14298	26685.83	1603.22
57	June- Sept,2010	Southwest Monsoon	Heavy Rains/ Floods	22	8.95	65	7236	11022	277000	5776.6
58	Oct-Nov,2010	29th Oct to 8th Nov-2010	Heavy Rains/ Floods/JAL Cyclone	13	16.98	63	1140	20554	483000	2496.98
59	Dec,2010	5th Dec to 8th Dec-2010	Heavy Rains/ Floods	15	8.16	21	3026	3169	1208000	2739.33

Table 8-4: Loss details due to extreme cyclone events during (1831-2014) for Odisha

Sl.No.	Date/Year	Category of Cyclone	Landfall and loss
1	31 October, 1831	Very Severe Cyclonic Storm	Crossed Odisha Coast near Balasore, Loss of life-50,000
2	22 September, 1885	Super Cyclone	Crossed Odisha Coast at False Point, Loss of life- 5000
3	24-27 October , 1909	Very Severe Cyclonic Storm	Crossed Odisha Coast Near Gopalpur
4	27 September -2 October , 1959	Very Severe Cyclonic Storm	Crossed north of Balasore in the night of 30th September
5	8-11 October, 1967	Very Severe Cyclonic Storm	Crossed Odisha Coast between Puri and Paradeep
6	26-30 October, 1971	Very Severe Cyclonic Storm	Crossed Odisha Coast near Paradip, Loss of life- 10,000;; 50,000 Cattle heads perished; 8,00,000 Houses damaged
7	7-14 September , 1972	Very Severe Cyclonic Storm	Crossed Odisha Coast near Barua
8	20-25 September , 1972	Very Severe Cyclonic Storm	Crossed Odisha Coast near Gopalpur
9	6-12 October , 1973	Cyclonic Storm	Crossed Odisha Coast Chandbali, Loss of life- 100
10	3-9 November, 1973	Severe Cyclonic Storm	Crossed Orissa coast close to and north of Paradip
11	31 May - 5 June, 1982	Severe Cyclonic Storm	Crossed Odisha Coast near Paradip, Loss of life- 245
12	9-14 October, 1984	Cyclonic Storm	Crossed North Odisha coast near Chandbali
13	23-27 May, 1989	Severe Cyclonic Storm	crossed 40 Km northeast of Balasaore, Loss of life- 61
14	7-10 November , 1995	Very Severe Cyclonic Storm	Crossed Odisha Coast near Gopalpur, Loss of life- 96, 28,4253 hectares of crops damaged
15	15-19 October , 1999	Very Severe Cyclonic Storm	Crossed Odisha Coast near Berhampur, Loss of life- 205; 331000 houses damaged;158000 cropped area damaged.and 5181 villages were affected.
16	25-31 October, 1999	Super Cyclone	Crossed Odisha Coast near Paradeep at noon of 29 October
17	08-14 October, 2013	Very Severe Cyclonic Storm	Crossed Odisha Coast & adjoining north Andhra Pradesh coast near Gopalpur; 18,370 villages affected; 132,00,000 people affected; 44 human casualities

Table 8-5: Loss details due to extreme flood events during (1960-2008) for Odisha

Sr. No.	Year	Month of Occurrence	Rivers	Affected District / Area	Loss/Damage Reported		
					Human	Live Stock	Public Utility
1	1960	Aug.	9 Mahanadi, Brahmnai, Baitarani, Burhabalanga & Subarnarekha	Cuttack, Puri, Dhenkanal, Balasore, Mayurbhanj & Keonjhar - 6 districts.	NA	NA	18.65 lakh Ac. of cropped area damaged and loss of Rs.11.70 crores.
2	1961	July-Sept.	10 Mahanadi, Brahmnai, Baitarani, Burhabalanga & Subarnarekha	Cuttack, Puri, Dhenkanal, Balasore, Mayurbhanj & Keonjhar - 6 districts.	NA	NA	1.429 lakhs Ac. of cropped area damaged with a loss of Rs.2.54 crores.
3	1964	July-Aug.	Mahanadi, Brahmani, Baitarani & Rushikulya	Cuttack, Puri, Bolangir, Dhenkanal, Balasore, Sambalpur, Ganjam, Phulbani & Keonjhar - 9 districts.	NA	NA	4.08 lakh Ac. of cropped area damaged.
4	1971	July-Oct.	Mahanadi, Brahmnai, Baitarani & Subarnarekha	Cuttack, Balasore, Puri, Mayurbhanj, Bolangir, Sundergarh & Keonjhar - 7 districts.	26	265	11.719 lakh Ac. of cropped area damaged. 95043 no. of houses damaged. Total loss of Rs.31.71 crores.
5	1974	August	11 Mahanadi, Brahmnai, Baitarani, Burhabalanga & Subarnarekha	Cuttack, Balasore, Puri, Dhenkanal & Keonjhar - 5 districts.	NA	NA	5.40 lakh Ha. of cropped area damaged.
6	1980	Sept.	Mahanadi, Brahmnai, Baitarani & Vamsadhara	Balasore, Bolangir,Cuttack, Dhenkanal, Ganjam, Kalahandi, Koraput, Phulbani, Puri, Sambalpur - 10 districts.	82	16669	3.19 lakh Ha. of cropped area damaged. Rs.65.00 crores of PU damaged.
7	1982	Aug.-Sept.	Mahanadi, Rushikulya	Cuttack, Puri, Bolangir, Phulbani, Ganjam, Sambalpur, Dhenkanal & Kalahandi - 8 districts.	126	26359	12.00 lakh Ha. of cropped area damaged. Rs.616.00 crore of PU damaged.

Sr. No.	Year	Month of Occurrence	Rivers	Affected District / Area	Loss/Damage Reported		
					Human	Live Stock	Public Utility
8	1984	June-Sept.	Subarnarekha, Brahmani, Baitarani, Mahanadi, Vamsadhara, Indrabati	Cuttack , Balasore, Puri, Phulbani, Koraput, Ganjam , Dhenkanal, Keonjhar - 8 districts.	27		3.92 lakh Ha. of cropped area damaged.
9	1985	Aug.-Sept.	Mahanadi, Rushikulya, Baitarani, Brahmani, Subarnarekha,	Balasore, Bolangir, Cuttack, Ganjam, Puri, Phulbaani, Keonjhar, Kalahandi, Sambalpur - 9 districts	22	5281	3.10 lakh Ha. of cropped area damaged.
10	1986		Mahanadi, Subarnarekha, Indravati	Balasore, Bolangir, Cuttack, Dhenkanal, Koraput, Mayurbhanj, Puri, Phulbaani, Sambalpur - 9 districts.	24	337	1.08 lakh Ha. of cropped area damaged. Rs.55.31 crore of PU damaged.
11	1991	July-August	Mahanadi, Brahmani, Baitarani, Subarnarekha, Vamsadhara	Cuttack, Puri, Balasore, Ganjam, Phulbani,Dhenkanal, Sambalpur, Kalahandi, Koraput, Keonjhar - 10 districts.	52	1145	6.62 lakh Ha. of cropped area damaged.
12	1992	June-Aug.	Mahanadi, Subarnarekha, Vamsadhara	Cuttack, Puri, Bolangir, Balasore, Ganjam, Koraput, Phulbani, Samabalpur, Kalahandi, Dhenkanal, Sundergarh - 11 districts	43	1397	4.17 lakh Ha. of cropped area damaged. Rs.184.48 crore of PU damaged.
13	1994	July-Sept.	Mahanadi, Brahmani, Subarnarekha, Vamsadhara	Angul, Balasore, Bhadrak, Boudh, Cuttack, Jagatsinghpur, Jajpur, Jharsuguda, Khurda, Kendrapara, Kalahandi, Koraput, Malkanagiri, Nayagarh, Nowrangpur, Puri, Sambalpur, Sundergarh, Sonepur - 20 districts.	50		10.17 lakh Ha. of cropped damaged.

Sr. No.	Year	Month of Occurrence	Rivers	Affected District / Area	Loss/Damage Reported		
					Human	Live Stock	Public Utility
14	1995	May-Nov.	Mahanadi, Subarnarekha, Vamsadhara, Rushikulya	Angul, Balasore, Bhadrak, Boudh, Cuttack, Dhenkanal, Ganjam, Gajapati, Jagatsinghpur, Jajpur, Khurda, Koraput, Kalahandi, Kendrapara, Keonjhar, Kandhamal, Malkangiri, Nawarangpur, Nayagarh, Puri, Rayagada, Sambalpur, Sonepur - 23 districts.	76	372	16.09 lakh Ha. of cropped area damaged. Rs.112.42 crore of PU damaged.
15	1997	June & August	Mahanadi	Balasore, Bhadrak, Cuttack, Denkanal, Jagatsinghpur, Jajpur, Khurda, Kalahandi, Kendrapara, Kandhamal,Keonjhar,Mayurbhanj,Nuapara, Nawarangpur, Nayagarh, Puri, Sundergarh, Sambalpur - 18 districts.	29	52	5.27 lakh Ha. of cropped area damaged.
16	1999	July-August	Mahanadi, Brahmani, Baitarani, Subarnarekha, Rushikulya	Cuttack, Jagatsinghpur, Kendrapara, Jajpur, Bhadrak, Balasore, Mayurbhanj - 7 districts.	10		1.49 lakh Ha. of cropped area damaged. Rs.54.00 crores of PU damaged.
17	2001	July-August	Mahanadi, Brahmani, Baitarani, Subarnarekha, Burhabalanga, Vamsadhara, Rushikulya, Indravati	Angul, Balasore, Bhadrak, Boudh, Bolangir, Baragarh, Cuttack, Dhenkanal, Deogarh, Jagatsinghpur, Jajpur, Jharsuguda, Khurda, Koraput, Kalahandi, Kendrapara, Nuapara, Nawarangpur, Nayagarh, Puri, Rayagada, Sundergarh, Sambalpur, Sonepur - 24 districts	102	18149	7.99 lakh Ha. of cropped area damaged. Rs.883.42 crores of PU damaged.

Sr. No.	Year	Month of Occurrence	Rivers	Affected District / Area	Loss/Damage Reported		
					Human	Live Stock	Public Utility
18	2003	July-Oct.	Baitarani, Mahanadi, Rushkulya, Vamsadhara, Burhabalanga, Indrabati	Angul, Balasore, Bhadrak, Boudh, Bolangir, Baragarh, Cuttack, Deogarh, Ganjam, Gajapati, Jagatsinghpur, Jajpur, Jharsuguda, Khurda, Koraput, Kalahandi,Keonjhar, Kendrapara, Malkangiri, Nuapara, Nawarangpur, Nayagarh, Puri, Rayagada, Sambalpur, Sonepur - 26 districts.	92	2956	5.03 lakh Ha. of cropped area damaged. More than Rs.1000.00 crores of PU damaged.
19	2006	July - August	Mahanadi, Brahmani, Baitarani, Subarnarekha, Burhabalanga, Vamsadhara, Rushikulya	Angul, Balasore, Bargarh, Bhadrak, Bolangir, Boudh, Cuttack, Dhenkanal, Gajapati, Ganjam, Jagatsinghpur, Jajpur, Kalahandi, Kandhamal, Kendrapara, Keonjhar, Khurda, Koraput, Malkangiri, Mayurbhanj, Nawarangpur, Nayagarh, Nuapara, Puri, Raygada, Sambalpur, Sonepur - 27 districts.	90	1656	3.104 Lakh Ha. crop damaged, 0.27 lakh Ha. sandcast, house damaged 1,20,446 nos, Loss of P.U - Rs.2043.00 crores
20	2007	Jul-Aug-Sep		27, 12, 15 districts respectively			
21	2008	Jun & Sep	Subarnarekha, Burhabalang, Baitarani, Mahanadi, Rushikulya, Vansadhara	Angul, Balasore, Bhadrak, Boudh, Bolangir, Bargarh, Cuttack, Gajpati, Jagatsinghpur, Jajpur, Kendrapara, Khurda, Kalahandi, Keonjhar, Mayurbhanj, Nuapara, Nayagarh, Puri, Rayagada, Sambalpur, Sonepur - 21	110	50163	258155 houses damaged, 4.45 lakh Ha. cropped area, 0.14 th Ha sandcast, 651 breaches in rivers, 1276 breaches in canals.

