



# Kerala State Disaster Risk Financing Strategy

## COMPONENT 2: STATE CATASTROPHIC RISK PROFILE

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## Executive summary

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This study addresses the critical need for comprehensive disaster management and risk reduction strategies in Kerala, a state significantly impacted by natural disasters over the past three decades. The primary aim is to develop detailed databases of historical hazard events and their economic impacts, conduct risk assessments, and propose financial mechanisms to enhance resilience for future disasters.

Natural disasters such as floods, landslides, cyclones, storm surges, and droughts have caused substantial economic losses and human suffering in Kerala. The State is also vulnerable to coastal hazards (erosion and sea level rise), forest fires, earthquakes, tsunami, soil-piping, and lightning and thunderstorms.

The study seeks to compile a comprehensive database of major historical hazard events in Kerala, document the economic and financial losses resulting from these disasters, conduct hazard, vulnerability, and risk assessments, develop a state disaster risk financing strategy, and establish methodologies for prototype parametric risk transfer products to provide timely financial assistance.

The development of comprehensive hazard and financial loss databases, coupled with thorough risk assessments and innovative financial strategies, will position Kerala to better prepare for and respond to natural disasters. By supporting evidence-based decision-making and fostering collaboration among stakeholders, the state can enhance its resilience, reduce vulnerabilities, and safeguard its communities against future disasters. This study emphasizes the importance of proactive measures and strategic investments in building a disaster-resilient community in Kerala state.

This report, deliverable 3 and component 2 provides a comprehensive assessment of natural catastrophe (NatCAT) risks developed on RMSI Risk Modelling platform, focusing on literature review on

past hazard events, hazard modeling, exposure, and risk evaluation for floods, landslides, storms, and droughts. Using advanced methodologies and a combination of historical data and modern technologies, the study offers valuable insights into Kerala's vulnerability and resilience strategies.

### **Hazard Model Development:**

**Floods:** Rainfall data spanning 30 years (1994-2023) from IMD's gridded datasets (0.25° x 0.25° resolution) served as the basis for analyzing Kerala's rainfall patterns.

The Continuum Hydrological Model (HMC) was applied to simulate hydrological processes and generate flood predictions. Flood hazard maps were developed for 10, 25, 50, 100, 250 and 500. Notably, the 2018 Kerala floods, caused by extreme rainfall and mismanagement of reservoirs, emphasized the need for improved water management practices and predictive systems.

**Landslides:** A multi-faceted approach integrated critical variables like slope, geology, tectonic features, soil characteristics, land use, and rainfall data. Historical landslide inventories, comprising over 9,024 events, informed a Random Forest Regression (AI/ML) -based susceptibility model. Landslide-prone areas were mapped, categorizing zones from very low to very high risk.

Analysis identified prolonged rainfall events—80 to 150 mm over 3 to 5 days—as significant triggers for landslides. Probabilistic hazard models for rainfall return periods were developed to improve upon probabilistic landslide to landslides hazard modelling.

**Cyclones and Storm Surges:** High-resolution wind and storm surge models assessed the impacts of cyclonic events. Climate change projections under CMIP6 scenarios indicated a potential 4% increase in wind speeds by 2030. Coastal areas across 11 districts were mapped for vulnerability to storm surges and 14

districts were mapped for cyclonic wind hazard vulnerability.

**Droughts:** RMSI team chose to use Standardized Precipitation Evapotranspiration Index (SPEI) as the drought hazard index to quantify the drought in Kerala. The SPEI is based on a criterion for determining the beginning and end of drought or wet period spell. This index is designed to take into account both precipitation and potential evapotranspiration in determining the drought.

### Exposure Development

An extensive study has been conducted to assemble a comprehensive inventory of population and properties at risk in Kerala. Properties include Residential Buildings (Housing Sector), Govt. Buildings (Revenue offices, Panchayat offices, Municipality offices, Municipal Corporation offices, District and Tehsil headquarters offices, and other Govt. offices, such as Krishi Bhawan and KSEB buildings), Critical facilities (Schools, Hospitals, Fire stations, Police stations, Cyclone shelters), transportation network (Roads, Bridges and Bus stations); and Agriculture major crops [(Drought: Rice, Banana, Tapioca and Rubber); Flood (Paddy, Tapioca, and Banana); Cyclonic Wind (Paddy, Coconut, Arecanut, Banana); Storm-Surge (Paddy, Banana); Landslide (Paddy, Coconut, Arecanut, Banana)].

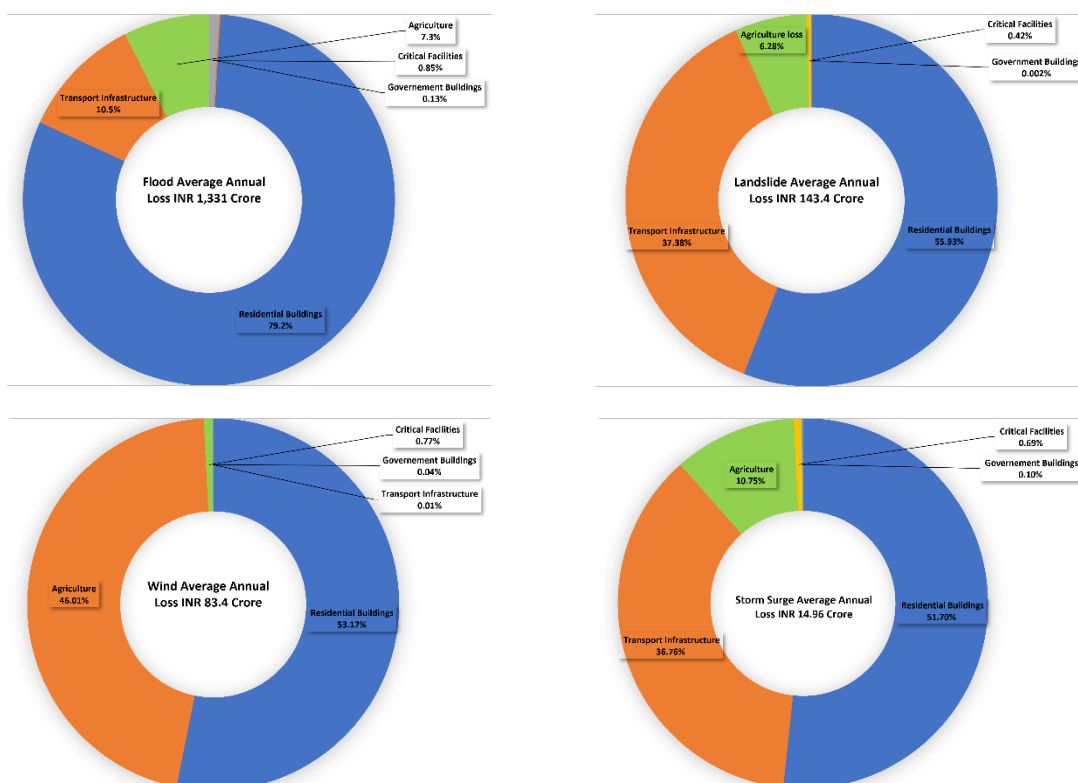
Exposure datasets were developed using high-resolution geospatial mapping and demographic statistics, supplemented by field surveys and remote sensing data. Building typologies, structural attributes, and occupancy details were key parameters considered. For example, structural classifications included masonry, reinforced concrete, and unreinforced buildings. The development process ensured granularity and accuracy to support effective risk assessments.

### Risk Assessment

Catastrophic risk assessment, being an important component of disaster risk reduction, which provides essential inputs for developing Disaster Risk Financing Strategy. Risk is the uncertainty of future losses – if we perfectly knew a future loss, it would simply be a cost, not a risk. Risk is uncertain with regard to the causative hazard event, its location, date and time of occurrence, and the degree or amount of damage to assets caused by the hazard event, and what economic losses accrue due to the damage. Sector wise distribution of Average Annual Losses (AAL) percentages for major perils are depicted in below figures.

This report deals with NatCAT modelling for flood, landslide, cyclonic wind and storm surge perils on key assets such as residential buildings, government buildings, critical facilities, transport infrastructure, and major agriculture crops in Kerala at the state, district, taluka and Local Self Government (LSG) levels. In addition, NatCAT modelling of drought hazard assessment has been carried out at district and Taluka levels for major agriculture crops. The outputs from these catastrophic models were utilized to estimate key return periods (10, 25, 50, 100, 250 and 500-years) for Probable Maximum Losses (PML) and AAL for each category of exposure elements, using the RMSI NatCAT Modelling Platform.

- The total estimated losses at the State, District, and Taluka levels are presented by aggregating the estimated losses at LSG level across various exposure elements (as detailed above).
- State level Exceedance Probability (EP) in percentage, PML and AAL are given in following table for total exposure and residential buildings respectively:



Sector wise distribution of Average Annual Losses (AAL) percentages for major perils

State level combined PML and AAL (INR Crore) for major perils

Table 2: State level combined PML&AAL (INR Crores) for major perils

Exceedance Probability (EP)	10%	4%	2%	1%	0.4%	0.2%	
Return Period (in Years)	10	25	50	100	250	500	AAL
Flood	3,752	6,760	7,718	12,498	21,002	23,355	1,332
Landslide	372	599	813	1,109	3,112	6,531	143
Cyclonic Wind	161	492	1,281	2,589	5,739	9,884	84
Storm Surge	51	62	102	156	233	296	15
Drought	354	595	619	630	NA	NA	149

NA-Not available/ not estimated

State level residential buildings PML and AAL (INR Crore) for major perils

Table 3: State level residential buildings PML&AAL (INR Crore) for major perils

Exceedance Probability (EP)	10%	4%	2%	1%	0.4%	0.2%	
Return Period (in Years)	10	25	50	100	250	500	AAL
Flood	3,029	5,667	6,285	10,395	17,680	19,372	1,082
Landslide	226	376	525	768	2,072	4,377	80
Cyclonic Wind	22	136	661	1,603	4,229	7,864	44
Storm Surge	31	34	54	79	123	157	8

**Flood and Landslide:** Kerala State level estimated AAL of INR 1,332 Crores due to floods is primarily from residential buildings, transport infrastructure and agriculture. The estimated AAL for the districts of Ernakulam and Alappuzha are INR 265.3, and 251 Crores, respectively. From Landslides, Kerala State estimated AAL is of INR 143 Crores. The major contributors to landslides damage/ losses are residential buildings, roads and agriculture.

**Cyclonic Wind:** Kerala State level estimated AAL from cyclonic winds is INR 84 Crores, with residential buildings and agriculture crops are major contributors. The estimated AAL for the districts of Palakkad, Malappuram, and Ernakulam are INR 13.5, 9.66, and 8.87 Crores, respectively. For a 250-year return period, the estimated damage/losses are highest in Palakkad district (INR 758.84 Crores) followed by Malappuram (INR 638.19 Crores).

**Storm Surge:** Kerala's State level estimated AAL from storm surge is INR 15 Crores, with residential buildings, transport infrastructure, and agriculture as major contributors. The estimated AALs for the

districts of Alappuzha and Ernakulam are INR 3.4, and 2.5 Crores, respectively. For a 250-year return period, the estimated PMLs for the districts of Alappuzha and Ernakulam are INR 67.3, 34.8 Crores, respectively.

**Droughts:** The estimated AAL is highest for Kottayam district (19.14 INR Crores), followed by Kollam (17.41 INR Crores). The Lowest AAL was observed at Kozhikod district (3.43 INR Crores). Paddy (Rice) exhibits the highest AALs among major agriculture crops, indicating greater sensitivity to water stress. Total state AAL due to drought is INR 149.43 INR crores

#### **Risk Zones of Kerala for Different Hazards:**

As mentioned earlier, probabilistic risk assessments for floods, landslides, cyclonic wind, storm surge and drought were conducted using the RMSI Risk Modelling Platform. Risk zones were delineated based on Average Annual Losses (AALs) at the LSG level for these perils across the state. However, drought risk zones were mapped at the Taluka level.

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## Abbreviations Used

Abbreviation/Acronym	Expanded form
AAL	Average Annual Loss
ADB	Asian Development Bank
AI	Artificial Intelligence
ANN	Artificial Neural Networks
AORI	Atmosphere and Ocean Research Institute
CCSR-NIES	Centre for Climate System Research-National Institute for Environmental Studies
CMIP6	Coupled Model Intercomparison Project Phase 6
CR	City Roads
CS	Cyclonic Storm
DDM	Drought Damage Matrix
DDR	Disaster Risk Reduction
DEM	Digital Elevation Models
DR	District Roads
DRF	Disaster Risk Financing
DSSAT	Decision Support System for Agrotechnology Transfer
DT	Decision Trees
ECDF	Empirical Cumulative Distribution Function
EM_DAT	Emergency Events Database
EP	Exceeding Probability
ESCS	Extremely Severe Cyclonic Storm
ESM	Earth System Model
FES	Finite Element Solution
FP	Footpaths
GBM	Gradient Boosting Machines
GEBCO	General Bathymetric Chart of the Oceans
GoF	Goodness of Fit
GSI	Geological Survey of India
IBTrACS	International Best Track Archive for Climate Stewardship
IMD	Indian Meteorological Department
IPCC-AR6	Intergovernmental Panel on Climate Change
JRDNA	Joint Rapid Damage and Needs Assessment
KSDMA	Kerala State Disaster Management Authority
LEC	Loss Exceedance Curve
LLJ	Low Level Jet
LSG	Local Self Government
MAI	Moisture Availability Index
MDR	Mean Damaging Ratio
ML	Machine Learning
MSP	Minimum Support Price
MSW	Maximum Sustained Winds
NatCAT	Natural Catastrophic
NDC	National Data Center

Abbreviation/Acronym	Expanded form
NDEM	National Database for Emergency Management
NDMA	National Disaster Management Authority
NDMIS	National Disaster Management Information System
NH	National Highways
NHO	National Hydro- graphic Office
NRSC	National Remote Sensing Centre
OSM	Open Street Maps
PDNA	Post-Disaster Needs Assessment
PDSI	Palmer Drought Severity Index
PET	Potential Evapotranspiration
PML	probable maximum losses
PNRF	Percent of Normal Rainfall
REI	Rainfall Extreme Index
RF	Random Forest
RFR	Random Forest Regression
RMSE	Root Mean Square Error
RP	Return period
SCS	Severe Cyclonic Storm
SH	State Highways
SMS	Surface Modeling System
SPEI	Standardized Precipitation Evapotranspiration Index
SPI	Standardized Precipitation Index
SuCS	Super Cyclonic Storm
SVM	Support Vector Machines
TCRM	Tropical Cyclone Risk Model
TEJ	Tropical Easterly Jet
USD	United States Dollar
VR	Village Roads
VSCS	Very Severe Cyclonic Storm

## Introduction

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### 1.1 Background

Natural disasters, such as floods, landslides, cyclones, storm surges, and droughts, have brought significant economic and human tolls in Kerala over the past three decades. The State is also vulnerable to coastal hazards (erosion and sea level rise), forest fires, earthquakes, tsunami, soil-piping, and lightning and thunderstorms. Understanding the historical occurrence of these hazards and their financial ramifications are paramount for effective disaster risk reduction strategies.

This study aims to compile comprehensive databases documenting major historical hazard events and the resulting economic losses caused by disasters over the past 30 years in Kerala.

Furthermore, the study endeavors to develop exposure database, and conduct hazard, vulnerability, and risk assessments based on state-of-art NatCat risk modeling methodology, with the objective of developing Kerala State Catastrophic Risk Profile.

Additionally, it seeks to develop a Kerala State Disaster Risk Financing Strategy and establish a methodology for designing a Prototype for Parametric Risk Transfer Products with a focus on housing sector (residential building) and Government Buildings. These proposed products are intended to mitigate the financial impact of disasters by providing efficient and timely financial assistance to affected communities and stakeholders.

### 1.2 Objectives

#### 1.2.1 DATABASE OF MAJOR HISTORICAL HAZARD EVENTS:

The first objective of this study is to construct a database of major historical hazard events in Kerala, focusing on floods, landslides, cyclones, storm surges, and droughts. Data collection involves reviewing existing records and consolidating information from various

sources, including the Emergency Events Database (EM-DAT), National Database for Emergency Management (NDEM), National Disaster Management Information System (NDMIS), and other portals. It also involves, identification of the independent reporting/ monitoring agencies for each of the major perils. The data sets are collected from Kerala State Disaster Management Authority (KSDMA) and various other published sources. The information and data regarding the historical events, especially, for the past 30 years has been consolidated.

The database includes (for each of major historical events) at least the following information: occurrence date (start and end date), location (e.g., latitude and longitude of the storm's eye for tropical cyclones), physical characteristics (e.g., central pressure along the track for tropical cyclones), affected area, damage and loss information including causality, etc. It serves to support and calibrate the probabilistic catastrophic risk models., In a nutshell, we aim to improve our understanding of Kerala State Disaster Risk Profile by documenting the occurrence of these hazards. In this study, as part of Component-1 Report (Deliverable -2), we have developed a comprehensive database of major historical disaster events for Floods, Landslides, Cyclones, Storm Surges, and Droughts.

#### 1.2.2 ECONOMIC AND FINANCIAL LOSS OF MAJOR DISASTERS

The second objective of this project is to develop a database of Economic and Financial losses caused by major disasters in Kerala over the past 30 years. Key actions include, but not limited to review of damage assessment reports, insurance reports, etc. and develop a consolidated database of financial and economic losses caused by natural disasters.

The economic losses are provided in the local currency (INR) and US\$, adjusted

from inflation and/or currency exchange rate. Datasets are collected from Disaster Memorandums, Post Disaster Need Assessment (PDNA) Reports, Insurance Records, and other relevant sources.

In this study, as part of Component-1 Report (Deliverable -2), we have developed a consolidated database of major natural disasters affecting Kerala over the past 30 years, including specific details about disasters caused by Floods, Landslides, Cyclones, Storm-Surges, and Droughts. This database also includes details on Economic and Financial Losses in addition to their other details discussed above, which helps in improving the understanding of Kerala State Disaster Risk Profile.

Hence, as part of Component-1 Report (Deliverable -2), a comprehensive Geo-Referenced Catalogue of historical major disaster events have been developed. Key parameters included in this catalogue are the date, location (latitude and longitude), type of event, areas impacted including damages and losses, number of deaths, number of injured, project damages and losses, affected economic sectors, and sources of information, etc.

### **1.2.3 STATE CATASTROPHIC RISK PROFILE:**

The third objective of this study is to conduct comprehensive hazard assessment, exposure development, vulnerability, and risk assessment for major hazards in Kerala using state-of-art

catastrophic risk modeling methodology in order to develop Kerala State Catastrophic Risk Profile. This involves modeling key hazards (floods, landslides, cyclones, storm surges, and droughts), developing exposure database, assessing vulnerability of communities and assets, and evaluating potential risks. This Report (Deliverable -3) caters to this Objective of this study.

#### **Disaster Risk Financing Strategy**

The fourth objective of this study is development of Disaster Risk Financing Strategy for Kerala State with a focus on Housing sector and Government Building (Deliverable -4).

### **1.2.4 DESIGN OF PARAMETRIC INDICES**

The fifth objective of this study is the design of parametric indices to be used for financial transactions and design Prototype Parametric Risk Transfer Instruments including indemnity and parametric-based catastrophe (property) insurance products (Deliverable -5).

## **1.3 About this Report**

This report (*Component -2*) is the third deliverable of the study. It dovetails NatCAT based hazard, exposure, vulnerability and risk assessment based on RMSI Risk Platform for key hazards, demarcation of risk zones and development of a brochure on State Catastrophic Risk Profile.

## 2 Review of Scientific Studies

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### 2.1 Severity and Frequency of Major Perils in Kerala

The purpose this chapter is to evaluate existing scientific literature on the frequency, severity, and spatial distribution of the disasters caused by various hazards such as flood and landslide, cyclonic wind and storm surge and drought in the State. It also touches upon review of other natural hazards (*though not scope of present study*) such as earthquake, tsunami, sea-level rise (taken into consideration in storm-surge hazard), erosion, soil-piping, lightning and thunderstorm impacting Kerala State. The hazard wise detail is given below:

#### 2.1.1 FLOODS

##### 2.1.1.1 Historical flood event review

Increasingly erratic rainfall patterns, possibly due to climate change, have contributed to the frequency and severity of floods in Kerala. Deforestation, unplanned urbanization, and poor land-use practices have further exacerbated the impact of flooding.

Approximately 44 rivers originate from the Western Ghats, with 41 of them flowing into either the backwaters and or the Arabian Sea. These rivers are primarily fed by the monsoon rains and are largely perennial. During the rainy season, they flow with turbulence, and the larger rivers often rise 30 to 40 cm above their danger levels, leading to significant flooding in the midland and coastal areas. The combined water volume of Kerala's rivers is approximately 250,000 million cubic feet, accounting for about 5% of India's total water potential<sup>1</sup>.

The rivers of Kerala have not only shaped the geographical landscape but have also played significant roles in the political and

military history of the state. For instance, the floods in the Periyar river in 1341 altered the course of history by blocking the mouth of the Cranganore harbor, rendering it unusable for trade. This event led to the rise of Cochin as a prominent trading center, eventually surpassing Cranganore's importance. Additionally, the floods of 1341 are said to have created the *Island of Vaipin*, with some sources attributing the commencement of the Puduvaipu era in 1341 to this event<sup>1</sup>.

Moreover, the same river, Periyar, played a crucial role in military affairs. In 1789, floods in the Periyar prevented Tipu Sultan from advancing further south of Alwaye and launching an attack on Travancore. This natural barrier influenced the course of Tipu Sultan's military campaign, highlighting the strategic significance of Kerala's rivers in shaping historical events<sup>1</sup>.

In 1924, Kerala experienced unprecedented floods, causing significant loss of life, property, and crops. The heavy rainfall, triggered by the south-west monsoon, affected the entire region from July 16 - 18, 1924. Devikulam town in Kerala recorded 484 mm of rainfall in a single day (24 hours), while Munnar saw 897 mm over three days (72 hours), highlighting the severity of the event<sup>2</sup>. The extent of paddy crops lost was roughly estimated to be 30,000 acres as shown in Figure 2-1. The memory of the devastating floods of 1924 still lingered in the minds of Kerala's residents when, in 1961, the state faced another incidence of heavy rainfall and flooding. Unlike typical monsoon seasons, where heavy precipitation occurs over 7 to 10 days, the floods of 1961 were unusually prolonged and intense. The monsoon season began fiercely in late

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<sup>1</sup> Padmanabhan, N. (2013). History of Kerala i. New writing, 164, 194.

<sup>2</sup> Central Water Commission. (2018). Study Report: Kerala Floods of August 2018. Ministry of Water Resources,

River Development & Ganga Rejuvenation, Government of India, New Delhi. <http://cwc.gov.in/main/downloads/KeralaFloodReport/Rev-1.pdf>.

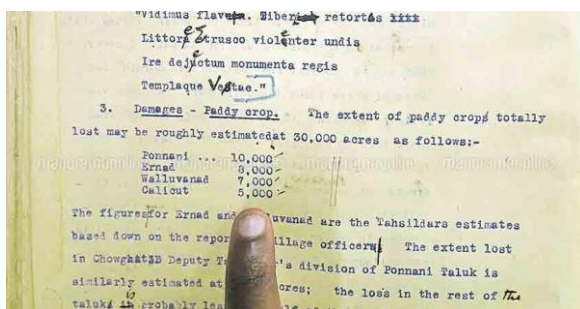
June, with torrential rains persisting until early August, primarily impacting the southern region and gradually spreading

across the entire state by July's second week.



July and August flooded most part of Travancore, Kochi, and Malabar in 1924

Roads and bridges washed away in the floods of 1924



Incessant rain caused widespread damage; the documents prove in 1924

Water level marked at Chaliyar river below Feroke bridge during the 1961 floods

Figure 2-1: Few photographs of flood incidents during 1924 and 1961 floods (Source: Manorama<sup>3</sup>)

In 1961, the Periyar sub-basin bore the brunt of the deluge, affecting other sub-basins as well. Critical infrastructure, including major and minor roads, succumbed to the rising waters. As the monsoon intensified further in mid-July, the northern regions also experienced severe flooding. Overall, the average rainfall during this period surged to 56% above normal levels, exacerbating the flood situation across Kerala. The impact of the floods and landslides in 1961 was devastating, with 115 lives lost and over 50,000 houses suffered partial or complete damages. Additionally, approximately 115,000 acres of paddy fields were severely affected, highlighting the

widespread destruction caused by the disaster.

Rajeevan et al. (2012)<sup>4</sup> analyzed historical rainfall data and hydrological modeling to study extreme rainfall events leading to floods in Kerala. Their study highlighted the influence of synoptic weather systems such as depressions and low-pressure systems in causing intense rainfall during the monsoon season. Research conducted by Singh and Kumar (2013) shed light on the occurrence and impact of flood events across India from 1978 to 2006<sup>5</sup>. Their study revealed significant insights into Kerala's vulnerability to flooding during this period. Specifically, Kerala ranked as the 4<sup>th</sup> most affected state in terms of the

<sup>3</sup> <https://www.onmanorama.com/news/kerala/2018/08/22/kerala-people-escape-99-floods-kozhikode-kochi.html>  
<sup>4</sup> Rajeevan, M., Unnikrishnan, C. K., Bhate, J., Niranjan Kumar, K., & Sreekala, P. P. (2012). Northeast monsoon

over India: variability and prediction. *Meteorological Applications*, 19(2), 226-236.  
<sup>5</sup> Singh, O., & Kumar, M. (2013). Flood events, fatalities and damages in India from 1978 to 2006. *Natural hazards*, 69, 1815-1834.

frequency of flood events, 15<sup>th</sup> in terms of fatalities, and the 14<sup>th</sup> in case of casualties among all Indian states.

One of the primary drivers behind the floods in Kerala during 1995 and 2005 was the relentless onslaught of heavy rains. These rainfall patterns exacerbated the region's susceptibility to inundation, leading to considerable damages and loss of life. Singh and Kumar (2013) findings underscore the scale of the challenge posed by flooding in Kerala. They reported a total of 1,437 flood events during the examined period, accounting for 3.2% of all flood events in India. Additionally, the *flood death rate per million in Kerala was recorded at 36.6*, highlighting the significant human toll exacted by these calamities<sup>5</sup>.

In August 2018, state of Kerala was ravaged by severe floods, precipitated by an unprecedented deluge during the monsoon season. Regarded as the most devastating flood in Kerala in the past century, the calamity resulted from exceptionally high rainfall. Official records and various sources indicate that the *death toll surpassed 483 individuals*, with 14 individuals still unaccounted<sup>6</sup>. Nearly one million people were evacuated from affected areas during the crisis, prompting a state of emergency across all 14 districts. The Kerala government reported that approximately one-sixth of the state's population bore direct consequences from the floods and associated incidents. Recognizing the severity of the situation, the Government of India classified the *disaster as a L3 Calamity*<sup>7</sup> (corresponds to a nearly catastrophic situation or a very large-scale disaster that overwhelms the State and District authorities, signifying its grave nature). This catastrophe stands as the worst flood to afflict Kerala since the catastrophic inundation of 1924, known as the "**Great Deluge of '99**".

In 2020, four districts in Kerala were flooded on 7 August 2020 (*Idukki, Wayanad, Malappuram and Kottayam*). Major reported incidents in relation to flooding include a landslide in Idukki district on 6 August, claiming 66 lives and an Air India plane crash that caused the death of 21 people<sup>8</sup>. The 2020 flood in Kerala marked the third year in a row of severe monsoon flooding.

In October 2021, Kerala experienced a severe rainfall event that led to devastating floods and landslides, particularly impacting the districts of Kottayam and Idukki. As the rain intensified on October 15 and continued through the weekend, these areas were battered by exceptionally high rainfall 305.5 mm in Idukki and 164.5 mm in Kottayam triggering widespread landslides and river flooding. This natural disaster caused significant infrastructure damage, with roads being washed away, homes destroyed, and trees uprooted. Many villages, especially in hilly regions, were completely cut off, and at least 26 lives were tragically lost due to landslides and flooding<sup>9</sup>.

The deadly floods and resulting landslide of July 30, 2024 (**known as Wayanad Landslide 2024**, detailed under *Landslide section*) is a reminder of the increasing vulnerability of the State.

In summary, floods are a recurring natural hazard in Kerala, often exacerbated by heavy monsoon rains both in frequency and intensity due to the impact of climate change and topographical factors. Historical events such as the floods of 1924, 1961, 2018, 2019, 2020, 2021 and 2024 have had significant socio-economic impacts in the State. These disasters have prompted extensive scientific research in the State to understand increasing flood dynamics and Govt. of Kerala is fully geared-up for mitigating their impacts.

<sup>6</sup> Sharma, A., & Sharma, B. Flood disasters in India: lessons from Kerala floods. *Culture of Learning and Experimentation*, 191.

<sup>7</sup> High Power Committee Report on Disaster Management (2001)

<sup>8</sup> Achu, A. L., Joseph, S., Aju, C. D., & Mathai, J. (2021). Preliminary analysis of a catastrophic landslide event on 6 August 2020 at Pettimudi, Kerala State, India. *Landslides*, 18, 1459-1463.

<sup>9</sup> <https://reliefweb.int/report/india/situation-report-kerala-floods-and-landslides-date-18-10-2021>

Review of Flood Atlas of India by NRSC<sup>10</sup>: “Flood Atlas of India” was prepared by National Remote Sensing Centre (NRSC) and published by NDMA (2023) reported

that major flood events in Kerala (Table 2-1) and district wise flood affected area in Kerala for the period of 1998-2022 as shown in Table 2-2.

Table 2-1: Major flood events in Kerala (Source: NRSC)

S. No.	Year	Description of the flood event	Districts affected
1	2005	Floods occurred during 5 <sup>th</sup> -12 <sup>th</sup> , Aug 2005 due to heavy rains.	3
2	2010	Floods were reported in many parts of Kerala due to heavy rains during 4 <sup>th</sup> week of Nov 2010.	2
3	2011	Heavy rains lashed many parts of Kerala during the 1 <sup>st</sup> week of June 2011.	1
4	2012	Floods were reported in Kerala during 1 <sup>st</sup> week of Aug 2012 due to torrential rains.	4
5	2018	Floods occurred during 16 <sup>th</sup> -21 <sup>st</sup> July, 9 <sup>th</sup> - 27 <sup>th</sup> Aug due to heavy rains	8
6	2019	Floods were reported in Kerala due to heavy torrential rains during second week of August, 2019. 10 <sup>th</sup> -14 <sup>th</sup> Aug 2018	7
7	2020	Floods were reported in Kerala during second week of Aug, 2020. 8 <sup>th</sup> - 12 <sup>th</sup> Aug 2020 due to heavy rains	5
8	2022	Floods occurred due to heavy rains were reported in Kerala state during the last week of July 2022	7

Table 2-2: District wise statistics of Flood affected areas in Kerala (Source: NRSC)

S. No.	District	Flood Affected Area (ha)
1	Kottayam	21,379
2	Thrissur	19,562
3	Alappuzha	12,187
4	Ernakulam	7,663
5	Pathanamthitta	6,052
6	Malappuram	5,989
7	Palakkad	4,137
8	Kollam	1,829
9	Wayanad	469
10	Kozhikode	110
TOTAL		79,377

### 2.1.1.2 Frequency of Floods in Kerala

Kerala experiences significant flooding almost every year due to the south-west monsoon (June to September). The intensity of these floods varies, but some districts like Kottayam, Thrissur, Ernakulam, Alappuzha, and Kozhikode are

particularly prone. Historically, Kerala has seen several severe floods, with major events recorded in 1924, 1961, 2018, 2019, 2020, 2022, and 2024. The floods of 2018 were among the worst in terms of socio-economic losses in nearly a century, when the State received 42% more rainfall

<sup>10</sup>

[https://ndma.gov.in/sites/default/files/PDF/FHA/Flood\\_Affected\\_Area\\_Atlas\\_of\\_India.pdf](https://ndma.gov.in/sites/default/files/PDF/FHA/Flood_Affected_Area_Atlas_of_India.pdf)

than normal between June and August in two episodes.

### 2.1.1.3 Severity of Floods in Kerala

- **2018 Kerala Floods:** The 2018 floods were catastrophic, resulting in over 400 deaths, displacement of over 1 million people, and damages estimated at ₹20,642 crores (excluding employment and livelihoods)<sup>11</sup>. The floods were caused by unusually high rainfall and the release of water from several dams.
- **2019 Floods:** Following a similar pattern, the 2019 floods also caused widespread devastation with over 120 fatalities, significant property damage, and disruption of lives.
- **Impact on Agriculture and Infrastructure:** The severity of the floods in Kerala often leads to extensive damage to housing, agriculture, and infrastructure. Floods also cause landslides in hilly areas, leading to additional loss of life and property.

## 2.1.2 LANDSLIDES

### 2.1.2.1 Review of Historical landslides

Landslides in Kerala, particularly in the Western Ghats region, have been a recurring hazard with significant socio-economic and environmental implications.

In Kerala State, with the exception of the coastal district of Alappuzha, all 13 out of the 14 districts are susceptible to landslides. Approximately 8% (1,400 sq. km) of the area in the Western Ghats region of Kerala is categorized as a **critical zone for mass movements** (Thampi et al., 1995)<sup>12</sup>. This region experiences various types of landslides, particularly during the monsoon season, including rock falls, rock slips, slumps, creeps, debris flows, and rotational slides in some instances. Among these, the most common and devastating

type of mass movement observed in Kerala is the "*debris flow*," locally known as "**Urul Pottal**". This phenomenon is characterized by *the rapid and sudden downhill movement of highly water-saturated material, ranging from soil particles to large boulders, which destroys and carries away everything in its path*<sup>13</sup>.

Several studies have focused on landslide hazard assessment and mapping in Kerala, utilizing a variety of methodologies and approaches. Thampi et al. (1995) conducted a pioneering study on landslide hazard zonation mapping in Kerala, identifying critical zones for mass movements using geospatial techniques. In 1998, Thampi et al. (1998) conducted a detailed analysis of various landslide types observed in Kerala, including rock falls, rock slips, slumps, creeps, and debris flows. The study emphasized the prevalence of debris flows, locally known as "*Urul Pottal*," as the most destructive type of landslide in Kerala due to their rapid and unpredictable nature. Understanding the characteristics and behavior of different landslide types (Figure 2-2 and Figure 2-3) is crucial for assessing their potential impacts and suggesting effective mitigation measures.

Building upon this work with subsequent studies by Kumar et al. (2016) and Narendran et al. (2019), the RMSI team employed remote sensing and GIS techniques to map landslide susceptibility and monitor changes in landslide-prone areas over time. These studies have contributed valuable insights into the spatial distribution of landslide hazards.

The triggering factors of landslides in Kerala are multifaceted and include both natural and anthropogenic factors. Heavy rainfall is a primary trigger for landslides in the region (Kumar et al., 2016). Geological factors such as slope steepness, soil composition, and geological structure also

<sup>11</sup> Kerala Post disaster Needs Assessment report jointly developed by international development partners- European Union, World Bank, ADB and UN systems ( PDNA 2018).

<sup>12</sup> Thampi, P. K., Mathai, J. O. H. N., & Sankar, G. (1995, August). A regional evaluation of landslide prone areas in

the Western Ghats of Kerala. In national seminar on landslides in Western Ghats (pp. 29-30).

<sup>13</sup> Thampi, P. K., Mathai, J., Sankar, G., & Sidharthan, S. (1998). Evaluation study in terms of landslide mitigation in parts of Western Ghats. Kerala, Centre for Earth Science Studies, Government of Kerala, Thiruvananthapuram, India, 100.

play a significant role in landslide susceptibility (Narendran et al., 2019). Additionally, land cover changes, deforestation, road construction, and other human activities have been identified as

contributing factors to landslide occurrence (Gowtham et al., 2020). Understanding the complex interactions between these factors is essential for effective landslide risk assessment and mitigation planning.

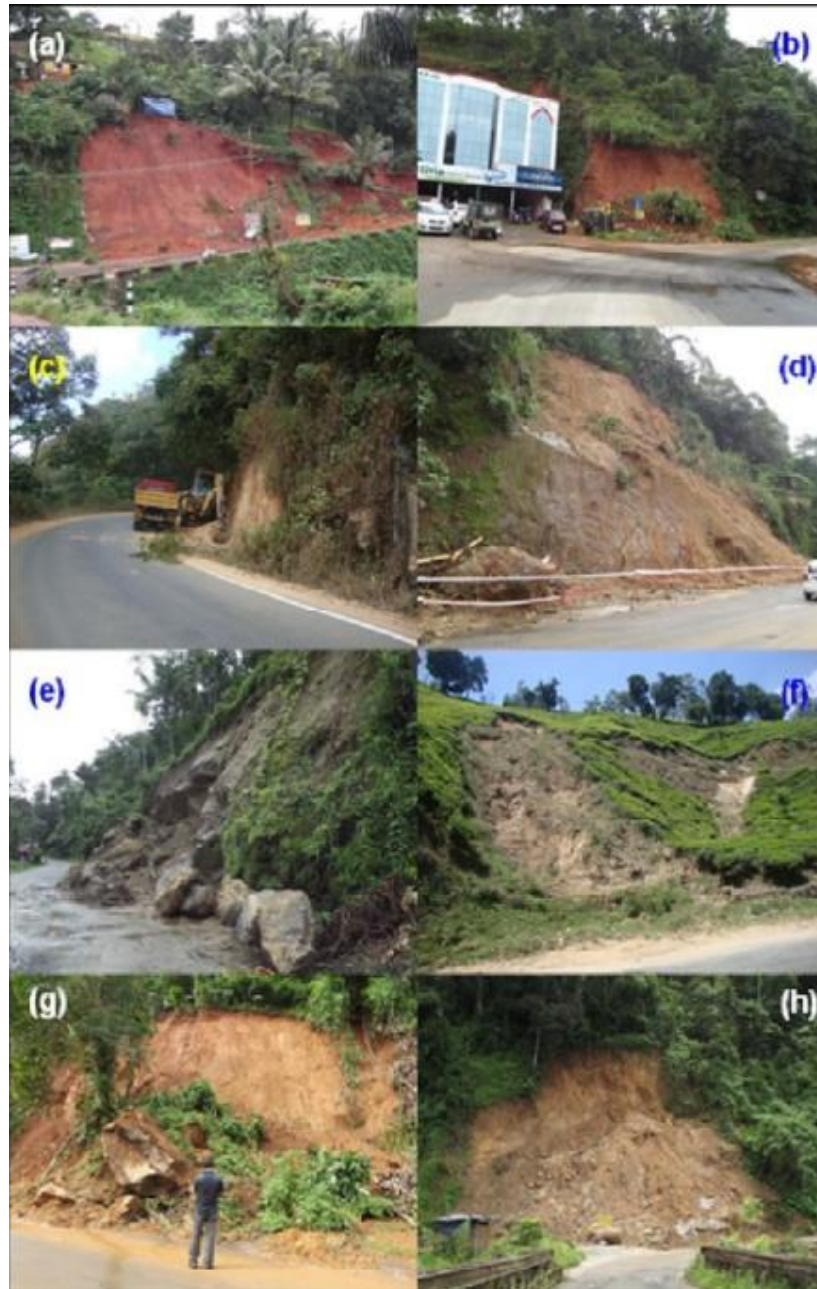


Figure 2-2: Landslides in different parts of Idukki district caused due to the removal of toe for construction of road. a) Cheruthoni, b) Irumbupalam, c) Chinnakanal, d) Cheeyapara, e) Kirithodu, f) Munnar, g) Adimall and h) Kallar (Modified after GIS 2013 report)



Figure 2-3: Landslides in different parts of Idukki district caused due to the heavy rainfall a) Cheruthoni, b) Irumbupalam, c) Chinnakanal, d) Cheeyapara, e) Kirithodu, f) Munnar, g) Adimall and h) Kallar (Modified after GIS 2013 report)

Assessing the socio-economic and environmental impacts of landslides is crucial for identifying vulnerable areas and populations and prioritizing mitigation measures. Kumar et al. (2020) conducted a vulnerability assessment of landslide-prone areas in Kerala, considering factors such as population density, infrastructure, and land use patterns. The study highlighted the disproportionate impacts of landslides on marginalized communities

and emphasized the need for targeted interventions to enhance resilience and reduce vulnerability.

In addition to 2018 landslides, the 2019 landslides, such as the *Kavalappara landslide of 2019*, have resulted in significant loss of life and property (Srinivas et al., 2020). The July 30, 2024 floods and resulting in Wayanad, Kerala, 2024 is among the deadliest landslides the state

has seen in recent decades. This landslide, triggered by unusually heavy monsoon rains claimed hundreds of lives and swept away hundreds of buildings, leaving vast areas uninhabitable. A review of satellite imagery of the region revealed extensive damage that stretched downhill and into river basins. Mundakkai and Chooralmala are the two of the worst-affected villages, which experienced extensive damage and destruction of life and property.

### 2.1.2.2 Review of Landslide Atlas of India by NRSC<sup>14</sup>

Landslide atlas prepared by NRSC and published by NDMA ranked various districts of India for their exposure to landslides. Table 2-3 displays the ranks of Kerala districts for their incidence to landslide exposure.

### 2.1.2.3 Frequency of Landslides in Kerala

Landslides in Kerala have been reported with increasing frequency and intensity, particularly over the last decade. On average, Kerala experiences several hundred landslides annually. A study by the Geological Survey of India (GSI) highlights that more than 20 major landslides occurred in Kerala between 2018 and 2022, with many landslides often going

unreported, particularly, those happened in forest areas.

### 2.1.2.4 Severity of Landslides in Kerala

The severity of landslides in Kerala varies, with some leading to catastrophic consequences. The 2018 and 2019 landslides were among the most severe, caused widespread damage, loss of lives, and displacement of people. The 2018 landslide in the Idukki district alone resulted in over 59 deaths. The 2019 monsoon-triggered landslides in Wayanad, Malappuram, and Kozhikode districts were devastating, leading to extensive damage to infrastructure, property, and agriculture, with more than 80 deaths reported. The severity of landslides is exacerbated by deforestation, unregulated construction, and changes in land use patterns, particularly in ecologically sensitive zones.

- **Annual landslide incidents (2010-2022):** Kerala has seen a significant rise in landslide events, with around 4,000 landslides reported in 2018 alone.
- **Casualties (2018-2022):** Over 200 lives have been lost due to landslides in this period, with the highest fatalities recorded during the monsoon seasons of 2018 and 2019.

Table 2-3: Table shows the rank of districts of Kerala for their exposure to landslides.

District Rank	District	State
3	Thrissur	Kerala
5	Palakkad	Kerala
7	Malappuram	Kerala
10	Kozhikode	Kerala
13	Wayanad	Kerala
15	Ernakulam	Kerala
18	Idukki	Kerala
24	Kottayam	Kerala
26	Kannur	Kerala
28	Thiruvananthapuram	Kerala
33	Pathanamthitta	Kerala
44	Kasaragod	Kerala
48	Kollam	Kerala
138	Alappuzha	Kerala

<sup>14</sup>

[https://ndma.gov.in/sites/default/files/PDF/Landslide\\_Atlas\\_2023.pdf](https://ndma.gov.in/sites/default/files/PDF/Landslide_Atlas_2023.pdf)

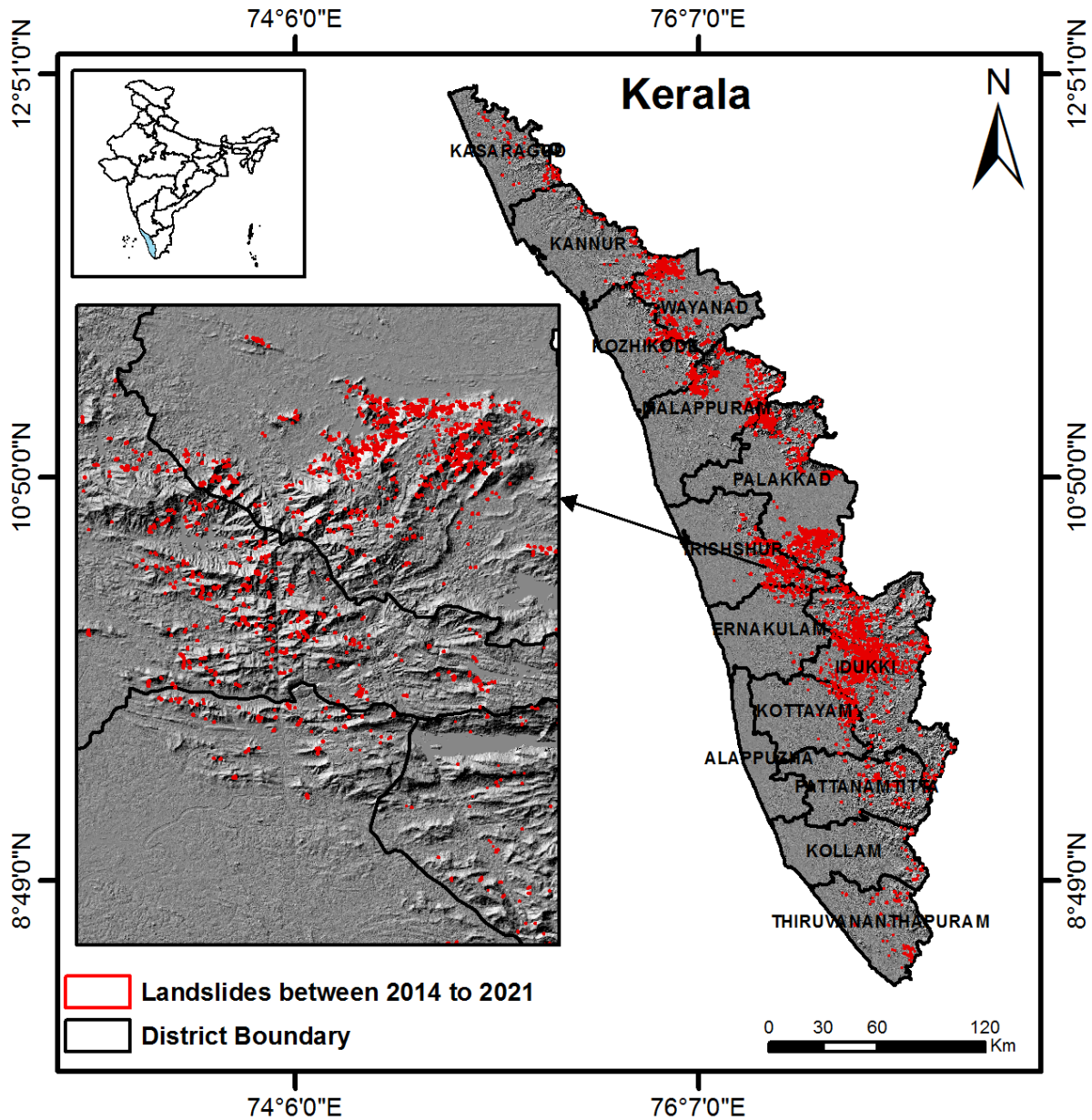


Figure 2-4: Landslides mapped using high-resolution satellite data in Kerala which, occurred between 2014 to 2021 (Source: NRSC).