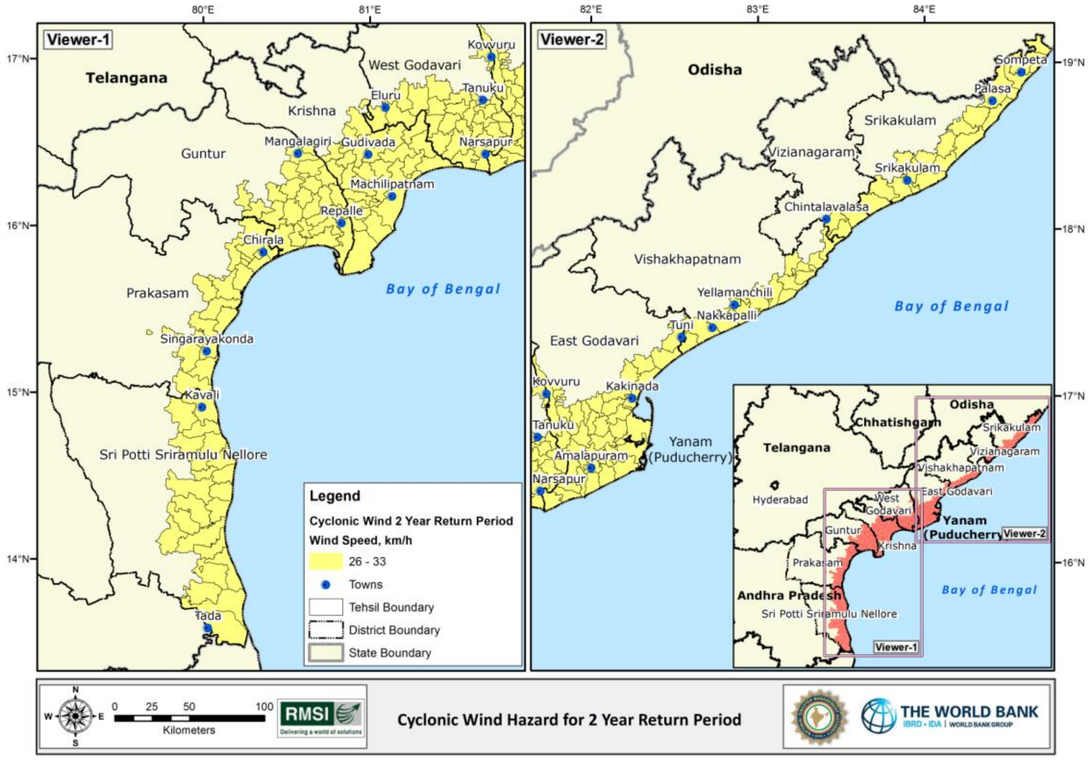

Figure 8-1: Cyclone hazard map of Andhra Pradesh for 2-year return period

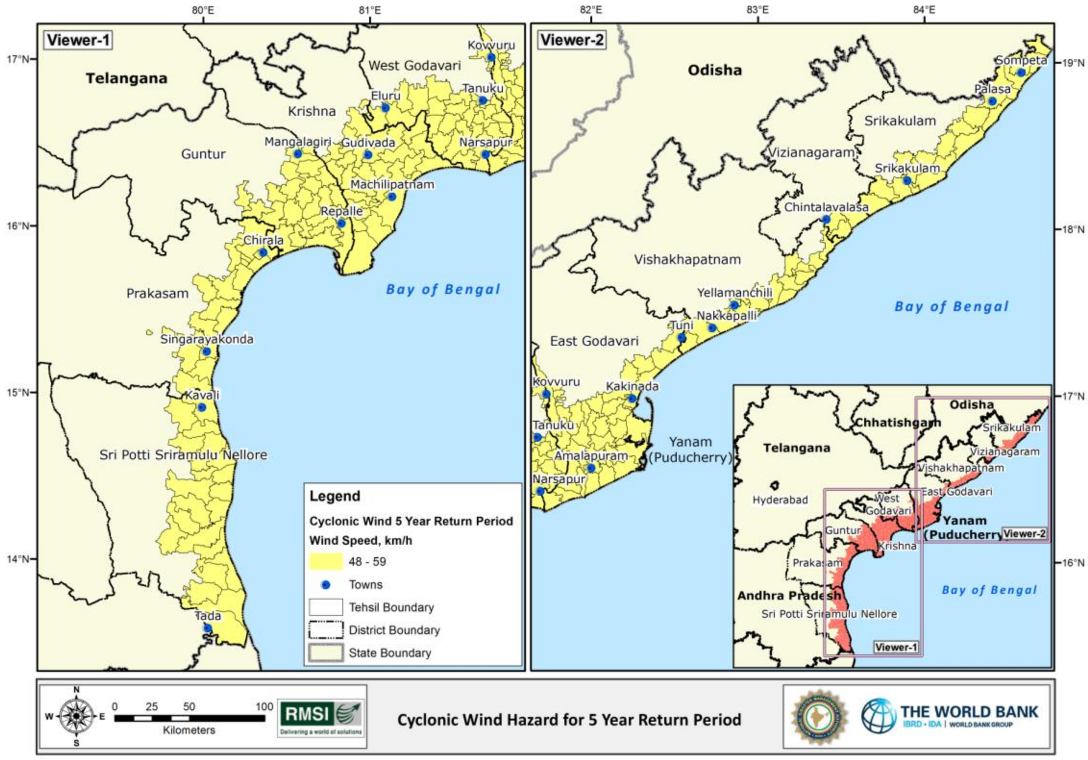

Figure 8-2: Cyclone hazard map of Andhra Pradesh for 5-year return period

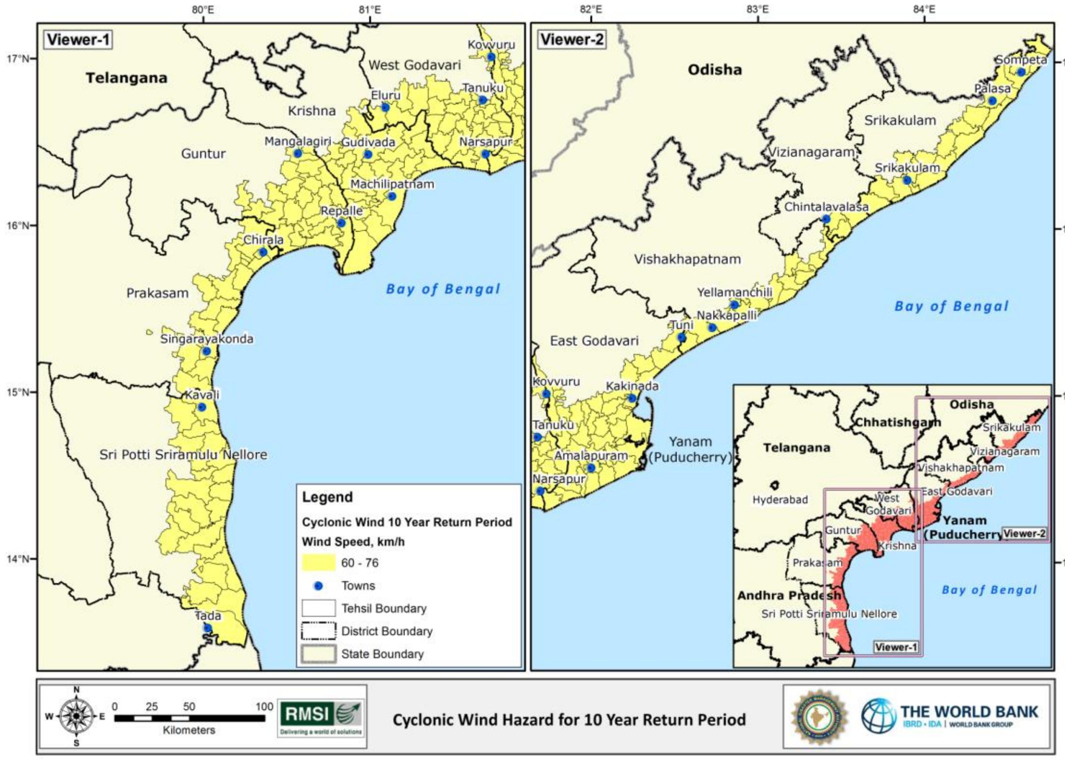

Figure 8-3: Cyclone hazard map of Andhra Pradesh for 10-year return period

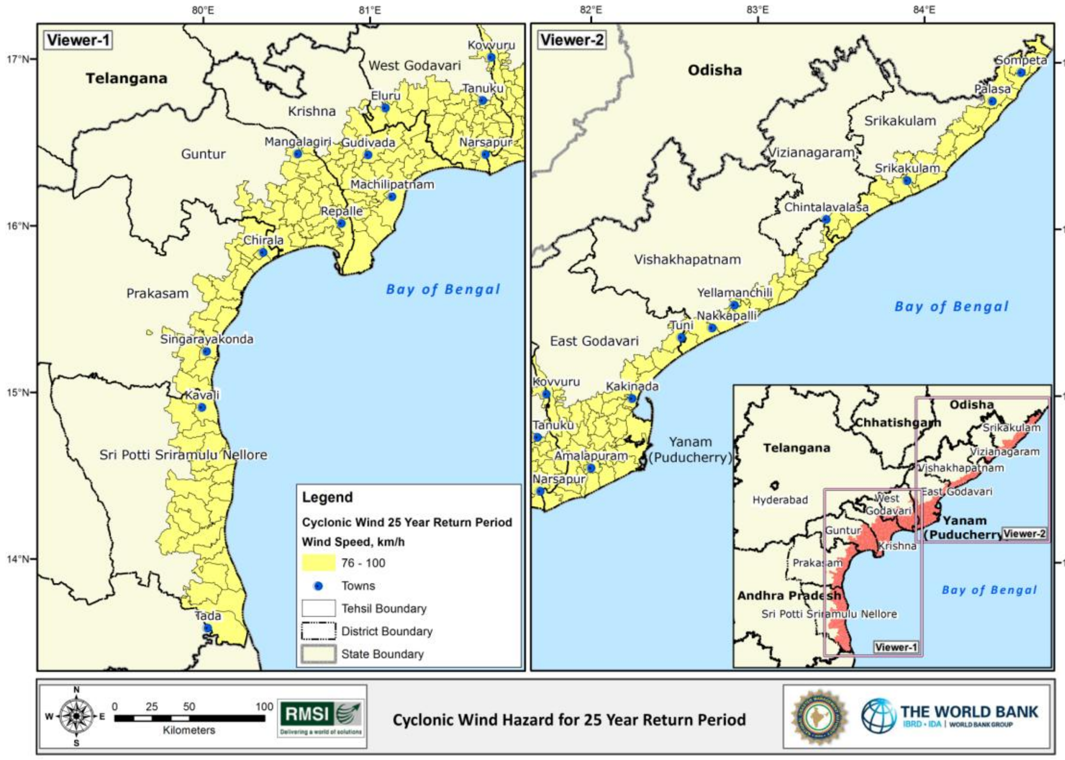

Figure 8-4: Cyclone hazard map of Andhra Pradesh for 25-year return period