The landslides in Kerala are characterized by high frequency and significant severity, driven by a combination of natural factors and human activities. The region's vulnerability underscores the need for

sustainable land use practices, improved early warning systems, and robust disaster management strategies to mitigate future risks.

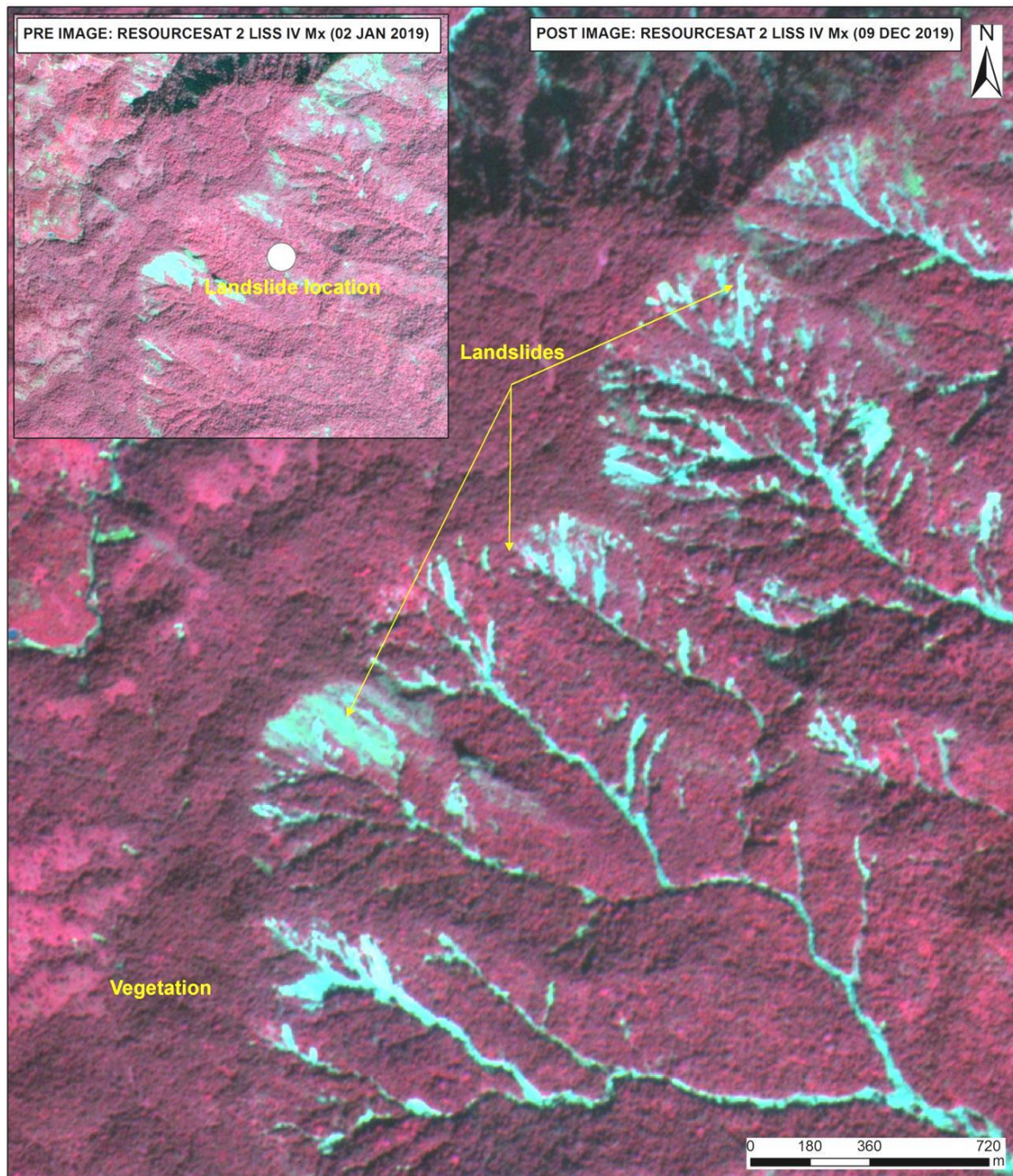


Figure 2-5: Landslide from Puthumala region, Wayanad district, Kerala. Most of these landslides are channelized debris flow

### 2.1.2.5 Floods and Landslides

RMSI team has also reviewed some of the research publications/reports on floods and landslides available in the public domain

and their reference along with brief details are summarized in Table 2-4.

Table 2-4: Literature review for flood and landslide

S. No.	Peril	Title	Details
1.	Landslide	History of landslide susceptibility and a chorology of landslide-prone areas in the Western Ghats of Kerala, India  Author: Sekhar L. Kuriakose, G. Sankar, C. Muraleedharan Year: 2009  Year of Occurrence: 1984 to 2008	<ul style="list-style-type: none"> <li>This study surveyed 29 major landslide events in Kerala that occurred from 1984 to 2008 and suggested that the initiation zones of most of the landslides were typical hollows, generally having degraded natural vegetation.</li> <li>Except coastal district of Alappuzha, majority of districts in Kerala are prone to landslides.</li> <li>Wayanad and Kozhikode districts are prone to deep seated landslides, while Idukki and Kottayam districts are prone to shallow landslides.</li> </ul>
2.	Flood and Landslide	Landslides and Flood Losses – 2012  Author: Department of Disaster Management, Government of Kerala Year: 2012  Year of Occurrence: 2012	<ul style="list-style-type: none"> <li>Landslides were reported from six districts namely Kannur, Kozhikode, Palakkad, Ernakulam, Idukki, and Kottayam.</li> <li>Due to heavy rainfall, Pazahsshi Dam in Iritty town overflowed aggravating the disastrous situation and led to 16 casualties.</li> <li>Landslides caused severe damages to 541 hectares of perennial crops</li> </ul>
3.	Flood, Landslide and Wind	Monsoon Calamity Losses – 2013  Author: Department of Disaster Management, Government of Kerala Year: 2013  Year of Occurrence: 2013	<ul style="list-style-type: none"> <li>Landslides were reported from Kozhikode, Palakkad, Idukki, and Pathanamthitta districts of Kerala due to the unexpected exceed of South West Monsoon between 1<sup>st</sup>-30<sup>th</sup> June, 2013</li> <li>Floods, windfall and landslides have caused severe damages to the crops.</li> </ul>
4.	Landslide	Monsoon Calamity Losses - 2014  Author: Department of Disaster Management, Government of Kerala Year: 2014  Year of Occurrence: 2014	<ul style="list-style-type: none"> <li>Intense pre-monsoon rainfall in the month of April, 2014, especially along the southern districts of Kerala (Thiruvananthapuram to Ernakulam) led to some isolated cases of landslides.</li> </ul>
5.	Flood and Landslide	Kerala Floods – 2018  Author: Department of Disaster Management, Government of Kerala Year: 2018  Year of Occurrence: 2018	<ul style="list-style-type: none"> <li>96% excess rainfall than the average long period rainfall from South west monsoon caused significant damages to life and property.</li> <li>Kerala State Disaster Management Plan (SDMP) identified 14.4% of the State as landslide prone. Land Revenue Department reported 331 landslides, rock slides, and landslips in all districts in Kerala, of which</li> </ul>

S. No.	Peril	Title	Details
6.	Flood and Landslide	<p>Kerala Floods – 2019</p> <p>Author: Department of Disaster Management, Government of Kerala Year: 2019</p> <p>Year of Occurrence: 2019</p>	<p>Idukki district was the most badly affected.</p> <ul style="list-style-type: none"> <li>Between August 8 and 31, 2019, Kerala experienced flood and landslides due to the influence of low-pressure area and depression formed over the Bay of Bengal and strengthening of Monsoon winds, Kerala.</li> <li>Kerala received 123% excess rainfall than the average long period rainfall in August.</li> <li>13 out of 14 districts in Kerala were notified as affected by floods &amp; landslides and have caused exorbitant damages to the agriculture sector.</li> </ul>
7.	Landslide	<p>Land Degradation in the Western Ghats: The Case of the Kavalappara Landslide in Kerala, India</p> <p>Author: Nirmala Vasudevan, et. al. Year: 2022</p> <p>Year of Occurrence: 2019</p>	<ul style="list-style-type: none"> <li>Kavalappara landslide that occurred in 2019 resulted in the loss of 59 lives and considerable damages to property.</li> <li>This study suggested that the human activities aggravated the slope instability such as, conversion of natural vegetation to plantations, step cutting of slopes, construction of soak pits, construction of homes on natural drainage channels, and improper methods of drainage.</li> </ul>
8..	Landslide	<p>Preliminary analysis of a catastrophic landslide event on 6 August 2020 at Pettimudi, Kerala State, India</p> <p>Author: Achu et al., 2021</p> <p>Year of Occurrence: 2020</p>	<ul style="list-style-type: none"> <li>Pettimudi landslide was one of the disastrous landslides that occurred in the Pettimudi village of Idukki district, Kerala and this study suggested that it was initiated on the steep slopes of Shola Forest and its lid through the tea plantations and approx. 70,125 m<sup>2</sup> area was estimated to be affected by the landslide.</li> </ul>
9.	Landslide	<p>The tale of three landslides in the Western Ghats, India: lessons to be learnt.</p> <p>Author: Ajin et. al., 2022</p> <p>Year of Occurrence: 2021</p>	<ul style="list-style-type: none"> <li>This study observed three landslides that occurred on 16<sup>th</sup> October 2021: Kokkayar landslide, Plappally landslide, and Kavali landslide.</li> <li>Study suggested that Kokkayar landslide was completely caused by humans; Plappally landslide was affected by geomorphic and tectonic causes, and Kavali landslide was caused by forest fragmentation.</li> </ul>
10.	Landslide	<p>Impact of anthropogenic activities on landslide occurrences in</p>	<ul style="list-style-type: none"> <li>This study suggests that the Landslide hotspots are</li> </ul>

S. No.	Peril	Title	Details
11.	Landslide	<p>southwest India: An investigation using spatial models</p> <p>Author: Jone et. al., 2021</p> <p>Evaluating the relation between land use changes and the 2018 landslide disaster in Kerala, India</p> <p>Author: Hao, et. al., 2022</p>	<p>concentrated in Idukki, Ernakulam, Kottayam, Wayanad, Kozhikode and Malappuram districts of Kerala.</p> <ul style="list-style-type: none"> <li>Nearly 59.38% of total landslides in Kerala have occurred in the plantation areas and about 64.76% of the state's total landslides have happened in the human-modified land-uses.</li> <li>LULC classes from 8 years (from 2010 to 2018) were correlated at the landslide initiation points. Highest landslide density found in the built-up areas within Idukki district and were related to cut slope failures.</li> </ul>

#### 2.1.2.5.1 Extreme Rainfall and associated floods and landslides (2012) <sup>15</sup>

In 2012, floods and landslides were reported from six districts namely Kannur, Kozhikode, Palakkad, Ernakulam, Idukki, and Kottayam. Flood situation prevailed in Iritty town in Kannur district as the region has experienced very heavy rainfall. As a consequence, Pazahsshi Dam in Iritty town overflowed and aggravated the disastrous situation Figure 2-6 shows the photographs depicting damages due to landslides and floods in Kerala, 2012.

- Kannur: Two landslides were reported from Karikottakiri and Murikkan Kara in Ayyankunnu Village, Thalasherry Taluka on 6<sup>th</sup> and 7<sup>th</sup> August. On these days, the region experienced a >100-year return interval rainfall which resulted in the flooding of Iritty township and the overflowing of Pazahsshi Dam. One fatality was reported. On 26<sup>th</sup> August a landslide was reported from Thirumeni village

- and Thalasherry Taluka which damaged the arterial road of the village.
- Kozhikode: Over 35 minor and major debris flows were reported from Pulloorampara Anakkampoyil region on 6<sup>th</sup> August 2012. Acres of crop land perished and 8 fatalities were reported.
- Palakkad: A debris flow occurred at 100 acres, Ambalappara, Kottappadam Panchayath within the Silent Valley National Park Buffer Zone. The event was reported on 22<sup>nd</sup> August as the region is only accessible by foot and is an abode of forest dwelling tribal communities. The actual date of occurrence is unknown. The hill which was affected is the origin of Vaniyampara river and it houses numerous medicinal plants thus resulting in loss of biodiversity.
- Ernakulam: A major debris flow occurred in Kadavoor village of Kothamangalam Taluka on 17<sup>th</sup> August 2012. Six fatalities were reported, in addition to significant loss to property.
- Estimated loss as per CRF Norms: Rs. 2,656.54 lakhs (Rs. 26.57 crores)

<sup>15</sup> <https://sdma.kerala.gov.in/wp-content/uploads/2018/11/9.Memorandum-Landslides-2012.pdf>



Figure 2-6: Various photographs depicting damages due to landslides and floods in Kerala, 2012

#### 2.1.2.5.2 Kerala Floods & Landslides (2018)<sup>1617</sup>

##### **Monsoon related disasters - 29<sup>th</sup> May to 31<sup>st</sup> July 2018:**

In total 363 villages have been affected due to monsoon related disasters. Forty-seven (47) landslides occurred in the state. According to National Remote Sensing Agency of ISRO, 55,007 ha of land in Kerala was inundated on 16-7-2018. Such catastrophe due to monsoon rainfall has been witnessed for the first time since 1924, in the state.

##### **Monsoon related disasters 1st August to 31st August 2018:**

The heavy monsoon of 2018 in particular brought widespread flooding to several districts of Kerala state and triggered a large number of small to big landslides. The extreme and prolonged rainfall spell in August 2018 led to the worst flooding in Kerala in nearly a century impacting almost 5.4 million people - one-sixth of the State's population. Several districts were inundated for more than two weeks due to heavy rains induced floods. The torrential

rains triggered several landslides and forced the release of excess water from 37 dams across the State, adding to the impact of floods. Nearly 341 major landslides were reported from 10 districts. Idukki district was ravaged by 143 landslides. 1,260 out of 1,664 villages spread across its 14 districts were affected. Seven districts were worst hit: Alappuzha, Ernakulam, Idukki, Kottayam, Pathanamthitta, Thrissur, and Wayanad where the whole district was notified as flood affected. Figure 2-9 represents spatial distribution of landslide/ mudslides that occurred in 2018.

According to KSDMA memorandum reports, the combined estimated losses from these two events were INR 789 crore for reconstruction and INR 2,658 crore for the economic sector. The Post-Disaster Needs Assessment (PDNA) estimates that the total damages amount to approximately INR 10,557 crore and total losses to be around INR 16,163 crore, resulting in a combined disaster effect of approximately INR 26,720 crore (USD 3.8 billion)<sup>18</sup>.

<sup>16</sup> <https://sdma.kerala.gov.in/wp-content/uploads/2019/08/Memorandum1-Floods-2018.pdf>

<sup>17</sup> <https://sdma.kerala.gov.in/wp-content/uploads/2019/08/Memorandum2-Floods-2018.pdf>

<sup>18</sup> <https://www.undp.org/publications/post-disaster-needs-assessment-kerala#:~:text=December%2012%2C%202018&text=Near ly%20341%20landslides%20were%20reported,state's%20 14%20districts%20were%20affected.>

Table 2-5: Monsoon calamity losses due to 29<sup>th</sup> May to 31<sup>st</sup> July 2018 floods and landslides (Modified after KSDMA 2018 memorandum1)

District	Total Deaths	No People Affected	No Houses damaged	PWD Roads (Km)	Bridges	Schools	Primary Health Centres	Agriculture land affected (ha)	Total Economic loss (INR Crore)
Thiruvananthapuram	7	626	1,319	202.00	-	44	14	325.59	44.42
Kollam	3	606	788	354.57	-	3	2	354.87	34.73
Pathanamthitta	8	14,607	1,544	844.65	23	19	7	91.53	42.08
Kottayam	9	61,155	781	-	12	85	29	5,103.46	72.49
Alappuzha	12	4,98,518	619	380.63	27	148	57	13,087.75	88.23
Idukki	5	278	855	933.57	-	16	8	2,608.17	28.50
Ernalulam	6	7,557	531	527.56	-	26	9	589.72	71.34
Thrissur	11	10,935	338	557.87	2	16	7	812.82	41.18
Palakkad	4	250	527	1,163.42	1	194	63	2,140.57	59.21
Malappuram	13	286	602	1,991.00	3	-	-	1,020.50	26.93
Kozhikode	21	6,083	2,518	760.00	-	4	-	278.17	44.41
Wayanad	5	5,780	430	436.44	-	-	6	541.04	11.48
Kannur	22	106	965	581.95	-	-	1	294.87	50.65
Kasaragod	12	80	285	46.70	-	1	-	110.08	12.57

Source: KSDMA memorandums

These figures do not include damage estimates from the Joint Rapid Damage and Needs According to KSDMA memorandum reports, the combined estimated losses from these two events were INR 789 crore for reconstruction and INR 2,658 crore for the economic sector. The Post-Disaster Needs Assessment (PDNA) estimates that the total damages amount to approximately INR 10,557 crore and total losses to be around INR 16,163 crore, resulting in a combined

disaster effect of approximately INR 26,720 crore (USD 3.8 billion)<sup>19</sup>. These figures do not include damage estimates from the Joint Rapid Damage and Needs Assessment (JRDNA) conducted by the World Bank and the Asian Development Bank (ADB). The total estimated damages exclude those to private buildings and properties, such as shops, showrooms, business units, private hospitals, educational institutions, and private vehicle

<sup>19</sup> <https://www.undp.org/publications/post-disaster-needs-assessment-kerala#:~:text=December%2012%2C%202018&text=Nearly%20341%20landslides%20were%20reported,state's%2014%20districts%20were%20affected.>

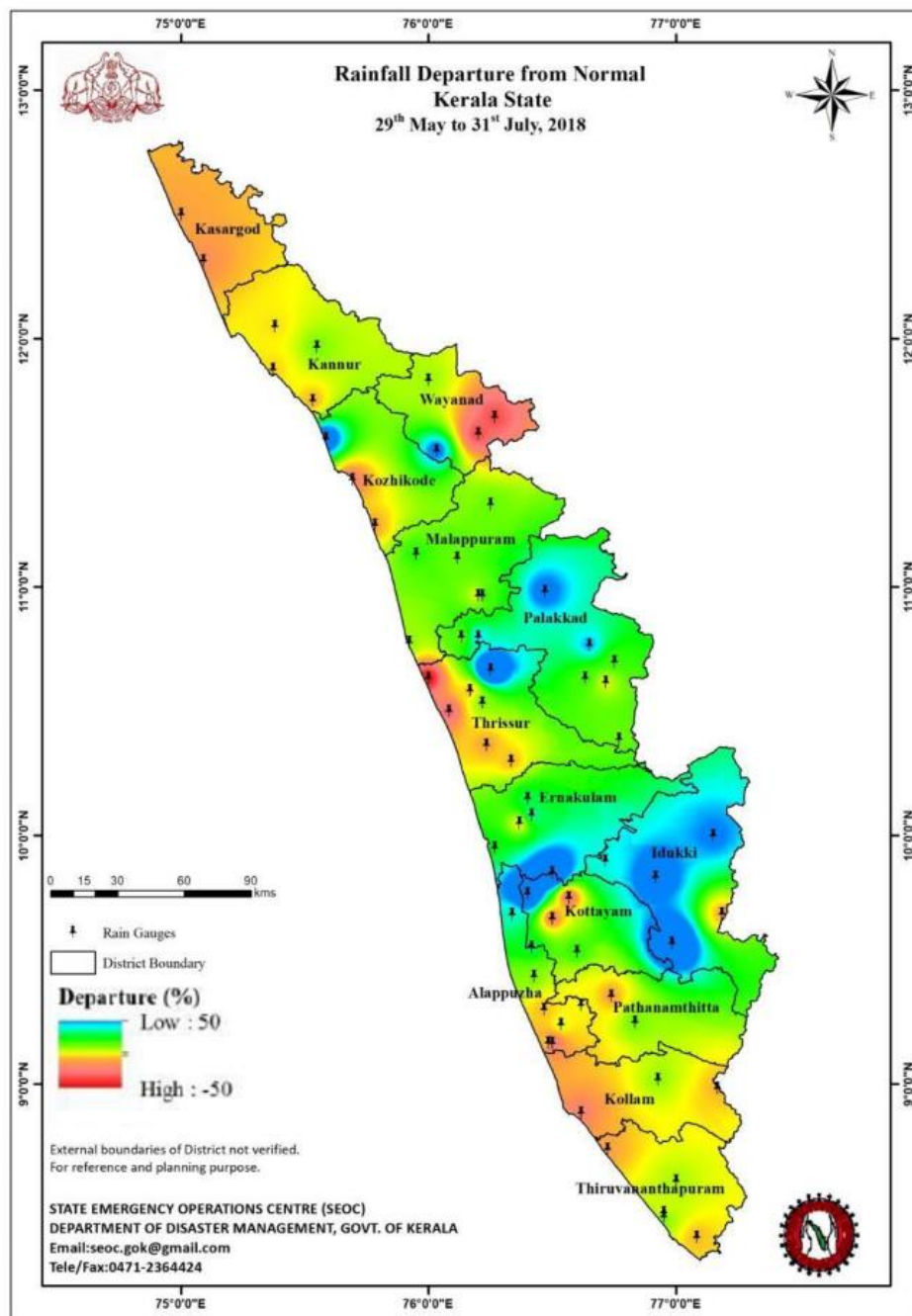


Figure 2-7: Rainfall departure 2018 (29th May to 31st July) (Source: IMD)

Additionally, the losses incurred by private traders and business units, as well as the damage and loss suffered by Kochi airport, road transport, and waterways, are not accounted for in this estimate. If these were included, the total damage and loss, currently estimated at INR 26,720 crore, would be significantly higher.

The total recovery needs are reportedly estimated at INR 31,000 crore (USD 4.4 billion), which includes the recovery needs assessed by the JRDNA (Table 1). This assessment spans across social, productive, infrastructure, and cross-cutting sectors, and includes both private and public losses.

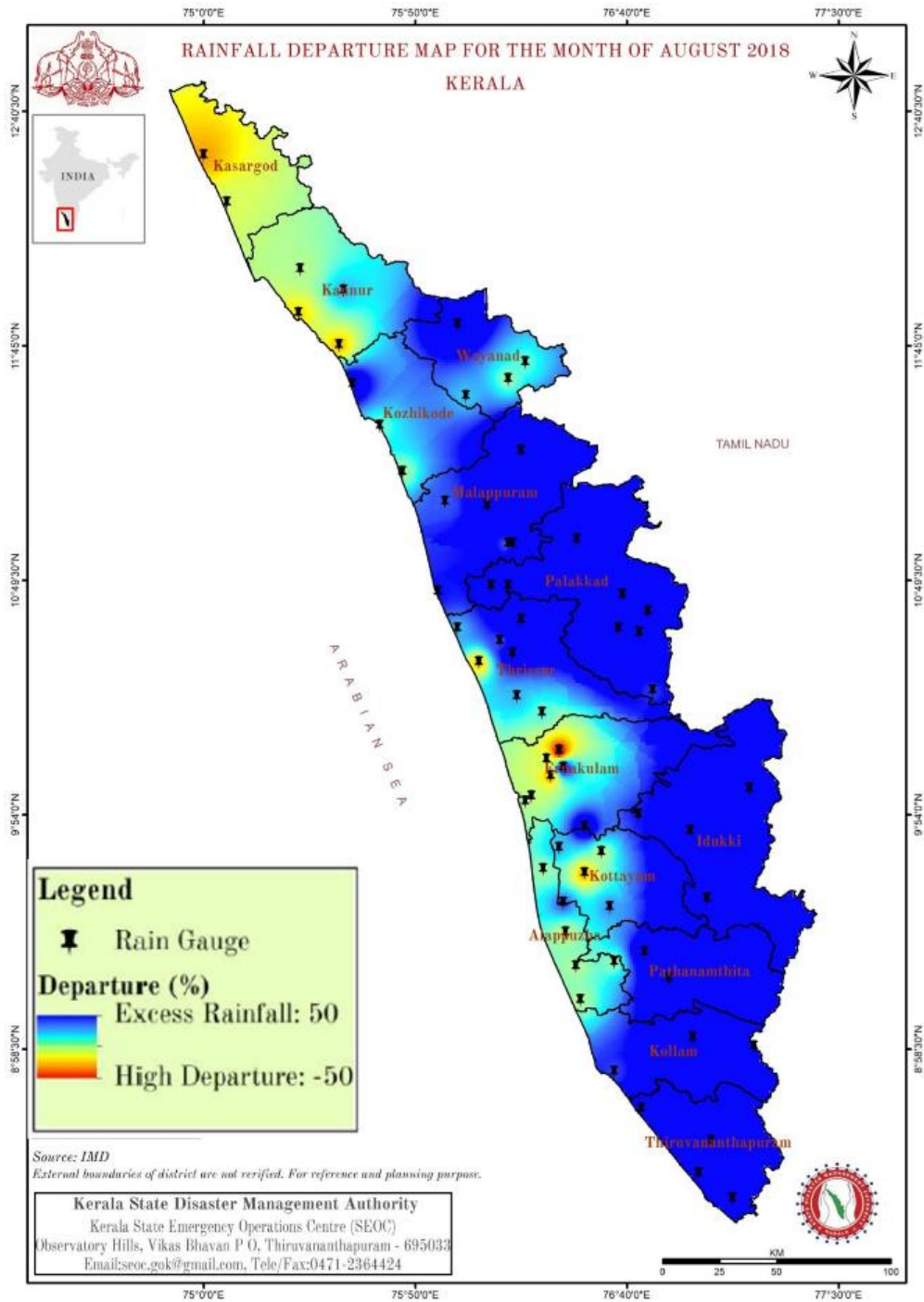


Figure 2-8: Rainfall departure for the month of June 2018 (Source: IMD)

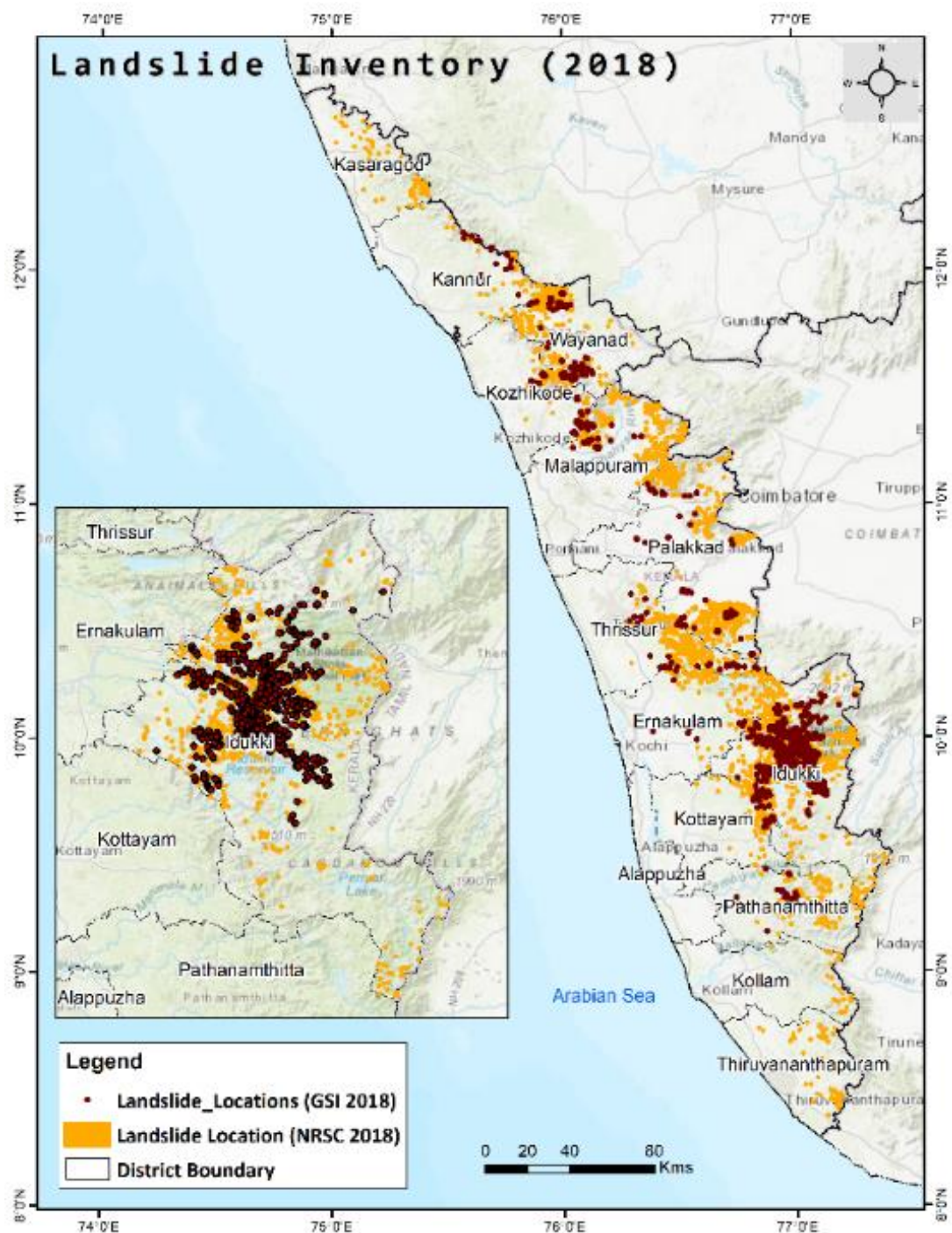


Figure 2-9: Spatial distribution of landslide locations in Kerala, 2018

Table 2-6: Monsson calamity losses due to 1<sup>st</sup> to 31<sup>st</sup> August 2018 floods and landslides (Modified after KSDMA 2018 additional memorandum)

District	Total Deaths	No People Affected	No Houses damaged	PWD Roads (km)	Bridges	Schools	Primary Health Centers	Agriculture land affected (ha)	Total Economic loss (INR Crore)
Thiruvananthapuram	11	8,662	3,051	475.00	5	6	2	1,356.96	40.80
Kollam	5	21,550	1,433	340.00	48	28	8	869.73	24.93
Pathanamthitta	3	8,07,911	33,516	550.00	68	46	4	12,085.05	359.24
Alappuzha	43	7,36,316	21,065	241.00	56	90	42	12,095.55	237.29
Kottayam	14	2,49,085	732	291.00	6	33	4	7,170.71	28.42
Idukki	54	2,498	2,299	2,105.00	121	37	20	5,745.97	61.30
Ernalulam	58	8,46,419	2,611	2,130.00	13	56	22	1,296.66	96.91
Thrissur	72	5,14,366	21,130	598.00	41	15	15	3,569.25	244.82
Palakkad	20	16,684	4,722	164.00	78	26	22	6,250.43	76.57
Malappuram	30	42,099	4,231	1,231.00	18	24	27	5,275.40	76.67
Kozhikode	16	53,636	1,445	332.00	8	7	7	627.04	24.57
Wayanad	6	60,847	9,952	565.00	9	35	6	1,876.80	34.64
Kannur	6	2,498	3,337	100.00	20	9	6	926.53	41.66
Kasaragod	1	375	77	416.45	19	4	3	199.29	7.36

Source: KSDMA memorandums

### 2.1.2.5.3 Kerala Floods & Landslides - 2019<sup>20</sup>

Year 2019 marked as yet another year when Kerala received significantly heavy rainfall all across the state. It resulted in a large number of landslide and mudslide incidences of varying intensities.

Table 2-7 shows villages affected by floods and landslides in Kerala, 2019.

<sup>20</sup> <https://sdma.kerala.gov.in/wp-content/uploads/2020/03/Memorandum-pages-deleted-Copy-compressed.pdf>

Table 2-7: Losses due to 2019 flood and landslide (Modified after KSDMA 2019 memorandum)

District	Total Deaths	No Houses damaged	PWD Roads (Km)	Bridges	Schools	Primary Health Centres	Agriculture land affected (ha)	Total Economic loss (INR Crore)
Kollam	-	915	108.88	-	-	1	278.76	11.56
Pathanamthitta	-	4,056	110.32	-	-	-	335.89	15.97
Alappuzha	6	16,210	56.75	7	3	-	3,644.13	86.62
Kottayam	2	26,722	323.02	2	4	1	2,862.05	83.45
Idukki	5	954	489.74	2	4	2	999.28	19.81
Ernalulam	-	14,441	320.53	11	-	2	1,294.21	59.45
Thrissur	9	23,913	458.96	13	7	6	2,653.42	102.59
Palakkad	1	9,408	379.48	21	10	7	10,885.86	81.97
Malappuram	60	52,216	414.76	14	10	10	1,611.30	218.46
Kozhikode	17	48,702	202.50	9	6	6	274.80	180.81
Wayanad	14	16,781	401.28	3	13	4	3,661.18	114.34
Kannur	9	17,344	132.03	11	12	6	14,963.00	101.17
Kasaragod	2	5,652	226.21	-	6	4	388.26	27.28

Source: KSDMA memorandums

#### 2.1.2.5.4 Extreme rain induced hazards in Kerala (2021)<sup>21</sup>

In October 2021, once again the state of Kerala was hit by torrential rain causing flooding and triggering a series of landslides. Extreme rainfall events in Kerala from 11<sup>th</sup> to 26<sup>th</sup> October 2021

resulted state to receive widespread heavy rainfall. The cyclonic circulation in the North Andaman Sea and the neighborhood strengthened the monsoon westerlies and has caused widespread very heavy rainfall over the Kerala state. Figure 2-10 to Figure 2-13 show photos taken from some of the locations affected by landslides in 2021.



Figure 2-10: Aerial view of the Kootickal landslide location

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<sup>21</sup> [https://sdma.kerala.gov.in/wp-content/uploads/2022/05/Event-report\\_October-2021.pdf](https://sdma.kerala.gov.in/wp-content/uploads/2022/05/Event-report_October-2021.pdf)



Figure 2-11: Landslide location at Kokkayar where rescue operations are carried out



Figure 2-12: Photograph showing a destroyed house at Kootickal



Figure 2-13: Rescue operations carried out at the landslide location near Mackochi in Kakkayar village

#### 2.1.2.5.5 Wayanad flood and landslide July 30, 2024

One notable historical instance occurred in August 2019, when Wayanad experienced severe landslides following incessant rainfall. The landslides were part of a broader disaster across Kerala that year, resulting in loss of life, displacement of people, and extensive damage to property. The 2018 Kerala floods, which were among the worst in nearly a century, also triggered several landslides in Wayanad, further highlighting the vulnerability of the region.

So, it is well known, that Wayanad area is an area having high susceptibility to landslides. Wayanad, a hilly district in the Western Ghats Mountain range, is prone to landslides during heavy and consistent rains particularly during the monsoon season. Due to heavy rainfall in the area on July 30, 2024 a major landslide event occurred which cause widespread damage to property and also resulted in loss of several hundred precious lives. An estimated 570 mm of rainfall was recorded in the two days preceding the disaster.



Figure 2-14: Some of the images from Wayanad post landslide event on July 30, 2024

A landslide happened on July 30, 2024, at 02:17 hours, near Mundakki, Chooralmala, Vellarimala Village in Meppadi Panchayat, Vythiri Taluk, Wayanad District, as a result of continuous heavy to extremely severe rains. The landslide diverted the Iruvazhinji River, resulting in flash floods and washing away the Chooralmala village. Approximately families were stranded in Mundakkai and Attamala following the collapse of the only bridge connecting the settlements and Chooralmala. Overall, six villages, namely Punjirimattom, Meppadi, Mundakkai, Attamala, Chooralmala, and Kunhome, were affected by the landslides.

Wayanad landslide on 30<sup>th</sup> July has been the worst landslide event in the known history of Kerala state resulting into death of 298 people (*personal communication*), leaving hundreds injured and hundreds of others missing.

RMSI has conducted a detailed study on landslide susceptibility mapping at high resolution (100m x 100m) using machine

language (ML) modelling approach. Study indicates that the major parts of the impacted villages in Wayanad were mapped as high to very high landslide prone areas. The landslide occurred on one of the old landslide sites at least 6 km uphill away from the most impacted villages.

Although excessive rains and climate changes has been pointed out as sole cause of this devastation; however, land use change in last couple of decades is not being blamed. In fact, land use in the landslide affected areas takes fair contribution of the disastrous impact. Construction of lot of residential and commercial properties within the river plain and immediate vicinity was probably the reason of blocking/ hindering the active channel to flow/ accommodate such an extensive amount of water resulting into flash flood on either side of the channel. This flash flood water was also laden with debris from the landslide increasing the impact of the flood and washing away almost everything which came in its way.

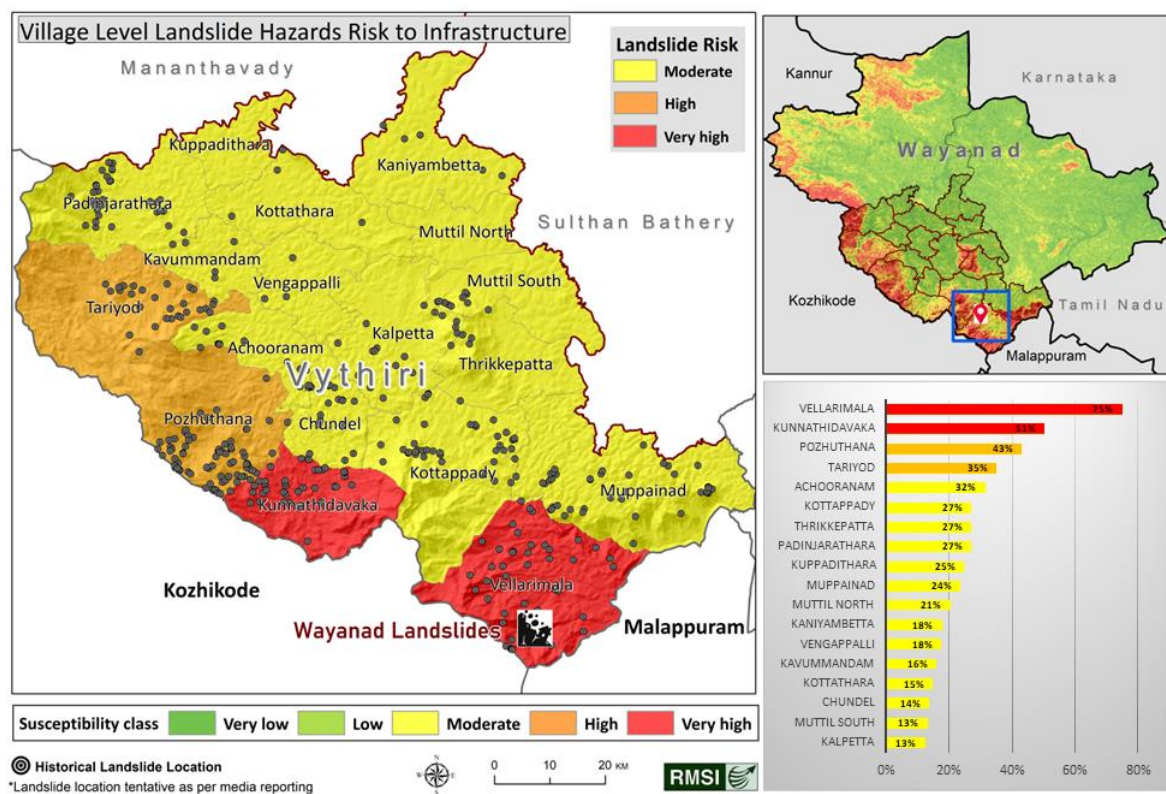


Figure 2-15: Landslide susceptibility map of Wayanad

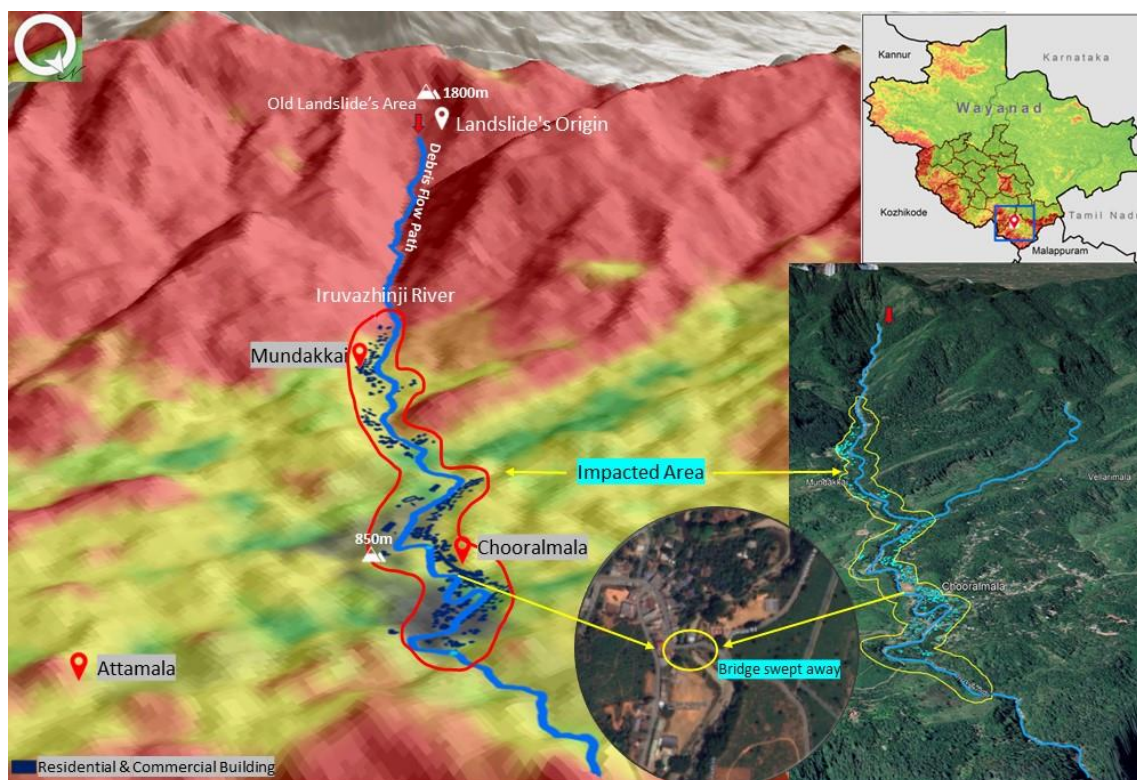


Figure 2-16: showing origin point of landslide and buildings impacted along the stream channel

Table 2-8: Distribution of historical landslide with respect to distance from streams and rivers

S. No	No of landslides in (0-200 m)	No of landslides in (200-400 m)	No of landslides in (400-600 m)	No of landslides in (>600 m)
1	2874	1976	1642	1112

Review of historical landslides in Kerala particularly the once occurred in recent years show proximity of the events with early order stream channels. Table 2-8 shows spatial distribution of recent landslide events in Kerala and stream channels whereas Figure 2-16 shows distance of these landslides (m) from the nearest stream channels.

Additionally, closer look of the most of the houses and infrastructures hit by landslides in these events indicate that people living in close proximity to these streams/rivers are the ones who were impacted the most.

Similar behavior was also noticed during most of the landslides in 2018 floods and

one which occurred in Wayanad on 30<sup>th</sup> July 2024.

It is important to note that Wayanad landslide/mudslide event is one, in which most of the casualties and devastation occurred at least 6 km away from the landslide origin point. It was mostly the flash flood water loaded with debris from landslide which caused the damage to the structures located in the immediate vicinity of the stream channel. Hence, this event may be referred as *Wayanad Flood & Landslide July 30, 2024*, instead of 2024 Wayanad Landslide.

## 2.1.3 CYCLONES

### 2.1.3.1 Review of Historical cyclones

The west coast of India is comparatively less vulnerable to storm surges than the east coast of India in terms of both the height of storm surge as well as frequency of occurrence. However, so far Kerala state (*located on the Arabian Sea coast*) has experienced only three Very Severe Cyclonic Storm (VSCS) due to its geography and low latitude (Table 2-9).

There are several instances when Bay of Bengal cyclones crossed the east coast of India, maintained their intensity over land, and gradually weakened before emerging into the Arabian Sea off Kerala coast. Hence, there are comparatively fewer events that impacted the State from Arabian sea.

Historical cyclonic events, such as Cyclone Ockhi in 2017, have impacted the state (Kumar et al., 2019)<sup>22</sup>. Scientific research has focused on understanding cyclone behavior and enhancing preparedness measures. Mohapatra et al. (2019) analyzed historical cyclone tracks and intensity over the Bay of Bengal and Arabian Sea. Their study highlighted an increasing trend in the frequency of severe cyclones affecting Kerala and emphasized the need for robust disaster preparedness measures. Kumar et al. (2018) conducted a detailed analysis of Cyclone Ockhi, assessing its meteorological characteristics and socio-economic impacts. They underscored the importance of early warning systems and evacuation protocols in reducing cyclone-related casualties. Gupta et al. (2019)<sup>23</sup> studied the Impact of climate change on tropical cyclones frequency and intensity on Indian

coasts with the past more than 140 years of and concluded that Cyclone Intensity is increasing both in Bay of Bengal (BoB) and Arabian Sea (AS).

According to the KSDMA report titled “An Integrated Approach to the Preparedness and Mitigation of Cyclone Tauktae: The Case of Kerala<sup>24</sup>”, Kerala has been hit mainly by 5 cyclones over the last 127 years. Recently, there were two cyclones, Gaja (16 November, 2018) and Ockhi (28 November- 7 December, 2017), and 2 earlier in 1912 (19-22 November 1912, 17-19 December 1912) and one cyclone in 1925 (06-10 November). The cyclone, which occurred in 1925 (November 06-10), passed through north Kerala on November 10. The cyclone that occurred in November 1912 passed through the southern coasts of Kerala and Tamil Nadu. Ockhi was the fourth cyclone to form in the Comorin Sea (South of Kerala and Tamil Nadu, and west of Sri Lanka). It was after 92 long years that a cyclone passed through the Kerala coast. But Ockhi (2017) did not cross the Kerala-Tamil Nadu coast.

On November 8, 2018, low pressure system formed between Thailand's sea and the Malay Peninsula, entered the Andaman coast in the Bay of Bengal and became the Gaja cyclone. Gaja travelled along the longest track in recent times, crossed the Indian Peninsula for the first time and entered the Arabian Sea at extreme low pressure over Kerala in the afternoon of November 16. Since 1990, this was the first cyclone that formed in the Bay of Bengal and reached the Arabian Sea through Kerala.

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<sup>22</sup> Kumar, K., E. K., Vijaykumar, P., Sahai, A. K., Chakrapani, B., & Gopinath, G. (2019). Changing characteristics of droughts over Kerala, India: inter-annual variability and trend. *Asia-Pacific Journal of Atmospheric Sciences*, 55(1), 1-17.

<sup>23</sup> Gupta S., Indu J., Johari P, and Lal, M. (2019). Impact of climate change on tropical cyclones frequency and intensity on Indian coasts, In: Rao, P., Rao, K., Kubo, S.

(eds) Proceedings of International Conference on Remote Sensing for Disaster Management. Springer Series in Geomechanics and Geoenvironment. Springer, Cham. [https://doi.org/10.1007/978-3-319-77276-9\\_32](https://doi.org/10.1007/978-3-319-77276-9_32)

<sup>24</sup> [https://sdma.kerala.gov.in/wp-content/uploads/2021/10/Cyclone-Tauktae\\_Case-Study\\_09-Oct-2021\\_2300-1.pdf](https://sdma.kerala.gov.in/wp-content/uploads/2021/10/Cyclone-Tauktae_Case-Study_09-Oct-2021_2300-1.pdf)

Table 2-9: Number of historical cyclone events considered for Kerala (1891-2023)

Category	No. of Cyclonic Disturbances
Depression	3
Deep Depression	3
Cyclonic Storm	8
Severe Cyclonic Storm	3
Very Severe Cyclonic Storm	15
Extremely Severe Cyclonic Storm	4
Super Cyclonic Storm	-

#### 2.1.3.1.1 Severe cyclonic storm (SCS) of November 1977

This storm reportedly caused extensive damage in Kerala and Lakshadweep. About 72 people died and 8,400 houses were damaged. Tidal waves were reported to have damaged 620 fishing vessels in coastal areas of Kerala state. Total loss was estimated to be about 10 crores (SMRC, 1998)<sup>25</sup>.

#### 2.1.3.1.2 Severe cyclonic storm (SCS) of November 1992

This cyclone crossed the Kerala and Karnataka coast near Honavar town causing extensive damage to the property in the coastal districts of Tamil Nadu and Kerala. Heavy rains caused flash floods and landslides resulting in considerable damage to the standing crops and houses in Karnataka, Kerala, and Tamil Nadu. According to the press reports about 175 persons lost their lives and 160 people reported missing in Tamil Nadu and Kerala<sup>26,27</sup>.

#### 2.1.3.1.3 Cyclone Ockhi - 30 November, 2017

On 30 November, 2017, the Cyclone Ockhi passed by about 70 km away from Kerala coast. Kerala in the last 100 years had not experienced a major Cyclonic Storm impact of this magnitude<sup>28</sup>. As per a report from KSDMA, Kerala state witnessed loss of lives of 51 persons, 234 injured, and 9,134 affected. About 3,744 houses were damaged by cyclone Ockhi in Kerala<sup>29</sup>. A few damage photographs from cyclone Ockhi in Kerala are presented in Figure 2-17 to Figure 2-19<sup>30</sup>.

Extremely Severe Cyclonic Storm Tauktae (14<sup>th</sup> -19<sup>th</sup> May, 2021) generated squally winds<sup>31</sup> of 50-60 kmph with gusts up to 70 kmph along and off the Kerala coast on May 15<sup>th</sup>. A total of 1,532 houses were damaged in Kerala. Figure 2-20 and Figure 2-21 depict the damage photographs caused by the Extremely Severe Cyclonic Storm Tauktae in Kerala. Besides the above, Kerala witnessed several storms ranging from tropical depressions (31-61 km/h) to very severe cyclonic storms (88-118 km/h).

<sup>25</sup> 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.

<sup>26</sup> IMD Report on cyclonic disturbances over North Indian Ocean in 1992- RSMC Tropical Cyclones (1993)

<sup>27</sup> 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.

<sup>28</sup> Govt. of Kerala, 2017. Memorandum – Cyclone Ockhi. 30<sup>th</sup> November 2017 to 17<sup>th</sup> January 2018. Department of Disaster Management, Govt. of Kerala. Submitted on: 17-01-2018

<sup>29</sup> Memorandum-Ockhi-2017 by Additional Chief Secretary, Disaster Management, Govt. of Kerala (KSDMA).

<sup>30</sup> IMD Report: 2018, Very Severe Cyclonic Storm, 'OCKHI' over the Bay of Bengal (29 Nov - 05 Dec 2017)

<sup>31</sup> IMD Report: 2021, Extremely Severe Cyclonic Storm TAUKTAE over the Arabian Sea (14th -19th May, 2021)



Figure 2-17: A car stuck in mud at Pampa, Triveni (Source: The New Indian Express 01st Dec 2017)-IMD Report (2018)



Figure 2-18: A tree fell over auto rickshaw at Sreekanteshwaram in Thiruvananthapuram<sup>32</sup>



Figure 2-19: Tree falls observed in Thiruvananthapuram, (Source: United News of India, Thiruvananthapuram dated 30th Nov; IMD Report (2018)

#### 2.1.3.1.4 Extremely Severe Cyclonic Storm Tauktae 14<sup>th</sup> -19<sup>th</sup> May, 2021



Figure 2-20: Indian Navy in the coastal village of Chellanam in Ernakulam district, Kerala (left) which was heavily hit by tidal waves; House Collapses into the sea in Kasaragod, Kerala due to the effect of Cyclone Tauktae (right) (Source: IMD Report, 2021)

32 Source:<http://english.mathrubhumi.com/news/kerala/cyclone-ockhi-closes-in-on-kerala-coast-1.2424815>-IMD Report (2018)



Figure 2-21: House damaged in Malappuram district due to Cyclone Tauktae (Source: District Emergency Operations Centre, Malappuram) (left); House damaged in Palakkad district due to Cyclone Tauktae (Source: District Emergency Operations Centre, Palakkad) (right) (Source: KSDMA)

### 2.1.3.2 Frequency of Cyclones in Kerala

Kerala is less prone to cyclones compared to the eastern coast of India, which regularly experiences cyclonic activity. According to the India Meteorological Department (IMD), Kerala has experienced around 17 cyclonic disturbances in the past century. Cyclones affecting Kerala generally occur during the pre-monsoon (April-June) and post-monsoon (October-December) seasons.

- **Historical Data:** The frequency of cyclones in Kerala is low, with severe cyclones occurring once every few decades. In the last 50 years, only a handful of cyclones have made a significant impact on the state, with most cyclones weakening before making landfall.
- **Changing Patterns:** Climate change and warming sea surface temperatures may lead to changes in the frequency and intensity of cyclones impacting Kerala. Recent studies suggest an increasing trend in cyclone intensity, though their frequency remains relatively low.

### 2.1.3.3 Severity of Cyclones in Kerala

Cyclones in Kerala, though less frequent compared to other coastal regions of India, have the potential to cause significant damage due to the state's densely

populated coastal areas and infrastructure. Kerala's coast is occasionally impacted by cyclones that originate in the Bay of Bengal and the Arabian Sea. Historically, Kerala has experienced both low to moderate intensity cyclones, with severe cyclones being rare. However, when cyclones do impact Kerala, they bring intense rainfall, storm surges, and strong winds, leading to flooding, landslides, and coastal erosion.

- **Recent Cyclonic Events:** In November 2017, Cyclone Ockhi was a significant event that affected Kerala, leading to the loss of lives and widespread damage to property and livelihoods
- **Potential Impacts:** While the severity of cyclones in Kerala is typically lower than in the eastern coast of India, the state's vulnerability to heavy rainfall and landslides exacerbates the impact of even moderate cyclonic events.

### 2.1.3.4 Review of Historical drought

Studying long-term changes and associated extreme hydrological events over a smaller region like Kerala, a Southern Peninsular Indian state, is challenging due to the large heterogeneity in the complex terrain bounded by the Arabian Sea on the west and the Western Ghats on the east. Across the small average width of 100 km in the zonal direction over the complex terrain of Kerala, there exists significant heterogeneity in the land surface and land use characteristics.

Agriculture in Kerala is predominantly rainfed, with less than 30% of the agricultural land relying on irrigation. Reports indicate that rainfall over Kerala decreased by 10-20% between 1901 and 1980, particularly during the second half of this period<sup>33</sup>. In 2016, Kerala experienced one of its most severe droughts, posing a significant threat to both agriculture and hydrology. Additionally, it has been observed that the frequency of drought years has been increasing in Kerala in recent decades. Rajeevan and Pai (2017) analyzed the 2017 drought in Kerala, attributing it to El Niño and the Indian Ocean Dipole. They assessed meteorological factors contributing to the drought and emphasized the importance of drought preparedness measures and water conservation strategies. Studies have also reported weakening trend in land-sea thermal gradient due to rapid ocean warming in contrast to slower land warming and resulting drying of Indian subcontinent<sup>34</sup>. The strongest rainfall decreases are observed in July, along the

southwest coast of India. In this region (the Western Ghats run parallel to a narrow coast, with an average elevation of 700 m), the reduction of precipitation is likely due to the weakening of vertical velocities caused by upper tropospheric warming<sup>35</sup>. The reduction in rainfall over extreme southern peninsular Indian region is caused due to the poleward shift in monsoon Low Level Jet (LLJ) in response to widening of tropical belt under global warming<sup>36</sup>. Consistent with this, prominent upper-level circulation feature during monsoon season known as Tropical Easterly Jet (TEJ) is also weakening due to the warming of middle to upper troposphere over equatorial Indian ocean region<sup>37,38</sup>. Any changes in the pattern of rainfall can have significant impact on the availability of water resources, agriculture and eco system. In 2023, Kerala experienced more deficit in rainfall in June and August months, as compared with the year 2016 as shown in Table 2-10 (Bulletin: on Manorama).

Table 2-10: Comparison of rain short fall for 2016 and 2023 years

Rain short fall (%)		
Month	2016	2023
June	8	67.5
July	39	2.75
August	45	85.75
Rainfall (mm)		
June-July-August	1,268.6 mm (Deficit -466.80)	909.5 mm (Deficit -825.5)

According to the Indian Meteorological Department (IMD), Kerala experienced 10 moderate drought events and 8 drought-prone years between 1875 and 2004. The state also witnessed drought incidents in

three consecutive years: 1951-1952, 1965-1966, and 2002-2003. Kerala has endured 66 drought years between 1881 and 2000, exacerbating water scarcity issues in both urban and rural regions due to dry rivers

<sup>33</sup> Abhilash, S., Krishnakumar, E. K., Vijaykumar, P., Sahai, A. K., Chakrapani, B., & Gopinath, G. (2019). Changing characteristics of droughts over Kerala, India: inter-annual variability and trend. *Asia-Pacific Journal of Atmospheric Sciences*, 55(1), 1-17.  
<sup>34</sup> Roxy, M., Ritika, K., Terray, P., Murtugudde, R., Ashok, K., Goswami, B.N.: Drying of Indian subcontinent by rapid Indian Ocean warming and a weakening land-sea thermal gradient. *Nat. Commun.* 6, (2015).  
<sup>35</sup> Rajendran, K., Kitoh, A., Srinivasan, J., Mizuta, R., Krishnan, R.: Monsoon circulation interaction with Western

Ghats orography under changing climate. *Theor. Appl. Climatol.* 110(4), 555–571 (2012).  
<sup>36</sup> Sandeep, S., Ajayamohan, R.: Poleward shift in Indian summer monsoon low level jetstream under global warming. *Clim. Dyn.* 45, 337–351 (2014).  
<sup>37</sup> Sathyamoorthy, V.: Large scale reduction in the size of the tropical easterly jet. *Geophys. Res. Lett.* 32(14), (2005).  
<sup>38</sup> Abish, B., Joseph, P.V., Johannessen, O.M.: Weakening trend of the tropical easterly jet stream of the boreal summer monsoon season 1950– 2009. *J. Clim.* 26(23), 9408–9414 (2013).

and declining water tables. The state has also witnessed one of the most distressing droughts in the year 2016, which imposed a severe threat to both agriculture and hydrology. It is also realized that the frequency of drought years is increasing over Kerala during recent decades. Each deficit rainfall year is unique in the sense that its impact on agriculture, hydrology, and the socio-economic sectors varies. Though the southwest monsoon during 2015 was unsatisfactory for Kerala, the annual water stress and severity of drought during 2015 didn't scale up to the level as that of the year 2016<sup>39</sup>.

As per SDMA drought situation assessment report for 2017, the

Directorate of Agriculture has reported that a total of 41,592 ha has been reported as damaged during 2016-17 Kharif and Rabi period together. Of this, 2286.77 ha were damaged during Kharif and the remaining during Rabi season<sup>40</sup>

According to the Department of Agriculture Development and Farmers' Welfare, Government of Kerala, crop loss FIR summary reports for the period from 01-04-2019 to 23-09-2024 indicate the crop area affected by drought, as shown in Table 2-11.

As per 2012 KSDMA drought situation report Kerala has experienced losses as given in Table 2-12 and Table 2-13.

Table 2-11: Crop area affected due to drought for the period of 2019 to 2024 (Source: Department of Agriculture, Govt. of Kerala)

Crop type	Area affected (ha)
Arecanut	476.82
Banana	9,863.20
Coconut	2,115.23
Paddy	5,998.15
Tapioca	13.19

39 Changing Characteristics of Droughts over Kerala, India: Inter-Annual Variability and Trend Abhilash S.1,2 & E. K. Krishnakumar & P. Vijaykumar & A. K. Sahai & B. Chakrapani & Girish Gopinath.

40 <https://sdma.kerala.gov.in/wp-content/uploads/2019/08/Drought-Situation-Assessment-2017-April.pdf>

Table 2-12: List of historical drought events in Kerala

Year	Drought Severity	Impact on Agriculture	Impact on Water Resources	Other Impacts	Source
1983	Moderate	Reduction in crop yields	Water scarcity in many areas	Increased irrigation needs, economic losses	Kerala State Disaster Management Authority (2016). Drought Assessment Report.
2002	Severe	Significant crop yield reduction	Severe water scarcity	Increased migration, economic losses	Rajeevan, M., & Pai, D. S. (2017). Droughts in India: Climatic factors and observations.
2004	Moderate	Decline in agricultural productivity	Water shortages, especially in rural areas	Strain on public utilities, health issues	National Institute of Disaster Management (2017). Drought Management in India: A Case Study of Kerala.
2012	Severe	Major reduction in crop production	Critical water shortages	Economic stress, higher food prices	India Meteorological Department (2017). Annual Climate Summary.
2016	Moderate	Decline in agricultural productivity	Acute water shortages, especially in rural areas	Strain on public utilities, health issues	Kerala State Disaster Management Authority (2016). Drought Assessment Report.

Table 2-13: 2012 Drought agriculture land affected and losses numbers (Source: KSDMA)

District	Agriculture land affected (ha)	Total Economic loss (INR Crore)
Thiruvananthapuram	29,935	904
Kollam	11,925	43
Pathanamthitta	27,422	507
Alappuzha	34,266	307
Kottayam	5,267	75
Idukki	15,079	228
Ernakulam	50	1
Thrissur	23,040	391
Palakkad	67,79,972	1,122
Malappuram	22,127	396
Kozhikode	3,500	61
Wayanad	63,929	1,766
Kannur	428	2
Kasargode	1,020	8

### 2.1.3.5 Frequency of Droughts in Kerala

- **Recurring Events:** Kerala faces drought conditions roughly every 3 to 5 years, with varying intensity. The frequency of droughts has increased in recent decades, partially due to climate change and land-use changes. The southwest monsoon's variability plays a critical role in determining the frequency of droughts in the region.
- **Climate Change Influence:** The changing climate is expected to increase the frequency and intensity of droughts in Kerala. Studies indicate that erratic monsoon patterns, rising temperatures, and changes in land use could further exacerbate drought conditions.

### 2.1.3.6 Severity of Droughts in Kerala

- **Historical Impact:** Kerala has experienced several significant droughts, particularly during years of monsoon failure. Notable drought years include 1965, 1976, 1983, 2000, 2003, 2004, 2012, and 2016. The 2016 drought was one of the most severe, affecting over 80% of the state. The severity of droughts is often intensified by erratic rainfall patterns, poor water management, and deforestation.
- **Agricultural Impact:** The agricultural sector is highly vulnerable to drought, with crops like paddy, rubber, and coconut experiencing significant yield reductions. During severe droughts, irrigation sources dry up, leading to crop failure and economic losses for farmers.
- **Water Scarcity:** Droughts led to acute water shortages, affecting both rural and urban areas. During the 2016 drought, many reservoirs and rivers dried up, resulting in drinking water scarcity and disruptions to daily life.

Droughts in Kerala are becoming more frequent and severe, posing significant challenges to water security, agriculture,

and livelihoods. Understanding the patterns and impacts of drought is crucial for developing effective mitigation and adaptation strategies.

### 2.1.4 EARTHQUAKES

Kerala State, a part of Stable Continental Region (SCR) of Peninsular India, is relatively at low-risk from earthquakes as compared to other parts of Peninsular India but has experienced occasional tremors due to tectonic movements in the Western Ghats and nearby fault lines<sup>41</sup>. The State falls in seismic zones II and III, indicating low to moderate seismic risk<sup>42</sup>. The Kerala state is also witnessing seismicity since historic time. It is noted that several of the Kerala tremors are spatially associated with some of the major drainage basins. The historical seismicity of the State suggests that the central part of Kerala (Wadakkancheri-Trissur and Idukki – Kottayam- Pala) of Kerala is more active seismically compared to other parts of Kerala. Around Thiruvananthapuram another cluster of microearthquakes are also noticed.

This region appears to have generated larger number of earthquakes; the prominent being the multiple events (doublets) of 1856 (*in the Thiruvananthapuram area*) and 1953 (*in the Idukki-Pala-Kottayam region*) equivalent to size of earthquake events that occurred in the year 2000 and 2001 (central Kerala) events. Recently, on June 15, 2024, few microearthquakes were felt in parts of Thrissur and Palakkad districts of Kerala. Occurrences of these historical events and the recent earthquakes, and the local geology indicative of pervasive faulting as shown by widely distributed pseudo tachylite veins suggest that the NNW-SSE trending faults in central midland Kerala may host discrete potentially active sources that may be capable of generating light to moderate

<sup>41</sup> Bansal, BK and Gupta, Sushil (1998). A glance through the seismicity of peninsular India, JGSI, V.52, 67-80 pp.

<sup>42</sup> IS 1893-2002 Seismic zonation map of India

size earthquakes<sup>43</sup>. The moderate size earthquake may also help in triggering landslides. Hence, there is a need for

closely monitoring seismicity of the State and strict implementation of building codes.

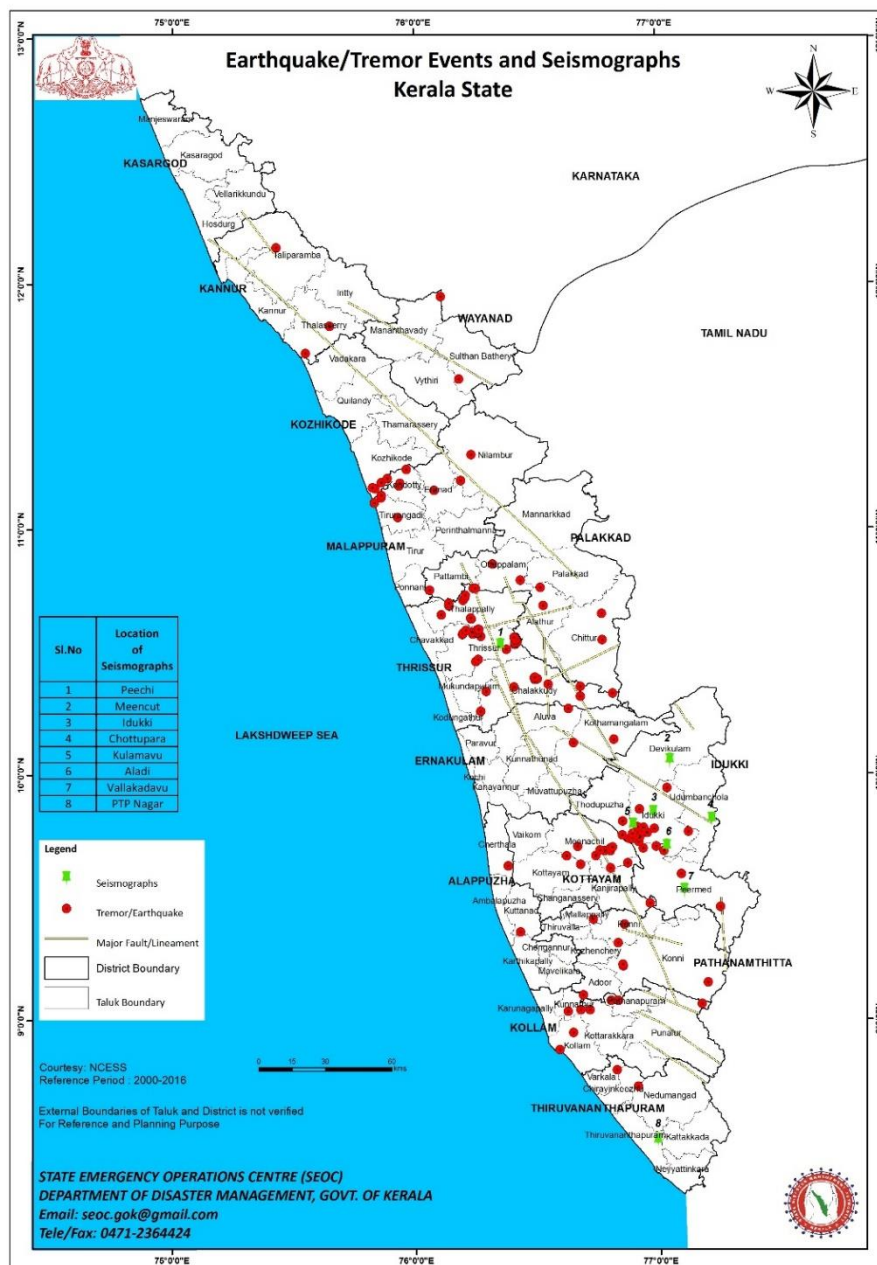


Figure 2-22: Seismicity and tectonics of Kerala (Source: KSDMA<sup>44</sup>)

### 2.1.5 TSUNAMI

Kerala's coastline was severely impacted by the 2004 Indian Ocean tsunami. Triggered by an undersea earthquake near

Sumatra, this tsunami caused waves along Kerala's coast that reached up to three meters in some areas. Coastal districts like Kollam, Ernakulam, and Alappuzha experienced loss of life, displacement, and

<sup>43</sup> Biju et al (2016). Seismicity of Kerala, An Update, Recent Advances in Rock Engineering (RARE 2016).

<sup>44</sup> <https://sdma.kerala.gov.in/earthquake/>

significant property damage. It has been reported that almost 1.3 million people in 187 villages of Kerala were affected by the 2004 Tsunami, with a death toll of 171 persons, 17381 houses damaged and the livelihood of the fishermen community were affected. Tsunami in Kerala is classified as medium hazard<sup>45</sup>. This means that there is more than a 10% chance of a potentially-damaging tsunami occurring in the next 50 years. Based on this information, the impact of tsunami should be considered in different phases of the project for any activities located near the coast. Project planning decisions, project design, and construction methods should take into account the level tsunami hazard. In response, the state government strengthened coastal monitoring, implemented early warning systems, and began awareness campaigns in communities vulnerable to tsunamis. These steps aim to mitigate future tsunami risks and minimize the impact on coastal residents.

### **2.1.6 COASTAL EROSION**

Coastal erosion in Kerala has become a major concern, with the state having the second-highest percentage (65%) of shoreline erosion in India, as reported by satellite-derived Shoreline Change Rate (SCR) data<sup>46</sup>. This ongoing erosion has severely impacted local fishing communities, especially after Cyclonic Storm Ockhi in 2017, which caused widespread destruction and displaced thousands of families. In response, the Kerala government launched the **Punargeham Project in 2019** to rehabilitate over 18,000 fisher families affected by coastal erosion (Times of India, 2020).

In villages like Chellanam, the situation is dire, with families repeatedly displaced by erosion, particularly during monsoon seasons. In 2020, the village witnessed more severe flooding and destruction amid the COVID-19 pandemic, highlighting the urgent need for sustained coastal management and rehabilitation efforts<sup>47</sup>. These challenges illustrate the ongoing vulnerability of coastal communities to the dual threats of erosion and sea level rise.

Kerala's coast, approximately 580 km long, faces extensive erosion due to natural forces, such as waves and tides, as well as human activities like sand mining and construction. Erosion hotspots, including areas near Vypin and Alappuzha, have witnessed accelerated land loss over recent decades, particularly during the monsoon season when wave action is intense. This erosion has had significant socio-economic consequences, damaging homes, displacing residents, and reducing agricultural land. Coastal erosion is expected to worsen due to infrastructure development, which disrupts natural sediment movement, and due to climate change effects. The Disaster Management Division, MHA, GOI, has taken coastal erosion as a serious hazard and allocated INR 1000 Crores to address the issue of resettlement of displaced people affected by erosion at the national level<sup>48</sup>.

### **2.1.7 FOREST FIRE**

Forest fires in Kerala predominantly occur in the dry season, especially in forested regions of the Western Ghats, such as Wayanad, Idukki, and Palakkad districts. Studies indicate that forest fires in these areas lead to biodiversity loss, soil degradation, and air pollution, affecting both local wildlife and human populations. A study emphasizes that forest fires in the

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<sup>45</sup> <https://thinkhazard.org/en/report/1495-india-kerala/TS#:~:text=In%20the%20area%20you%20have.in%20the%20next%2050%20years>

<sup>46</sup> Mohanty, P., Kumar, T. S., Mahendra R. S., & Nayak, R. K. (2019). *Impact of Sea Level Rise and Coastal Slope on Shoreline Change along the Indian Coast*. Indian National Centre for Ocean Information Services.

<sup>47</sup> <https://india.mongabay.com/2021/08/how-climate-change-is-taking-a-toll-on-livelihoods-of-small-scale-fishers-in-kerala/#:~:text=Like%20Ponnan%20and%20Unnikrishnan%2C%20as,Empty%20fishing%20baskets.>

<sup>48</sup> DMD (2024). Constitution and Administration of Recovery and Reconstruction Funding Window under NDRF and SDRF, on Aug 14, 2024, vide letter No. 33-7/2021-NDM.I., MHA, Govt. of India, New Delhi.

Western Ghats can have far-reaching ecological impacts on endemic species and contribute to habitat fragmentation<sup>49</sup>. Additionally, George and Suresh (2018) noted that human activities, such as encroachment and land clearance, increase the likelihood of forest fires in Kerala's vulnerable areas, making fire management a critical aspect of conservation efforts. Thus, it is important that measures to tackle Forest Fires are given due importance, in order to make Kerala State, disaster resilient.

### **2.1.8 LIGHTNING & THUNDERSTORM**

Kerala, a state situated along the southwestern coast of India, experiences frequent lightning and thunderstorms due to its tropical climate, mountainous terrain, and high levels of humidity. These phenomena are particularly common during the pre-monsoon (March to May) and monsoon seasons, with the pre-monsoon period witnessing the highest frequency of events (IMD, 2023)<sup>50</sup>. Regions near the Western Ghats, such as Idukki and Wayanad, are particularly prone to lightning & thunderstorms due to orographic lifting, which enhances convective activity. Coastal regions, while less affected than the highlands, also experience periodic lightning incidents due to interactions between the land-sea breeze and local weather patterns (KSDMA, 2021)<sup>51</sup>.

Lightning and thunderstorms significantly impact Kerala's population and infrastructure. The state records numerous lightning-induced fatalities annually, with agricultural workers, students, and individuals in open spaces being the most vulnerable (NCRB, 2022)<sup>52</sup>. Lightning also damages buildings, electrical systems, and communication networks, particularly in

rural areas that lack adequate protective infrastructure (Kerala Disaster Report, 2020)<sup>53</sup>. Additionally, lightning poses a threat to agriculture, causing crop destruction during critical growing seasons.

Studies on lightning activity in Kerala have revealed distinct patterns. Research using satellite data and ground-based lightning detection systems highlights a higher density of lightning strikes in central and northern Kerala compared to the southern regions (LIS, 2019)<sup>54</sup>. Seasonal variations show that pre-monsoon months experience the highest lightning activity, influenced by surface heating and high moisture content in the atmosphere (KUFOS, 2020).

Analysis of climatological data reveals that the peak of lightning activity in Kerala is observed in April, in the pre-monsoon season, with an average of  $0.2 \pm 0.05$  flashes per sq. km per day. Notably, the Kottayam district and its nearby areas exhibited high lightning frequencies of  $\geq 0.3$  flashes per sq. km per day during this period<sup>55</sup>. A secondary peak in lightning activity was recorded in October from the post-monsoon season, though comparatively less intense than during the pre-monsoon season ( $0.05 \pm 0.008$  per sq. km per day). However, the regions west of the Palakkad Gap (PG) experience less lightning incidence. Further, the spatial analysis of dynamic and thermodynamic parameters (Convective Available Potential Energy (CAPE)), K-Index, and pressure vertical velocity at 500 hPa) proved a clear and causative association with lightning occurrences in Kerala.

Efforts to mitigate lightning risks in Kerala include the establishment of early warning systems and awareness campaigns. Kerala State Disaster Management

<sup>49</sup> Menon, A. R. R., & Vishnu-Menon, R. G. (2022). Management strategies for prevention of forest fire and environmental degradation in tropics with special reference to Western Ghats of Kerala Region, India. *Journal of Tropical Forest Science*, 34(1), 24-33.

<sup>50</sup> IMD (2023). Annual Weather Report 2023. India Meteorological Department.

<sup>51</sup> KSDMA (2021). Kerala State Disaster Management Authority Annual Report 2021.

<sup>52</sup> NCRB (2022). Accidental Deaths and Suicides in India. National Crime Records Bureau.

<sup>53</sup> Kerala Disaster Report (2020). State-Level Lightning Incident Data. Kerala State Government.

<sup>54</sup> LIS (2019). Lightning Imaging Sensor Dataset. NASA Earth Observation Data.

<sup>55</sup> Nandhulal, K., Vishnu, R., Sreekanth, T. S., & Varikoden, H. (2024). Spatiotemporal changes of lightning incidence and its relationship with dynamic and thermodynamic factors over a lightning prone tropical region. *Natural Hazards*, 1-25.

Authority (KSDMA) is collaborating with meteorological agencies to provide real-time lightning alerts through platforms like mobile apps and public advisories (KSDMA, 2022). These initiatives aim to educate the public on safety practices during thunderstorms, such as avoiding

open fields and refraining from using electronic devices outdoors. Research has also emphasized the need to install lightning arresters in critical infrastructure, including schools and hospitals, especially in high-risk areas (Damini App Report, 2021)<sup>56</sup>.

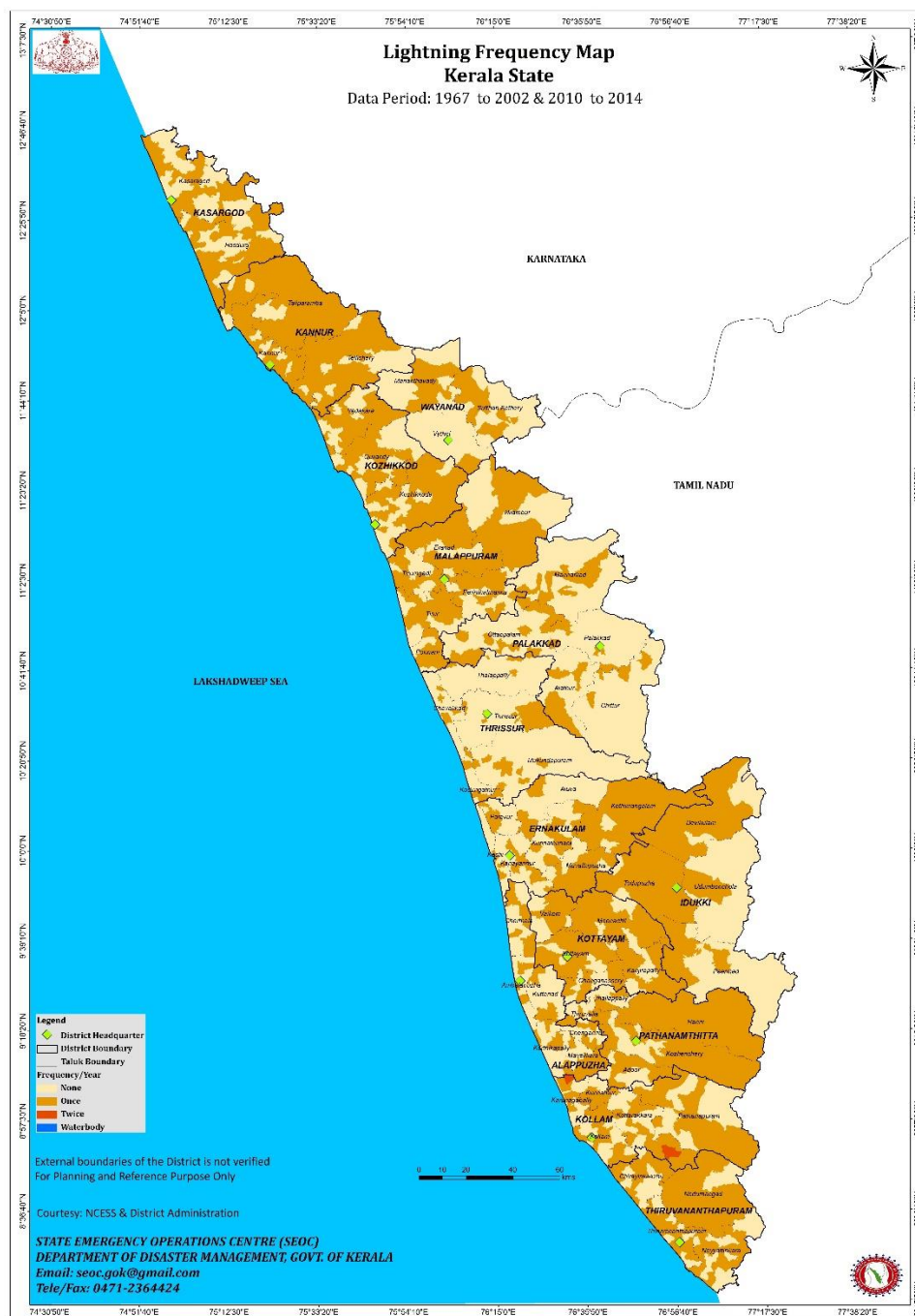


Figure 2-23: Lightning activity in Kerala (Source: KSDMA<sup>57</sup>)

56 Damini App Report (2021). Damini Lightning Alert System. Government of India.

57 <https://sdma.kerala.gov.in/lightning/>

In conclusion, lightning and thunderstorms are significant hazards in Kerala, posing risks to lives, livelihoods, and infrastructure. While past studies have improved understanding and mitigation efforts, addressing existing research gaps can further enhance resilience against these phenomena. Future research should focus on the long-term impact of climate change, advanced forecasting tools, and community-based approaches to lightning risk reduction.

### 2.1.9 SOIL PIPING

Soil piping, also known as subsurface erosion, is a significant geomorphological phenomenon in Kerala, particularly affecting areas with steep slopes, heavy rainfall, and highly erodible soil. *This process involves the formation of underground channels caused by the removal of soil material by subsurface water flow, eventually leading to land degradation, collapse, and gully formation.* The hilly regions of Kerala, especially, the districts of Wayanad, Idukki, and Palakkad, are particularly susceptible to soil piping due to their unique soil characteristics and intense monsoonal rainfall<sup>58</sup>.

Studies have revealed that soil piping in Kerala is closely linked to the region's tropical climate, agricultural practices, and deforestation. *The intensive cultivation of crops like Coffee and Arecanut, coupled with the removal of native vegetation, has been identified as a significant factor exacerbating soil erosion.* Research by Thomas et al. (2018) highlighted that poorly managed plantation agriculture and the construction of unscientific drainage systems often lead to increased water infiltration into the soil, triggering piping. Furthermore, *the state's lateritic soil, which is highly porous and prone to erosion, loses its strength as soon as it gets wet is another critical factor contributing to the prevalence of soil piping*<sup>59</sup>.

Piping-related land degradation has severe implications for Kerala's socio-economic and environmental sustainability. The collapse of subsurface pipes often results in extensive damage to agricultural fields, reducing soil fertility and crop productivity. Additionally, the formation of gullies and sinkholes poses a significant risk to rural infrastructure, including roads and buildings. *Studies have also documented the role of soil piping in triggering landslides, particularly during heavy rainfall events* (NCESS, 2021)<sup>60</sup>.

Efforts to address soil piping in Kerala have focused on awareness campaigns and adopting soil and water conservation measures. Techniques such as contour trenching, vegetative barriers, and check dams have been implemented in some regions to mitigate subsurface erosion<sup>61</sup>. Recent advancements in remote sensing and GIS have enabled researchers to identify and map areas vulnerable to soil piping more effectively.

Despite these efforts, several challenges remain. The lack of comprehensive long-term data on soil piping makes it difficult to predict its occurrence and impact accurately. Moreover, studies on the interplay between climate change and soil piping in Kerala are limited, even as changing rainfall patterns are expected to influence subsurface erosion processes. There is also a need for community-based approaches to soil conservation, emphasizing sustainable agricultural practices and land-use planning.

In conclusion, soil piping is a critical land degradation issue in Kerala, with significant environmental and socio-economic implications. While past studies have provided valuable insights into its causes and mitigation strategies, addressing existing research gaps is essential to developing effective and sustainable solutions. Hence, future research should focus on integrating traditional knowledge

<sup>58</sup> <https://sdma.kerala.gov.in/wp-content/uploads/2019/03/soilpiping-ndma-Final-Reort-with-Addendum-1-compressed.pdf>

<sup>59</sup> <https://sdma.kerala.gov.in/wp-content/uploads/2021/01/KSDMA-Land-Disturbance-Final-Report.pdf>

<sup>60</sup> NCESS (2021). Kerala's Land Degradation: A Case Study of Soil Piping. National Centre for Earth Science Studies Report.

<sup>61</sup> <https://sdma.kerala.gov.in/wp-content/uploads/2018/11/Soil-piping-Final-Report.pdf>

with modern technologies to enhance resilience against soil piping.

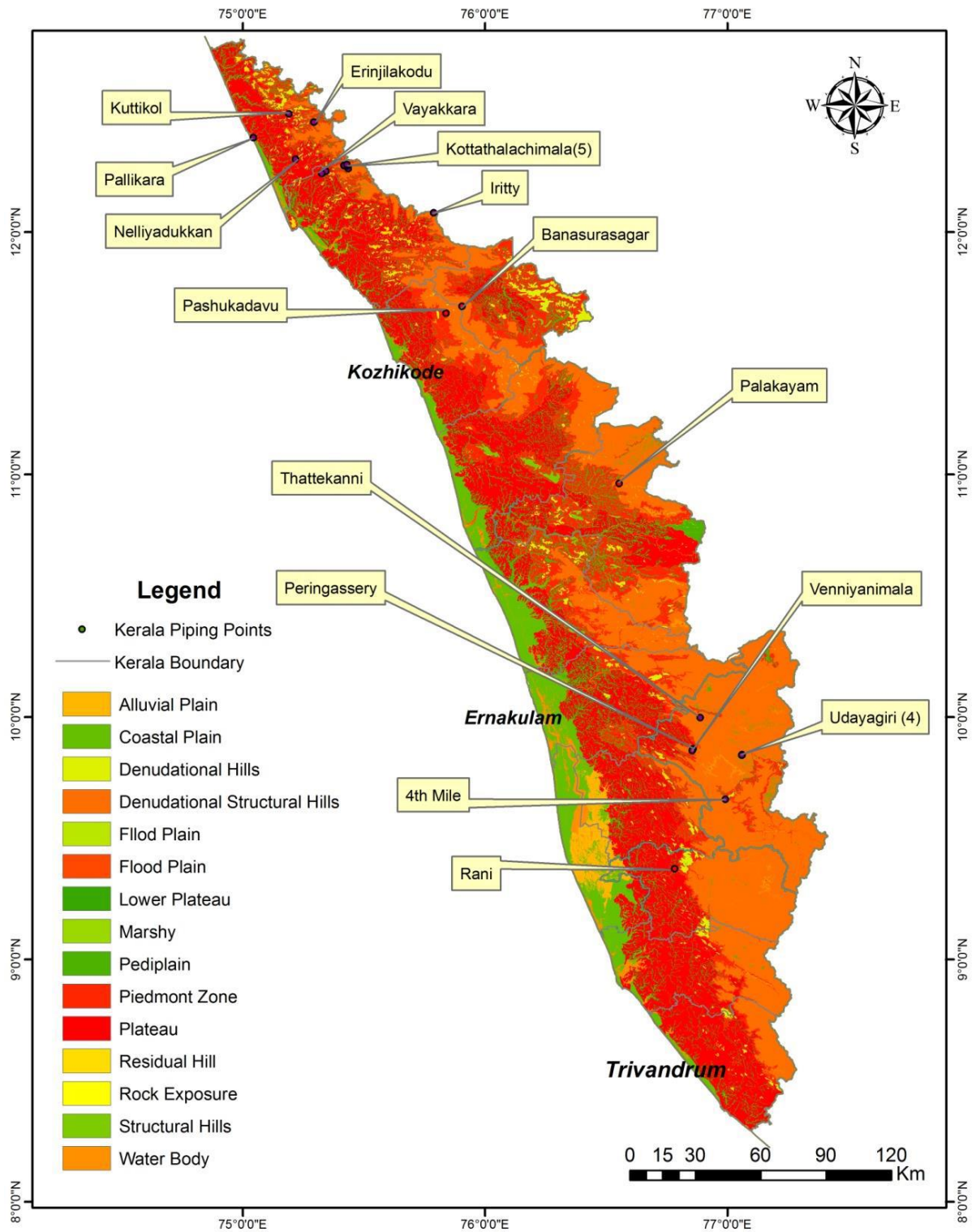


Figure 2-24: Geomorphology of Kerala with piping points (Source: KSDMA)

## 3 Hazard Module Development

### 3.1 Flood

#### 3.1.1 RAINFALL ANALYSIS

Rainfall is the major input for any flood event generated due to excessive rainfall in a basin. For preliminary analysis of rainfall in the study area, daily gridded rainfall data

from India Meteorological Department (IMD) for a period of 30 years (1994-2023) was considered. The resolution of IMD gridded rainfall is 0.25 x 0.25 degree<sup>62</sup>. As per RMSI team analysis, the State is divided into four major River basins as shown in Figure 3-1.

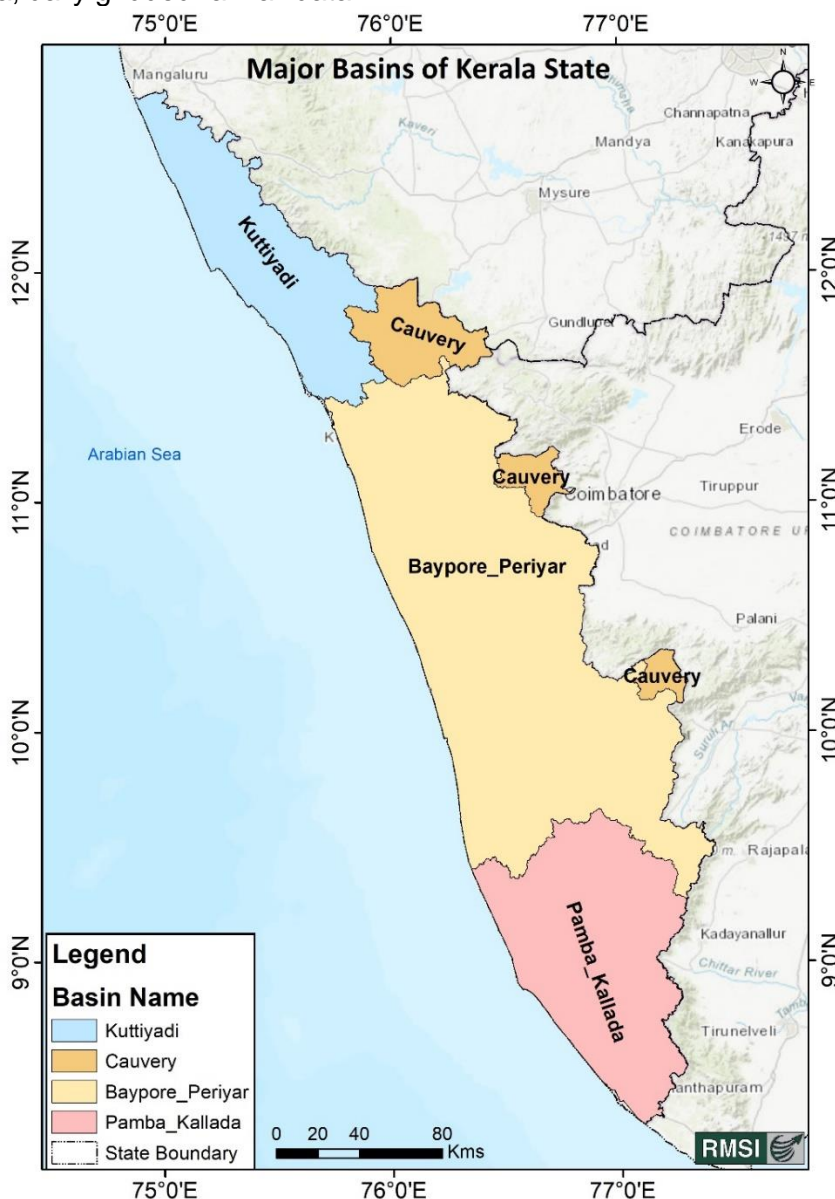


Figure 3-1: Major River basins in Kerala

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[https://www.imdpune.gov.in/cm/pg/Griddata/Rainfall\\_25\\_NetCDF.html](https://www.imdpune.gov.in/cm/pg/Griddata/Rainfall_25_NetCDF.html)

### 3.1.2 ANNUAL RAINFALL

Annual and monthly rainfall for different years for the study area has been computed using daily rainfall data of 30 years (1994-2023). Annual gridded rainfall for Kerala state and major basins of Kerala is given in Table 3-1 and Table 3-2, respectively. The average annual gridded

rainfall in the study area has been calculated as 2430 mm. Rainfall records show that Kerala state recorded the maximum annual rainfall of 3160.3 mm in 2021 and the minimum annual rainfall of 1575.2 mm was observed in 2016.