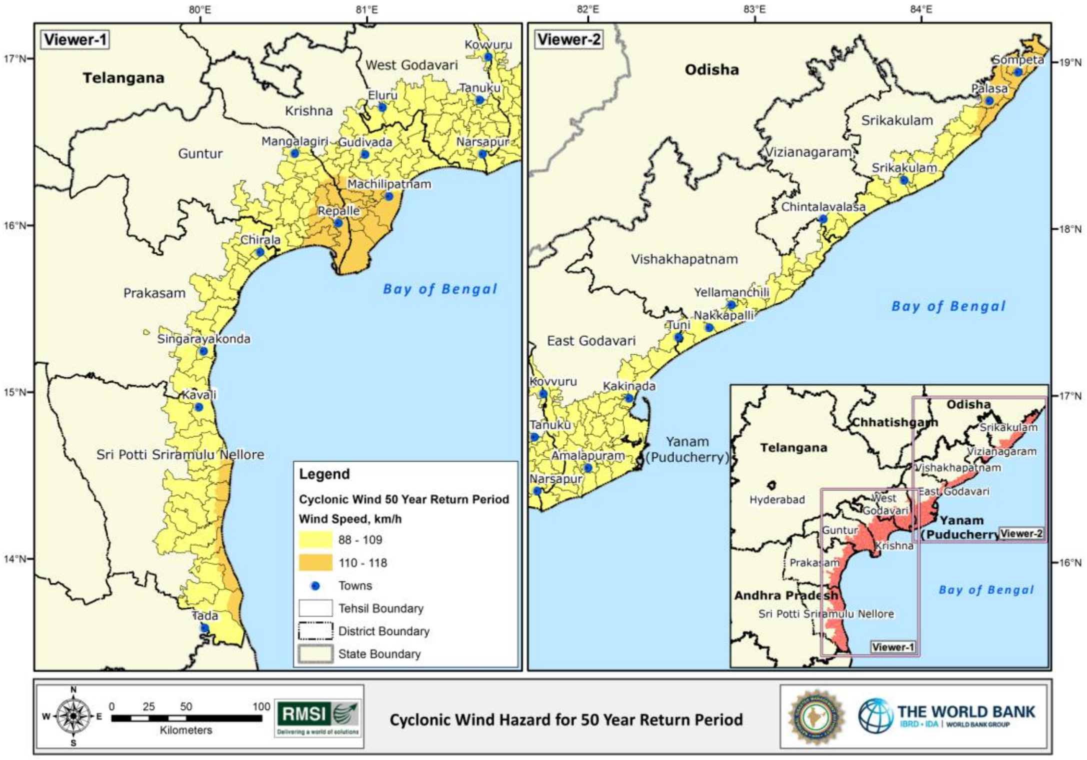

Figure 8-5: Cyclone hazard map of Andhra Pradesh for 50-year return period

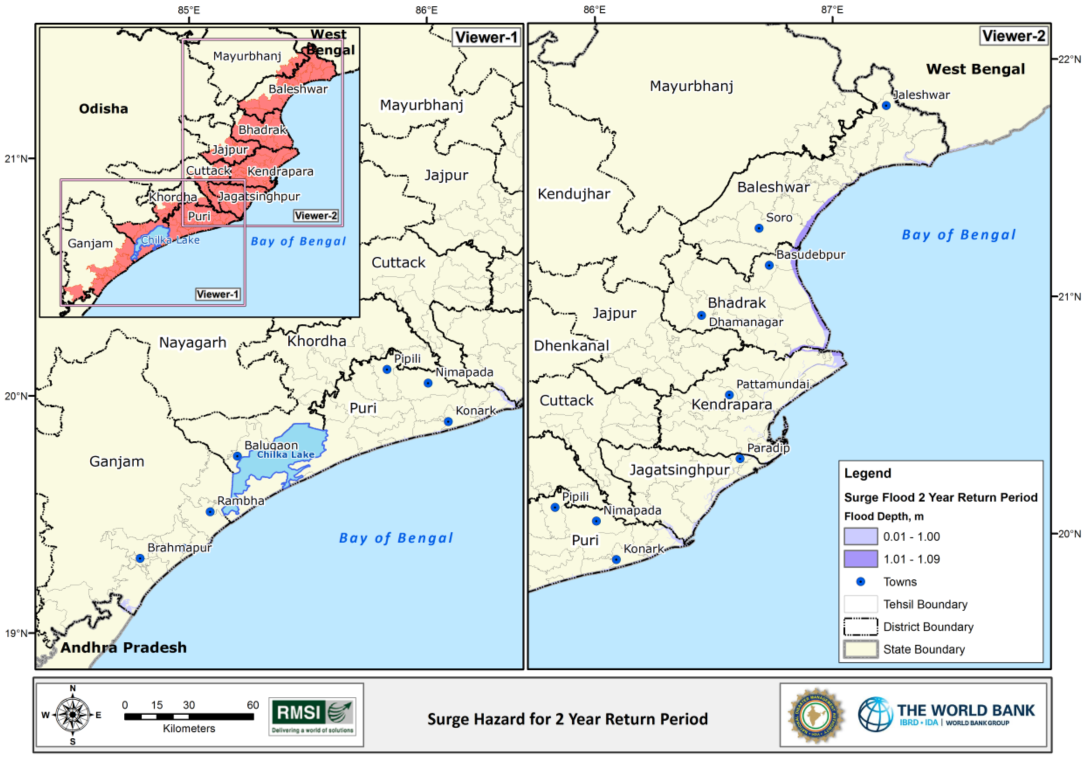

Figure 8-6: Storm surge flood hazard map of Odisha for 2-year return period

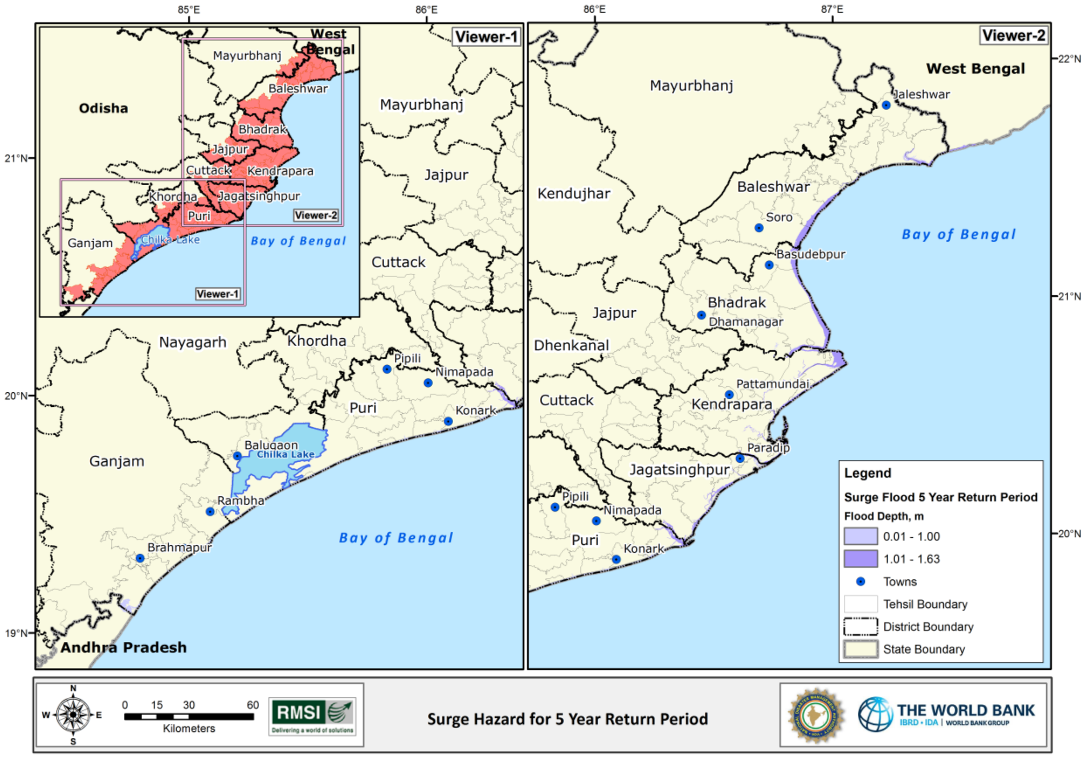

Figure 8-7: Storm surge flood hazard map of Odisha for 5-year return period

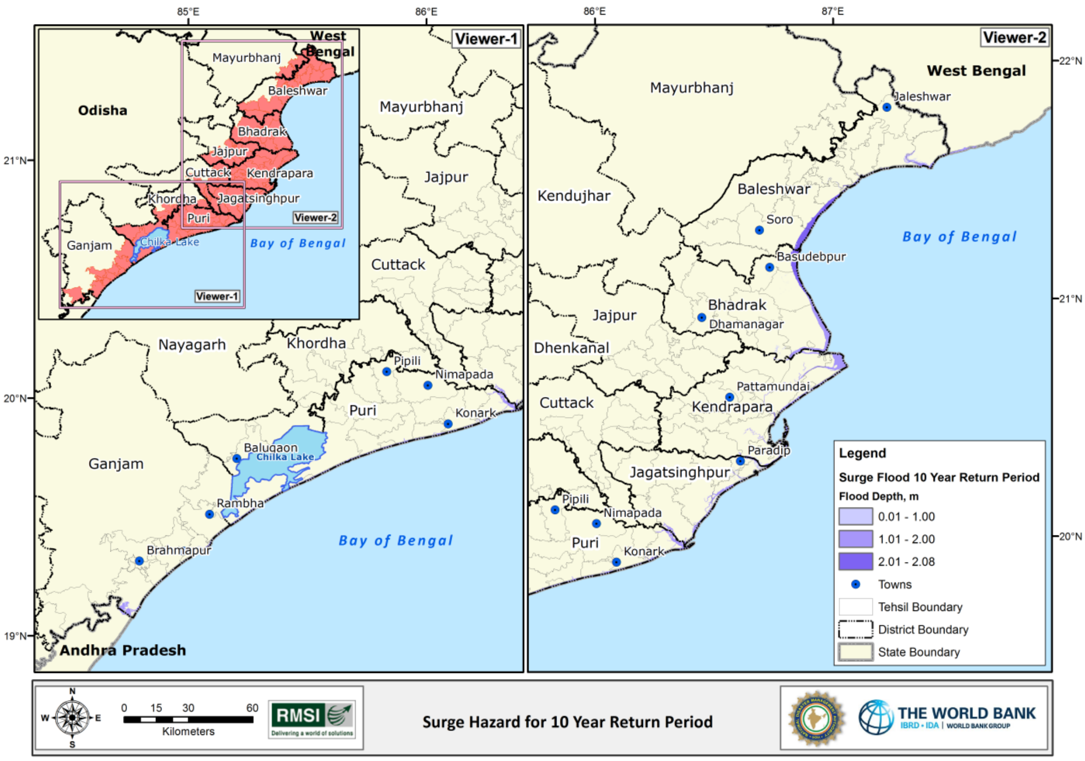

Figure 8-8: Storm surge flood hazard map of Odisha for 10-year return period

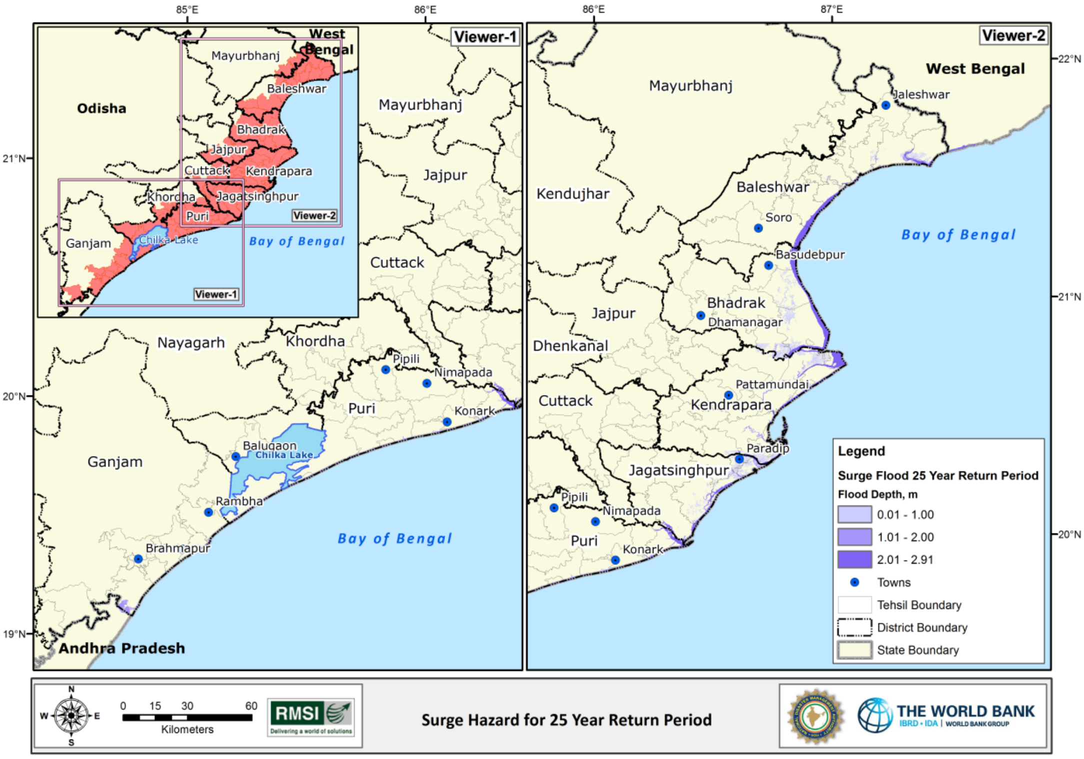

Figure 8-9: Storm surge flood hazard map of Odisha for 25-year return period

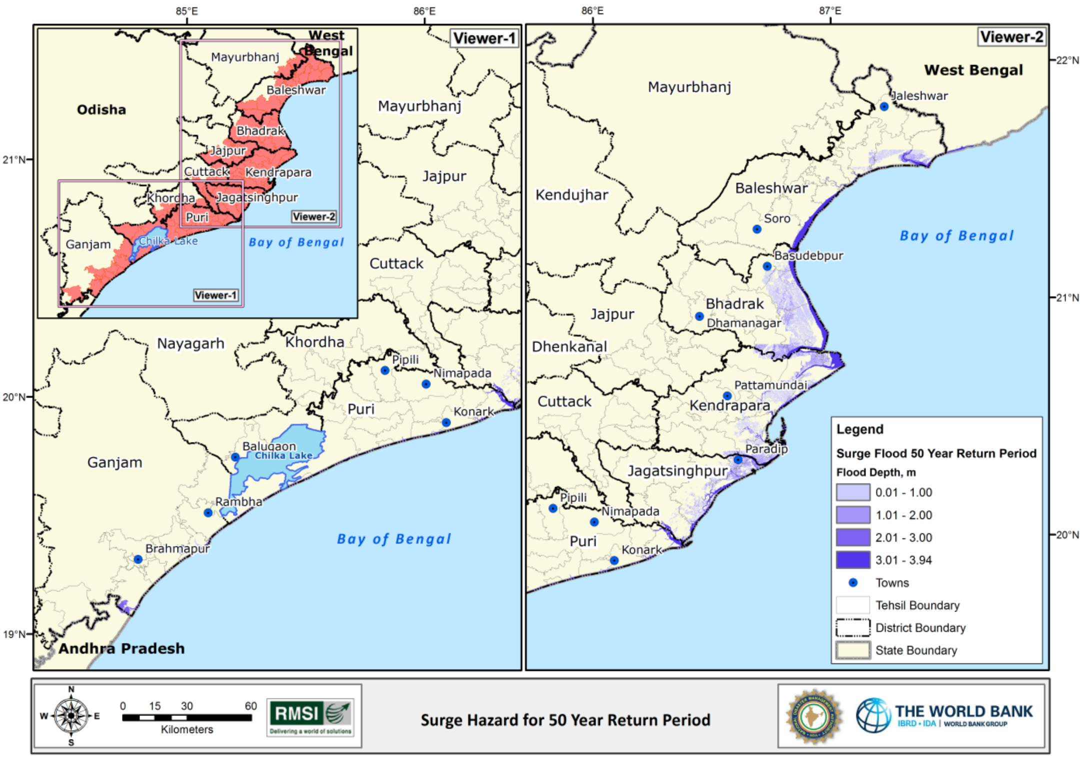

Figure 8-10: Storm surge flood hazard map of Odisha for 50-year return period

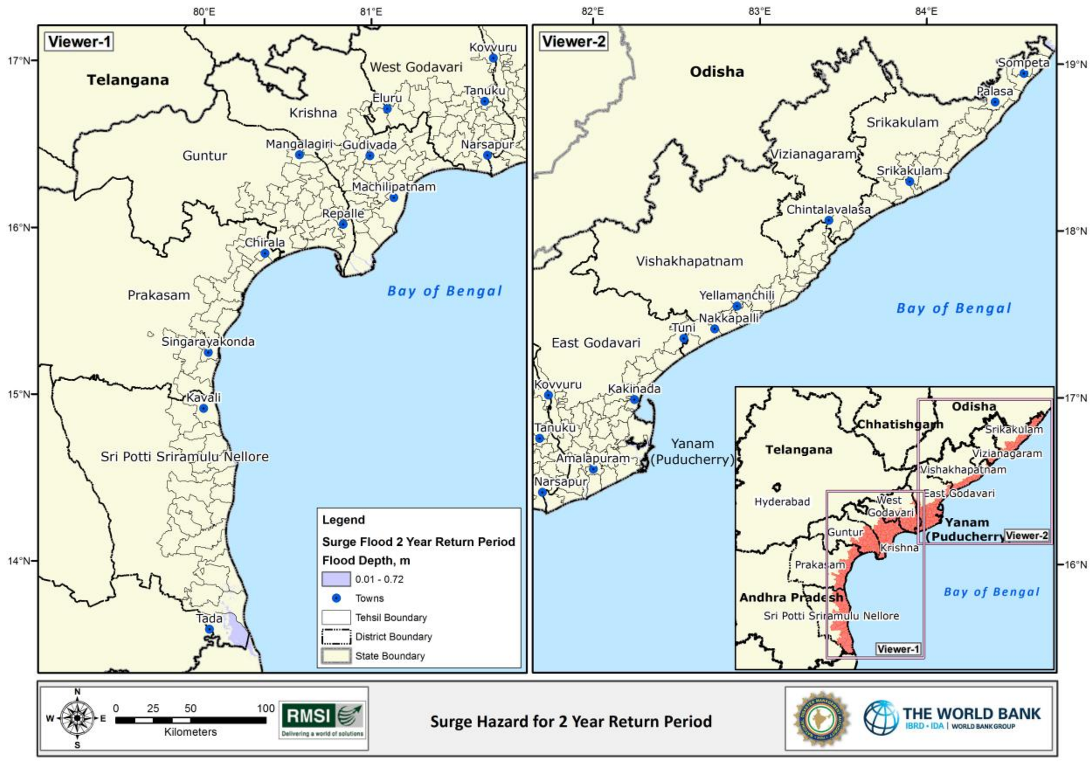

Figure 8-11: Storm surge flood hazard map of Andhra Pradesh for 2-year return period

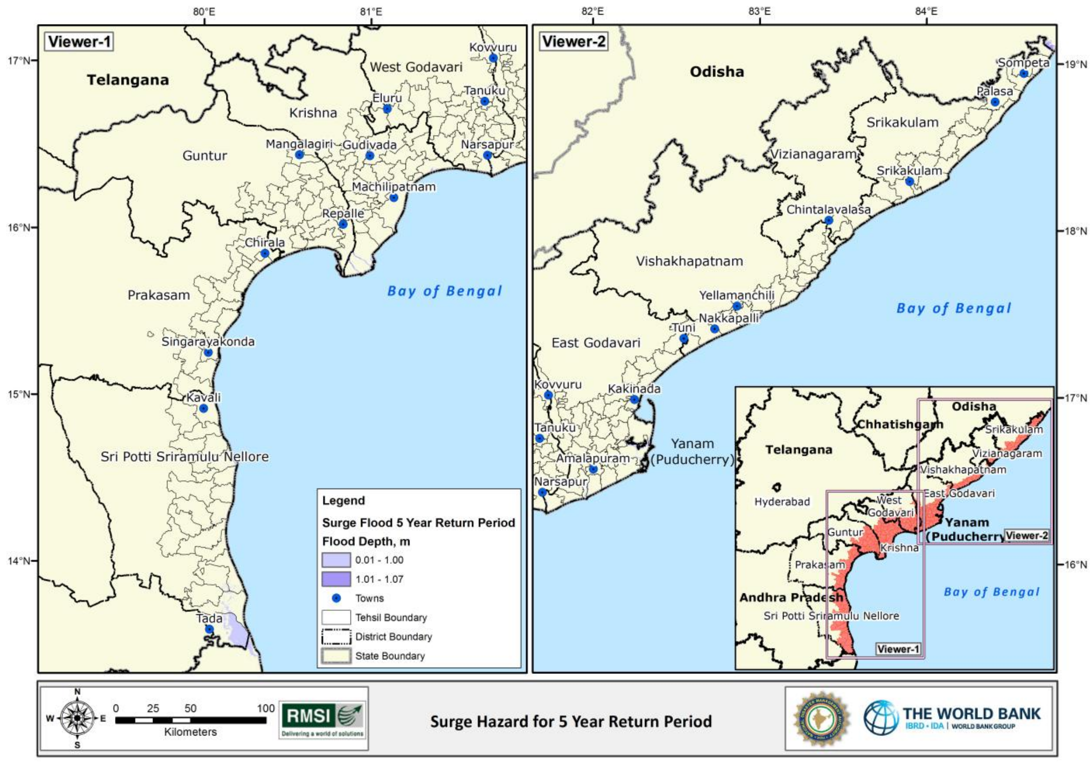

Figure 8-12: Storm surge flood hazard map of Andhra Pradesh for 5-year return period