Table 3-1: Annual gridded rainfall in the Kerala area (1994-2023)

Year	IMD Gridded Rainfall (mm)	Year	IMD Gridded Rainfall (mm)
1994	2910.8	2009	2482.2
1995	2417.6	2010	2682.6
1996	2226.8	2011	2525.9
1997	2820.2	2012	1876.2
1998	2746.6	2013	2751.0
1999	2502.1	2014	2611.0
2000	2195.2	2015	2286.6
2001	2217.8	2016	1575.2
2002	1905.3	2017	2274.0
2003	1805.3	2018	2424.7
2004	2391.3	2019	2758.0
2005	1753.4	2020	2645.1
2006	2995.6	2021	3160.3
2007	2823.9	2022	2727.0
2008	2261.4	2023	2147.3

Table 3-2: Annual gridded rainfall in sub-basins of Kerala State (1994-2023)

Year	Kuttiyadi	Cauvery	Baypore_Periyar	Pamba_Kallada
1994	4717.8	2072.6	3217.0	2017.2
1995	3637.9	1598.8	2782.6	1894.0
1996	3509.6	1718.9	2437.3	1622.2
1997	4355.8	2378.0	3096.1	1995.4
1998	3867.4	1918.2	3187.9	2138.4
1999	3485.8	1869.2	2850.7	2054.1
2000	3217.1	1855.4	2349.1	1755.4
2001	3357.5	1568.7	2600.4	1734.5
2002	3087.5	1354.8	2216.1	1399.2
2003	2996.6	1265.0	2098.3	1276.1
2004	3271.4	2174.4	2716.2	1851.6
2005	3301.2	1466.0	1499.5	1072.3
2006	4228.2	2185.7	3375.1	2470.4

Year	Kuttiyadi	Cauvery	Baypore_Periyar	Pamba_Kallada
2007	4052.8	2294.9	3300.0	2096.1
2008	3330.6	1853.4	2322.3	1946.5
2009	3747.1	2164.5	2795.2	1597.8
2010	3962.1	2010.3	3038.0	2215.1
2011	3537.3	2529.9	2492.1	2021.4
2012	2779.4	1864.6	1753.5	1506.1
2013	4232.5	2247.3	3173.7	1949.7
2014	3696.7	2387.6	2977.4	1932.3
2015	3168.5	1849.8	2457.0	2051.8
2016	2548.0	994.7	1765.2	1253.3
2017	3040.7	1654.4	2505.1	2096.0
2018	3214.9	2087.8	2878.6	1625.6
2019	4252.3	2463.6	3047.6	1819.2
2020	4199.9	2404.4	2845.0	1836.3
2021	3880.9	2641.4	3567.7	2814.8
2022	3735.0	2723.7	2980.8	1853.7
2023	2183.1	2375.2	2335.3	2004.1
Average Annual Rainfall (mm)	<b>3553.2</b>	<b>1999.1</b>	<b>2688.7</b>	<b>1863.4</b>

Annual rainfall distribution over a period of 30 years (1994-2023) using IMD gridded rainfall for Kerala State and four major

basins of Kerala state are shown from Figure 3-2 to Figure 3-6.

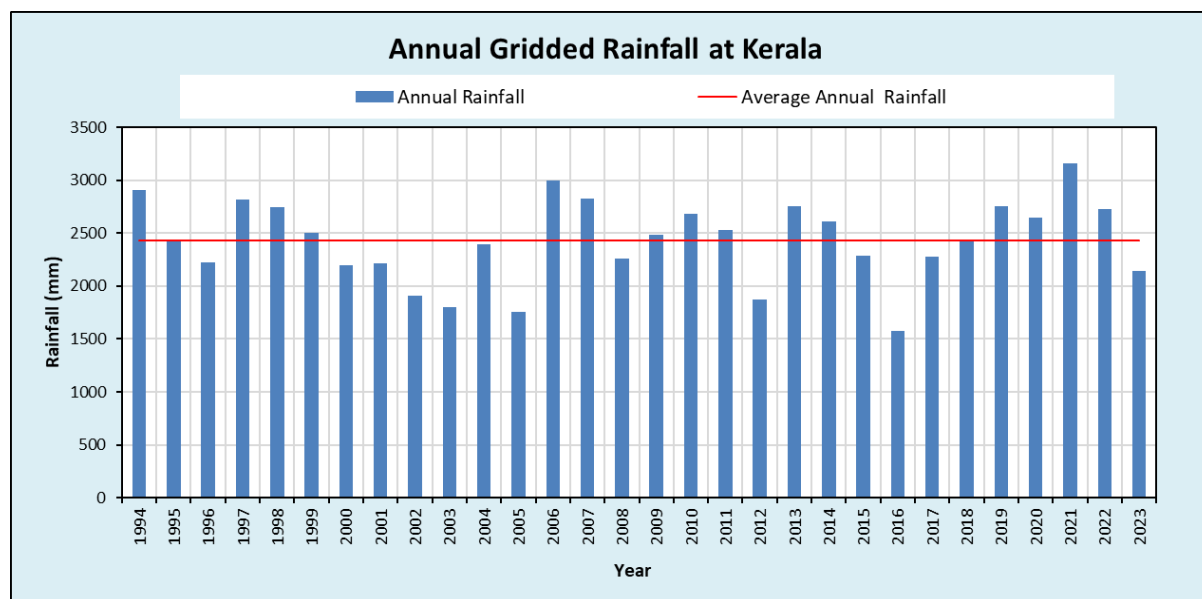


Figure 3-2: Distribution of annual rainfall at Kerala State (1994-2023)

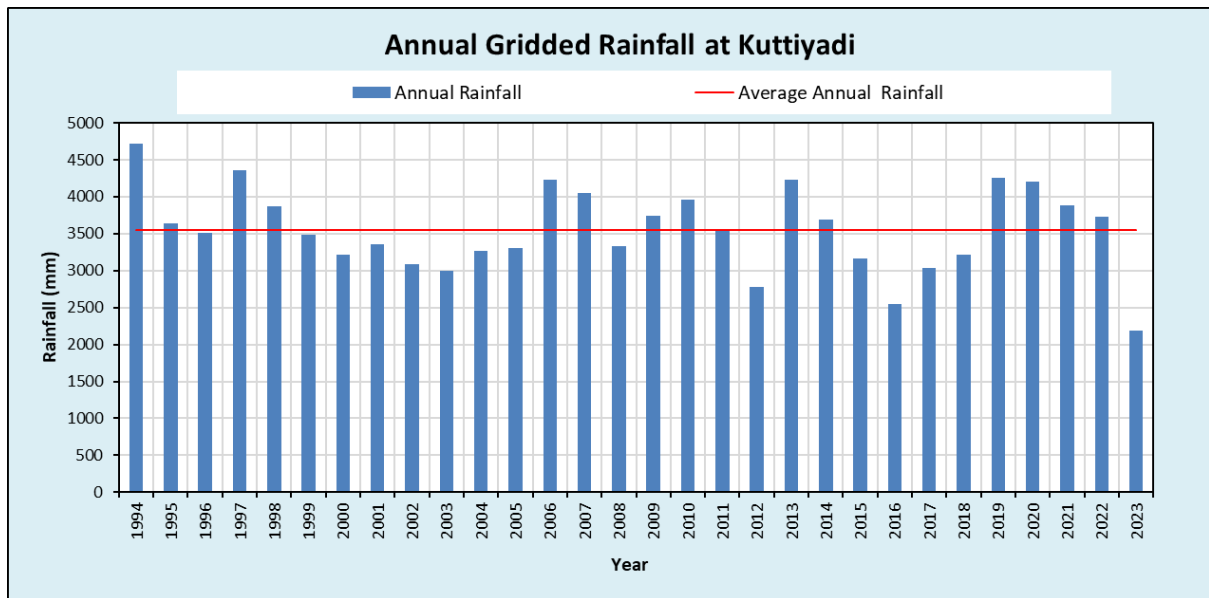


Figure 3-3: Distribution of annual rainfall at Kuttiyadi basin (1994-2023)

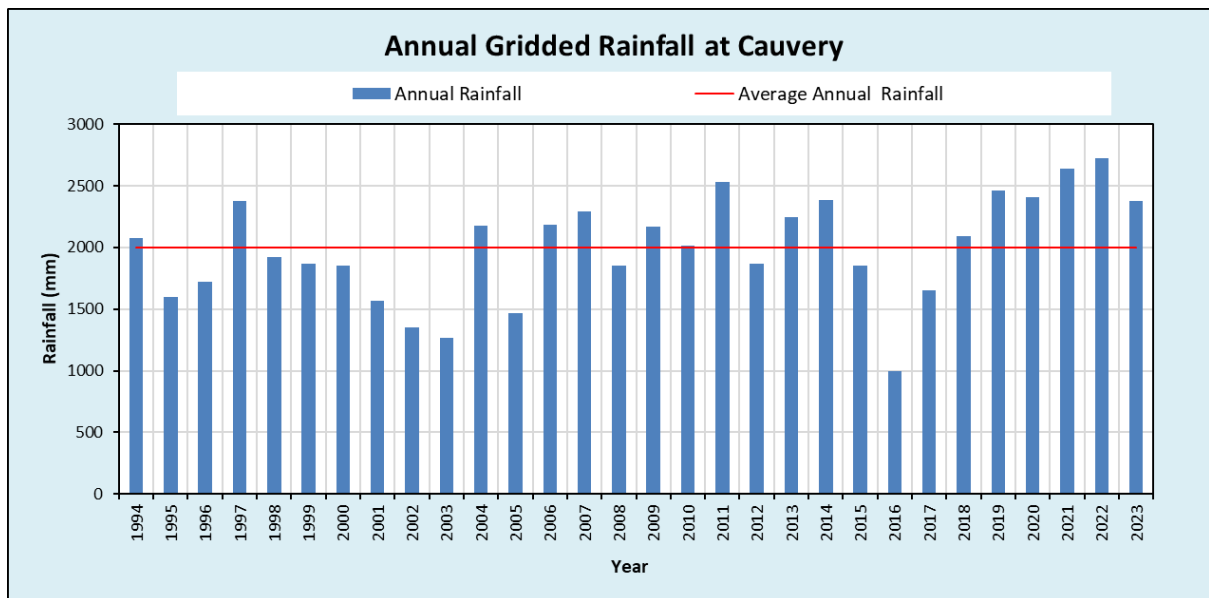


Figure 3-4: Distribution of annual rainfall at Cauvery basin (1994-2023)

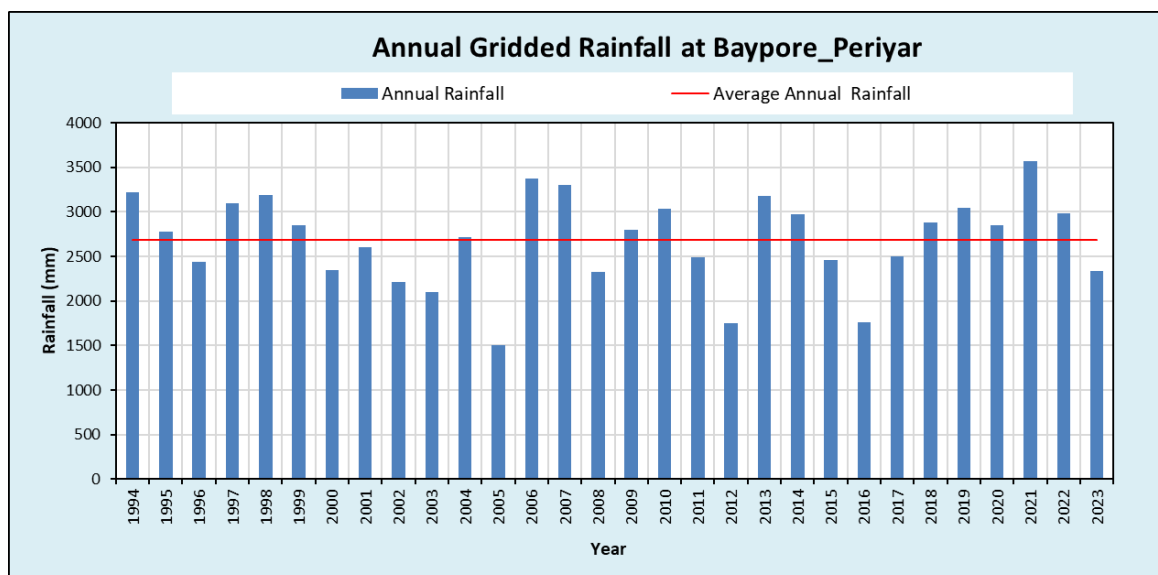


Figure 3-5: Distribution of annual rainfall at Baypore\_Periyar (1994-2023)

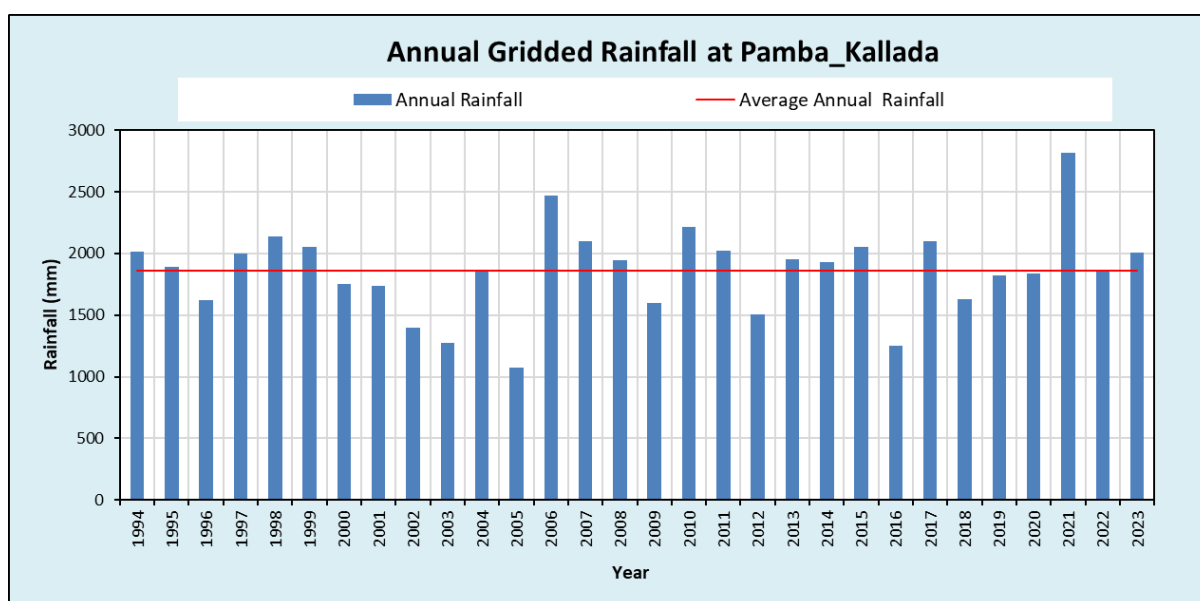


Figure 3-6: Distribution of annual rainfall at Pamba\_Kallada (1994-2023)

Map of annual rainfall distribution over a period of 30 years (1994-2023) using IMD gridded rainfall for Kerala State is shown in Figure 3-7. It is observed that upper part of Kerala (near to Kasaragod district) is

having annual rainfall of more than 4000 mm normally. Most of the part of Kerala is having rainfall ranges from 2500mm to 3000 mm.

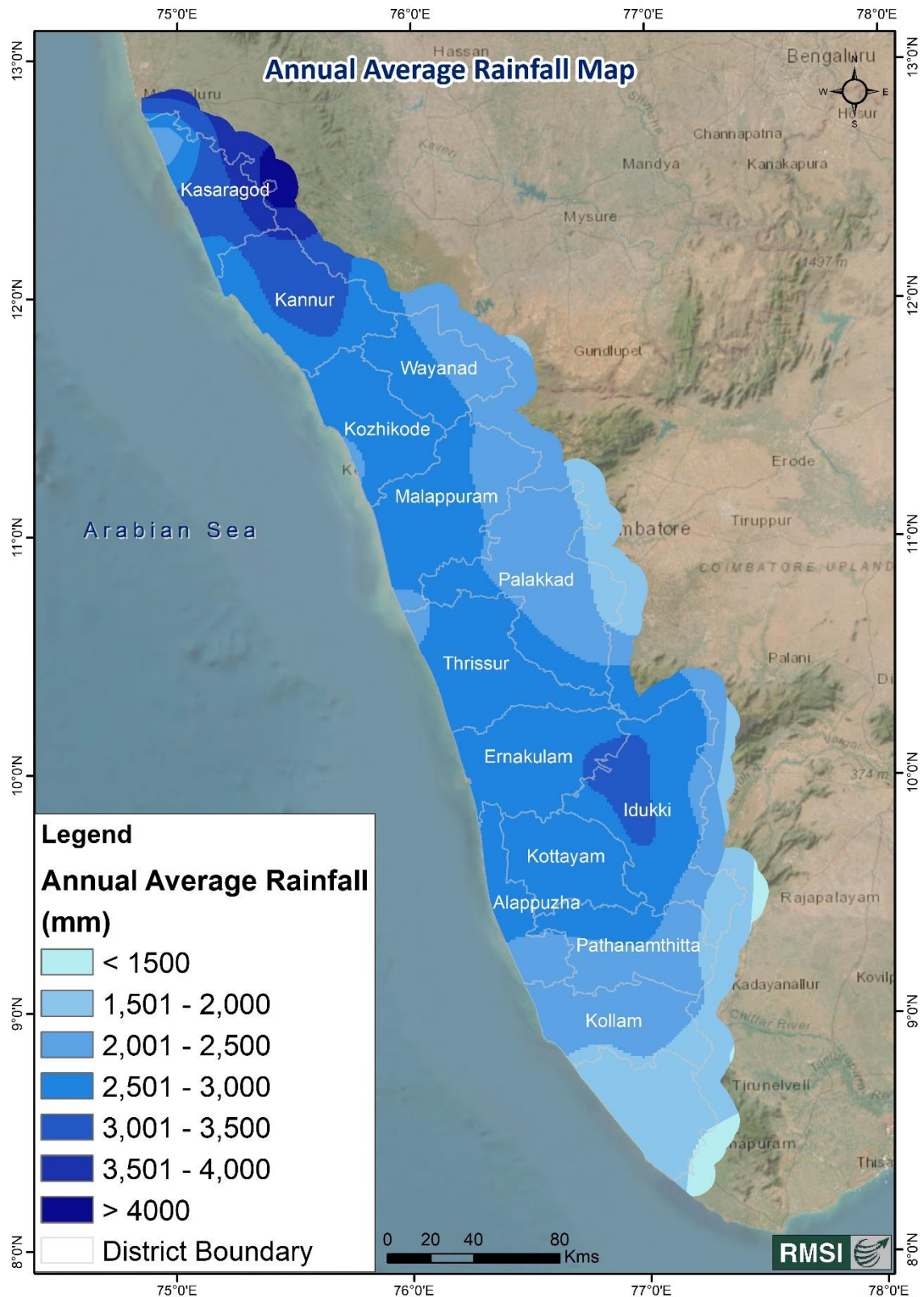


Figure 3-7: Statistical annual average rainfall at Kerala State (1994-2023)

### 3.1.3 MONTHLY RAINFALL

Mean monthly rainfall has been computed for the whole study area using 30 years (1994-2023) daily rainfall data published by

IMD. Monthly distribution of rainfall in the Kerala state and major basin of Kerala has been given in Table 3-3 and Table 3-4. From Table 3-3, it can be seen that the rain

mostly occurs during the months of June to October. It is also observed that most of the rainfall in the month of July. Rainfall occur in the month of October is due to cyclonic event which make a havoc in the lower part of Kerala state.

Table 3-4 shows that the month of July received the highest rainfall followed by June and August for the three basins

(Kuttiyadi, Cauvery and Baypore\_Periyar). However, the Pamba\_Kallada basin show highest rainfall in the month of October followed by June and November, due to unanticipated cyclone induced rainfall in the lower part of Kerala.

Monthly distribution of rainfall in the Kerala state and major basins of Kerala is presented from Figure 3-8 to Figure 3-12.

Table 3-3: Mean monthly rainfall in the study area

Months	IMD Gridded Rainfall (mm)
Jan	12.5
Feb	15.5
Mar	38.4
Apr	101.2
May	193.7
Jun	448.6
Jul	505.2
Aug	376.7
Sep	251.1
Oct	278.0
Nov	161.6
Dec	47.5
<b>Average Annual Rainfall (mm)</b>	<b>2430</b>

Table 3-4: Mean monthly rainfall in the study area

Months	Kuttiyadi	Cauvery	Baypore_Periyar	Pamba_Kallada
Jan	7.3	10.6	9.7	22.1
Feb	3.9	10.9	14.6	29.0
Mar	19.7	32.4	39.8	54.9
Apr	66.2	84.9	110.1	129.8
May	213.6	141.3	223.6	198.2
Jun	825.1	341.9	512.4	246.9
Jul	989.5	433.9	553.9	212.8
Aug	671.9	334.9	415.4	187.3
Sep	343.6	215.4	289.6	187.2
Oct	281.7	220.2	313.5	291.9
Nov	106.4	130.2	165.4	225.3
Dec	24.3	42.5	40.7	77.9
<b>Average Annual Rainfall (mm)</b>	<b>3553.2</b>	<b>1999.1</b>	<b>2688.7</b>	<b>1863.36</b>

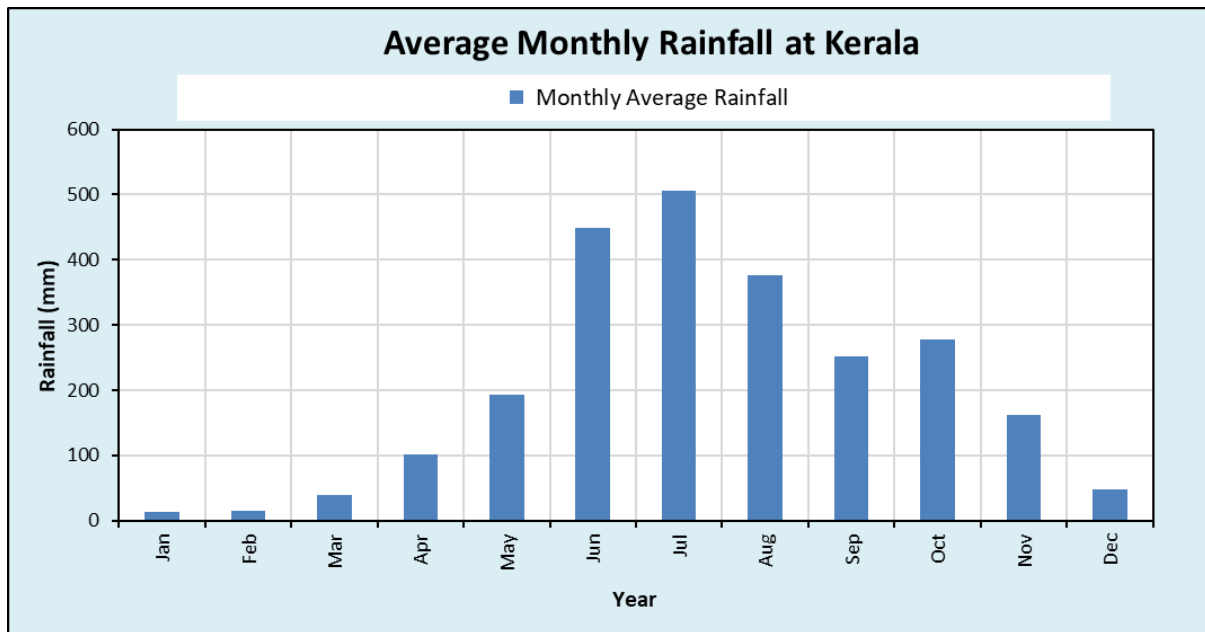


Figure 3-8: Average monthly rainfall for Kuttiyadi Basin (1994-2023)

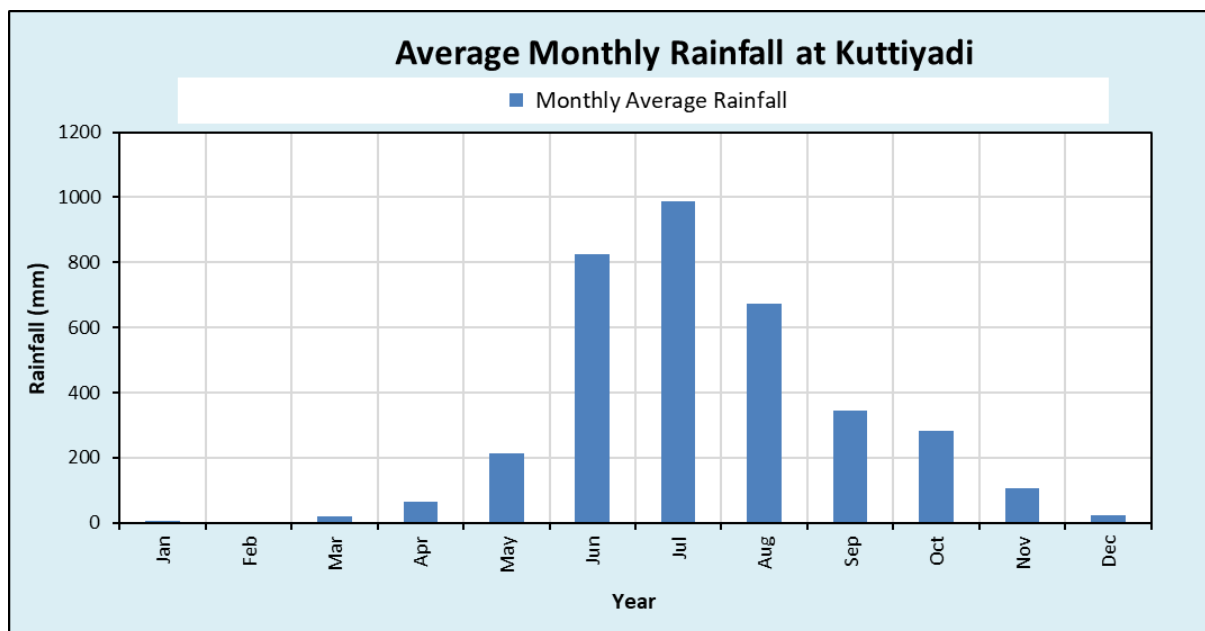


Figure 3-9: Average monthly rainfall for Kuttiyadi Basin (1994-2023)

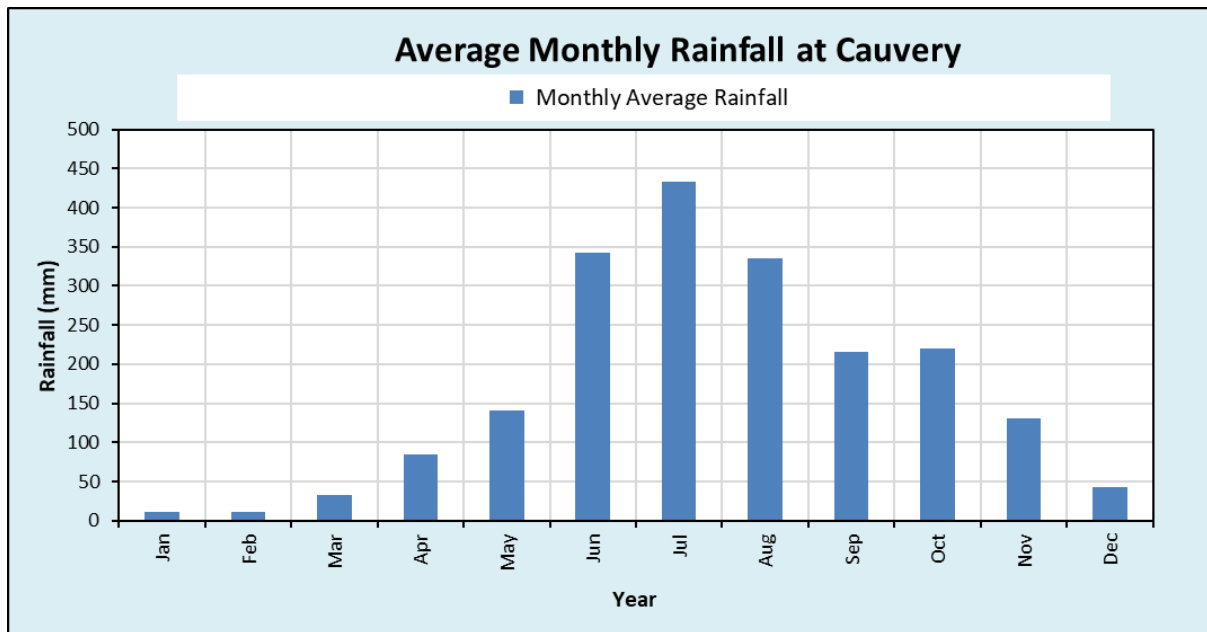


Figure 3-10: Average monthly rainfall for Cauvery Basin (1994-2023)

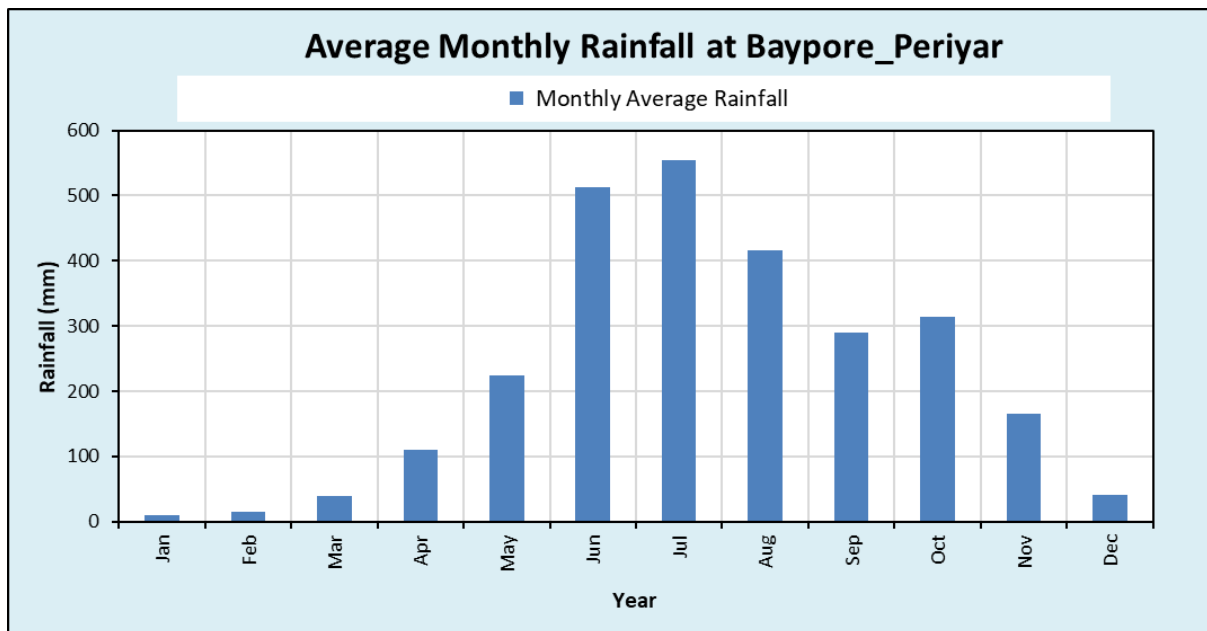


Figure 3-11: Average monthly rainfall for Baypore\_Periyar (1994-2023)

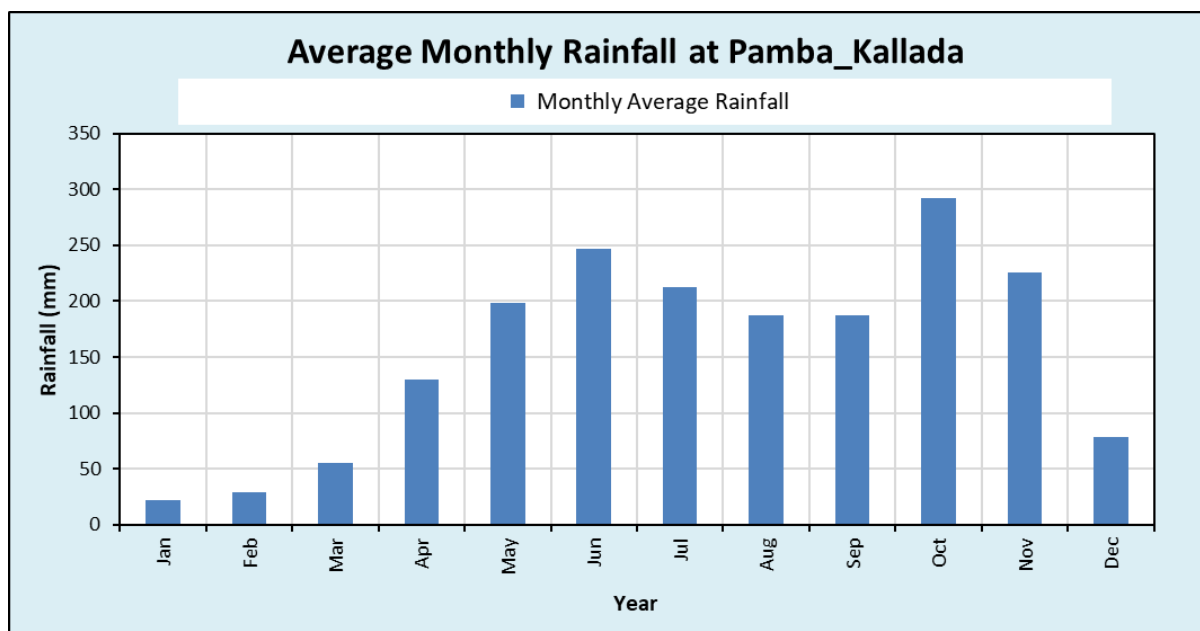


Figure 3-12: Average monthly rainfall for Pamba\_Kallada (1994-2023)

### 3.1.4 SEASONAL RAINFALL

In order to understand the seasonal distribution of rainfall, rainfall analysis has been carried out for two seasons, namely, monsoon season (June to September), and Non-monsoon (October to May). Seasonal distribution of gridded rainfall in the Kerala state and major basins of Kerala state is given in Table 3-5 and Table 3-6.

From Figure 3-13, analysis clearly shows that nearly 1548 mm of the annual rainfall

occurs during the monsoon season in this study area, contributing around 65 % to the annual rainfall.

It is observed from Figure 3-13, that nearly 2830 mm of the annual rainfall occurs during the monsoon season in the Kuttiyadi basin, contributing around 80% to the annual rainfall. Seasonal distribution of gridded rainfall in Kerala and major basins of Kerala state are shown from Figure 3-13 to Figure 3-17.

Table 3-5: Seasonal distribution of rainfall in the Kerala state.

Seasons	Kerala State	
	Rainfall (mm)	% of Annual Rainfall (mm)
Monsoon (Jun-Sep)	1582	65
Post-Monsoon (Oct-May)	848	35
<b>Average Annual Rainfall (mm)</b>	<b>2430</b>	<b>100.00</b>

Table 3-6: Seasonal distribution of rainfall in the basins of Kerala.

Seasons	Kuttiyadi		Cauvery		Baypore_Periyar		Pamba_Kallada	
	Rainfall (mm)	% of Annual Rainfall (mm)	Rainfall (mm)	% of Annual Rainfall (mm)	Rainfall (mm)	% of Annual Rainfall (mm)	Rainfall (mm)	% of Annual Rainfall (mm)
Monsoon (Jun-Sep)	2830.2	80	1326.0	66	1771.3	66	834.2	45
Non-Monsoon (Oct-May)	723.0	20	673.1	34	917.4	34	1029.2	55
<b>Average Annual Rainfall (mm)</b>	<b>3553.2</b>	<b>100</b>	<b>1999.1</b>	<b>100</b>	<b>2688.7</b>	<b>100</b>	<b>1863.4</b>	<b>100</b>

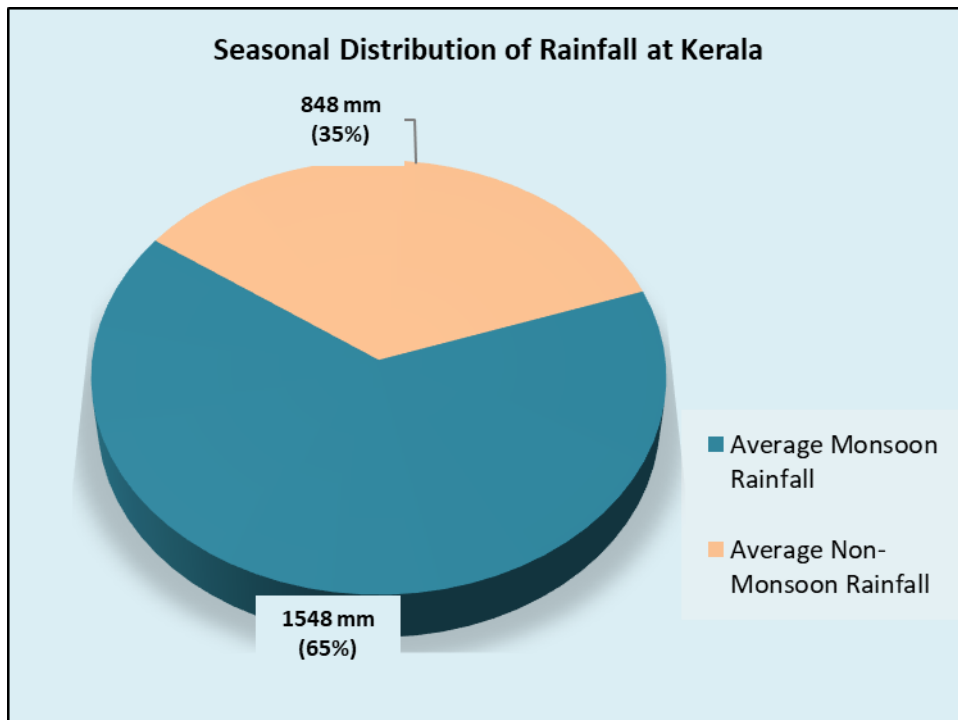


Figure 3-13: Seasonal distribution of rainfall in the Kerala State.

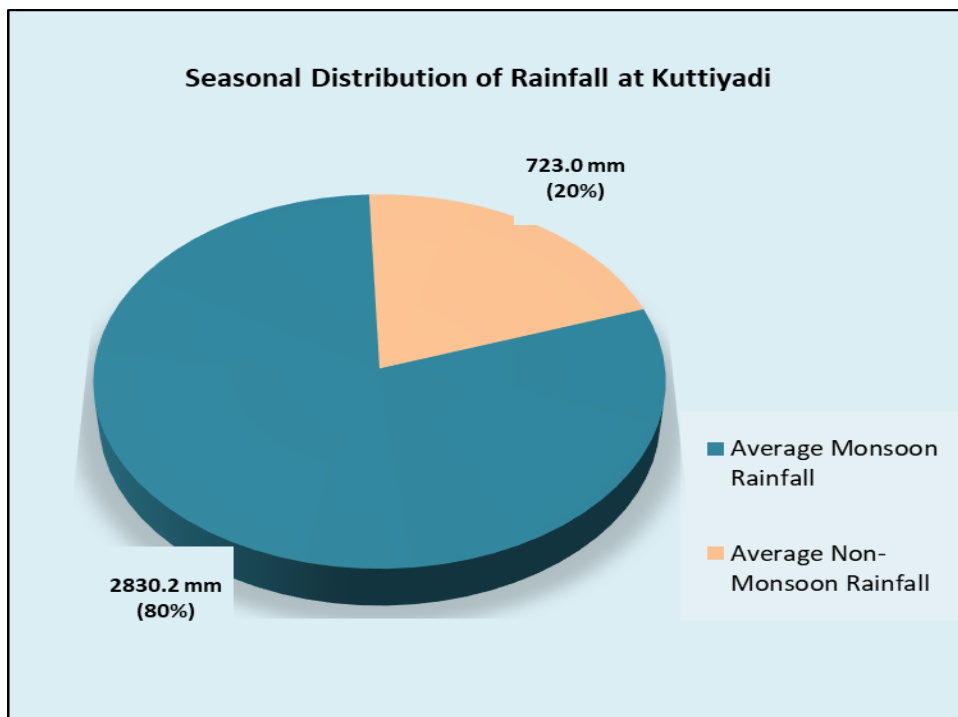


Figure 3-14: Seasonal distribution of rainfall in the Kuttiyadi basin

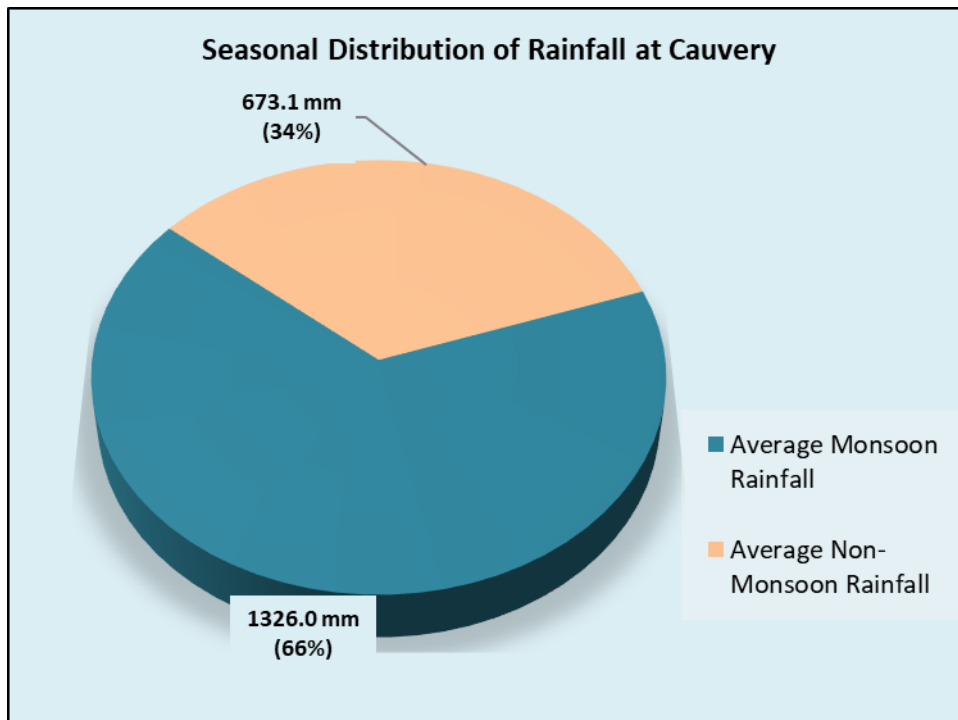


Figure 3-15: Seasonal distribution of rainfall in the Cauvery basin

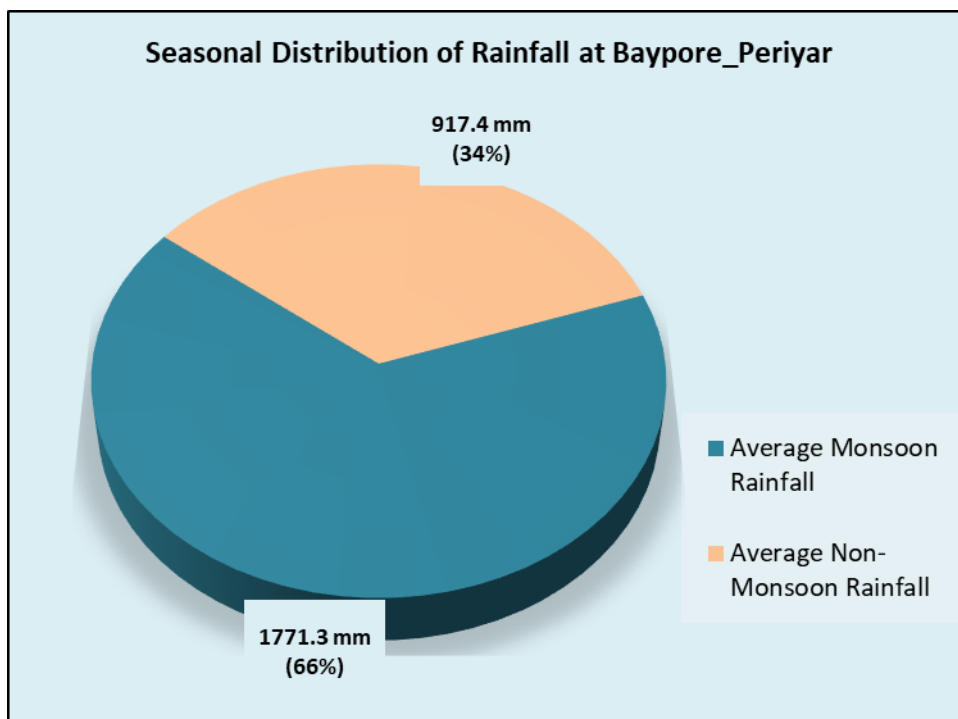


Figure 3-16: Seasonal distribution of rainfall in the Baypore\_Periyar basin.

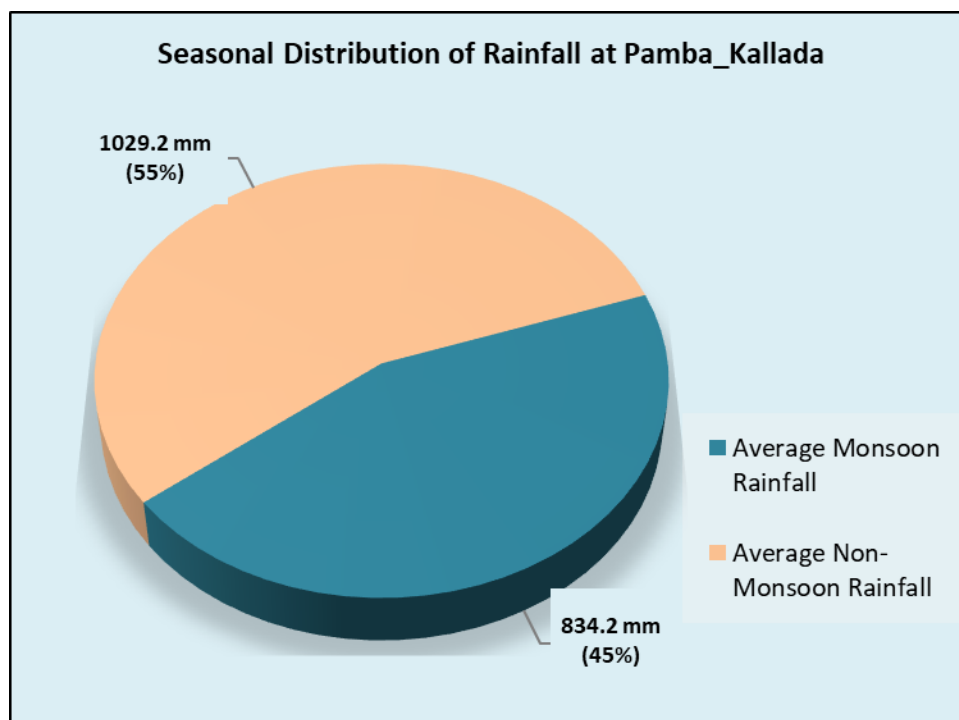


Figure 3-17: Seasonal distribution of rainfall in the Pamba\_Kallada basin.