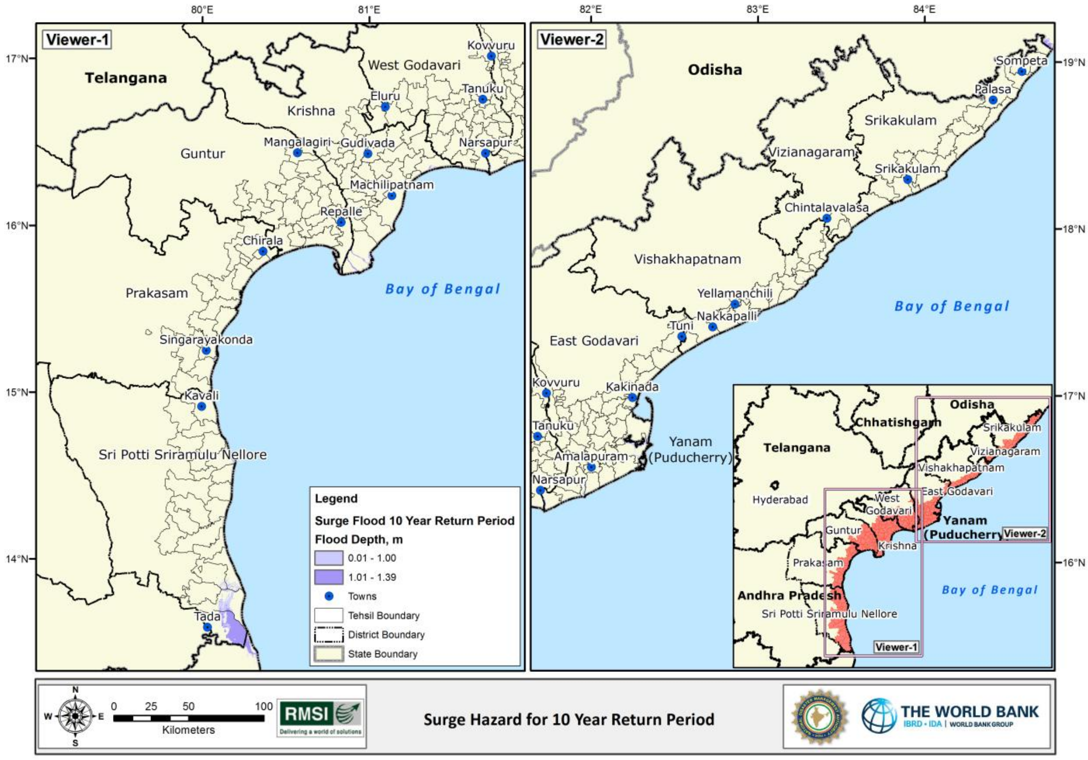

Figure 8-13: Storm surge flood hazard map of Andhra Pradesh for 10-year return period

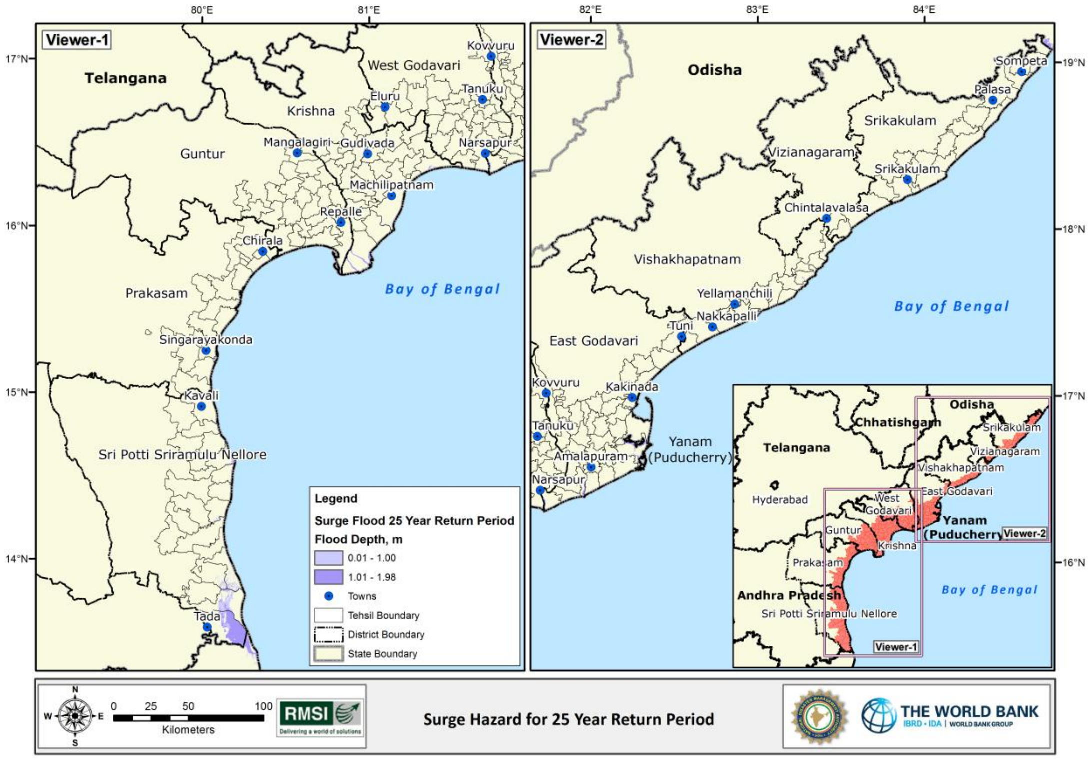

Figure 8-14: Storm surge flood hazard map of Andhra Pradesh for 25-year return period

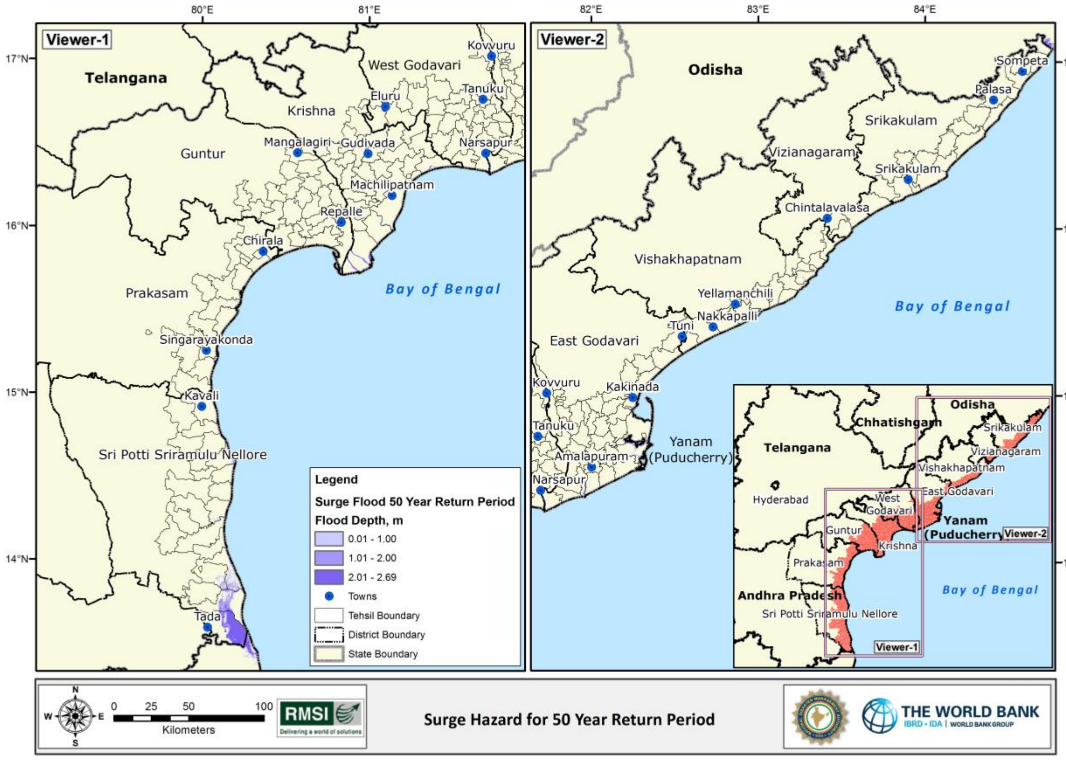

Figure 8-15: Storm surge flood hazard map of Andhra Pradesh for 50-year return period