### 3.1.5 ANNUAL MAXIMUM RAINFALL

Floods are generated due to heavy rainfall in the basin. Therefore, analysis of most severe events is essential to understand the flooding problems in any area.

Table 3-7 shows annual 1-Day maximum gridded rainfall of Kerala state, which is a valuable information on the extreme rainfall events that occurred in the study area over the past 30 years. While, Table 3-8 shows annual 1-Day maximum gridded rainfall of

major basin of Kerala state. This information can be used to assess the potential risks associated with heavy rainfall resulting in floods. Annual 1-Day maximum rainfall for Kerala state and major basins are shown from Figure 3-18 to Figure 3-22. Gridded Rainfall analysis shows that over a period of 30 years (1994-2023), maximum 1-Day annual rainfall (144.1 mm) occurred in the year 2019 in Kerala State.

Table 3-7: Annual 1-Day maximum rainfall in the Kerala state (1994-2023)

Year	1-Day Maximum Rainfall (mm)	Year	1-Day Maximum Rainfall (mm)
1994	79.3	2009	86.3
1995	50.0	2010	68.3
1996	62.1	2011	73.6
1997	86.5	2012	58.6
1998	65.2	2013	56.7
1999	59.8	2014	70.1
2000	63.6	2015	53.6
2001	59.3	2016	42.3

Year	1-Day Maximum Rainfall (mm)	Year	1-Day Maximum Rainfall (mm)
2002	62.3	2017	60.6
2003	56.9	2018	108.2
2004	88.9	2019	144.1
2005	43.5	2020	83.6
2006	87.4	2021	76.4
2007	93.8	2022	58.7
2008	54.7	2023	65.8

Table 3-8: Annual 1-Day maximum rainfall in the major basins of Kerala (1994-2023)

Year	Kuttiyadi	Cauvery	Baypore_Periyer	Pamba_Kallada
1994	149.7	77.4	95.4	82.2
1995	113.8	47.3	61.2	63.2
1996	164.8	47.0	72.4	72.3
1997	167.3	78.1	106.6	43.4
1998	131.5	55.9	89.5	82.9
1999	132.2	50.0	64.0	70.1
2000	82.2	64.5	78.4	68.3
2001	79.8	50.8	72.3	68.9
2002	145.4	34.5	92.8	42.0
2003	120.3	46.7	76.4	36.3
2004	130.0	80.7	114.2	64.6
2005	85.3	44.4	66.9	66.9
2006	133.5	61.9	151.3	95.3
2007	138.4	106.8	114.5	71.0
2008	106.8	65.6	56.0	61.6
2009	144.4	92.2	103.4	70.3
2010	131.7	69.1	95.1	68.3
2011	85.6	79.3	85.9	84.6
2012	86.6	77.9	61.7	51.1
2013	126.2	69.5	88.6	48.9
2014	130.1	58.4	86.8	92.4
2015	94.0	51.9	68.9	62.4
2016	74.6	51.2	41.1	60.6
2017	86.6	51.2	76.7	113.0
2018	118.2	92.6	166.4	96.3
2019	187.1	178.4	191.9	61.0
2020	141.2	119.6	105.8	50.5
2021	123.1	80.6	103.0	80.7
2022	107.1	63.9	91.0	62.8

Year	Kuttiyadi	Cauvery	Baypore_Periyer	Pamba_Kallada
2023	113.1	65.7	86.2	71.7

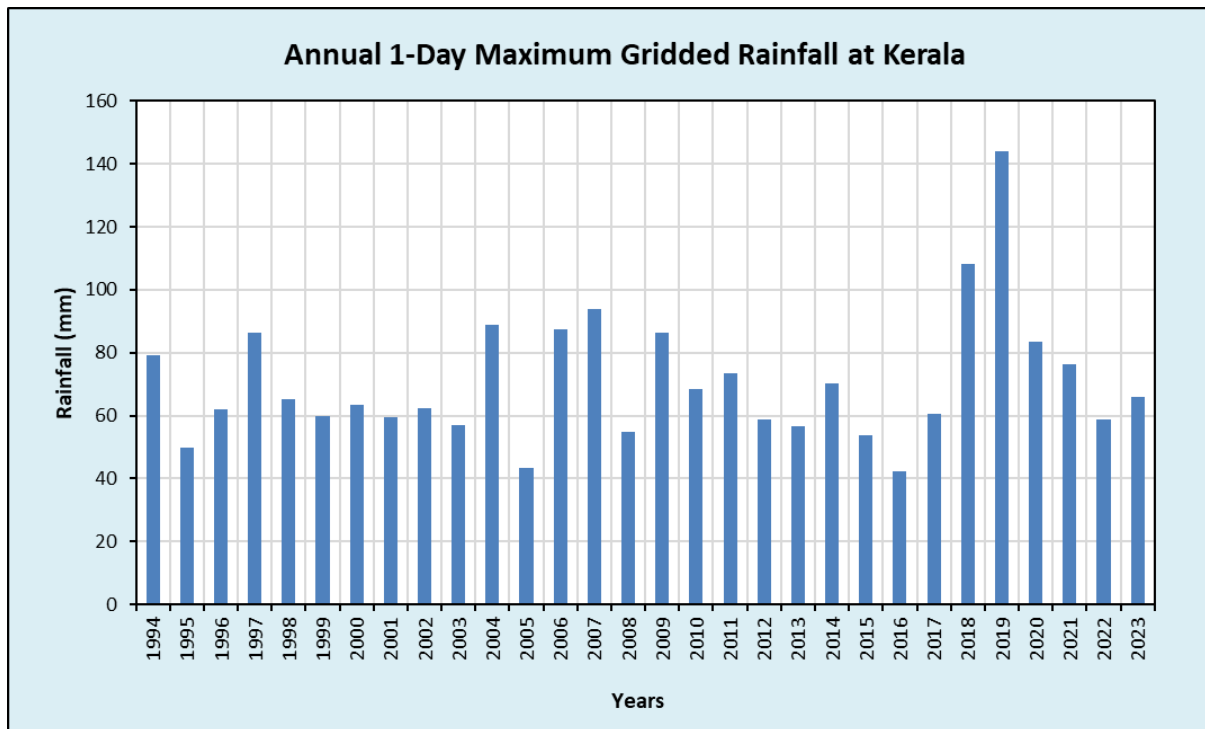


Figure 3-18: Annual 1-Day maximum rainfall at Kerala.

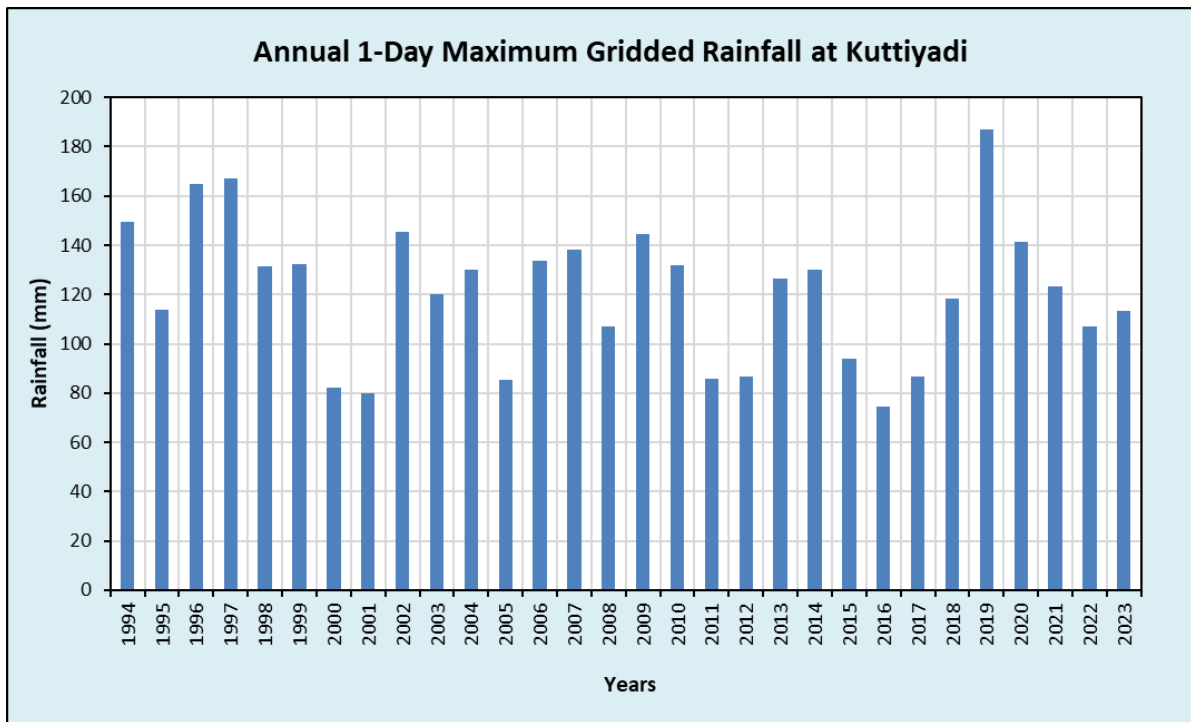


Figure 3-19: Annual 1-Day maximum rainfall at Kuttiyadi.

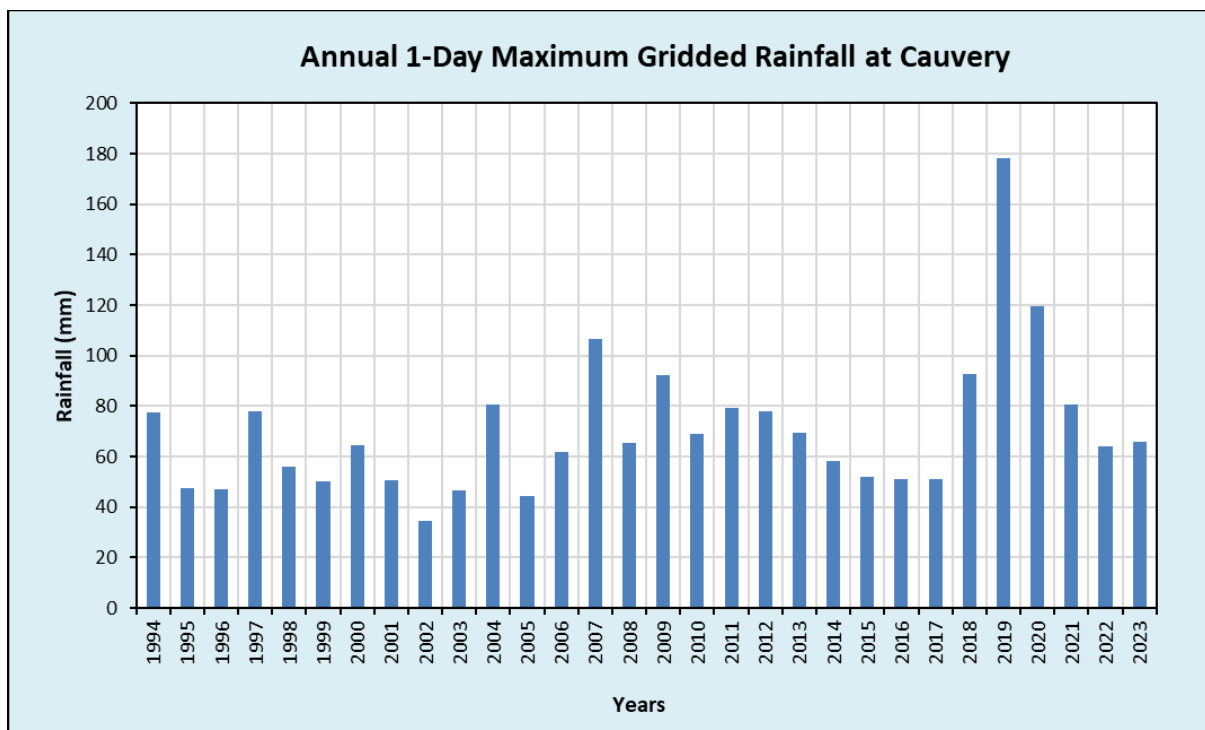


Figure 3-20: Annual 1-Day maximum rainfall at Cauvery

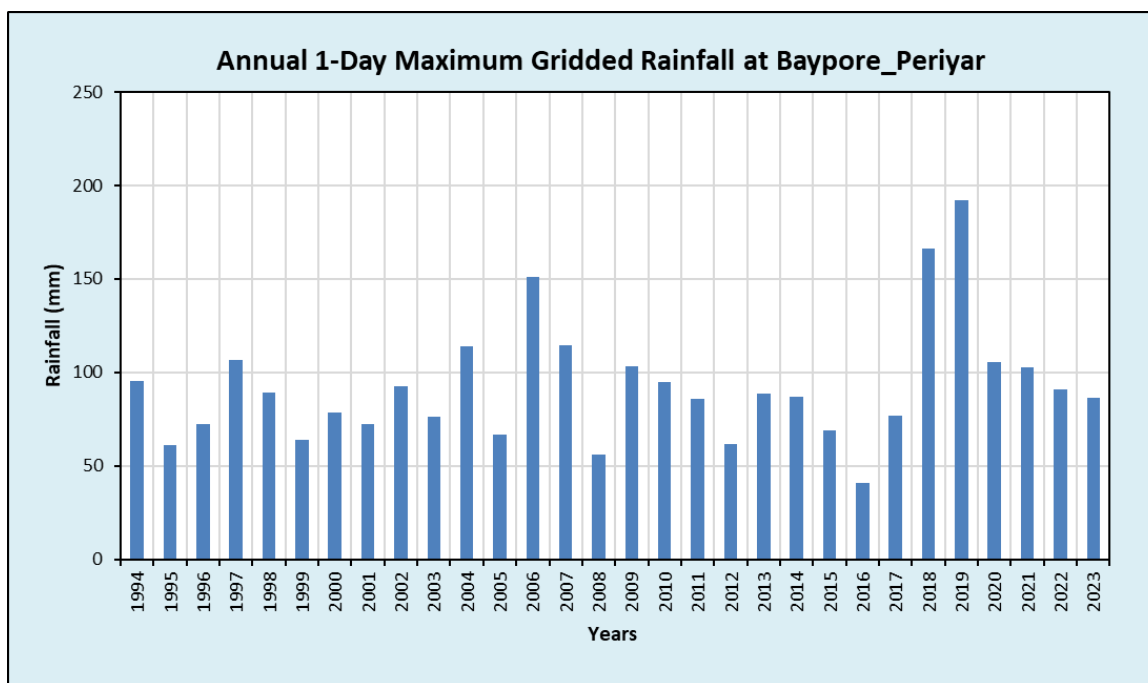


Figure 3-21: Annual 1-Day maximum rainfall at Baypore\_Periyar

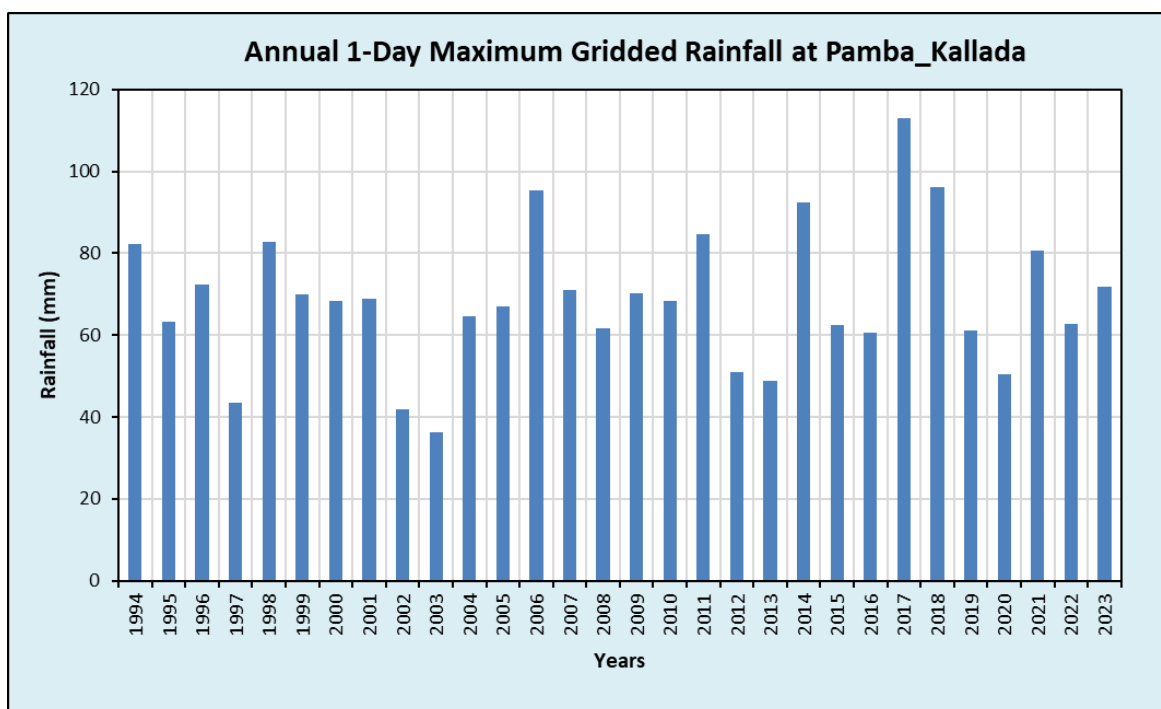


Figure 3-22: Annual 1-Day maximum rainfall in Pamba\_Kallada.

### 3.1.6 RAINFALL OF DIFFERENT RETURN PERIODS

Rainfall frequency analysis has been carried out for 1-Day annual maximum rainfall series derived from the IMD gridded precipitation data for a period of 30 years

(1994 to 2023). Frequency analysis has been carried out to calculate the rainfall depths for different return periods. Period rainfall was estimated using four frequency

analysis distributions: Normal, Log-Normal, Gumbel, and Log Pearson Type-III Distributions. Gumbel distribution was found as the most suitable distribution on the basis of goodness of fit tests and derived values of different return periods

were utilized for hydrological analyses across various return periods. Daily rainfall of 10, 25, 50, 100, 200 and 500 -year return periods are shown from Figure 3-23 to Figure 3-28.

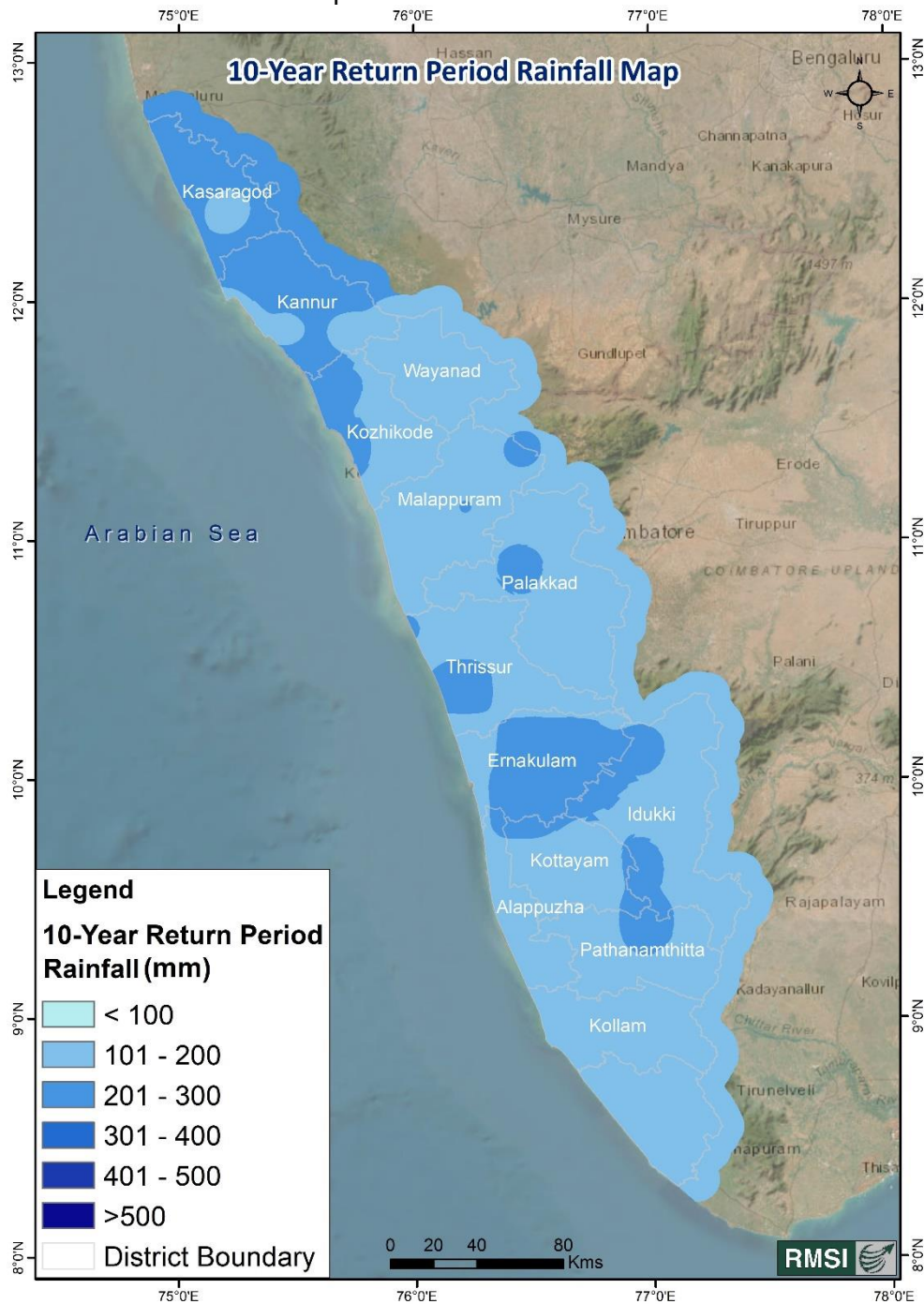


Figure 3-23: 10-year return period rainfall of Kerala state.

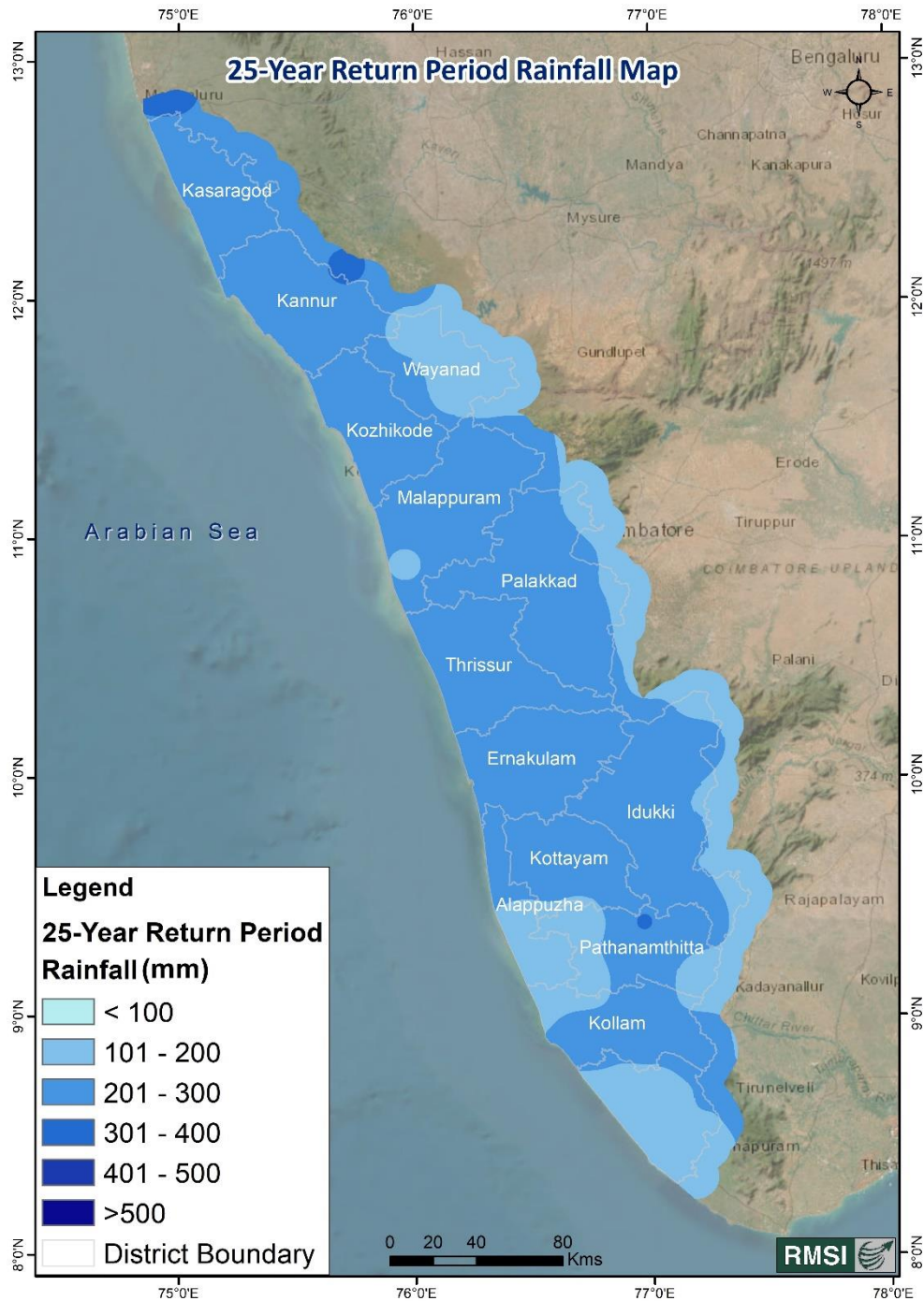


Figure 3-24: 25-year return period rainfall of Kerala state.

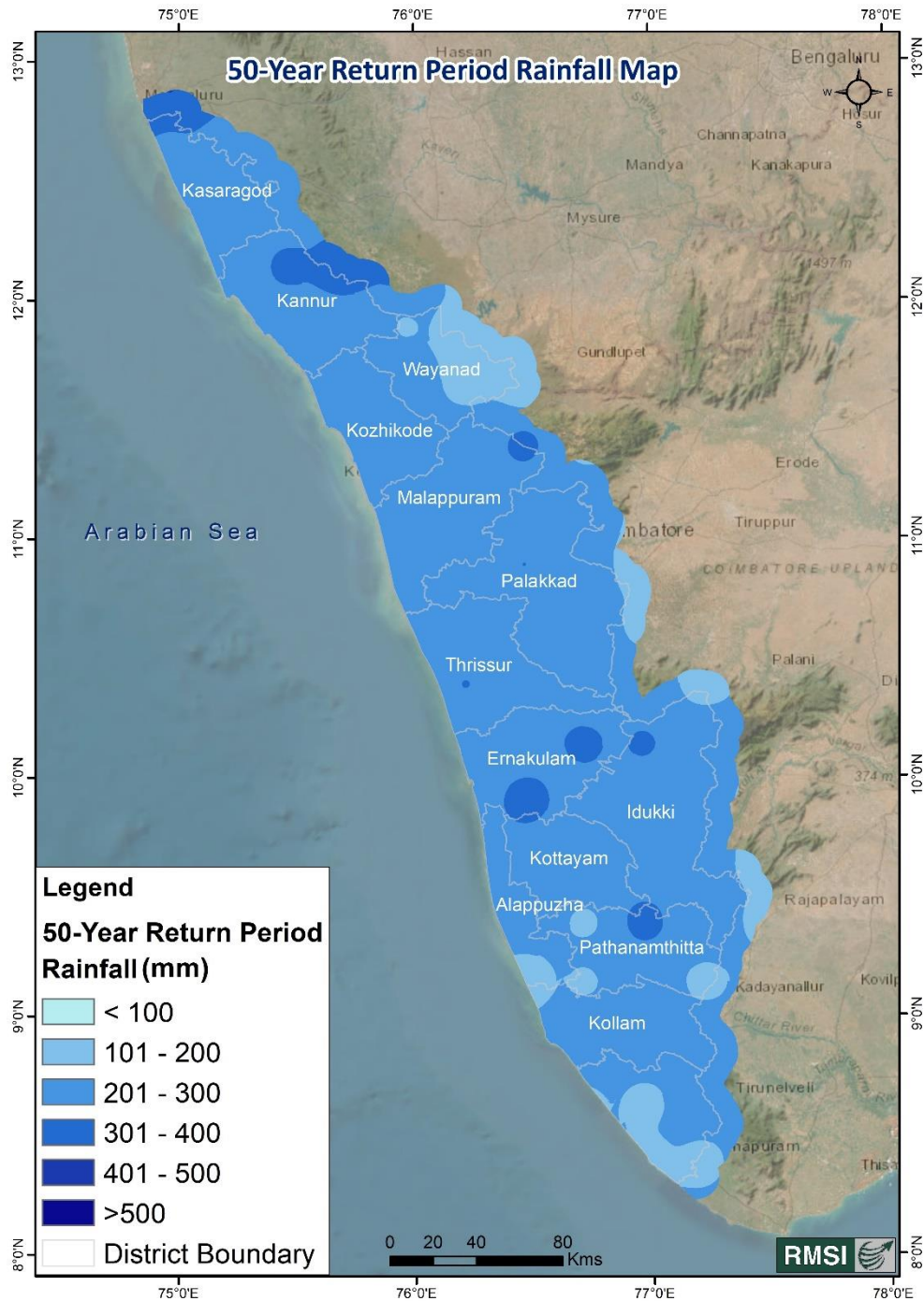


Figure 3-25: 50-year return period rainfall of Kerala state.

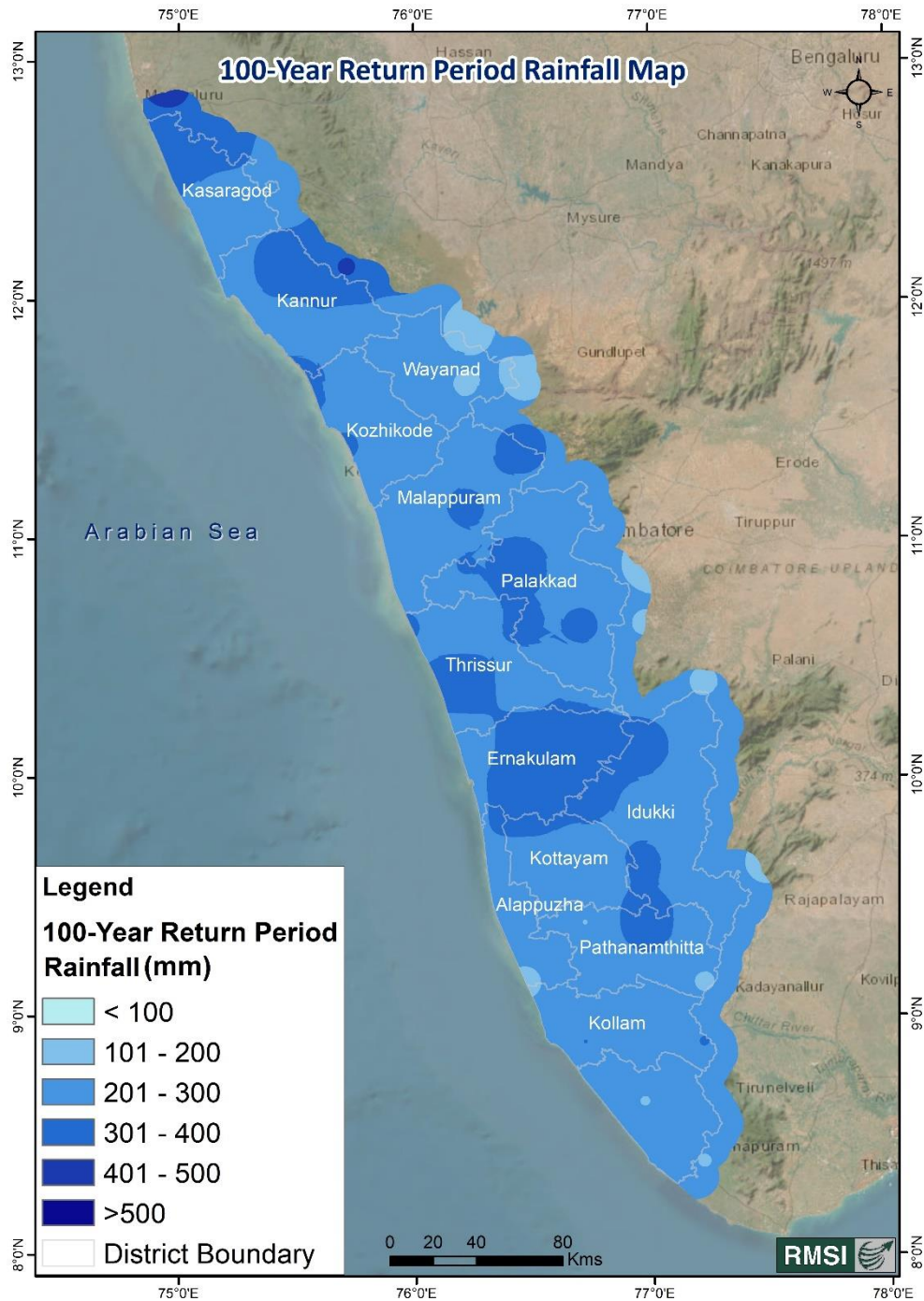


Figure 3-26: 100-year return period rainfall of Kerala state.

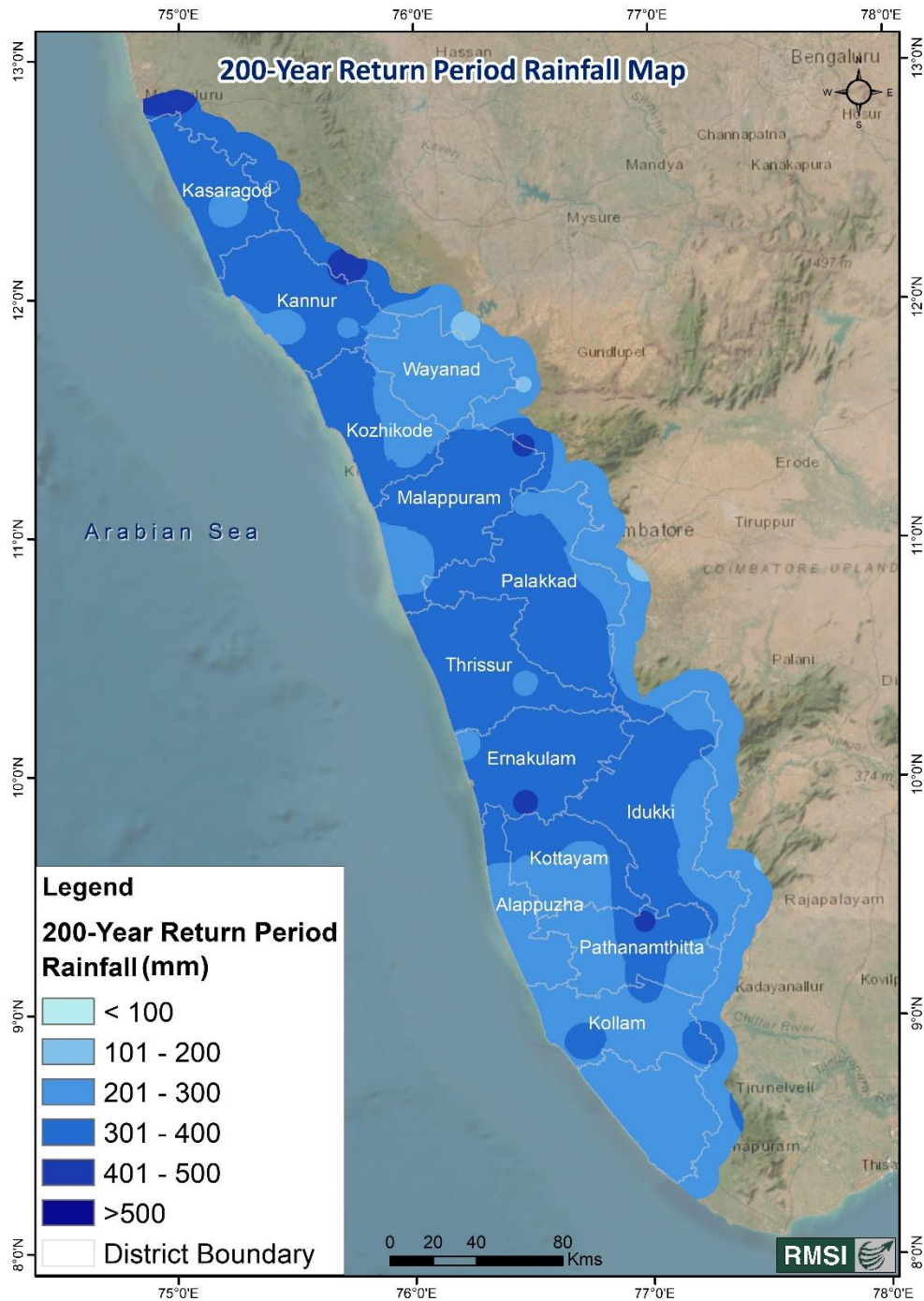


Figure 3-27: 200-year return period rainfall of Kerala state.

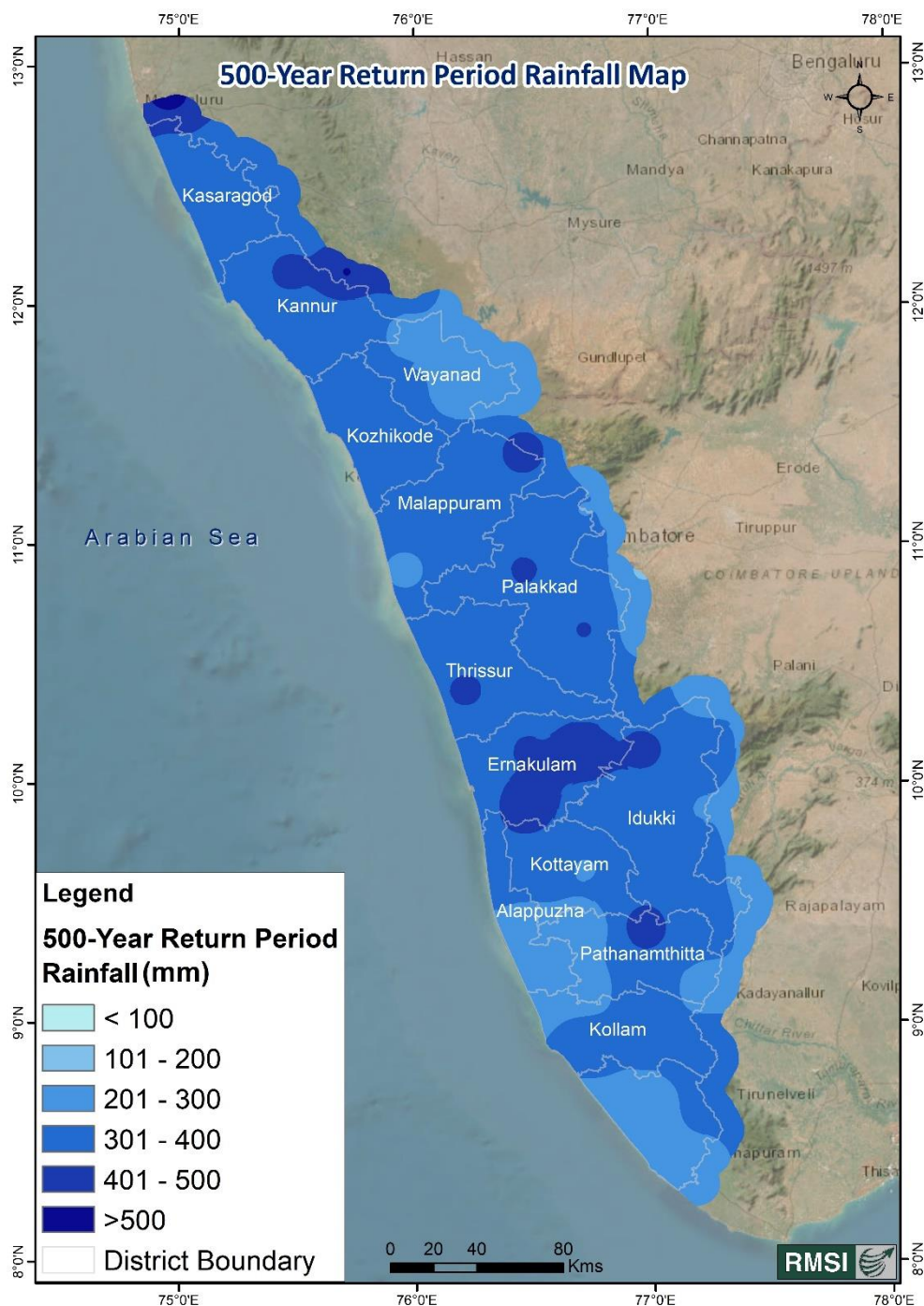


Figure 3-28: 500-year return period rainfall of Kerala state.

### 3.2 August 2018 Kerala flood Return Period and Role of DAM

Kerala is having 57 large dams out of which 4 dams are operated by Government of Tamil Nadu<sup>63</sup>. The combined total live storage capacity of these dams is 5.806

(BCM). This is equal to 7.4% of annual average runoff of all 44 rivers in Kerala, which is about 78 BCM (ref: Water

<sup>63</sup> [https://www.nationalheraldindia.com/india/in-kerala-theres-no-reason-to-damn-the-](https://www.nationalheraldindia.com/india/in-kerala-theres-no-reason-to-damn-the-dams#:~:text=There%20are%20other%20dams,storage%20capacity%20of%20670%20MCM.)

[dams#:~:text=There%20are%20other%20dams,storage%20capacity%20of%20670%20MCM.](https://www.nationalheraldindia.com/india/in-kerala-theres-no-reason-to-damn-the-dams#:~:text=There%20are%20other%20dams,storage%20capacity%20of%20670%20MCM.)

Resources of Kerala 1974)<sup>64</sup>. Out of the above, only 7 reservoirs are having a live storage capacity of more than 0.20 BCM and they constitute 74% of the total live storage in Kerala. Table 3-9 presented the storage capacity of reservoirs in Kerala.

The August 2018 Kerala Flood was most devastating flood event, cause losses to human lives and infrastructure have increased under the warming climate.

In August 2018, Kerala State witnessed large-scale flooding, which affected millions of people and caused 400 or more deaths. The return period of extreme rainfall and the potential role of 10 reservoirs in the recent flooding in Kerala has been examined and Kerala experienced 53% above normal rainfall during the monsoon season (till August 21st) of 2018<sup>65</sup>. Moreover, 1, 2, and 3-day extreme rainfall in Kerala during August 2018 had return periods of 75, 200, and 100 years.

Six out of seven major reservoirs were at more than 90% of their full capacity on August 8, 2018, before extreme rainfall in Kerala. Extreme rainfall at 1-15 days durations in August 2018 in the catchments upstream of the three major reservoirs (Idukki, Kakki, and Mullaperiyar-highlighted in red circle in the map shown in Figure 3-29) had the return.

Extreme rainfall and nearly full reservoirs led to a significant release of water within a short period. The combination of above-normal seasonal rainfall (prior to August 8, 2018), high reservoir storage levels, and unprecedented extreme rainfall in the catchment areas of the reservoirs exacerbated the flooding in Kerala. To mitigate such risks, reservoir operations should be enhanced by utilizing skillful long-range rainfall forecasts with a lead time of 4-7 days.

Table 3-10 shows the rainfall depths in various basins and rest of the Kerala from 15-17 August 2018.

Table 3-9: Storage capacity of major Reservoirs in Kerala<sup>66</sup>

Sl.No.	Name of Reservoir	Live Storage Capacity (MCM)
1.	Idukki	1460
2.	Idamalayar	1018
3.	Kallada	488
4.	Kakki	447
5.	Parambikulam (for use of TN)	380
6.	Mullaperiyar (for use of TN)	271
7.	Malampuzha	227

<sup>64</sup> <https://sdma.kerala.gov.in/wp-content/uploads/2020/08/CWC-Report-on-Kerala-Floods.pdf>

<sup>65</sup> Mishra, V., Aadhar, S., Shah, H., Kumar, R., Pattanaik, D. R., & Tiwari, A. D. (2018). The Kerala flood of 2018:

combined impact of extreme rainfall and reservoir storage. *Hydrology and Earth System Sciences Discussions*, 2018, 1-13.

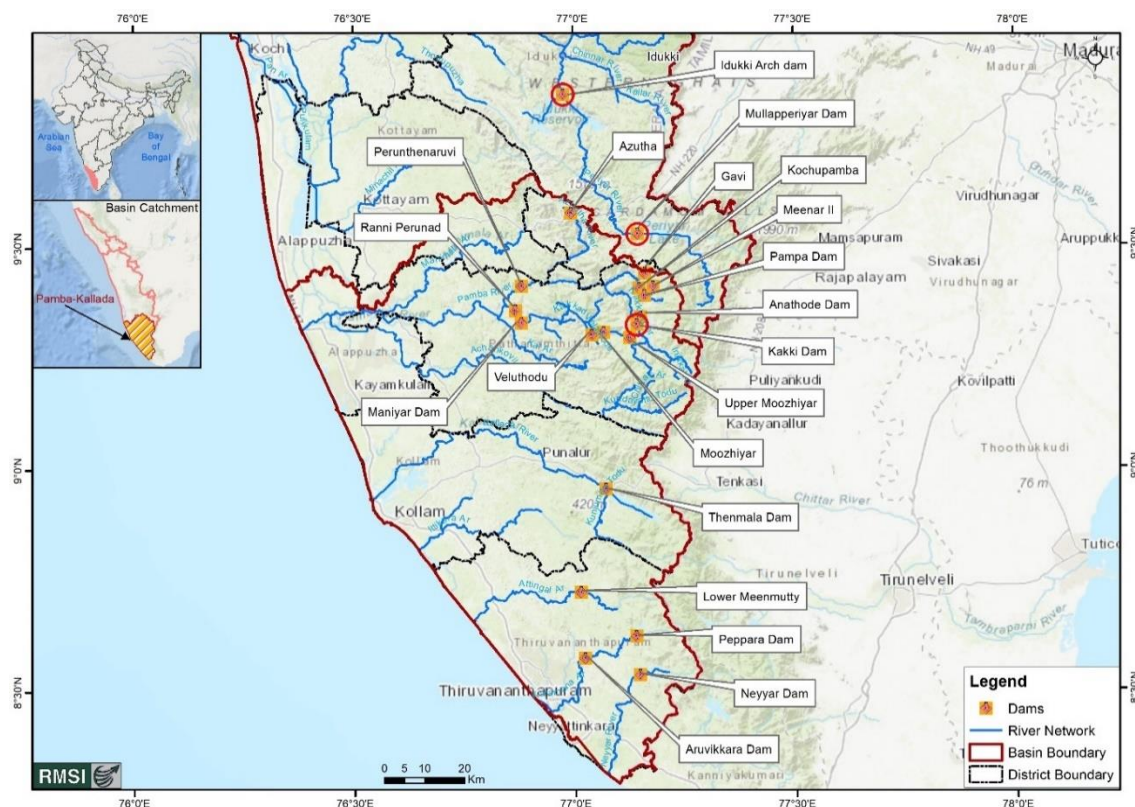


Figure 3-29: Location map of DAMs in Kerala

Table 3-10: Rainfall depths relisted in different sub-basins and rest of the Kerala in storm of 15-17, August 2018<sup>66</sup>

Sl. No.	NAME	AREA (Sq Km)	15 Aug 2018	15-16, Aug2018	15-17, Aug 2018	16 Aug 2018
			1 Day (mm)	2 Day (mm)	3 Day (mm)	1 Day (mm)
1	Rest of the Kerala	26968	132	279	364	155
2	Kallada	1139	129	208	289	83
3	Pamba	1620	176	397	538	217
4	Periyar	4035	198	452	588	248
5	Bharathapuzha	5784	114	297	373	182
6	Chaliyar	1992	128	256	331	141
7	Valapattanam	1019	180	263	336	83

### 3.2.1 FLOOD HAZARD MODELLING

The Continuum Hydrological Model (HMC), developed by Silvestro et al. (2013, 2015) was applied to study hydrological processes in Kerala. HMC is a continuous, spatially distributed model that operates on a regular grid to solve energy and mass

balance equations across the landscape. Integrated within the Flood-PROOFS Modeling System, HMC aids decision-makers in operational flood forecasting, nowcasting, and monitoring for catchments of varying scales.

<sup>66</sup> <https://sdma.kerala.gov.in/wp-content/uploads/2020/08/CWC-Report-on-Kerala-Floods.pdf>

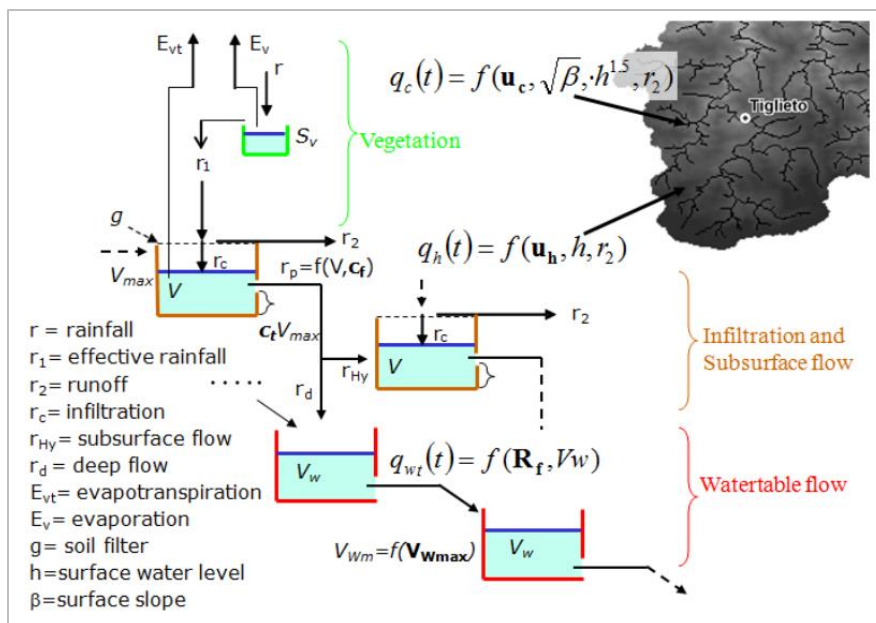


Figure 3-30: Flood model methodology flow chart<sup>67</sup>

The HMC includes several core modules:

- **Modified Horton Method for Infiltration:** This approach considers variations in land cover and climatic factors.
- **Runoff Routing and Subsurface Flow Routing:** These modules differentiate between hillslope and channel flow and employ a semi-empirical modification of Horton's algorithm for infiltration (Diskin & Nazimov, 1997).
- **Energy Balance:** Soil temperature is computed using the Force Restore Equation (Dickinson, 1988).
- **Water Table Dynamics, Deep Flow, and Snow Modeling:** These modules provide corrections based on soil moisture and energy balance.
- **Soil Moisture Adjustments:** Soil moisture data from SMAP satellite datasets enhances model accuracy by informing moisture conditions since 2015.

The basin is mapped onto a grid derived from a Digital Elevation Model (DEM), with flow directions established by calculating maximum slope directions. HMC differentiates hillslope and channeled flow based on drainage area and local slope, with flow accumulations weighted according to the morphological environment<sup>68</sup>. In mature terrains, the parameter  $k = 1.7^{48,69}$ , while the threshold  $C$  is calibrated through topographic routing<sup>70</sup>.

For Kerala, the HMC was calibrated using streamflow data from approximately 30 stations across the state. Additionally, soil moisture readings from SMAP provided essential data for soil condition analysis. Implemented across Kerala with a 1.4 km resolution and refined to 90 m for final flood mapping, HMC aims to optimize the representation of flow and moisture patterns and to improve flood prediction accuracy.

<sup>67</sup> Silvestro, F., Gabellani, S., Rudari, R., Delogu, F., Laiolo, P., & Boni, G. (2015). Uncertainty reduction and parameter estimation of a distributed hydrological model with ground and remote-sensing data. *Hydrology and Earth System Sciences*, 19(4), 1727-1751.

<sup>68</sup> □ Giannoni, F., Roth, G., and Rudari, R.: A semi-distributed rainfall-runoff model based on a geomorphologic approach, *Phys. Chem. Earth*, 25, 665–671, 2000.

<sup>69</sup> □ Giannoni, F., Roth, G., and Rudari, R.: Can the behavior of different basins be described by the same model's parameter set? A geomorphologic framework, *Phys. Chem. Earth*, 28, 289–295, 2003.

<sup>70</sup> □ Giannoni, F., Roth, G., and Rudari, R.: A procedure for drainage network identification from geomorphology and its application to the prediction of the hydrologic response, *Adv. Water Resour.*, 28, 567–581, 2005.

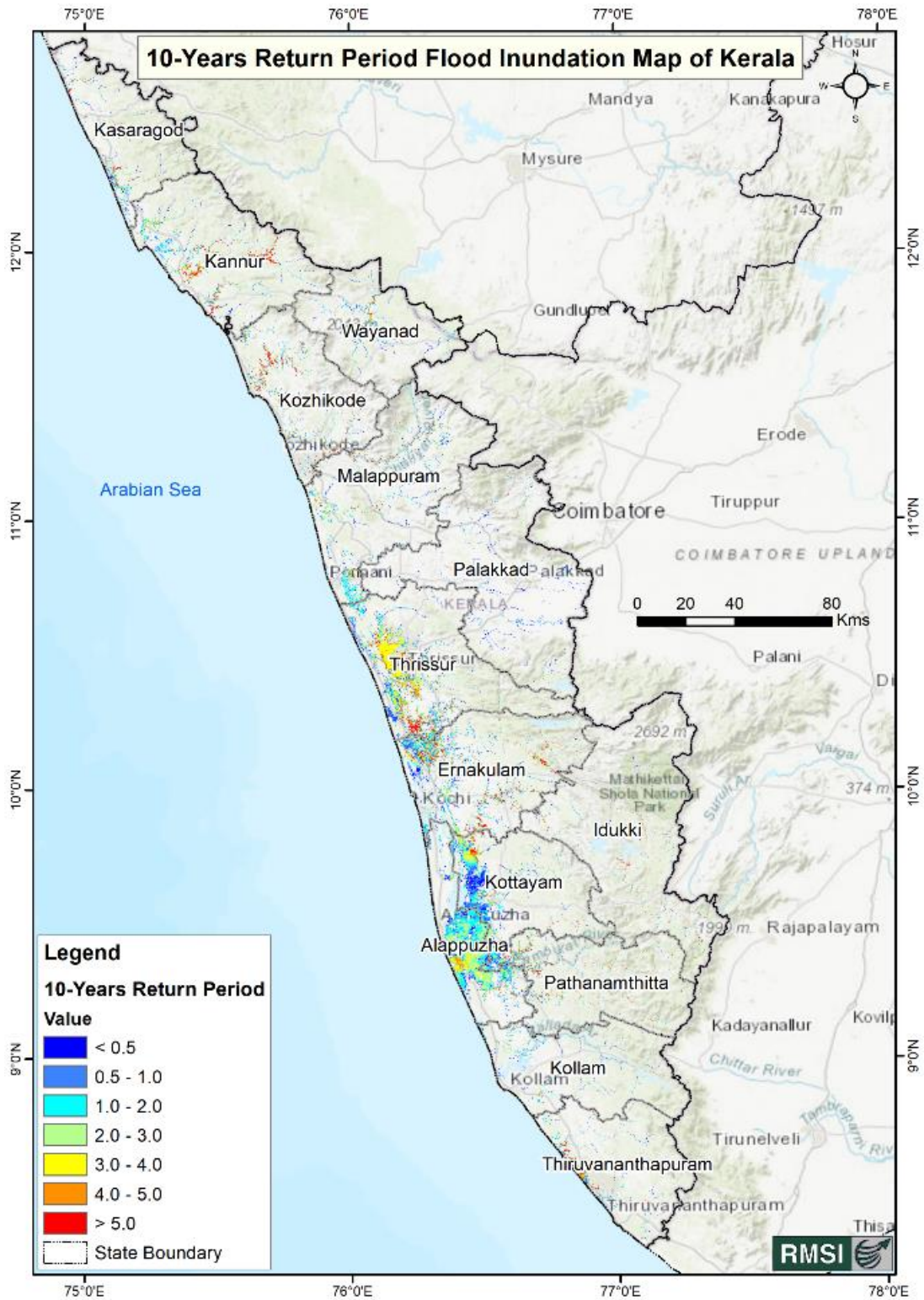


Figure 3-31: Flood hazard map of 10-year return period

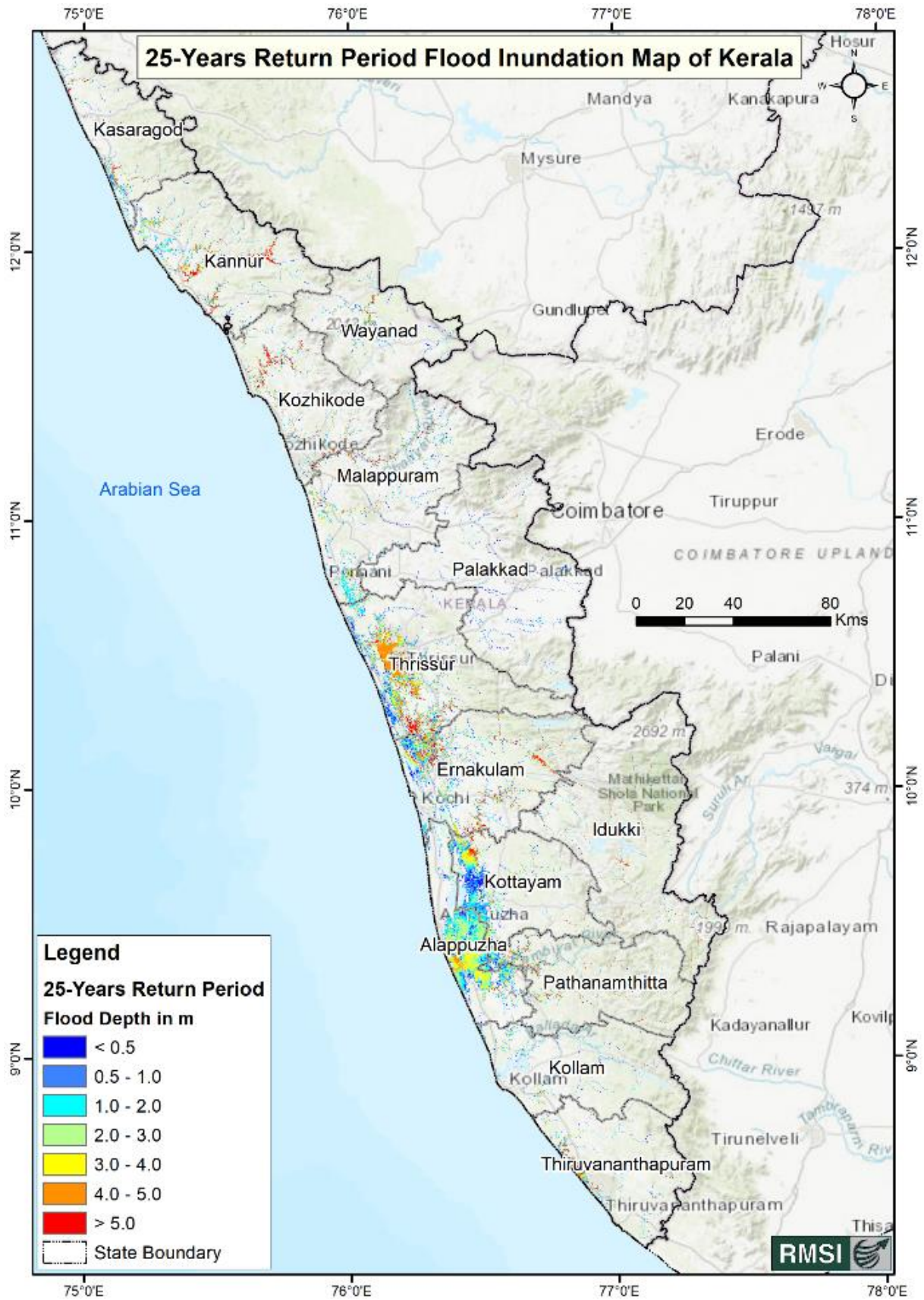


Figure 3-32: Flood hazard map of 25-year return period

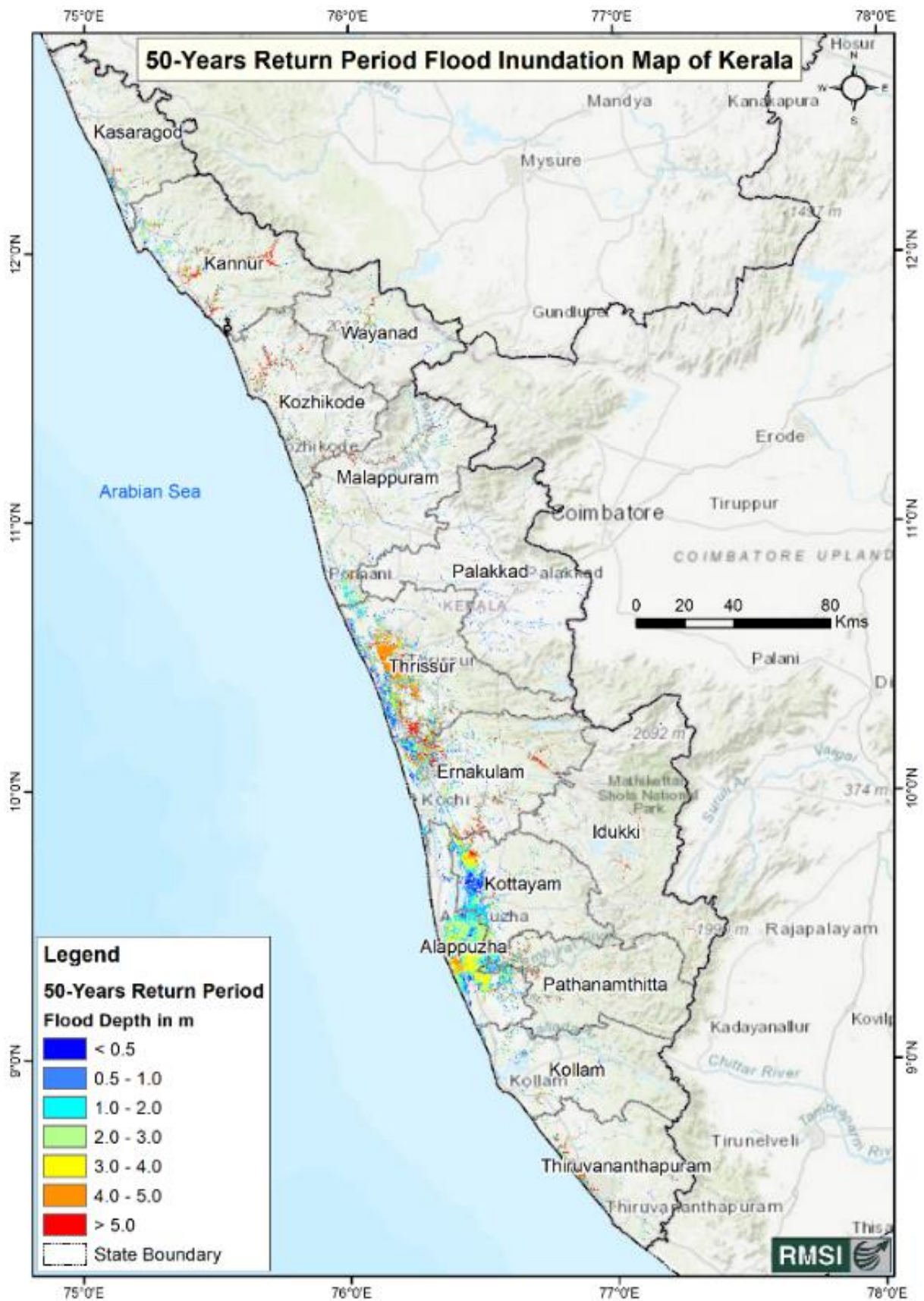


Figure 3-33: Flood hazard map of 50-year return period

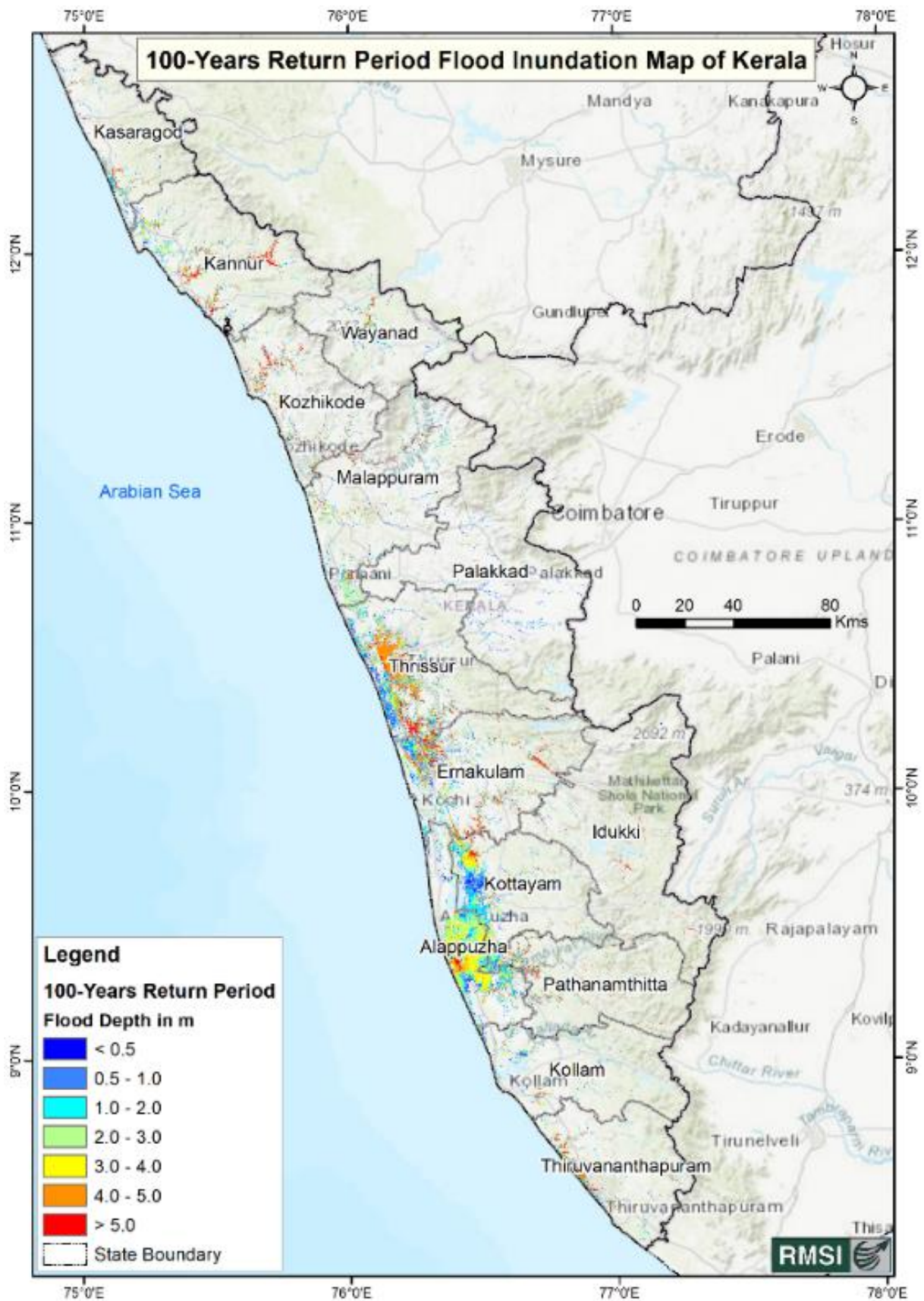


Figure 3-34: Flood hazard map of 100-year return period

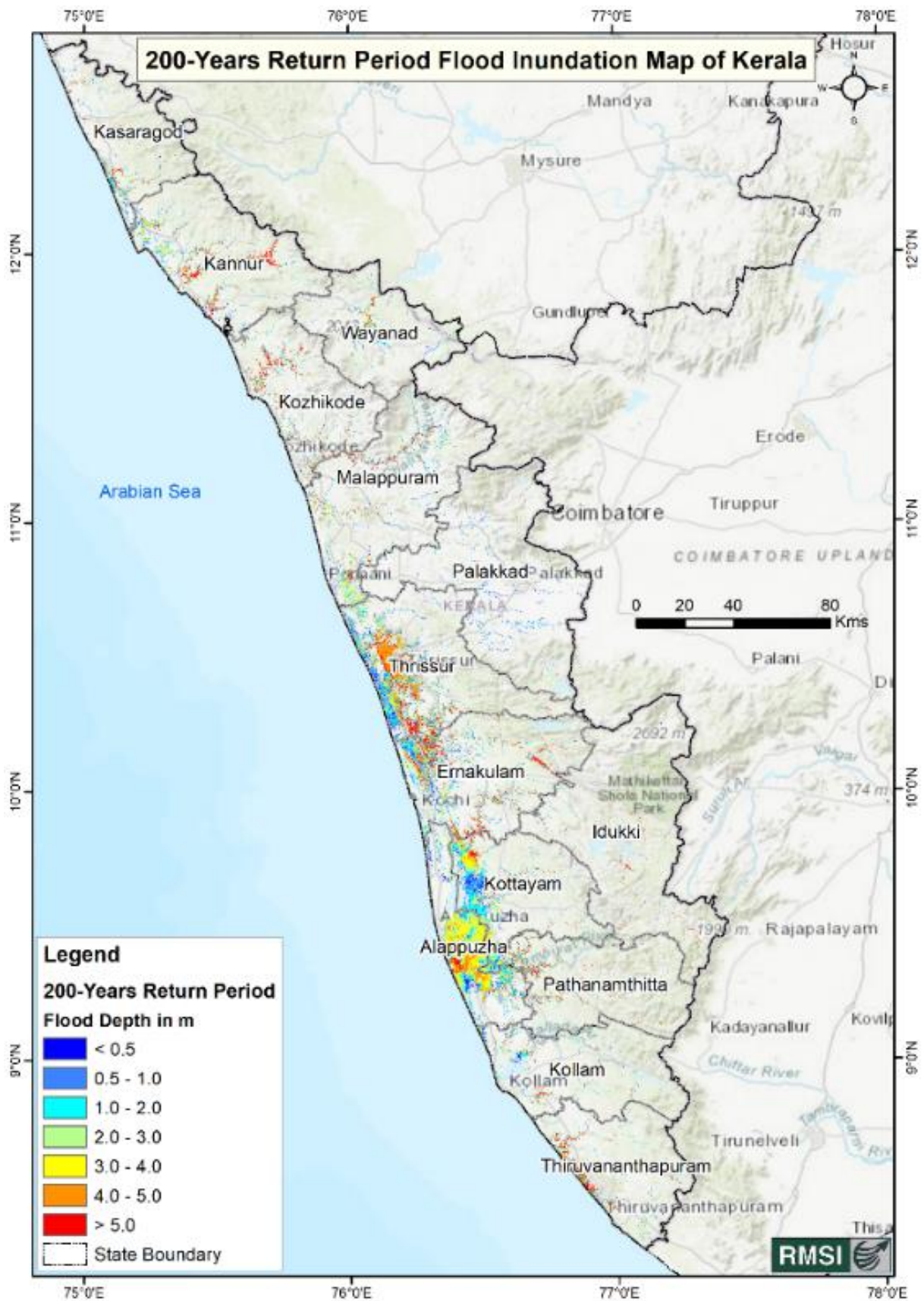


Figure 3-35: Flood hazard map of 200-year return period

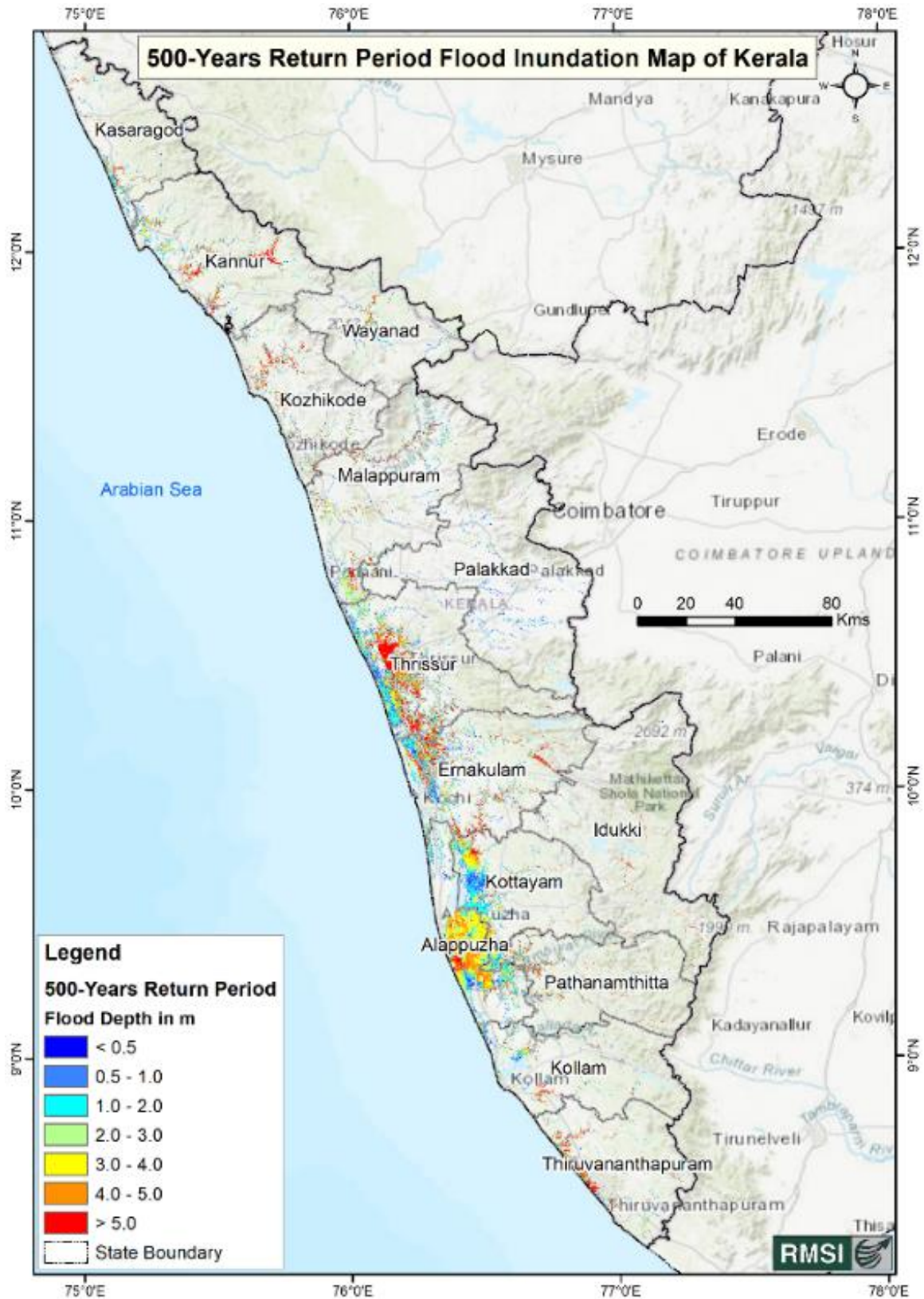


Figure 3-36: Flood hazard map of 500-year return period

## 3.3 Landslides

### 3.3.1 LANDSLIDE HAZARD

A landslide is a rapid mass wasting process that cause the downslope movement of a mass of rock, debris or earth material under the influence of gravity. Landslide occurrence depends upon different parameters such as geological and geomorphological processes, changes in vegetation cover, landuse and hydrogeologic conditions. Landslides are triggered by many factors including heavy precipitation, earthquakes, soil-piping, and human activities. In addition to loss of lives, landslides destroy residential, commercial and industrial areas and most importantly disrupt infrastructure such as transport system and negatively affect water quality in rivers and streams.

### 3.3.2 LANDSLIDE SCENARIO IN KERALA

Kerala is a unique physiographic province of 600 km long in NNW-SSE and 35–120 km wide in ENE-WSW directions. The physiography is marked with Western Ghat mountains occurring at 800 from mean sea level. in the eastern fringe forming and the eastern boundary of the state. Kerala is the third most densely populated state in India, of which 47% is occupied by the Western Ghats of peninsular India. Slope failures are very common along the hill ranges of Kerala particularly during the heavy rainfall periods. In the hilly regions, instability of slope is one of the major natural hazards that cause losses to lives and property. The west facing Western Ghats scarps that runs the entire extent of the mountain system is the most prone physiographic unit for landslides. The highlands of the region experience an annual average rainfall as high as 500 cm from the South-West, North-East and Pre-Monsoon

showers. All 13 of the 14 districts of Kerala except the coastal district of Alappuzha are prone to landslides. About 8% (1,400 Km<sup>2</sup>) of area in the Western Ghats of Kerala is classified as critical zone for mass movements (Thampi et al. 1995)<sup>71</sup>. Different types of slope failures such as debris flow, landslide, slump and rockfall have been reported by Seshagiri et al. (1982)<sup>72</sup>, Sankar (1991)<sup>73</sup> and Sreekumar and Aslam (2010)<sup>74</sup>. Kozhikode district is prone to deep seated landslides, while Idukki and Kottayam are prone to shallow landslides (Sekhar et al. 2009)<sup>75</sup>.

Historical landslides and their impact on Kerala have been discussed in section ahead.

### 3.3.3 INPUT DATA

Occurrence of landslides and associated phenomenon depend on various terrain and climatic conditions and therefore data related to various parameters defining these conditions have been collected from different nodal agencies and govt departments.

Effective landslide hazard modelling in Kerala demands a nuanced blend of data inputs. These include high-resolution digital elevation models (DEMs) to capture intricate topographic details. Geological and geotechnical data are essential for understanding soil composition, rock types, and structural stability. Meteorological data on rainfall patterns are crucial for assessing precipitation-triggered landslides. Historical landslide records offer valuable insights into past occurrences. Land cover and land use (LULC) data shed lights on different types of buildings, infrastructure, vegetation and urbanization. Satellite imagery also aids in monitoring and mapping landslide-prone areas. By integrating these diverse datasets, tailored

<sup>71</sup> Thampi, P.K., Mathai, J. and Sankar, G. (1995) A regional evolution of landslide prone areas in Western Ghats of Kerala. In: Abstracts of the national seminar on landslide in Western Ghats, Center for Earth Science Studies, Government of Kerala.

<sup>72</sup> Seshagiri, P.N., Upendran, R., Lakshmikanthan, C.B. and Subramanyan, K. (1982) Landslide zonation in Nilgiri Plateau, Tamilnadu, India. Pro. Of the 4th congress, international Association of Engineering Geology, v.1, pp.379-319.

<sup>73</sup> Sankar, G. (1991) Investigation of Landslides in Koodaranji and Koorachundu, Calicut district, Centre for Earth Science Studies ,Trivandrum.

<sup>74</sup> Sreekumar, S. and Arish Aslam. (2010) Macro zonation of landslide hazards in Idukki District, Kerala, GEOCON-2011, Govt. College of Engineering, Kannur, pp.32-38.

<sup>75</sup> Sekhar, L Kuriakose., Sankar, G. and Muraleedharan, C.(2009) History of landslide susceptibility and a chorology of landslide prone areas in the Western Ghats of Kerala, India. Environmental Geology, 57, pp.1553-1568.

landslide hazard model has been developed to address Kerala's unique geological and environmental dynamics.

Table 3-11 contains a list of relevant and useful data for effectively conducting landslide related study.

Table 3-11: List of input data, source and resolution

Input Data Requirements	Data Type	Source	Remarks	Open-Source data
Historical Landslide Inventory for last 25 to 30 years in GIS format	Shapefile	KSDMA/District local bodies	Location Specific	Historical data available in house lack volume, date and loss information
Geological maps	Shapefile	GSI	1:25K or better	Freely available geological data is available at 1:50 K from GSI
Soil data	Shapefile	Soil survey Dept./KSDMA	1:50K or better	Freely available soil data is available at 1:250 K from NBSS
LULC data in GIS format	Shapefile	KSREC	1:10K or better	In-house available LULC is of 25 m having 2015 vintage
High resolution DEM	Raster	KSREC		Freely available DEM is available at 30 m
Daily historical rainfall data (gridded) at best available scale for at least 25 to 30 years	Raster	IMD	Daily for 25 to 30 years	Freely available rain data of IMD is available at 25 km and ERA5 at 9 km
Daily historical station observed rainfall data	csv	IMD	Daily	

### 3.3.4 HISTORICAL LANDSLIDE INVENTORY

A large database of approximately 9,024 individual landslide events (mostly spanning between 1990 to recent) have been compiled in Kerala from various relevant sources including Geological Survey of India (GSI), National Remote Sensing Centre (NRSC), National Aeronautics and Space Administration (NASA), Kerala State Disaster Management Authority (KSDMA), published reports, research papers and media news. Additionally, as part of the study, RMSI team included some of the

recent landslide events based on interpretation of high-resolution satellite images. Figure 3-37 shows all the historical landslide events in Kerala.

Out of 9,024 number of individual event database, a subset of 346 landslide events which has details of locations and time of event information along with economic and social loss details have been considered for the generation of stochastic event sets in the study area. In addition to this, another subset of historical events 7,272 have been considered for the landslide susceptibility modelling study.

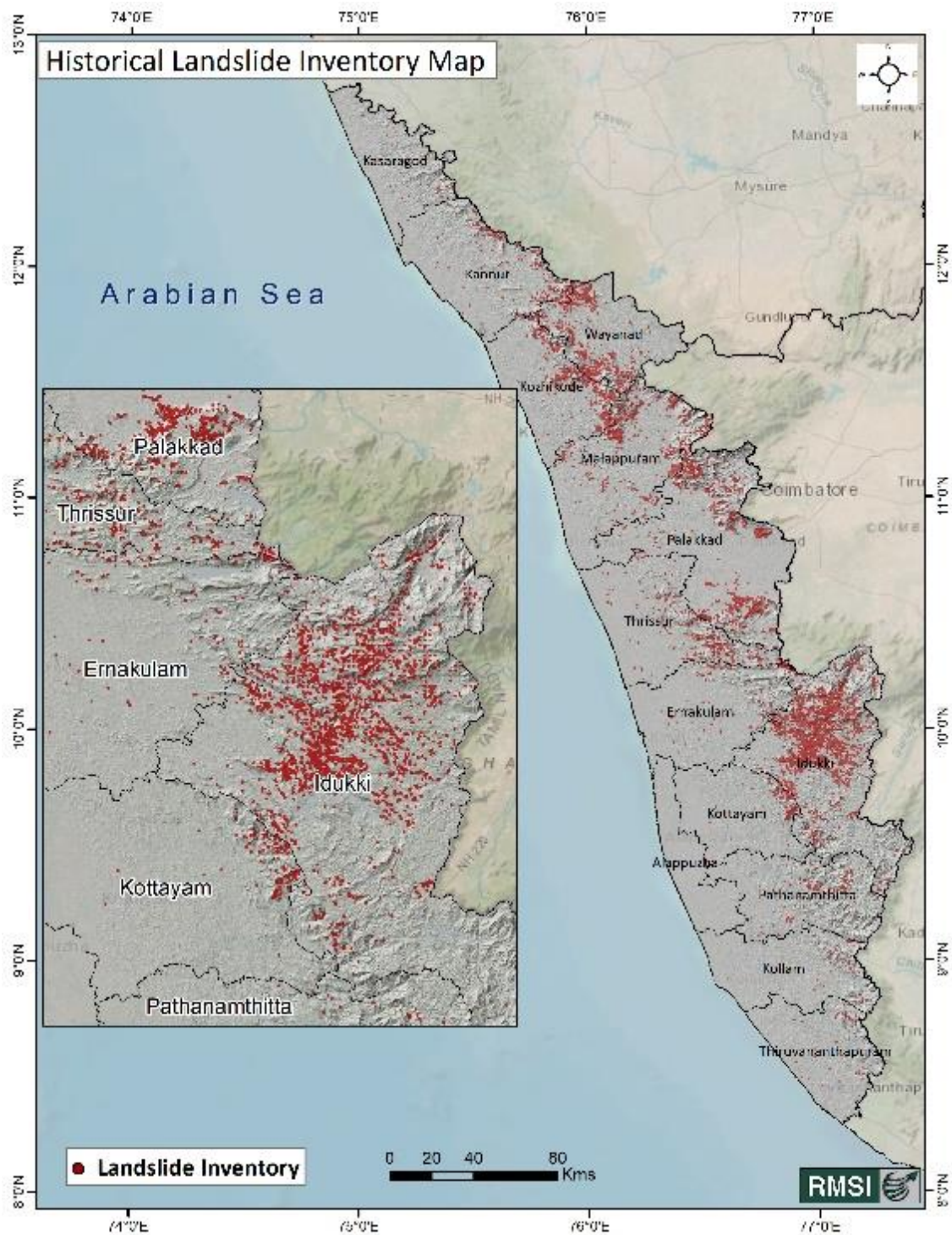


Figure 3-37: Historical landslide inventory used in modeling

### 3.3.5 THE MONTE CARLO SIMULATIONS FOR STOCHASTIC EVENTS GENERATION AND RETURN PERIODS

In this study, Monte Carlo simulation methods as given in Figure 3-38 have been adopted to generate stochastic sets of landslide events based on behavioral pattern of available historical landslide records from Kerala. Monte Carlo

methods, or Monte Carlo experiments, are a broad class of computational algorithms that rely on repeated random sampling to obtain numerical results. The underlying concept is to use randomness to solve problems that might be deterministic in

principle. By using Monte Carlo simulations, the parameter space of stochastic events can explore effectively while ensuring a representative and diverse sample of input conditions. This generally leads to more robust and reliable simulation results.

The input variables with random variables  $X_{input} = \{X_1, X_2, \dots, X_n\}$  where  $X_i$  replaces  $x_i$ . These random variables are generally chosen with associated distributions in order to match a desired uncertainty associated with an input, the distribution of possible values chosen for the input, or the lack of knowledge of the exact characteristics of an input. For a given set of random variables  $X_{input}$ , rather than having a single deterministic output, the output of the stochastic model is a set of associated output variables  $Y_{output} = \{Y_1, Y_2, \dots, Y_m\}$  where each  $Y_i$

represents a set of measurements produced for  $y_i$ . A depiction of a stochastic model can be seen in Figure 3-38.

The probability distributions that govern the behavior of each input variable has been determined. These statistical distributions could be uniform, normal, log normal, exponential, etc., depending on the nature of the stochastic process being modeled. The *correlation matrix* from the observed data has been calculated. This *matrix represents the pairwise correlations between the input variables*. For each set of input variables, we generated a random value for one variable and calculated the conditional distributions for the remaining variables based on the observed correlations.

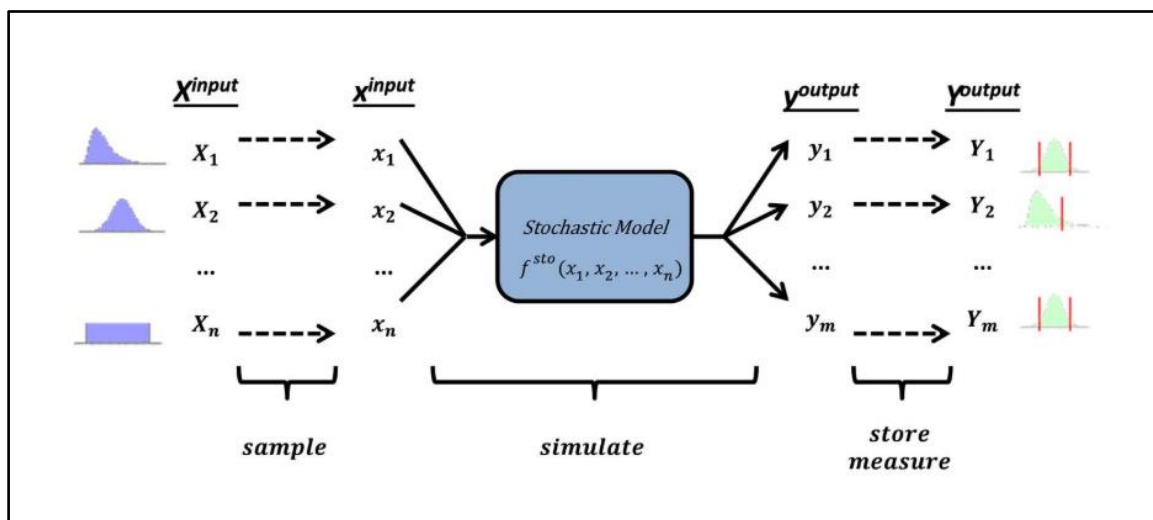


Figure 3-38: Stochastic Monte Carlo Simulation Model (Hudson, 2011)

### Methodology

The methodology adopted in the current study is similar to one used in the Global landslide susceptibility assessment and scenario-based hazard assessment by Norwegian Geotechnical Institute (NGI), Norway<sup>76</sup>. This approach was originally

proposed by Nadim et al. (2006)<sup>77</sup>, Nadim et al. (2013)<sup>78</sup>, and Jaedicke et al. (2014)<sup>79</sup>. In this methodology, a detailed and high-resolution landslide susceptibility map has been prepared using AI/ML based modelling technique (Random Forest Regression) followed by combining it by

<sup>76</sup> K. Subramanya, "Engineering Hydrology" Tata McGraw Hill Education Private Limited, Delhi (2011), ISBN-13: 978-0-07-064855-5/ISBN-10: 0-07-064855-7, pp. 255-257

<sup>77</sup> Nadim F, Kjekstad O, Peduzzi P, Herold C, Jaedicke C, Kjekstad O (2006) Global landslide and avalanche hotspots. Landslides 3:159–173. <https://doi.org/10.1007/s10346-006-0036-1>

<sup>78</sup> Nadim F, Jaedicke C, Smebye H, Kalsnes B (2013) Assessment of Global Landslide Hazard Hotspots. In: Sassa K, Rouhban B, Briceño S, McSaveney

M, He B (eds) Landslides: Global Risk Preparedness. Springer, Berlin, Heidelberg, pp 59–71

<sup>79</sup> Jaedicke C, Van Den Eeckhaut M, Nadim F, Hervás J, Kalsnes B, Vangelsten BV, Smith JT, Tofani V, Ciurean R, Winter MG, Sverdrup-Thygeson K, Syre E, Smebye H (2014) Identification of landslide hazard and risk "hotspots" in Europe. Bulletin of Engineering Geology and the Environment 73. <https://doi.org/10.1007/s10064-013-0541-0>

rainfall (most prominent triggering factor in Kerala) return period analysis to obtain probabilistic landslide hazard maps for various key return-periods.

Landslide Susceptibility Modelling in Kerala is crucial for disaster management and land-use planning, particularly in regions prone to landslides. There exist several methods and techniques for landslide susceptibility mapping. Traditional methods of landslide susceptibility analysis often rely on heuristic approaches or simple statistical techniques. However, the advent of Artificial Intelligence (AI) and Machine Learning (ML) has introduced more sophisticated and accurate methods for this more accurately mapping landslide susceptible areas with less uncertainty and effectively dealing with data complexity and unavailability. Among these techniques, the Random Forest Regression model has shown significant promise in enhancing the accuracy and reliability of landslide susceptibility maps.

AI encompasses a range of technologies designed to simulate human intelligence in machines, including problem-solving and decision-making capabilities. ML, a subset of AI, involves algorithms that improve their performance over time through exposure to data. In landslide susceptibility mapping, ML models learn from historical landslide data and environmental variables to predict future landslide-prone areas.

Different types of machine learning methods are:

- Support Vector Machines (SVM): Classify regions based on a hyperplane that separates landslide-prone from non-prone areas.
- Artificial Neural Networks (ANN): Mimic the human brain's structure and function to model complex relationships between environmental variables and landslide occurrences.
- Decision Trees (DT): Create a model that predicts landslide susceptibility based on a series of decision rules.
- Random Forest (RF): An ensemble method that builds multiple decision trees and merges their results to improve prediction accuracy.