12 Annexure 3: Cyclone Induced flooding

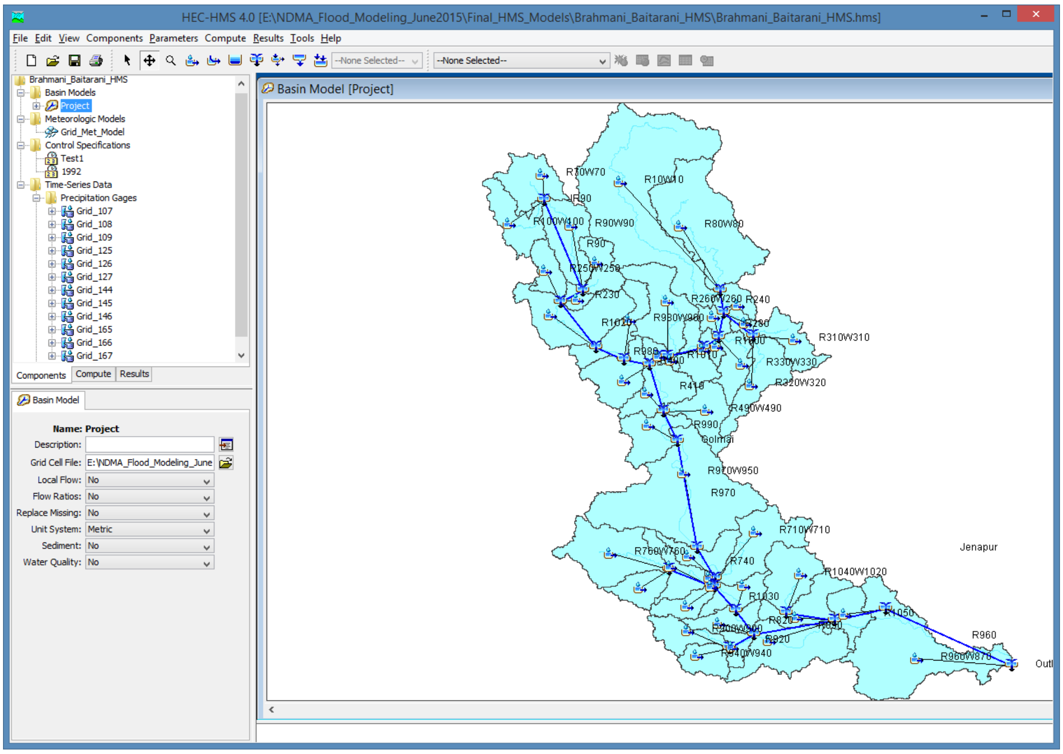

Figure 12-1: HEC-HMS model schematic for the Brahmani Basin

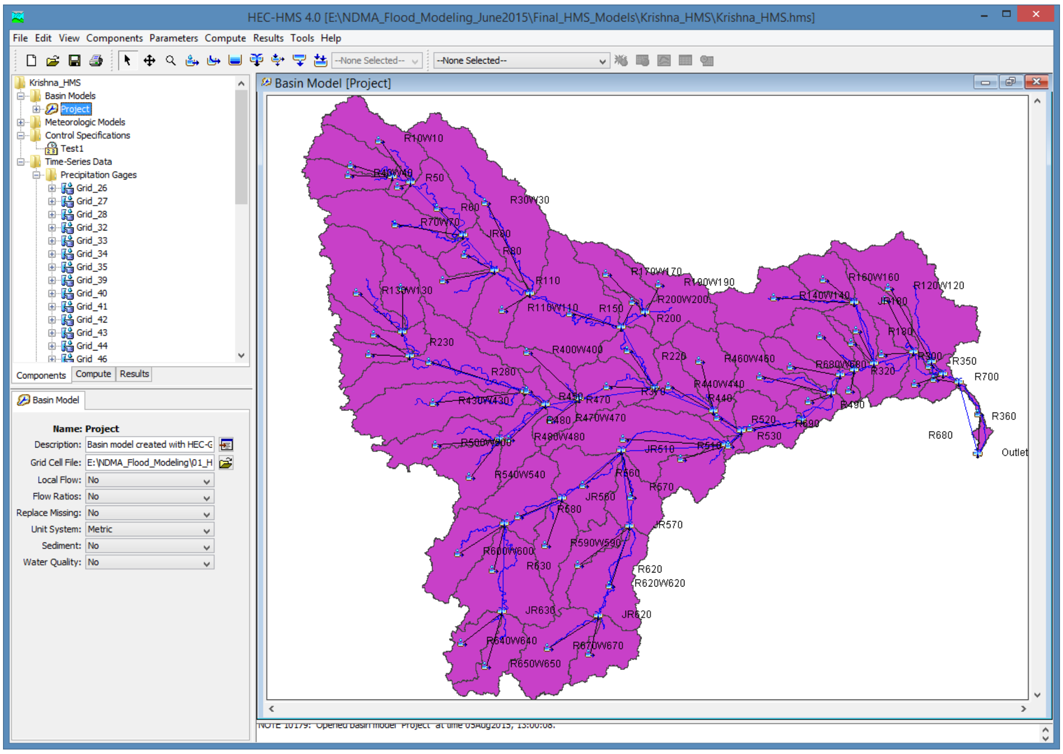

Figure 12-2: HEC-HMS model schematic for the Krishna Basin

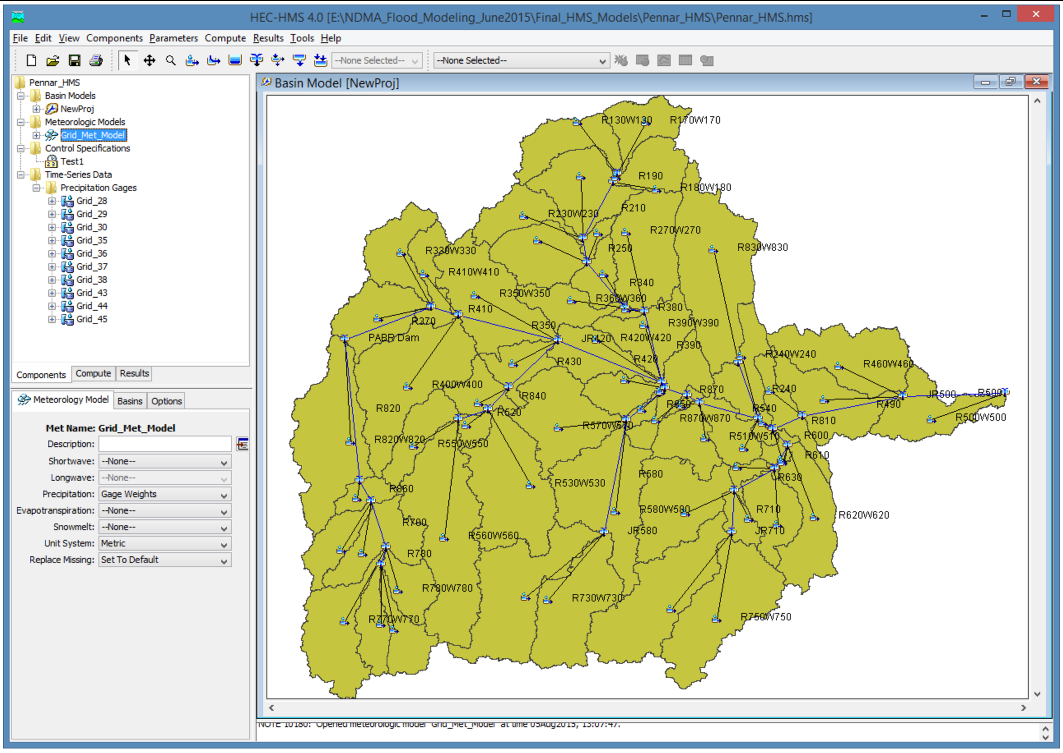

Figure 12-3: HEC-HMS model schematic for the Pennar Basin

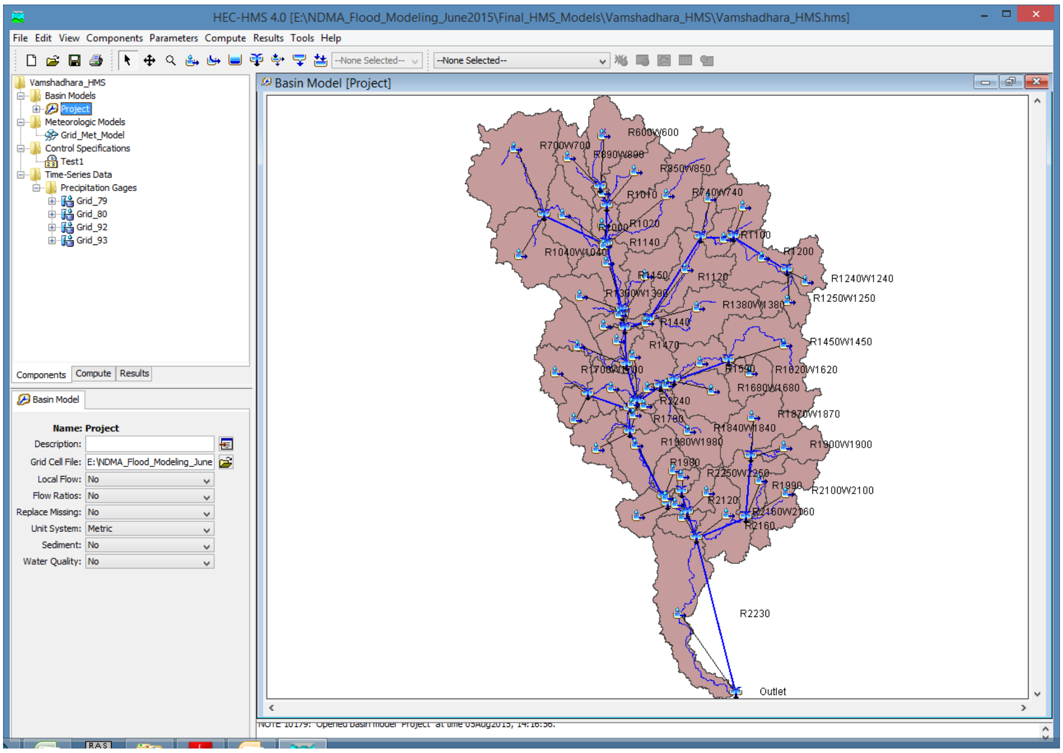

Figure 12-4: HEC-HMS model schematic for the Vamsadhara Basin

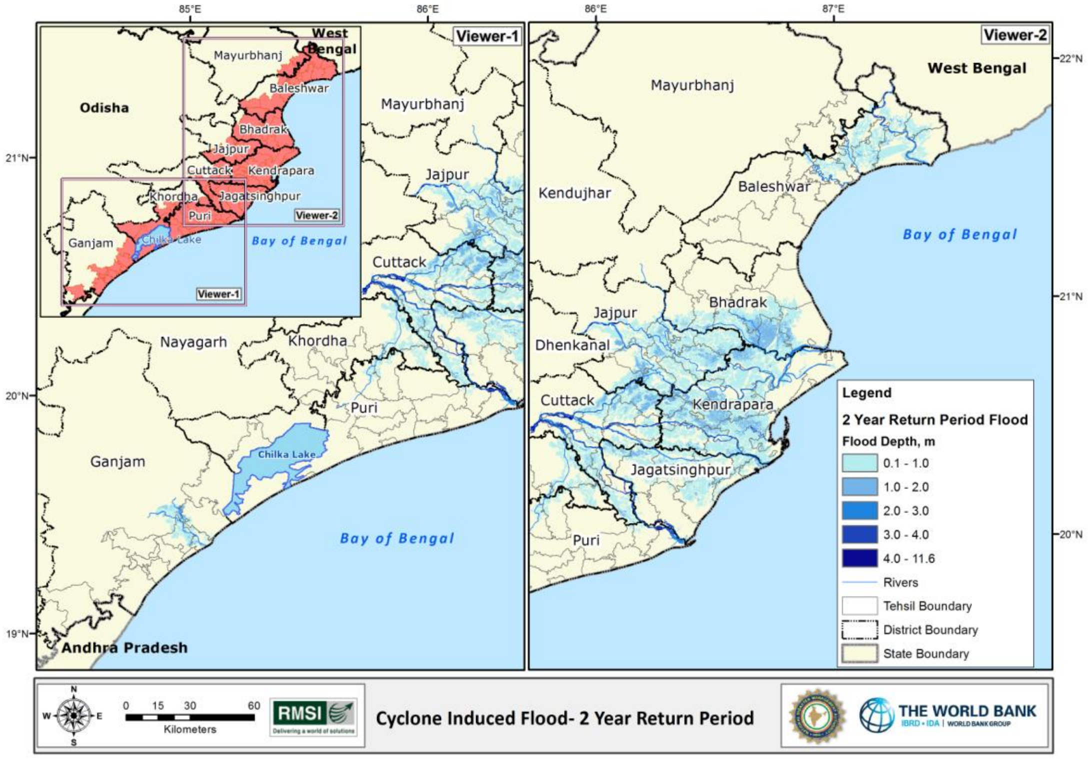

Figure 12-5: Cyclone induced flood map of Odisha for 2-year return period