- Gradient Boosting Machines (GBM): Combine multiple weak models to create a stronger predictive model by focusing on errors of previous models.

### **3.3.5.1 Random Forest Regression Model**

The Random Forest Regression model is an ensemble learning method that constructs a multitude of decision trees during training and outputs the average prediction (for regression) of the individual trees. It combines the concept of bagging (Bootstrap Aggregating) with decision trees, reducing variance and improving model performance.

Advantages for Landslide Susceptibility Mapping:

- Robustness: Random Forest is less prone to overfitting compared to single decision trees, making it suitable for complex and high-dimensional datasets typical in landslide studies.
- Handling Non-linearity: It can model non-linear relationships between predictors and landslide susceptibility without requiring complex transformations of the data.
- Feature Importance: Random Forest provides measures of feature importance, helping to identify which environmental factors most influence landslide susceptibility. This is crucial for understanding and prioritizing factors in susceptibility models.
- Handling Missing Data: It can handle missing data effectively by using surrogate splits, making it resilient in scenarios where some environmental data might be incomplete.

Numerous studies have demonstrated the effectiveness of Random Forest models in landslide susceptibility mapping. For instance, in regions like the Himalayas and other landslide prone parts of the world, Random Forest has been used to predict landslide-prone areas with high accuracy, aiding in disaster preparedness and mitigation efforts.

### 3.3.5.2 Random Forest Regression (RFR) Model

Random forest regression is an invaluable tool in data science. It enables us to make accurate predictions and analyze complex datasets with the help of a powerful machine-learning algorithm. A Random Forest regression model combines multiple decision trees to create a single model. Each tree in the forest builds from a different subset of the data and makes its own independent prediction. The final prediction for input is based on the average or weighted average of all the individual trees' predictions.

Random forest regression is a supervised machine learning algorithm. It uses an ensemble of decision trees to predict continuous target variables.

The individual decision tree models are constructed using a technique called bagging random forest. It involves randomly selecting subsets of the training data and building smaller decision trees from them.

After the bagging random forest step, we combine the smaller models to form the random forest model, which outputs a single prediction value. The technique helps reduce variance and improve accuracy by combining the predictions from several decision trees.

The mathematical formula of a random forest regression model can be broken down into several components. Here's a simplified explanation:

#### 3.3.5.2.1 Ensemble of Decision Tree

A random forest regression model is an ensemble of decision trees. Each decision

tree makes a prediction independently, and the final prediction is the average (in case of regression) or the mode (in case of classification) of predictions from all the trees

#### 3.3.5.2.2 Decision Tree Prediction

Each decision tree predicts the target variable  $Y$  based on a set of input features  $X$ . It makes predictions by recursively partitioning the feature space into regions and assigning a constant value to each region. This value is typically the mean of the target variable in that region.

#### 3.3.5.2.3 RFR Prediction

The prediction of the random forest model is the average of predictions from all the individual trees in the forest.

Mathematically, if we have  $N$  decision trees in  $\hat{Y}$  ie forest and  $f_i(X)$  represents the prediction of the  $i$ -th tree, then the prediction of the random forest for a given input  $X$  can be represented as:

$$\hat{Y}(X) = \frac{1}{N} \sum_{i=1}^N f_i(X)$$

Each  $f_i(X)$  is the prediction of the  $i$ -th decision tree in the random forest.

The random forest regression model aggregates predictions from multiple decision trees to make a final prediction. The formula simply averages the predictions of all the trees in the forest.

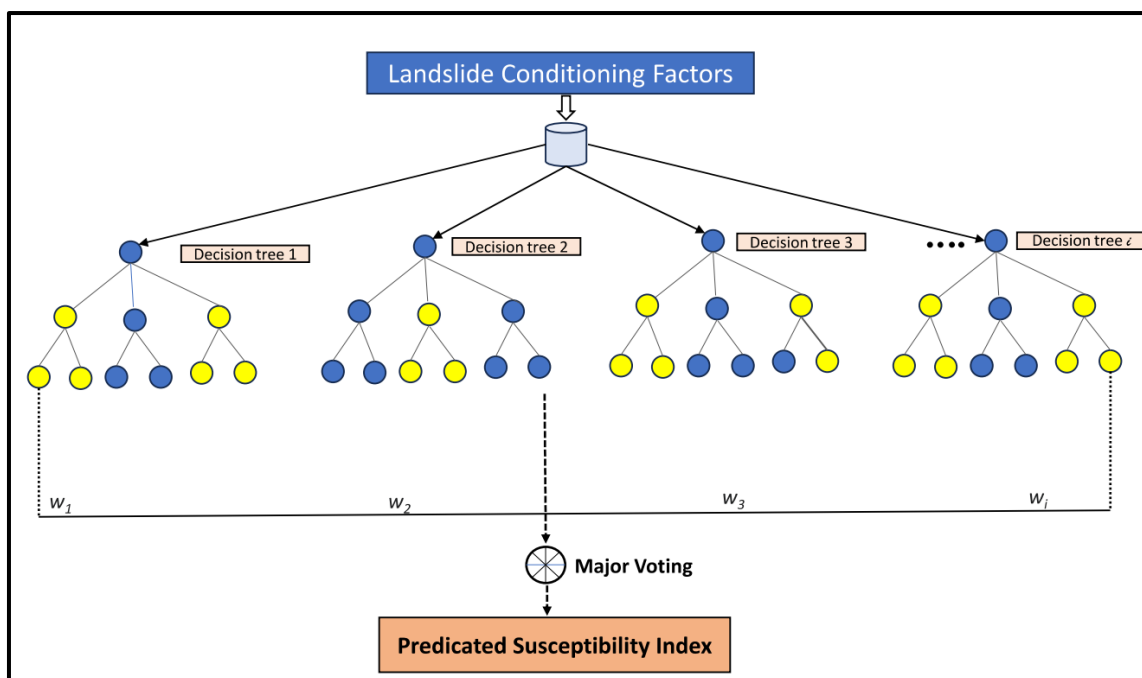


Figure 3-39: Schematic diagram showing working principle of random forest regression

In this study, random forest regression model was adopted. Seven landslide causal factor namely (slope, geology, tectonic structures, soil characteristics, landuse pattern, and rainfall) were identified as most critical variables that represent potential landslide/ debris flow. Furthermore, these variables were related to available historical landslide inventory in Kerala state. Model's size, which determines the number of trees in the forest and their depth. In this case we have considered 100 trees as the size of the random forest. Once these parameters were set and defined, model was trained and predictions were made.

#### 3.3.5.2.4 Selection of Training and Testing Data

The process of selection of training and testing data is critical for effective predictability power of any model. It is therefore important to select various causative factors carefully and check for their consistency and statistical significance in causing or non-causing of the events.

#### 3.3.5.2.5 Historical Landslide Events

Historical landslide events are of prime importance to understand behavioral pattern of various triggering factors. Historical landslide events are captured from various literature and scientific studies conducted in and around the study area. High resolution satellite images are often referred for demarcation of historical landslide events.

Once historical inventory and maps of all causative factors are prepared, training data is selected from the entire data set and is used to train the model based on which all predictions and probabilities are computed for entire dataset.

The most important point to be considered in selection of training and testing data is that this must be well represented by all range of causative factors. To ascertain this, likelihood or frequency ratio approaches are normally used as statistical means on the observed relationships between the distribution of landslides and each related factor and are used to reveal the correlation between event locations and factors in the study area.

#### 3.3.5.2.6 Data Normalization:

Normalization of input variable is an important step in any AI/ML modelling approach, because real data obtained from experiments and analysis is often distant from each other. The effect is significant, because the common activation functions such as sigmoid, hyperbolic tangent and Gaussian produce results that range between [0,1] or [-1,1]. It is important to normalize the values to be in that range. The common normalization approach includes Statistical normalization (using mean and standard deviation) and Min-Max Normalization.

### **3.3.6 LANDSLIDE SUSCEPTIBLE MAP OF KERALA**

Random forest regression model was used for landslide susceptibility modeling where in approximately 7,500 training data points were considered for model development and predictions were made on regularly

spaced points at 100m x 100m grids. Landslide probability values were generated for each grid points from the trained model (between 0 to 1) and then converted into raster and classified in 5 categories ranging from very low to very high levels of susceptibility.

Figure 3-40 shows landslide susceptibility map of Kerala state. It is evident from the map that 13 out of total 14 districts in Kerala are partially affected by landslide and associated risk except Alappuzha district. Some of the districts with significantly large part as hilly terrain in Kerala are relatively more prone to landslide and hundreds to thousands of landslides of varying intensity are reported every year. District and village level risk assessment of local population, buildings, roads and railway infrastructures are discussed in detail in the risk assessment chapter.

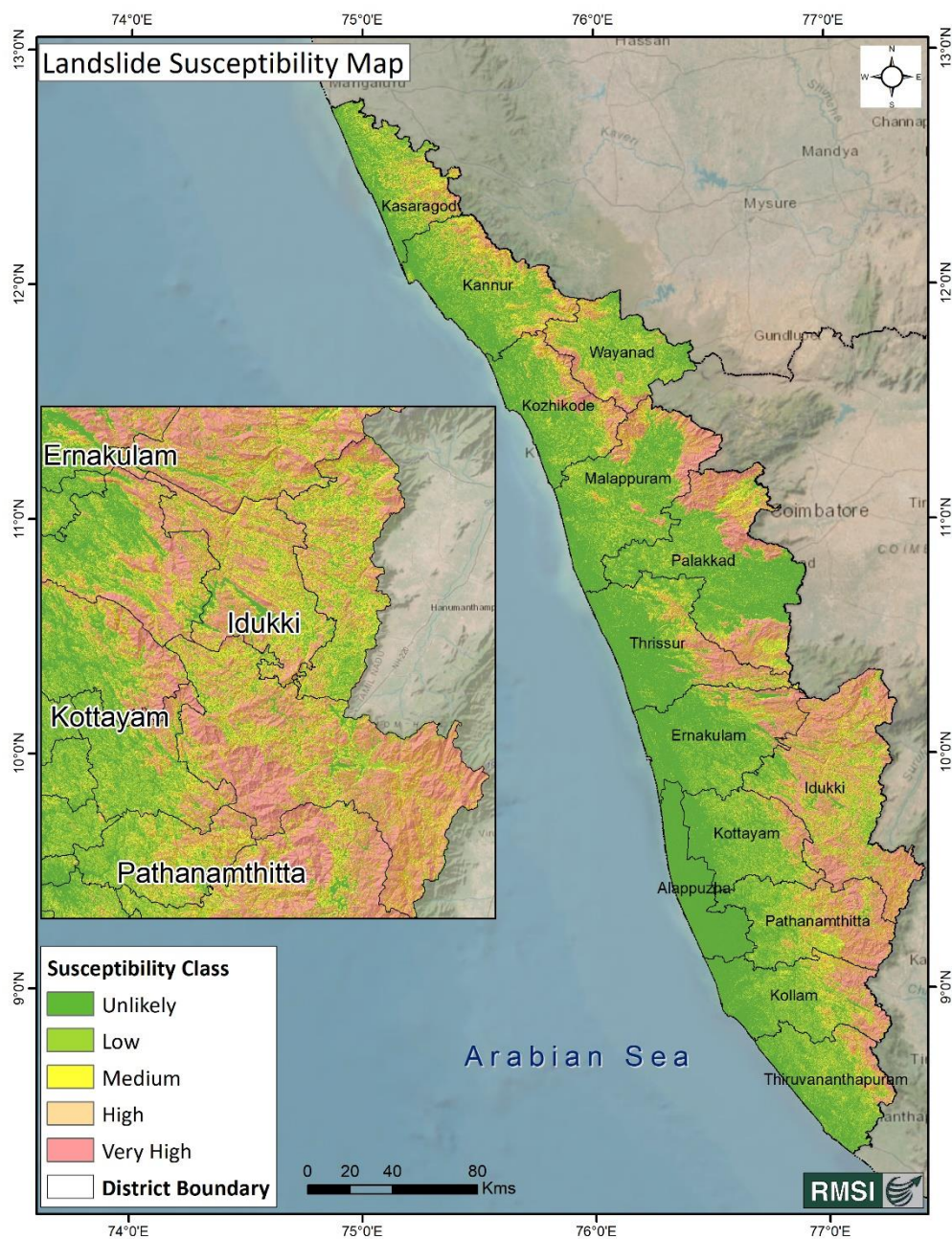


Figure 3-40: Landslide Susceptibility Map of Kerala

### 3.3.7 MODEL PERFORMANCE AND VALIDATION

Model validation is a crucial step in any modeling-based approach. For this, the confusion matrix (Table 3-12) is an effective approach to understand how well the model performs. However, it is not a substitute for on-field validation.

In total, 9,024 landslide points were used for the model development. Furthermore 3,877 landslide occurrence and non-occurrence data points were used for checking model performance. Confusion matrix of the against validation data is

given in table below. In total model has predicted historical landslide locations correctly 92 % of the times whereas model's performance was slightly better 94% while predicting non-landslide locations (safe areas).

Table 3-13 represents distribution of historical landslide events in the areas with different levels of susceptibility. In total 9,024 landslide locations were mapped within the Kerala State. As per the landslide susceptibility mapping in Kerala State,

approximately 69 % of mapped landslide events are falling in high to very high susceptible zones whereas another 21% is represented in the areas with moderate level of landslide susceptibility. About 10% of historical events are falling in the areas

of low to very low level of susceptibility. Such a high correlation of existing landslides numbers falling in predicted moderate to high levels of landslide risk areas indicates fairly good-fit of the model.

Table 3-12: Confusion Matrix

Predicted	Landslide	Non-Landslide	% model misfit
Landslide	1,655	153	8%
Non-Landslide	114	1,954	6%

Table 3-13: Distribution of historical landslides in different levels of susceptibility

LSI Class	No of Landslide Point	% of Landslide Events
Unlikely	382	4%
Low	574	6%
Medium	1853	21%
High	2077	23%
Very High	4138	46%

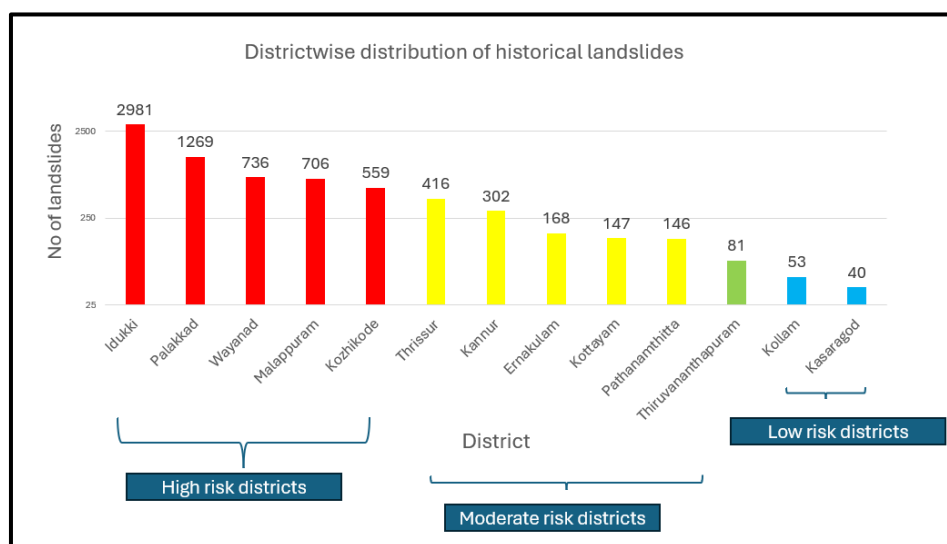


Figure 3-41: District wise Distribution of historical landslides in different levels of susceptibility

### 3.3.8 RAINFALL ANALYSIS AND PREPARATION OF RAINFALL RETURN PERIOD MAPS

Since rainfall is the most critical and prominent landslide triggering factor in

Kerala, it is important to review rainfall conditions on day of occurrence of

landslide as well as a few days prior to the event. For this purpose, daily rainfall data from India Meteorological Department (IMD) at 25 km grid resolution have been collected for the last more than 120 years (1901 to 2023) and summary of the same in context to major landslide events in Kerala are discussed below.

Data was available in netcdf format which have been processed and converted in raster format for ease of handling large data files. Data was extracted against all historical landslide events and analysis was conducted.

### **3.3.8.1 Estimating rainfall of different return periods**

Rainfall frequency analysis has been carried out using 1-Day, 3-day, 5-day, 7-day and 10-day annual maximum rainfall series derived from the IMD gridded precipitation data for a period of 123 years (1901 to 2023).

Frequency analysis was carried out to calculate the rainfall depths for different

return periods. Different frequency distributions methods were employed to compute daily rainfall for different return periods, namely 10, 25, 50, 100, 200, 500-years (Figure 3-42 to Figure 3-48).

Several frequency distribution methods are applied in order to calculate the return period rainfall. Some of the extreme value probability distributions usually used for hydrological analysis are Normal Distribution, Log-Normal Distribution, Gumbel Distribution, and Log Pearson Type III Distribution. In the present study, the design rainfall  $X_T$  has been estimated using four frequency analyses distributions, namely, Normal Distribution, Log-Normal Distribution, Gumbel Distribution, and Log Pearson Type-III Distribution. Best fit distribution among the four distributions were identified based on the goodness of fit test. Values obtained from the best-fit frequency distribution were adopted for hydrological analysis for different return periods.

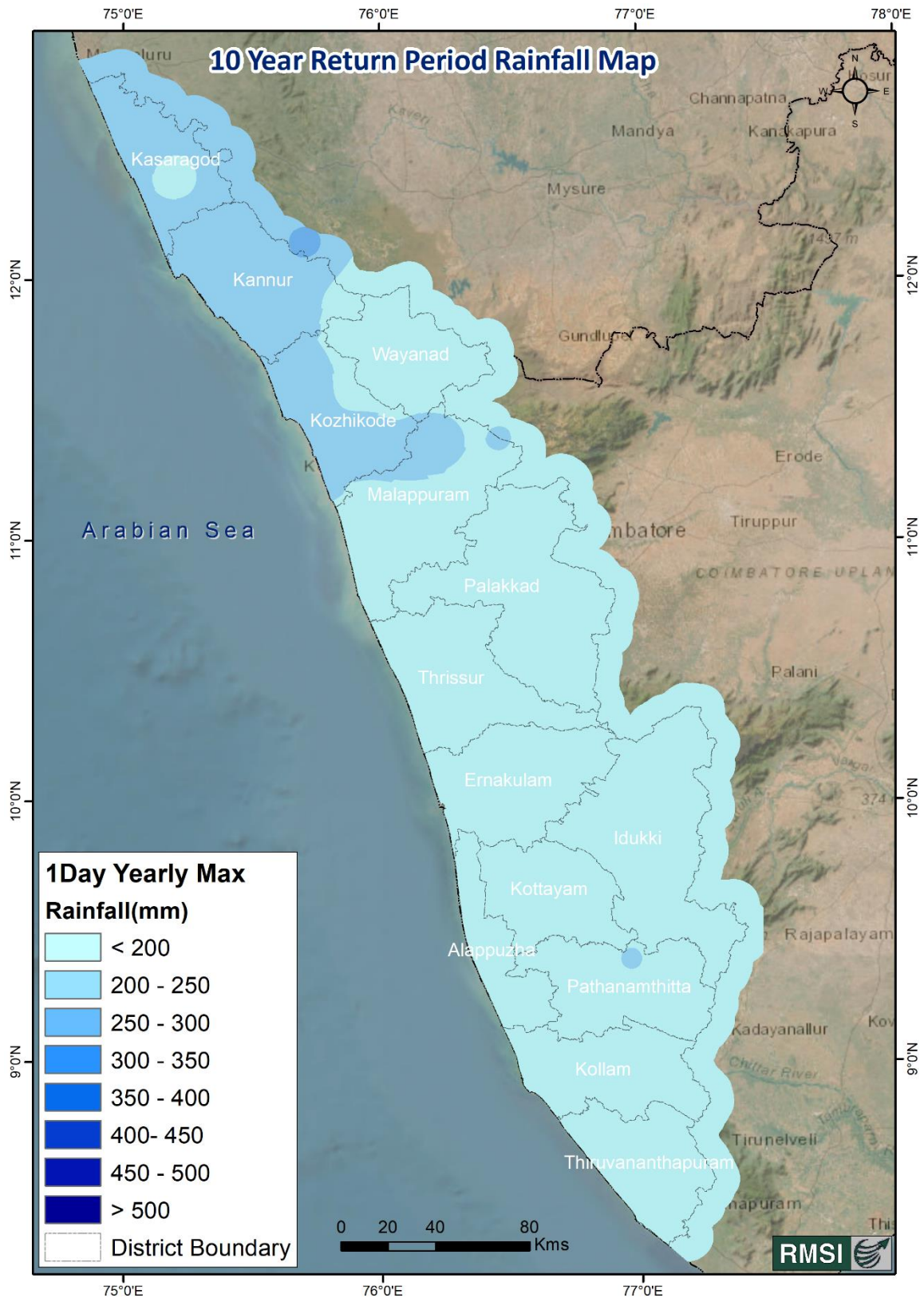


Figure 3-42: One day yearly maximum rainfall(mm)-10 Year return period

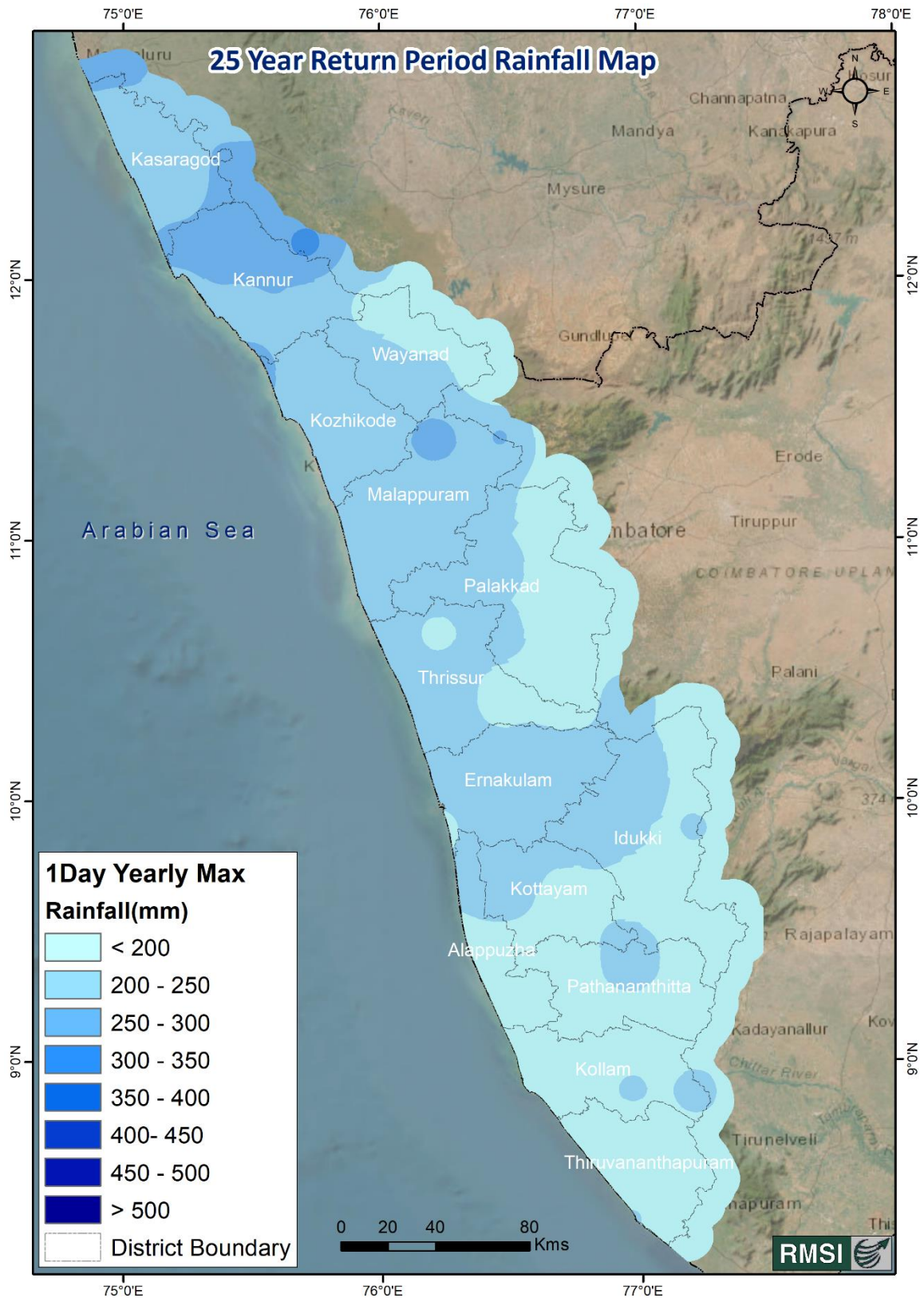


Figure 3-43: One day yearly maximum rainfall(mm)-25 Year return period

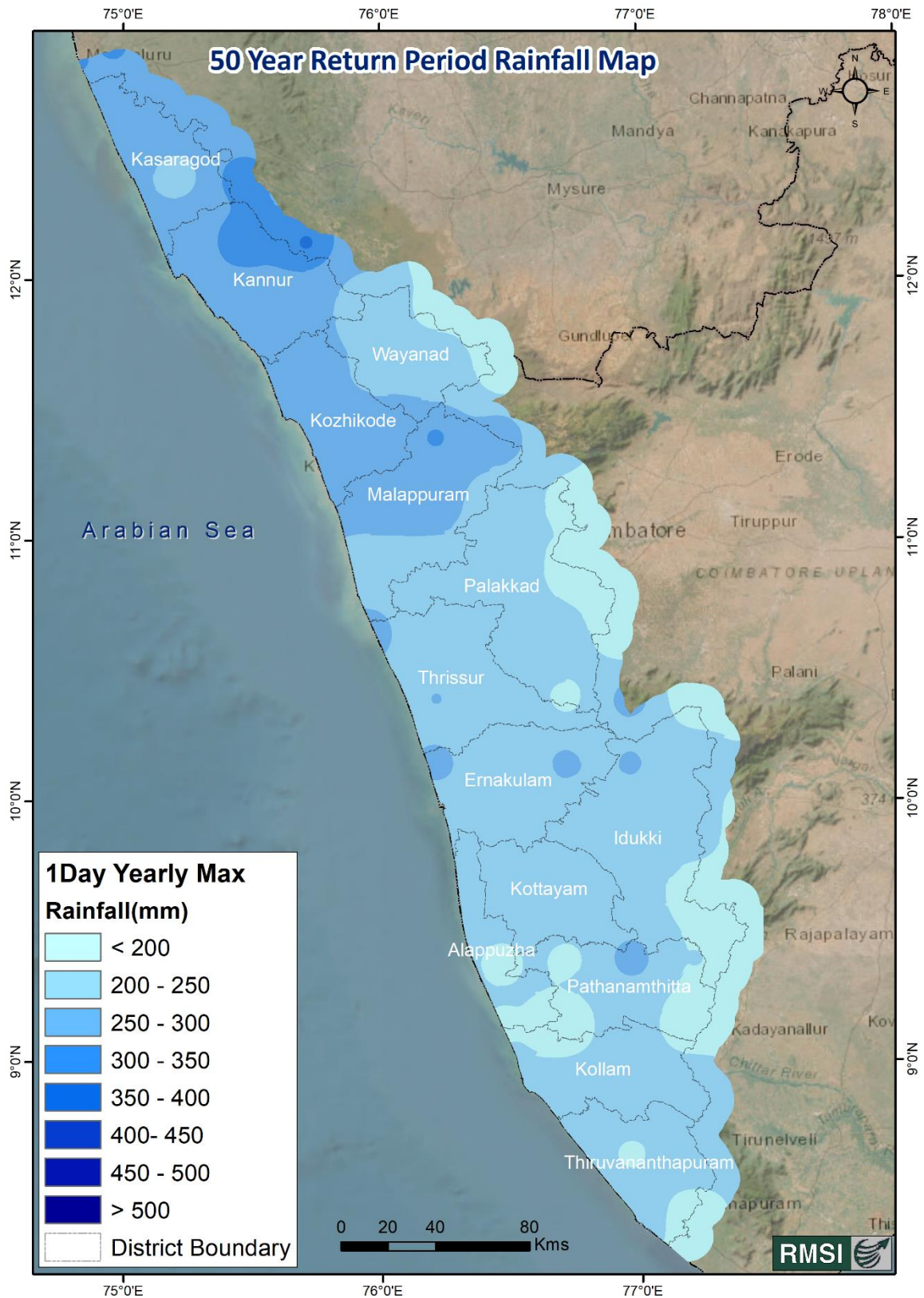


Figure 3-44: One day yearly maximum rainfall(mm)-50 Year return period

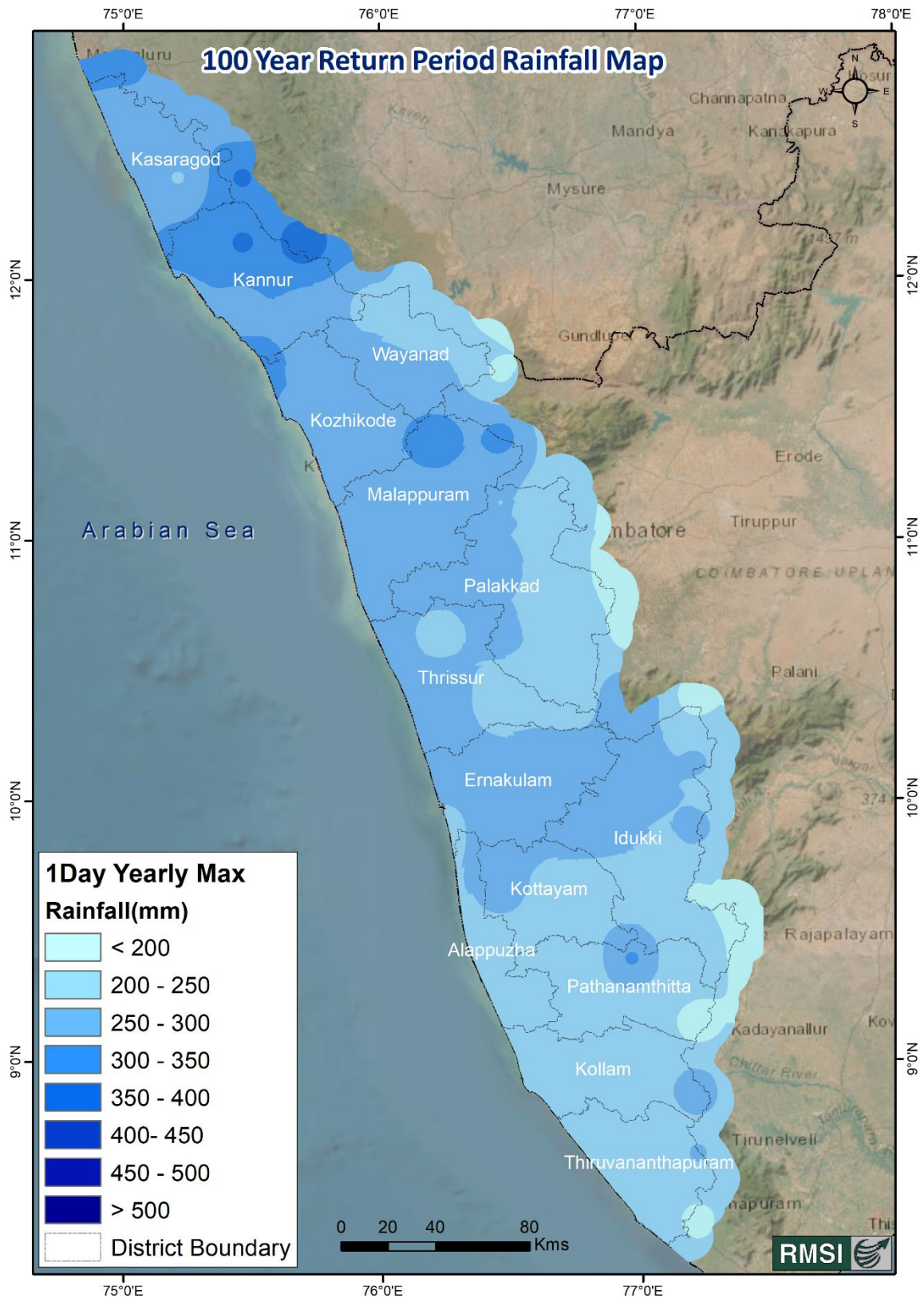


Figure 3-45: One day yearly maximum rainfall(mm)-100 Year return period

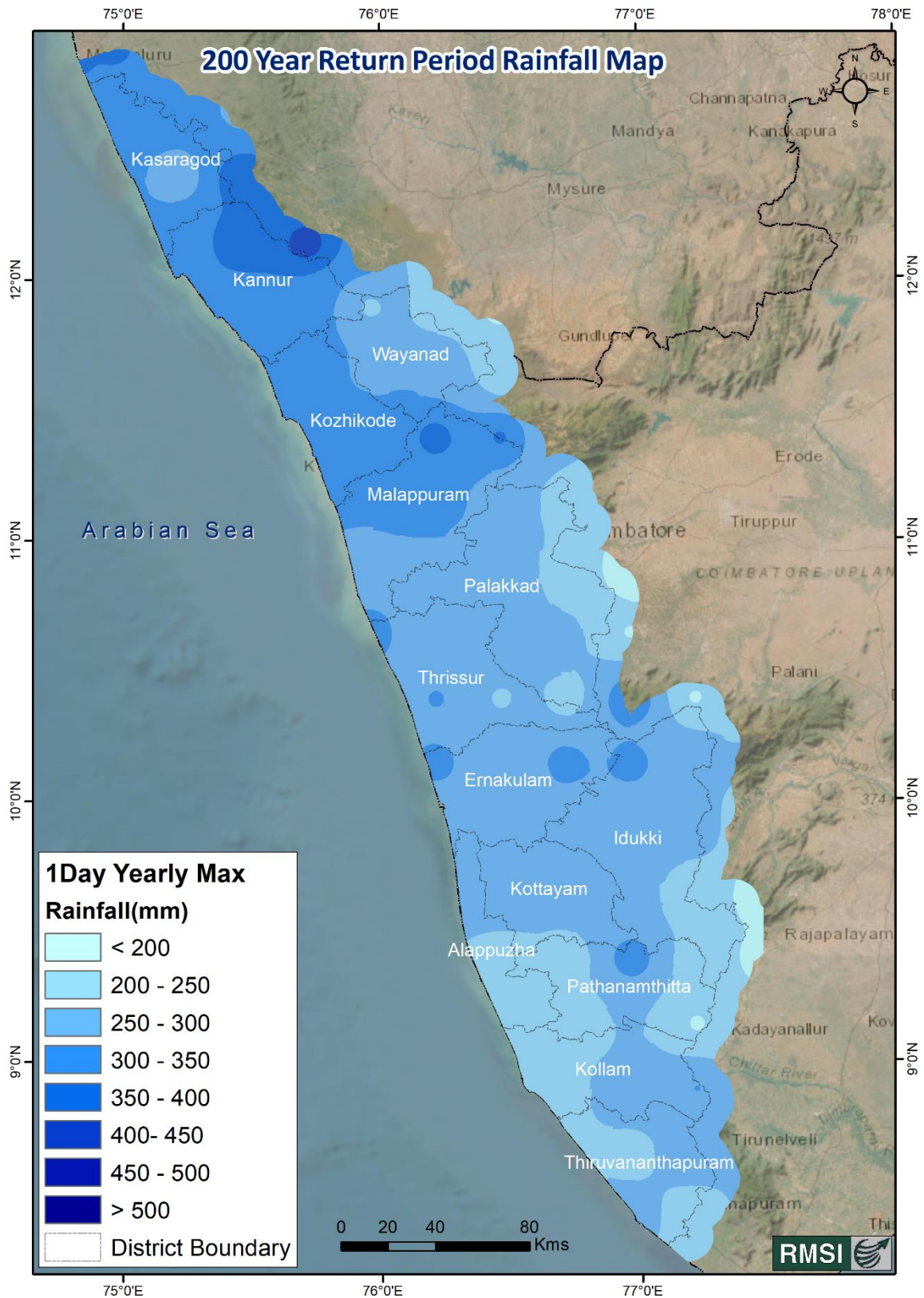


Figure 3-46: One day yearly maximum rainfall(mm)-200 Year return period

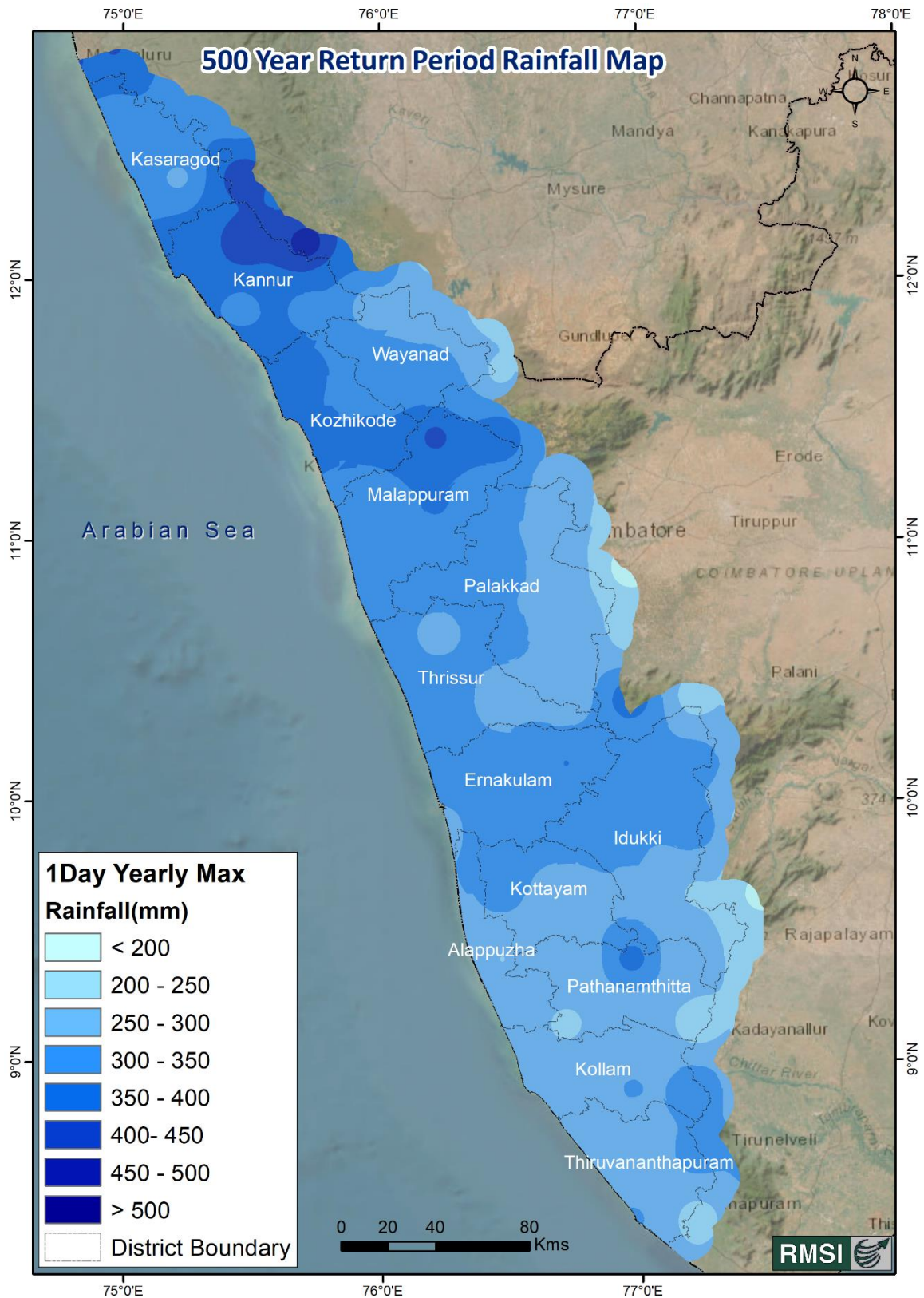


Figure 3-47: One day yearly maximum rainfall(mm)-500 Year return period

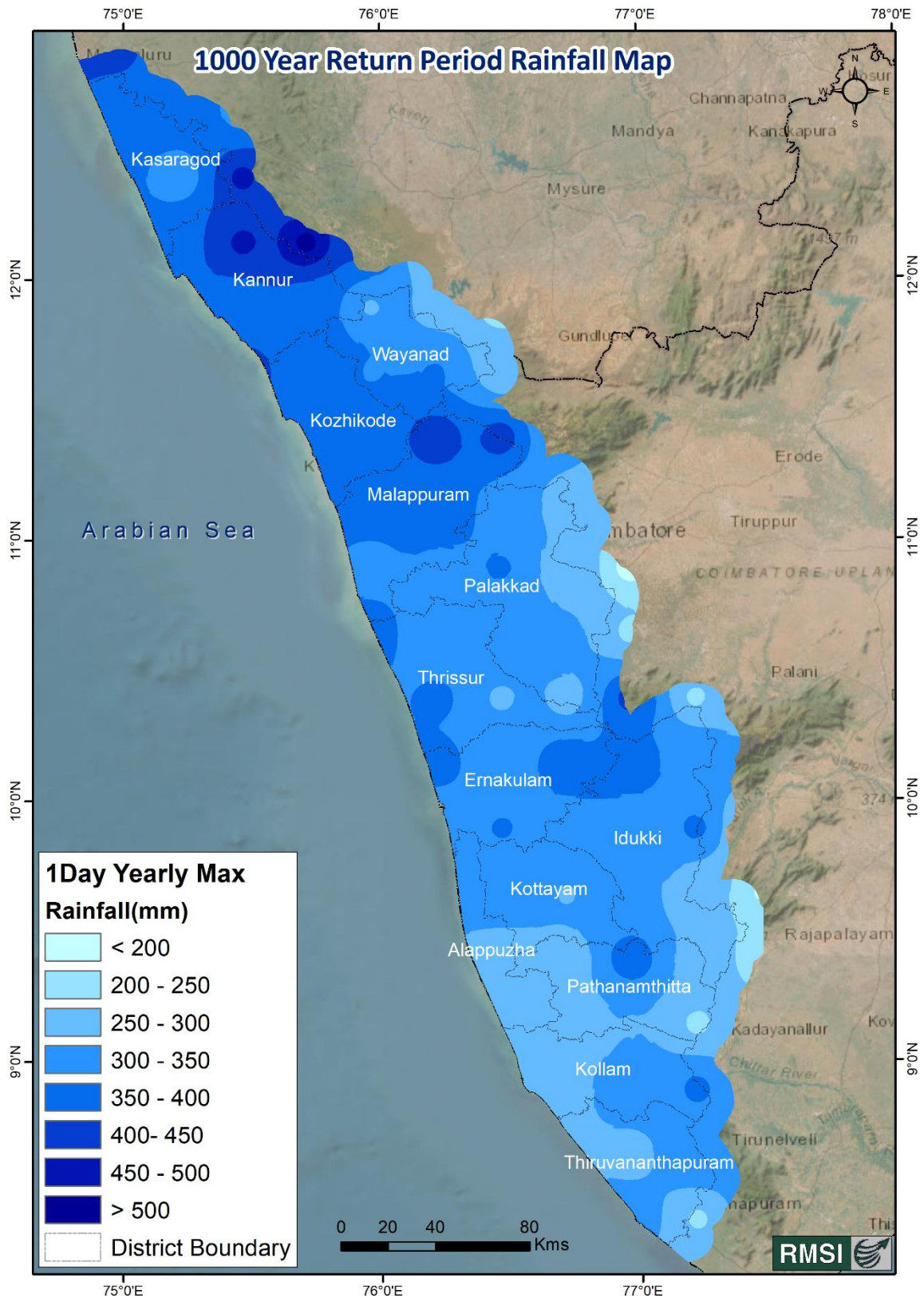


Figure 3-48: One day yearly maximum rainfall(mm)-1000 Year return period

### 3.3.9 PROBABILISTIC LANDSLIDE HAZARD

The "landslide hazard index", i.e., the probability of landslide occurrence for a specific triggering event, is derived from the combination of susceptibility index and the rainfall triggering conditions. The combination of the susceptibility and the rainfall triggering conditions is done

according to the hazard matrix in Table 3-14.

The landslide hazard index map has been integrated over rainfall events with different return periods to “translate” the combination of landslide hazard category and return period of the daily rainfall into the probability of landslide occurrence within an area.