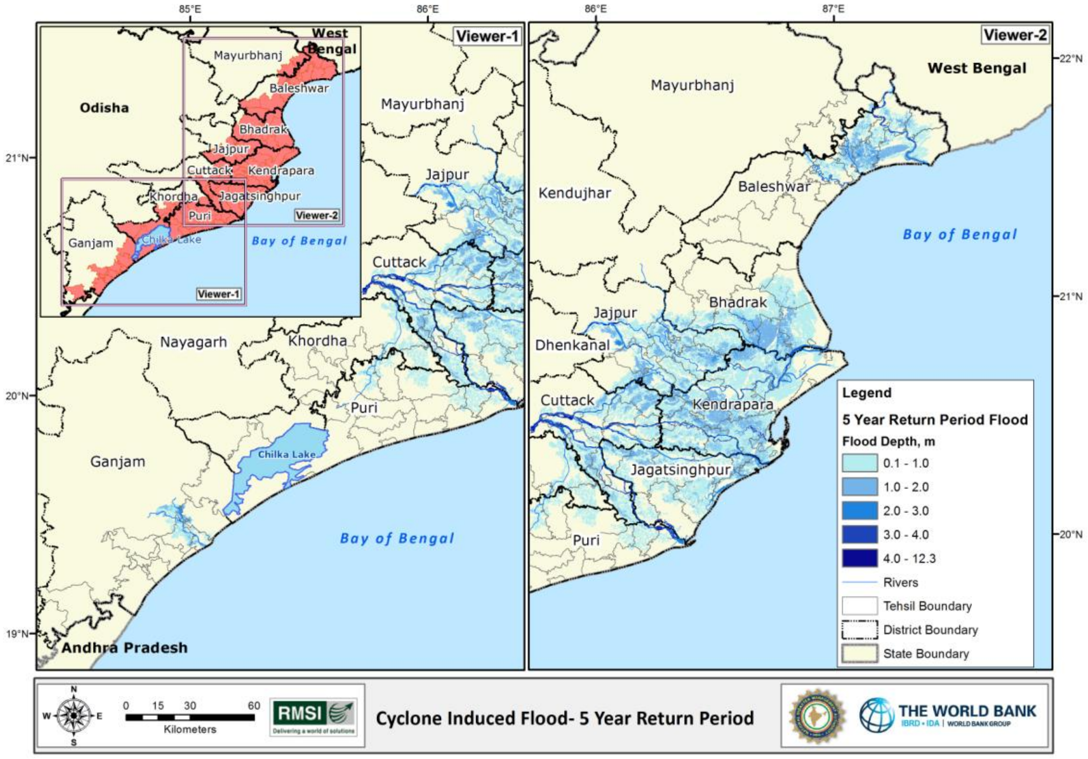

Figure 12-6: Cyclone induced flood map of Odisha for 5-year return period

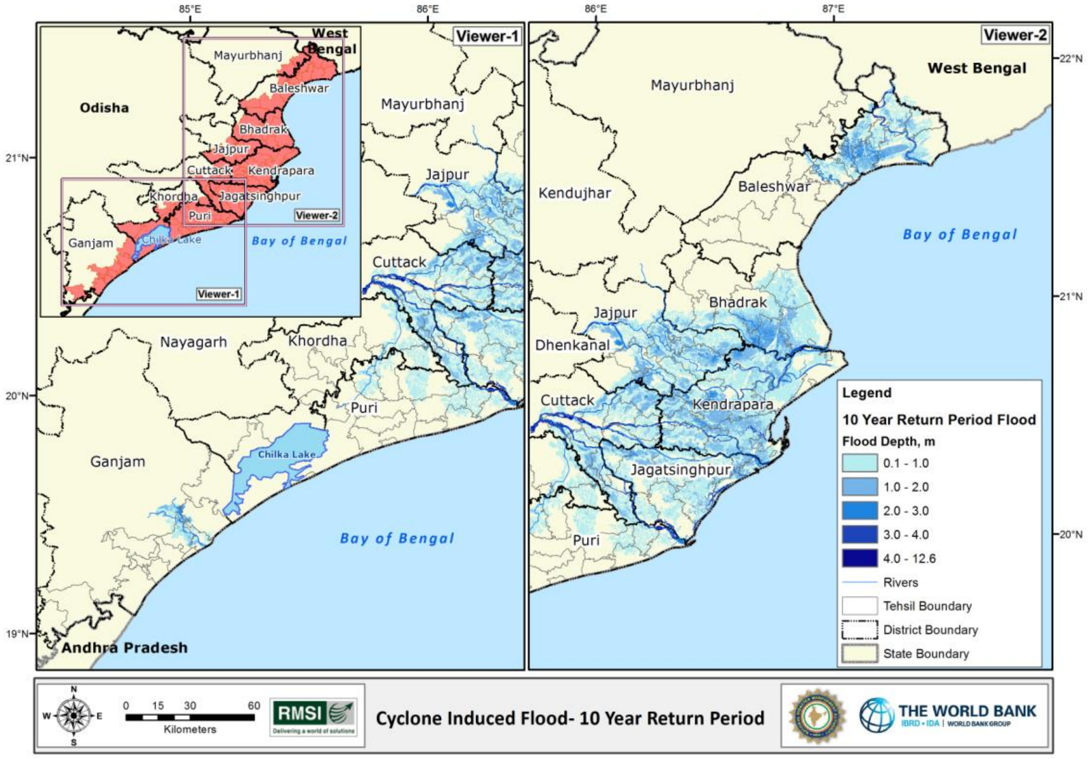

Figure 12-7: Cyclone induced flood map of Odisha for 10-year return period

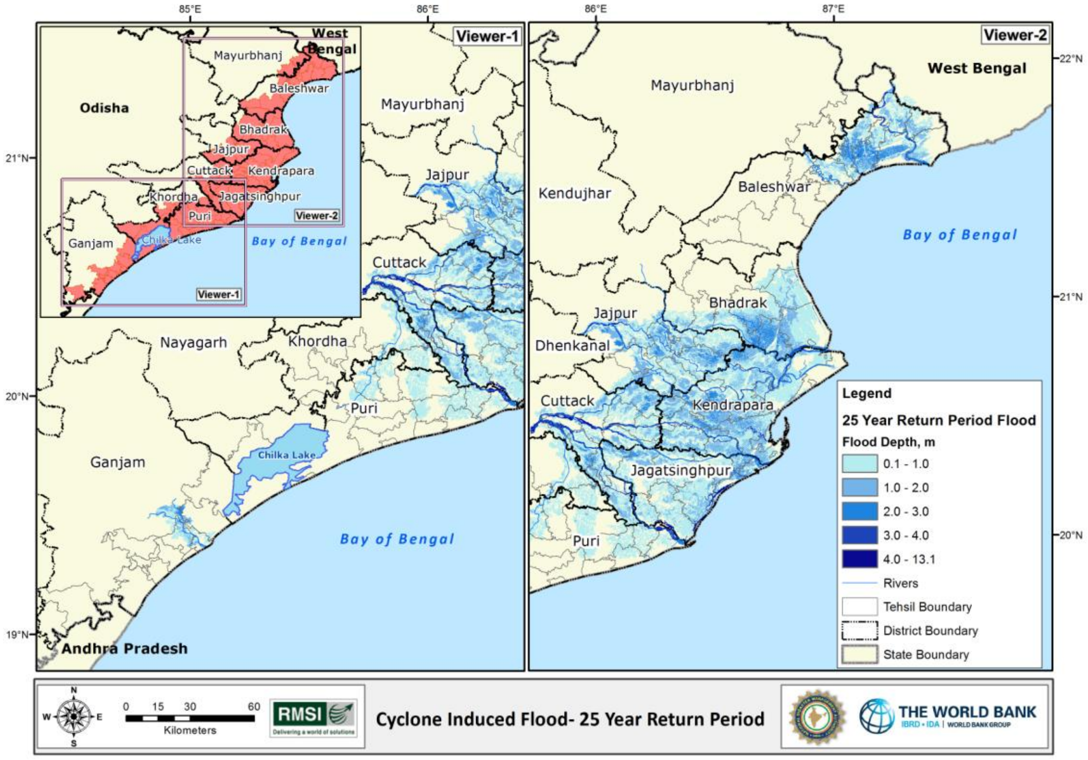

Figure 12-8: Cyclone induced flood map of Odisha for 25-year return period

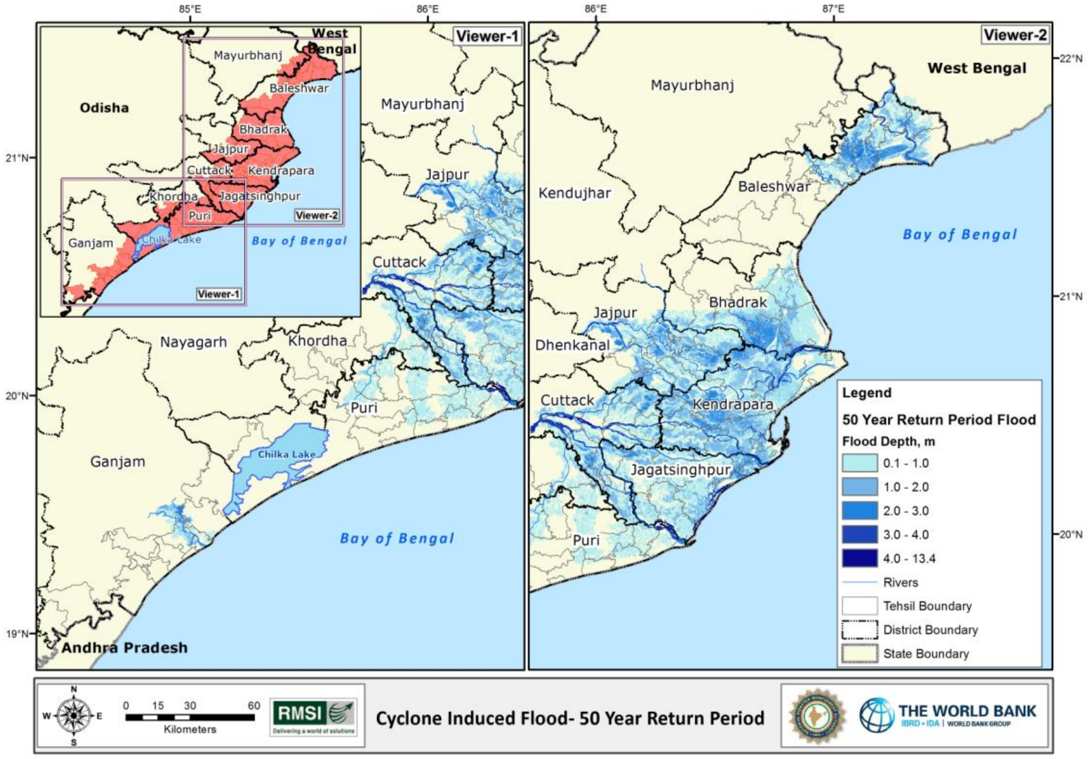

Figure 12-9: Cyclone induced flood map of Odisha for 50-year return period

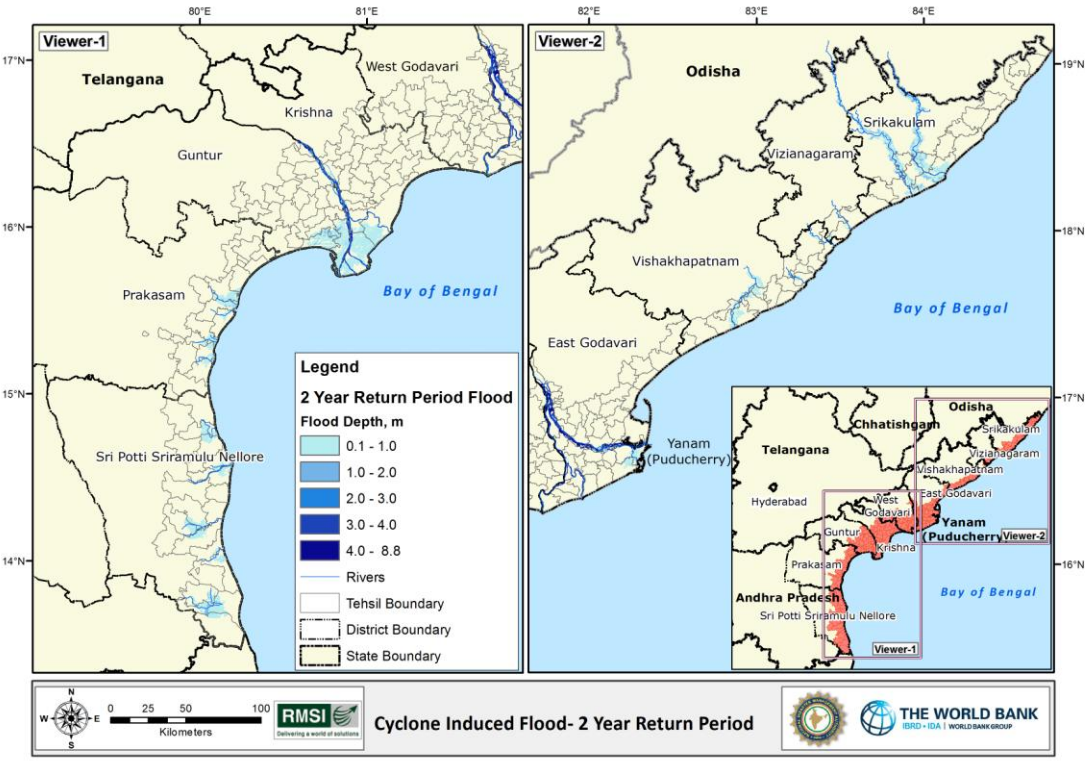

Figure 12-10: Cyclone induced flood map of Andhra Pradesh for 2-year return period

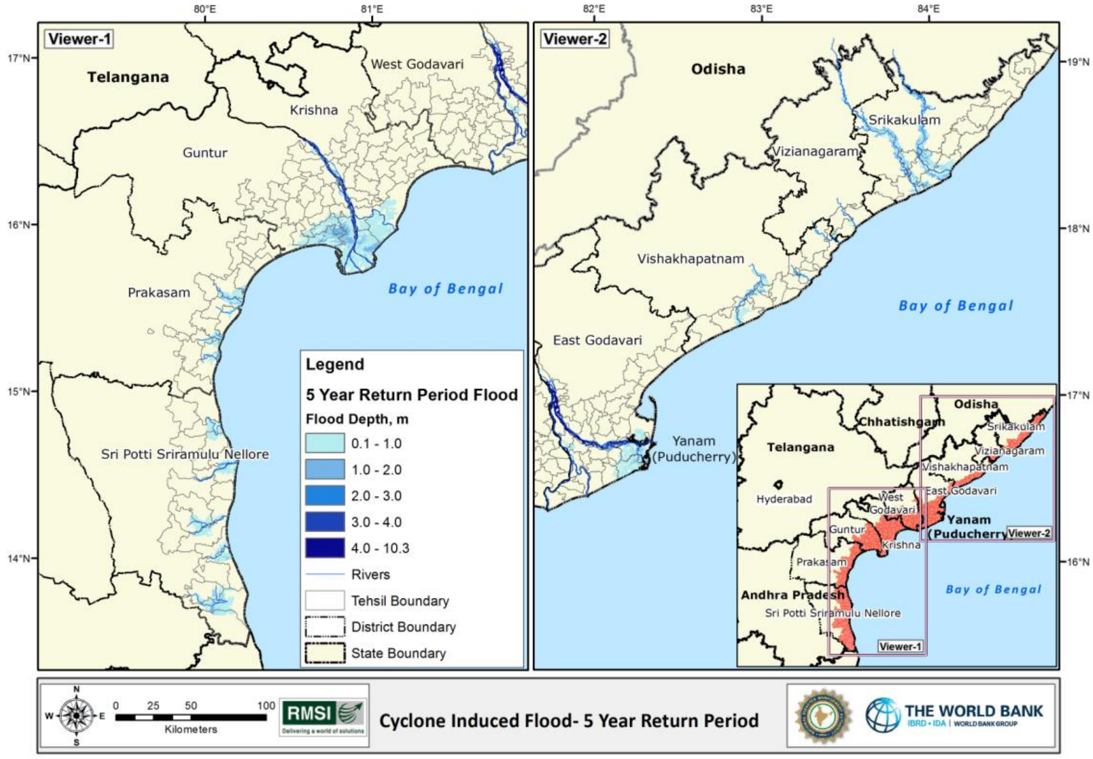

Figure 12-11: Cyclone induced flood map of Andhra Pradesh for 5-year return period

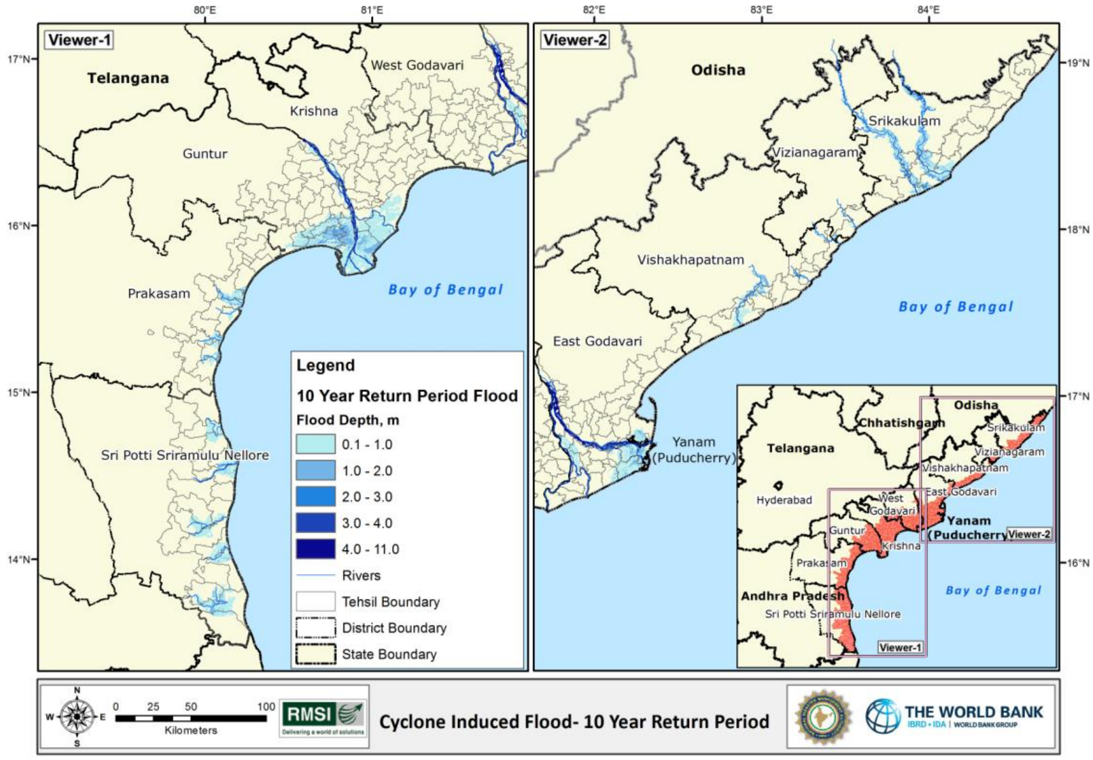

Figure 12-12: Cyclone induced flood map of Andhra Pradesh for 10-year return period

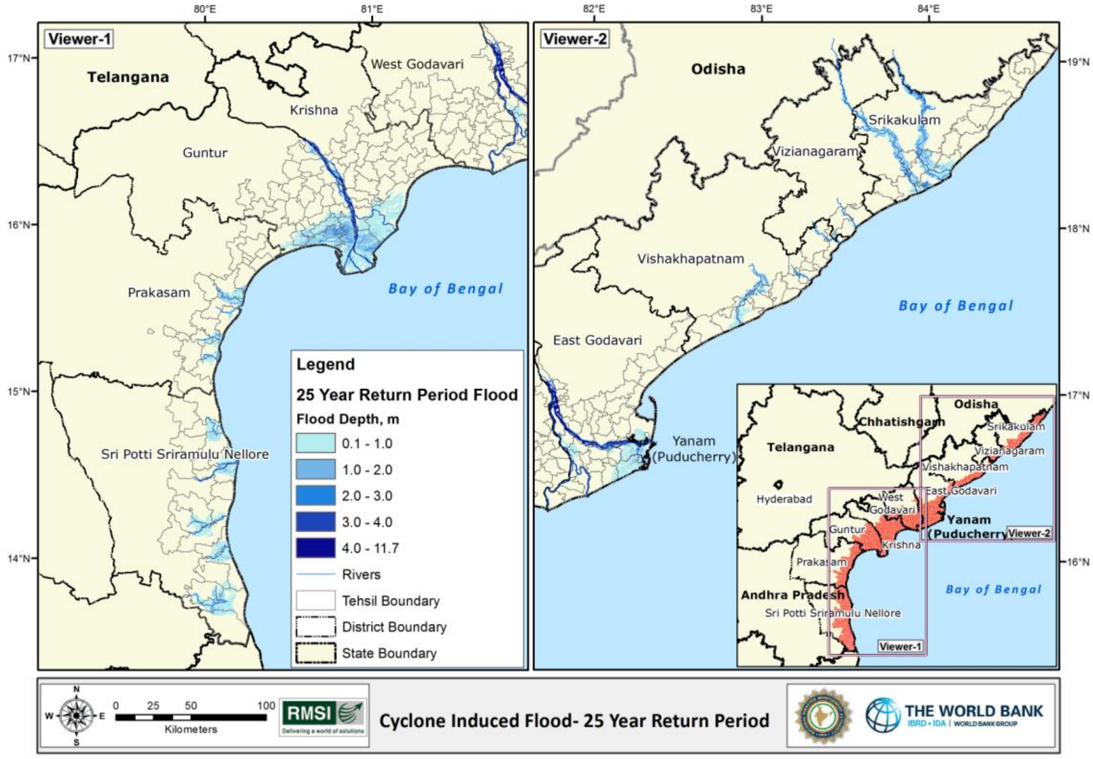

Figure 12-13: Cyclone induced flood map of Andhra Pradesh for 25-year return period

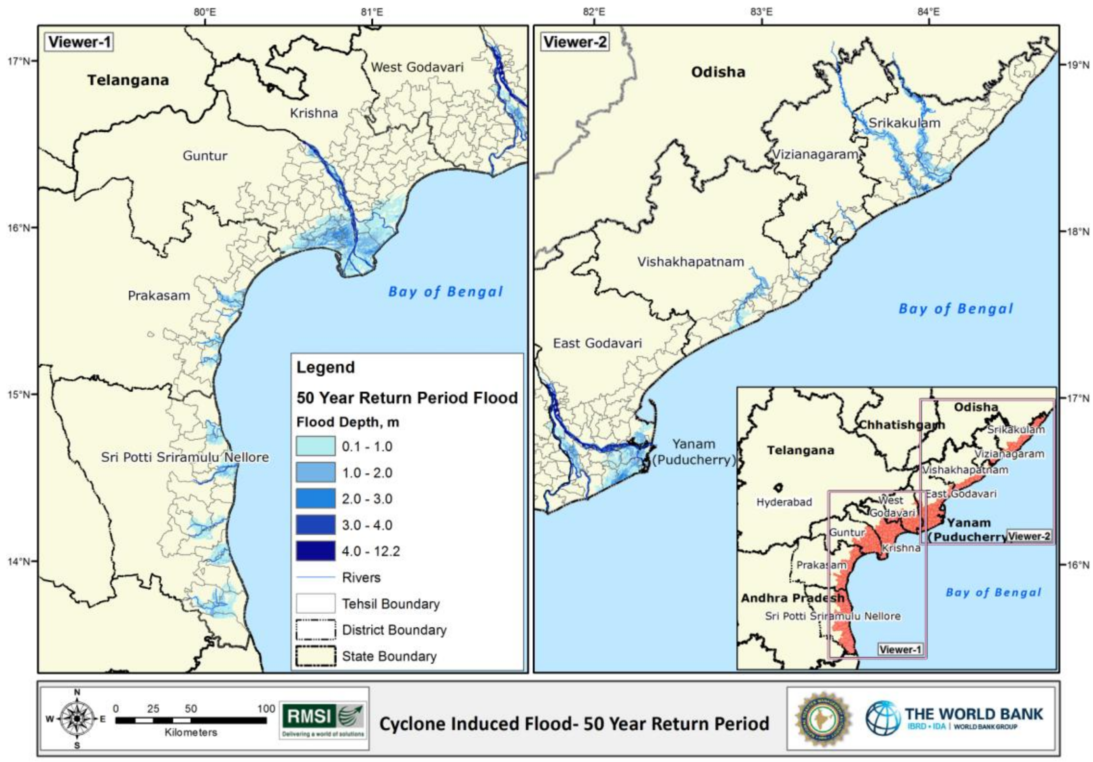

Figure 12-14: Cyclone induced flood map of Andhra Pradesh for 50-year return period

END OF REPORT