Table 3-14: Return period wise landslide susceptibility

Landslide Susceptibility/Rainfall Return Period	Susc-1 area	Susc-2 area	Susc-3 area	Susc-4 area	Susc-5 area
10 Return Period	0	2%	3%	4%	5%
25 Return Period	0	3%	4%	5%	6%
50 Return Period	0	4%	5%	6%	8%
100 Return Period	0	5%	6%	8%	10%
200 Return Period	0	6%	8%	10%	15%
500 Return Period	0	8%	10%	15%	18%

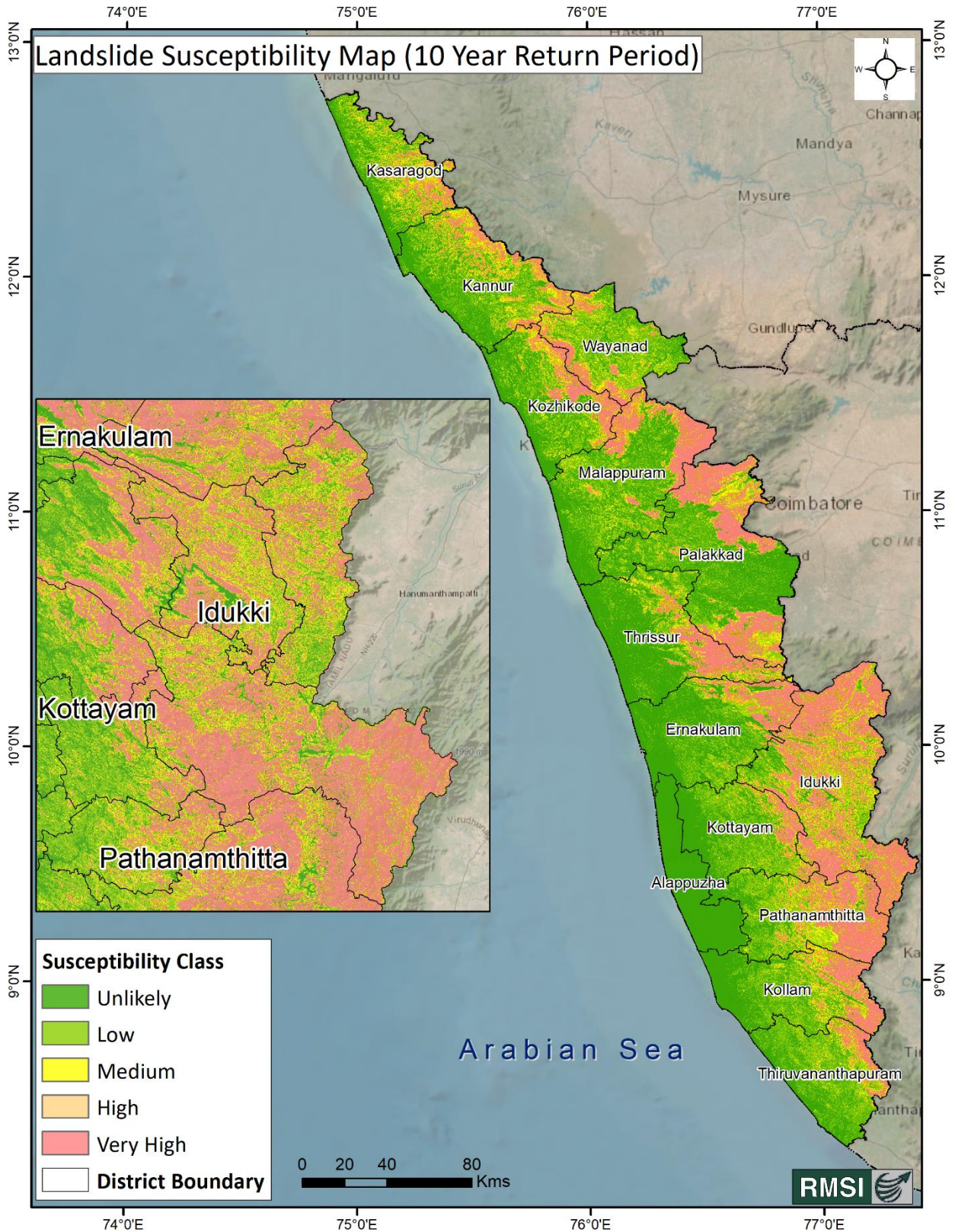


Figure 3-49: Landslide Susceptibility-10-year return period

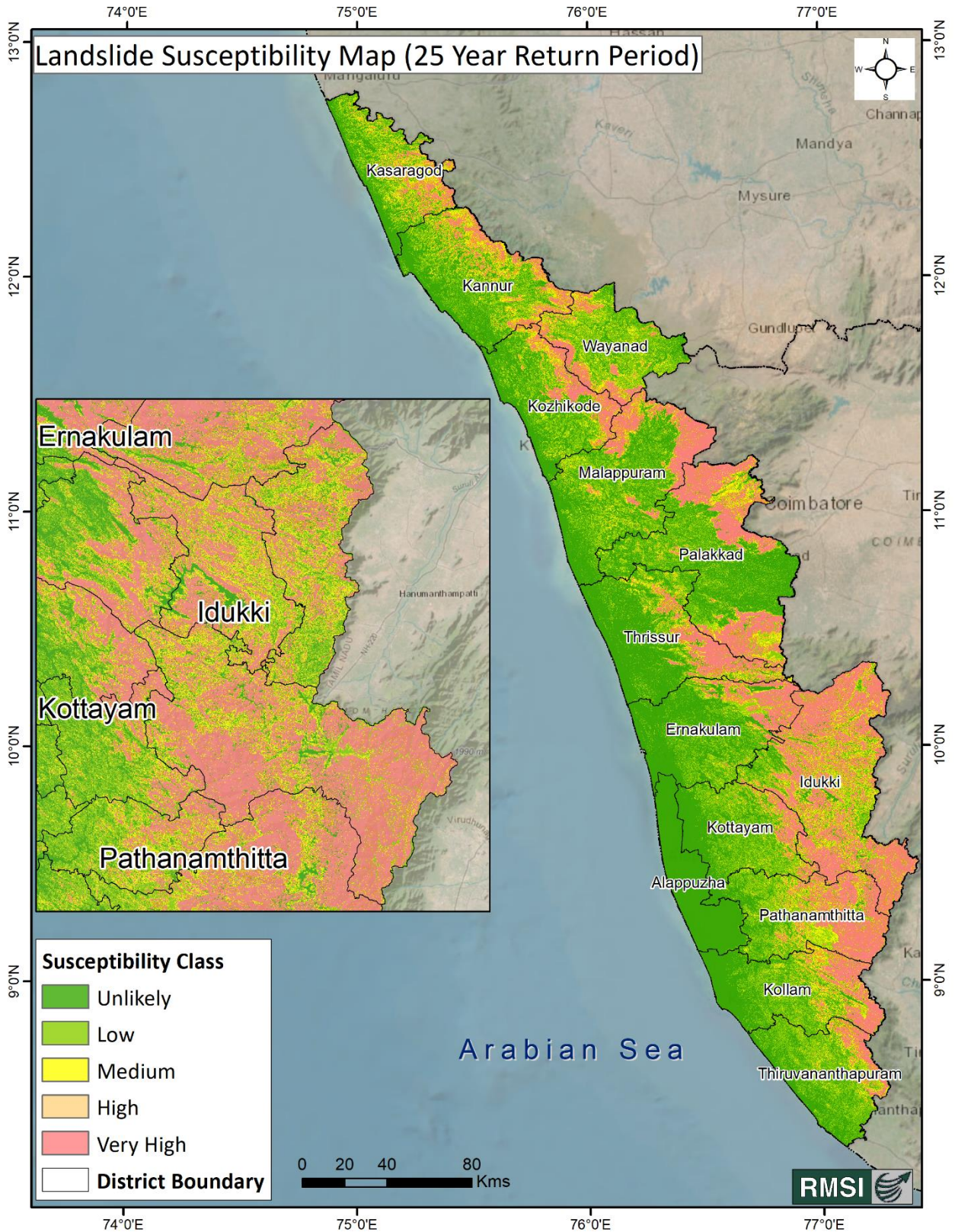


Figure 3-50: Landslide Susceptibility-25-year return period

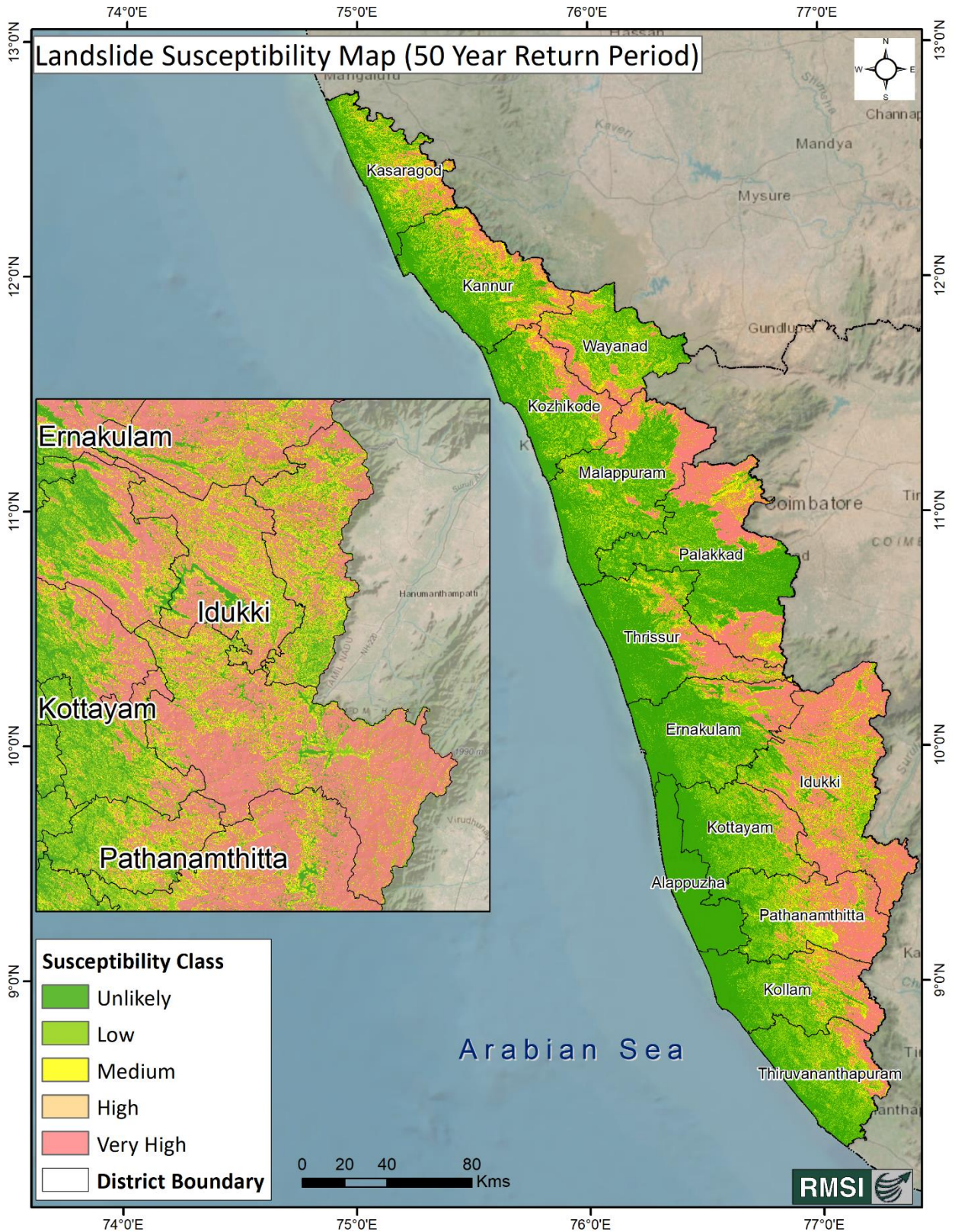


Figure 3-51: Landslide Susceptibility-50-year return period

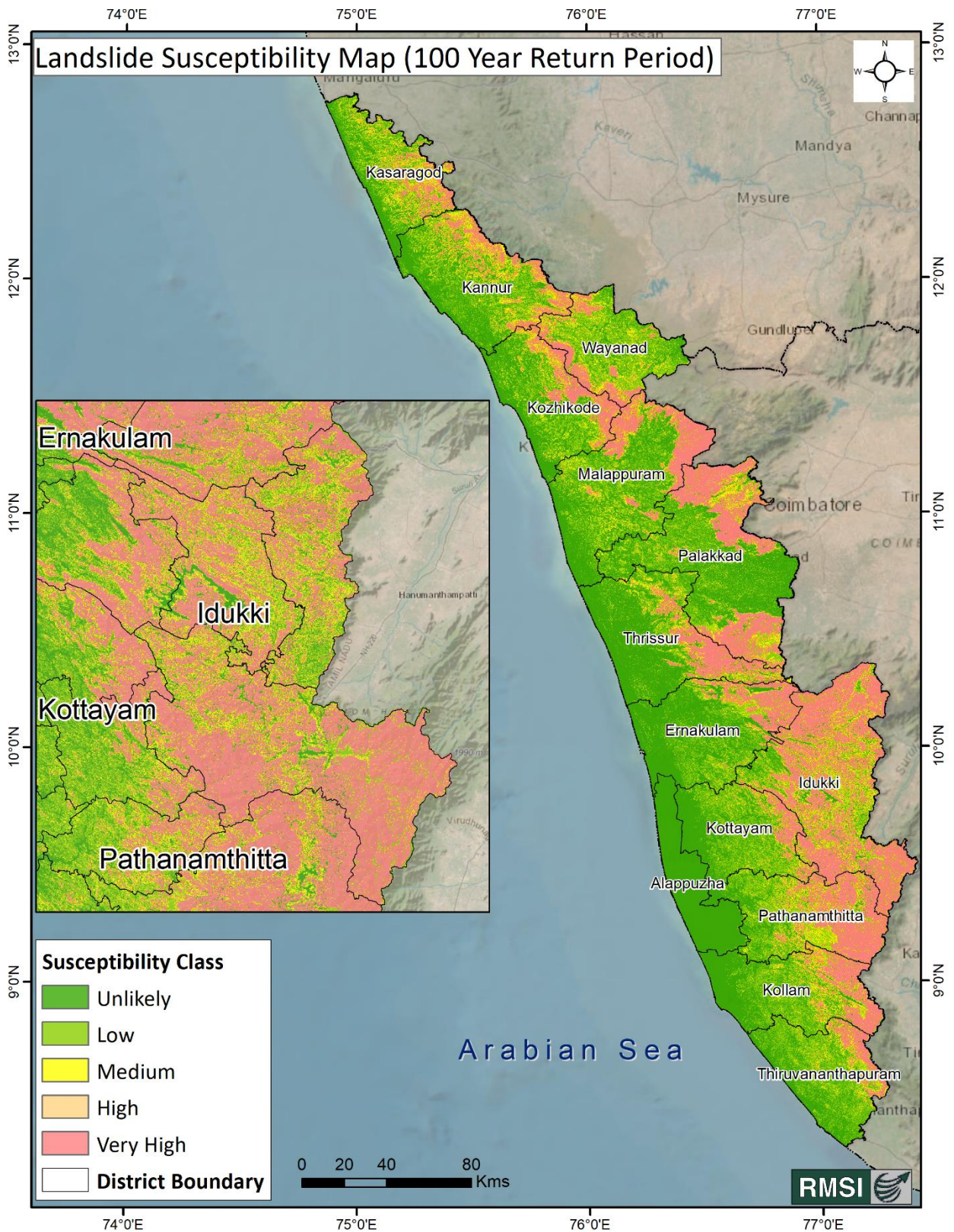


Figure 3-52: Landslide Susceptibility-100-year return period

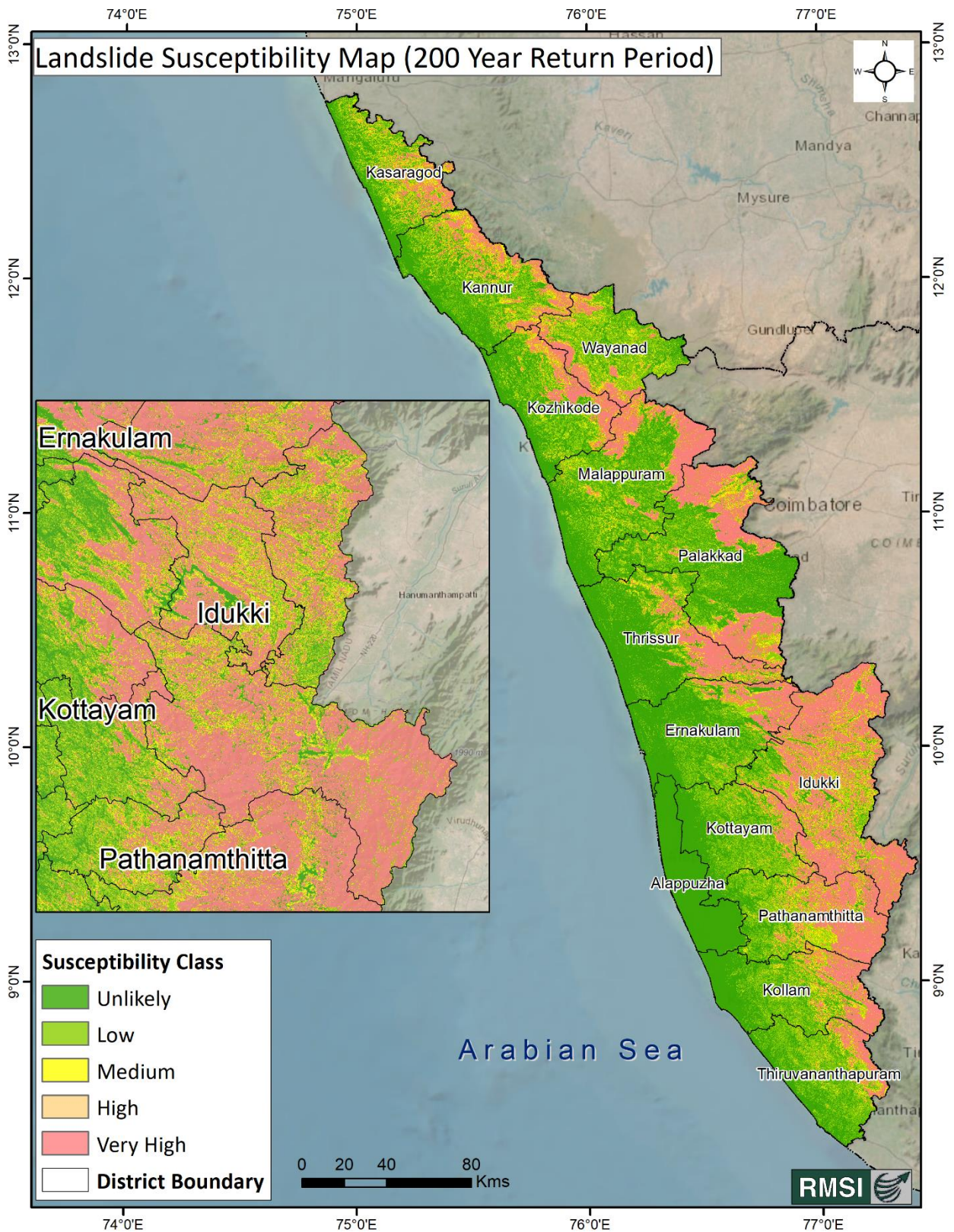


Figure 3-53: Landslide Susceptibility-200-year return period

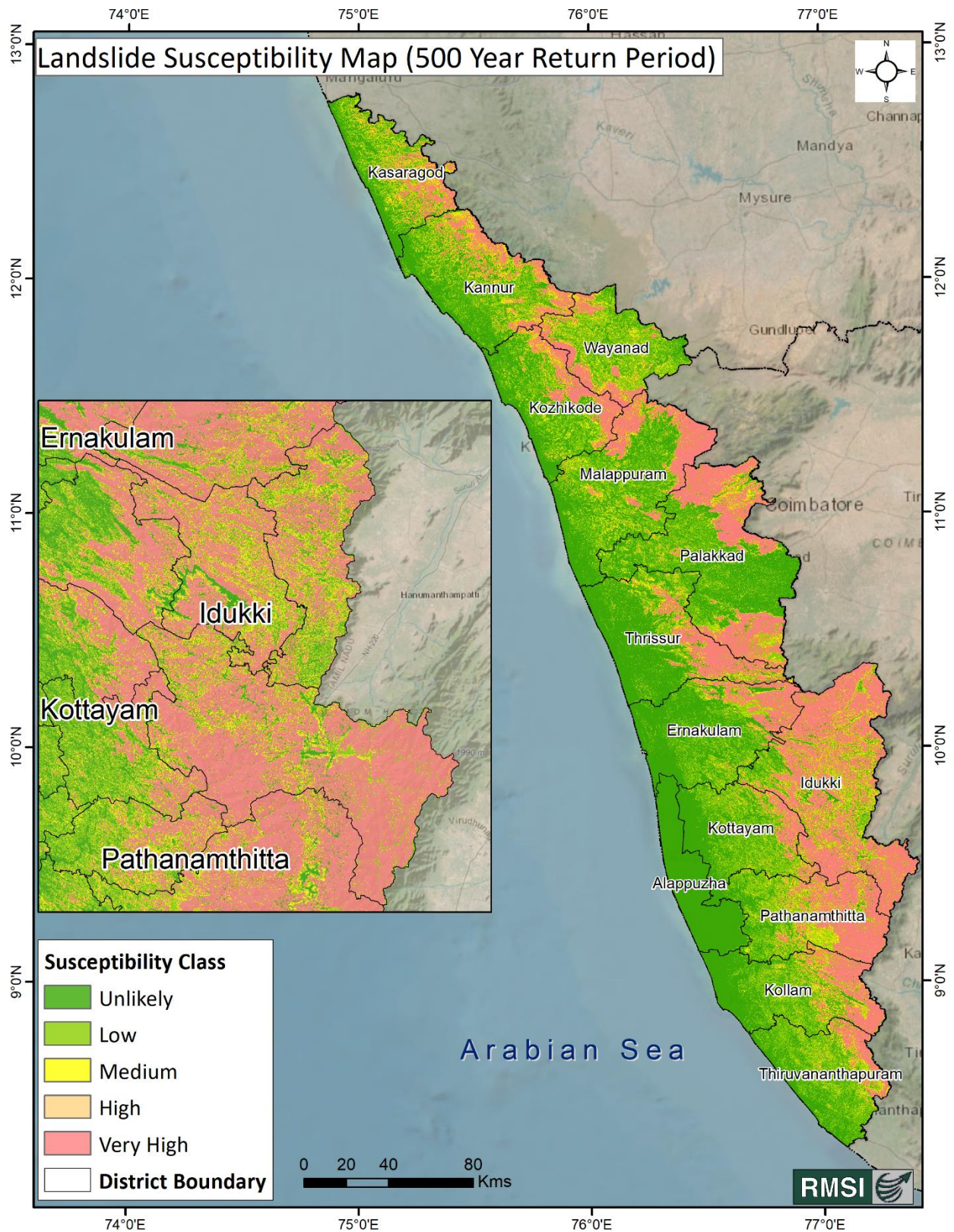


Figure 3-54: Landslide Susceptibility-500-year return period

Nearly 5% of the data from available historical landslide inventory from Kerala

(approximately 350 landslide events) is having details of date and time of

occurrence and exact location of occurrence were available from various sources. A separate study was conducted as part of the project to understand rainfall distribution patterns at the time of these events and following conclusions were drawn:

1. Roughly 70 % of the recent landslide in Kerala indicate that rainfall value on the day of occurrence was above 40mm (Figure 3-55).

2. Roughly 30 % of the events indicate extreme rainfall conditions (>100 mm) on day of event (Figure 3-55).  
 3. Overall, more than 90 % of the historical events indicate that landslide/debris flow in Kerala are mostly triggered by continuous rainfall (>80 to 150 mm in 3 to 5 days respectively) prior to the failures (Figure 3-56).

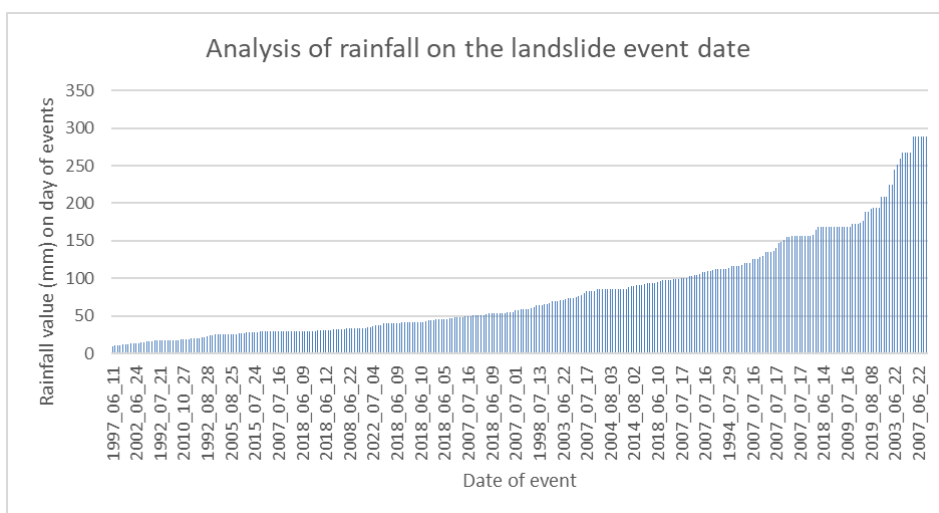


Figure 3-55: Analysis of rainfall on the landslide event date

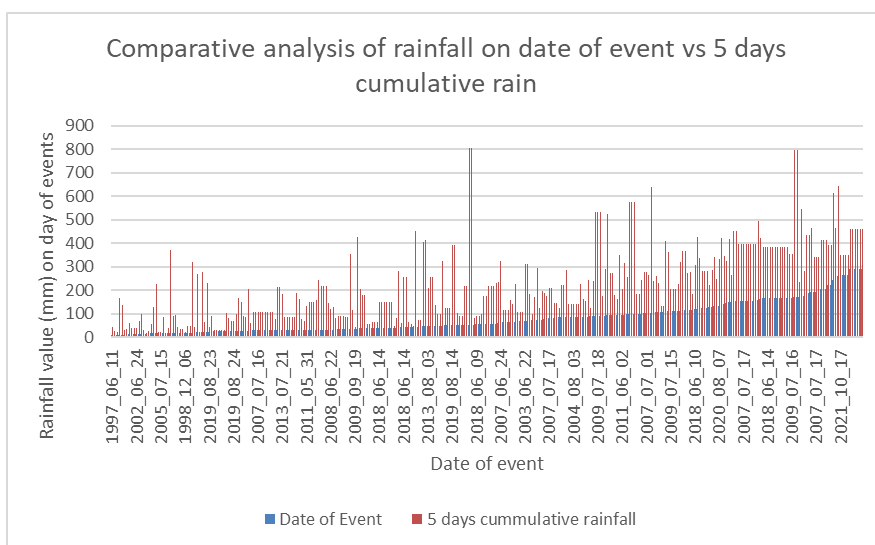


Figure 3-56: Comparative analysis of rainfall on date of event vs 5 days cumulative rain

## **3.4 Cyclones**

Kerala being a coastal state is also prone to cyclones and storm-surges. Cyclones that originate in the Arabian Sea and or the Bay of Bengal can create damage in Kerala State. Particularly near the coast, these cyclones have the potential to deliver severe winds, a lot of rain, and storm surges. Normally, the cyclonic system season lasts from May to November/ early December. Storm surges rising sea levels caused by cyclone-induced low pressure and strong winds are especially dangerous for Kerala's coastal regions. Kerala faces a threat from storm surge due to its coastal location and vulnerability to cyclones and severe weather events. Storm surge occurs when a storm, usually a tropical cyclone, causes a sudden rise in sea level, leading to widespread flooding, erosion, and damage to infrastructure and property. With a coastline spanning 580 km along the Arabian Sea, Kerala is at risk of cyclonic wind and storm surges during cyclonic disturbances. The state's low-lying coastal areas are especially prone to the devastating effects of storm surges. Out of 14 districts in Kerala, the coastal areas of 11 districts are vulnerable to storm surge with different degree of affect area.

### **3.4.1 DISCUSSION OF THE UNDERLYING EQUATIONS USED IN THE HAZARD MODULE**

This section discusses the approach to cyclone modeling and its application to the

coastal areas of Kerala. The focus of hazard assessment is to assess the impact of cyclonic wind and storm surge flooding along the coastal area of Kerala. Cyclonic wind and storm surge hazards assessment approach has been applied using high-resolution wind and storm surge models. The complex cyclone model comprises of two separates, but related, sub-models: 1) Wind model, 2) Storm surge model. Each of the two 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 is discussed in the Risk Assessment section.

- Cyclonic wind hazard assessment identifies and demarcates areas, which are exposed to strong winds associated with tropical cyclones. It provides information on the 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.

This information is useful to identify coastal stretches vulnerable to the impact of surge inundation and different parts of the State to the different degree of cyclonic wind hazard. The methodology used for cyclone hazard modeling is presented in Figure 3-57.

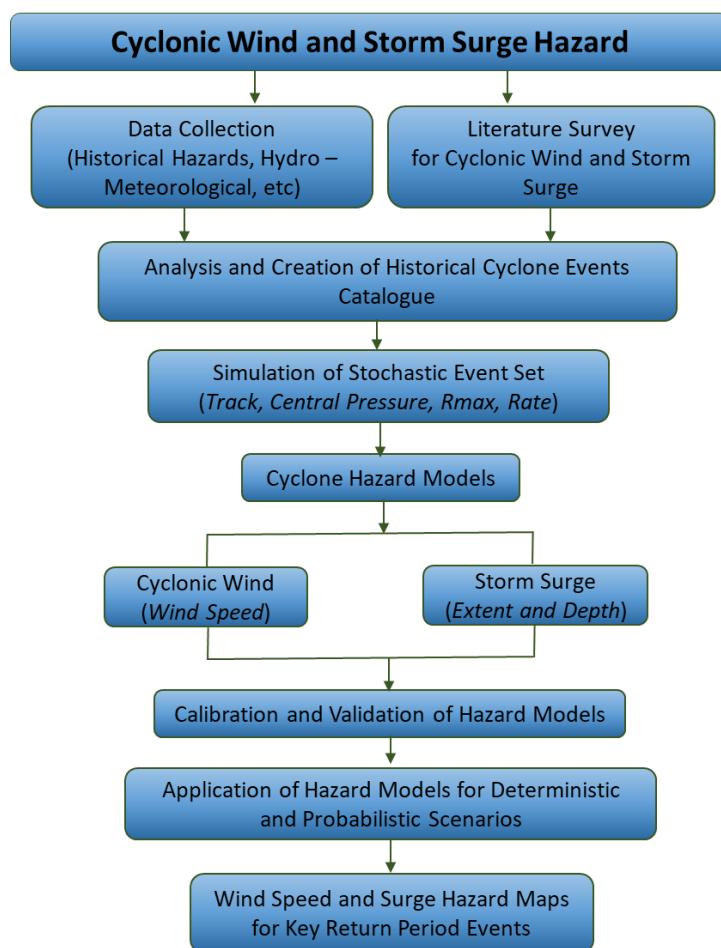


Figure 3-57: Flowchart showing approach for Hazard Assessment

### 3.4.1.1 Climate Change Analysis for Kerala

The climate change impact assessment on cyclonic wind and storm surge was carried out using Coupled Model Intercomparison Project Phase 6 (CMIP6) projected climate change data in conjunction with the current time period climate data using multiple climate change models.

### 3.4.1.2 Downscaling and Bias Correcting the ESM

The main data source for our analysis of future climate is obtained from the Earth System Model (ESM) which runs under CMIP-6 (Coupled Model Inter-Comparison Project Phase-6) [Eyring et al., 2016<sup>80</sup>]

developed in support of the Sixth Assessment Report of the

Intergovernmental Panel on Climate Change (IPCC-AR6).

The climate projections for each scenario are available at a spatial resolution of  $0.25^{\circ} \times 0.25^{\circ}$  (approximately 25 km x 25 km). The key climate variables include daily maximum temperature, minimum temperature, precipitation, and wind speed for the periods from 1951 through 2014 (“Historical”) and from 2015 to 2100 (“Futuristic scenario”). During the downscaling process, the historical simulations serve as the baseline data, and are compared against the observational climate records. The Bias-Correction step “corrects” the bias of the ESM data through

<sup>80</sup> Eyring et al. (2016): Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental

design and organization, *Geosci. Model Dev.*, 9, 1937–1958, <https://doi.org/10.5194/gmd-9-1937-2016>, 2016.

comparisons performed against historical data (Thrasher et al., 2022<sup>81</sup>).

In this study, we have selected seven of the best performing state-of-the-art ESMs as shown in Table 3-15.

The change in maximum wind speeds (%) simulated by the ESMs under Shared Socioeconomic Pathways (SSP 3-7.0) scenario for Kerala wrt to baseline period of 1971-2000 has been estimated and used to compute the return period wind speeds.

### 3.4.1.3 Cyclonic Wind Hazard Analysis for Climate Change Scenarios

The impact of climate change on cyclonic winds in Kerala under the SSP3-7.0 high-emissions scenario for the near-term period (2030s; 2001–2030) has been computed using a reference baseline wind dataset spanning 1971 to 2000. Projections based on ensemble models for future global emission pathways indicate a

variation in wind speed changes across Kerala, ranging from 0.5% to 11%, with an average increase of 4% in wind speeds expected by 2030. These projections have been utilized to estimate the return period wind speeds for the region.

### 3.4.1.4 Storm Surge Hazard Analysis for Climate Change Scenarios

Projected Sea Level Rise Under Different SSP Scenarios: Sea level change for Shared Socioeconomic Pathways (SSP) scenarios resulting from processes in whose projection there is medium confidence. Two low-confidence scenarios, indicating the potential effect of low-likelihood, high-impact ice sheet processes that cannot be ruled out, are also provided. Shaded ranges show the 17<sup>th</sup> -83<sup>rd</sup> percentile ranges and projections are relative to a 1995-2014 baseline. The Figure 3-58 shows the projection and uncertainties for 'Total Sea Level Change'.

Table 3-15: CMIP6 Earth System Models with a fairly high degree of simulation skill over Kerala

ESM Model Abbreviations	Modelling Center / Nation
MPI-ESM1-2-HR	Max Planck Institute for Meteorology, Hamburg (Germany) Model
MIROC6	Centre for Climate System Research-National Institute for Environmental Studies (CCSR-NIES) and Atmosphere and Ocean Research Institute (AORI), Japan
GFDL-ESM4	NOAA Geophysical Fluid Dynamics Laboratory, USA
MRI - ESM2-0	Meteorological Research Institute, Japan
IITM-ESM	Indian Institute of Tropical Meteorology, Pune
INM-CM5-0	Institute of Numerical Mathematics, Russian Academy of Science, Russia
ACCESS-CM2	Commonwealth Scientific and Industrial Research Organization, Australia

<sup>81</sup> Thrasher, B., Wang, W., Michaelis, A. Nemani, R. (2021): NEX-GDDP-CMIP6.

NASA Center for Climate Simulation, doi:10.7917/OFSG3345.

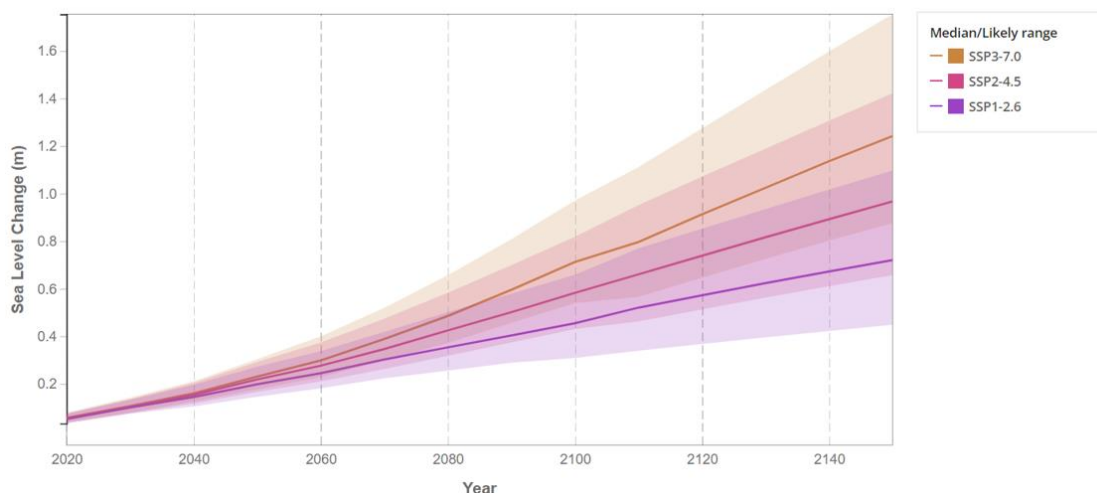


Figure 3-58: Projection and uncertainties for 'Total Sea Level Change'

In another study by CSTEP<sup>82</sup>, projected Sea Level Rise has been estimated under SSP 2-4.5 and SSP 5-8.5, and provided SLR (in cm) and impacted area (in sq. km) for the city of Kochi, Kozhikode, and Thiruvananthapuram for 2040, 2060, 2080 and 2100. The study inferred that, places in Kochi (Naval airport, Fort Kochi beach, Ernakulam Wharf, and Subash Bose Park); Kozhikode (Marad and Kamburam beach, Theeram Bliss park, Puthiyappa fishing harbour, and Jetty Park); Thiruvananthapuram (Airport, Pozhikkara beach, Valiathura beach, Shangumugham beach, Perumathura beach, and Akkulam lake) could submerge due to sea level rise as a result of global warming.

In our study, the projected sea level rise for the 2030s under the SSP3-7.0 high-emission scenario indicates variations along the Kerala coast, ranging from 0.08 to 0.14 m, with an average increase of 0.11 m expected by 2030. These projections have been used to estimate the return period storm surge heights for the study area.

#### Data Used

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, 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.

#### 3.4.1.5 Data Inputs for Cyclone and Storm Surge Hazard Modeling

The intensity of a cyclonic disturbance is measured by the strength of the winds around its center. Wind speeds of various categories of cyclonic disturbances provided by the India Meteorological Department (IMD) are given in Table 3-16.

The data along with sources used for cyclonic wind and storm surge hazard modeling are provided in Table 3-17.

The basic data collected from different sources is integrated into a GIS database that provides the framework for further analysis. The tracks of cyclonic disturbances with their categories that passed in and around the study area are depicted in Figure 3-59.

<sup>82</sup> CSTEP (2024). Sea Level Rise Scenarios and Inundation Maps for Selected Indian Coastal Cities, CSTEP-RR-2024-04.

Table 3-16: Classification of cyclonic disturbances (IMD)

Sl. No.	Storm category	Wind speed in knots	Wind speed in km/h
1	Low Pressure Area (L)	<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	89-117
6	Very Severe Cyclonic Storm (VSCS)	64-89	118-166
7	Extremely Severe Cyclonic Storm (ESCS)	90-119	167-221
8	Super Cyclonic Storm (SuCS)	120 or more	222 or more

Table 3-17: Cyclone data availability for cyclonic wind hazard modeling

Sl. No.	Data Description	Data Source	Data Availability
1	Cyclone track and intensity data since 1891	India Meteorological Department (IMD), International Best Track Archive for Climate Stewardship (IBTrACS)	IMD cyclone track data for 1891-2007 is available in CD version (2008 ed.) Cyclone track data for 1982-2023 is available at IMD website ( <a href="http://www.imd.gov.in">www.imd.gov.in</a> ) Cyclonic track data is available on public domain at six-hour intervals from 1842-2023 (IBTrACS)
2	Bathymetry data having high resolution for shallow sea levels	National Hydro- graphic Office (NHO), Dehradun; General Bathymetric Chart of the Oceans (GEBCO)	Coastal Bathymetry data received from NHO and GEBCO gridded bathymetry (resolution 30 arc-second) – Open source
3	Topographic Data	NRSA and SRTM 30 m	High-resolution DTM 10 m and SRTM 30 m data
4	Tides	Le Provost tidal database	Opensource – gridded 13 tidal constituents at 0.5° x 0.5° Finite Element Solution FES95.2

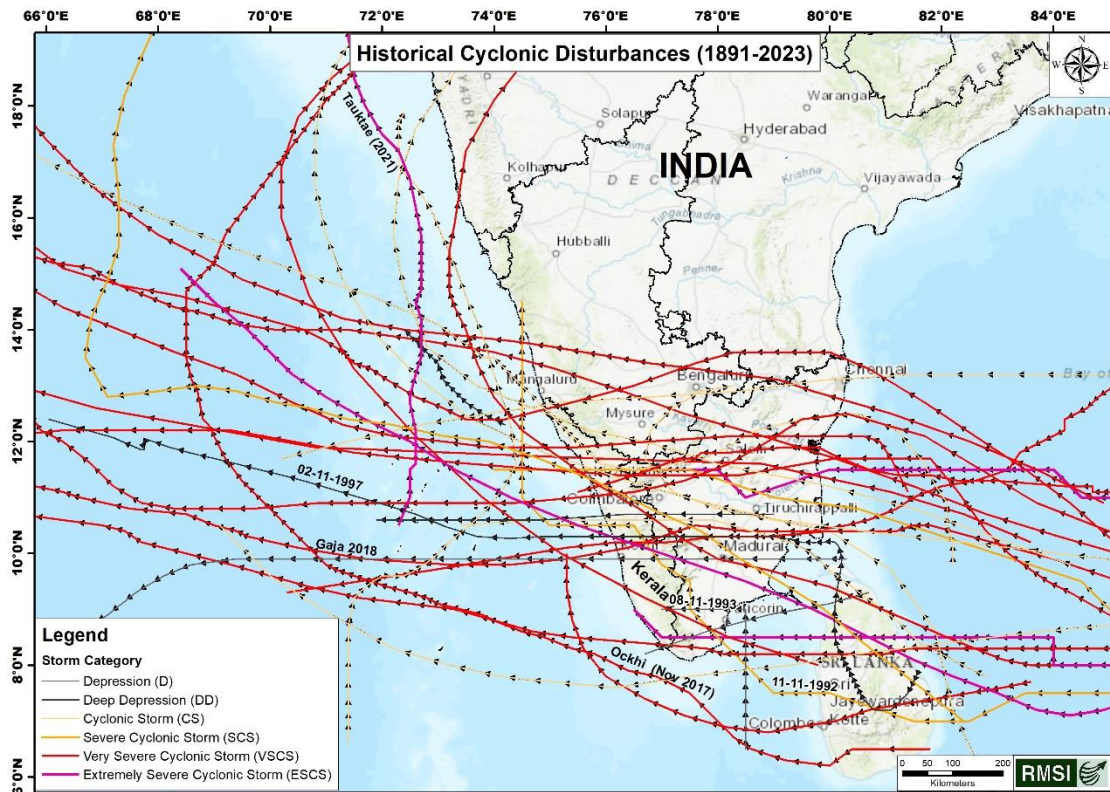


Figure 3-59: Tracks of cyclonic disturbances in and around Kerala (1891-2023)

Table 3-18: Historical storms over Kerala during (1981-2018)-Source: KSDMA

Sl. No.	Subbasin	Name	Year	Month	Day	Cyclone Type	Stage
1	AS	Nil	1981	10	27	Nil	Nil
2	AS	Nil	1984	12	2	Nil	Nil
3	AS	Nil	1987	12	6	Nil	Nil
4	AS	Nil	1992	9	29	Nil	Nil
5	AS	Nil	1992	11	14	Nil	Nil
6	AS	Nil	1993	11	9	Nil	Nil
7	AS	Nil	1993	11	9	Nil	Nil
8	AS	Nil	1997	11	8	Nil	Nil
9	AS	Nil	2000	11	30	Nil	Nil
10	AS	Nil	2000	12	28	Depression	Depression
11	AS	Fanoos	2005	12	11	Nil	Cyclonic Storm
12	AS	Nil	2013	11	17	Nil	Nil
13	AS	Gaja	2018	11	16	Depression	Severe Cyclonic Storm

### 3.4.2 CYCLONIC WIND HAZARD MODELING APPROACH

Dynamic Storm Model: Surface wind field associated with a tropical cyclone was derived using a dynamic storm model developed by Jelesnianski and Taylor (1973)<sup>83</sup>. Meteorological inputs required by 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 model was used for the computation of maximum wind at each grid point of the analysis area and retained these wind speeds to drive the surge model. The wind model was then calibrated and validated using available observed data related to important past cyclones.

Figure 3-60 explains the step-by-step approach used for cyclone hazard modeling.

Further, the validated wind hazard model was used for the computation of maximum sustained wind speeds associated with stochastic cyclonic event set that made landfall in and around the coast of Kerala. The Gumbel's<sup>84</sup> extreme value probability distribution was applied to the modelled

wind speeds at each grid point of the model domain and wind speeds for various key return periods (10, 25, 50, 100, 250, and 500 years) were also estimated. The key output of the wind model is a wind speed that provides maximum sustained winds at every grid point covering the area of impact. This output of the cyclone hazard analysis has been used to develop wind hazard maps at LSG level.

**Computing hazard footprints of wind field:** Zonal statistics (geo-spatial technique) was applied on maximum sustained wind speeds to get an aggregated value at LSG level. Cyclonic wind hazard maps at LSG level were prepared by integrating modelled wind speeds with various GIS themes to produce maps with varying wind speeds. The wind hazard maps represent the wind speeds over the study area for key return periods. Moreover, these wind hazard map at the LSG level may be used to identify strong wind prone extent delineation and would also help the state/district authorities to develop short and long-term disaster management plans in respect to cyclonic winds.

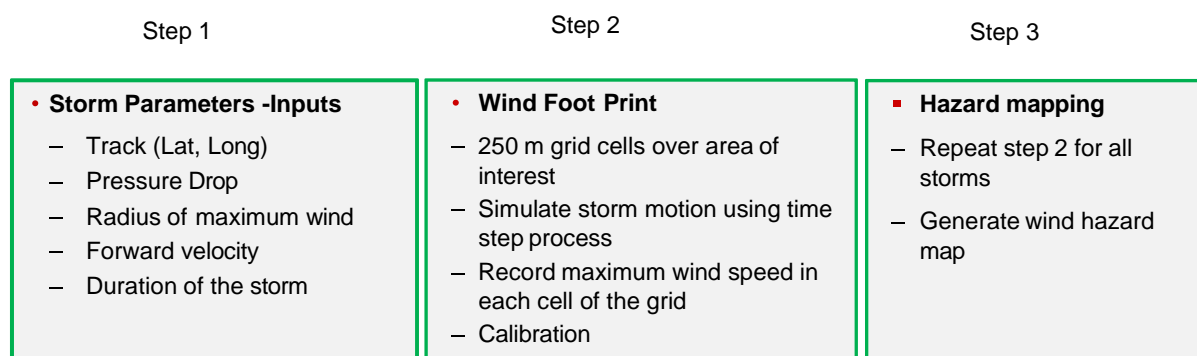


Figure 3-60: Steps for wind hazard assessment

<sup>83</sup>Jelesnianski CP and Taylor AD (1973) NOAA Technical Memorandum. ERL, WMPO-3, 33 pp.

<sup>84</sup> Gumbel, EJ (1954) Statistics of extremes. Nat. Bureau of Stand. App. Math. Series. 33, Washington D.C.

### 3.4.3 STORM SURGE HAZARD MODELING APPROACH

Storm surge hazard assessment identifies and demarcates areas, which are exposed to storm surge flooding. It provides information on the extent and depth of flooding for a range of events, which is the result of hazard assessment. This information is very useful to identify coastal stretches vulnerable to the impact of surge inundation. The storm surge hazard modelling approach is given in the following section.

Storm surge hazard modeling was performed using ADCIRC-2DDI hydrodynamic finite-element model. A finite-element mesh for the study area was constructed using the software package Surface Modeling System (SMS) (Westerink et al. 1994)<sup>85</sup>. A detailed description of the finite-element based hydrodynamic model ADCIRC-2DDI is available in Luettich et al (1992)<sup>86</sup>. 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 are obtained from the Le Provost tidal database, which represent 13 tidal constituents (K<sub>1</sub>, M<sub>2</sub>, N<sub>2</sub>, O<sub>1</sub>, P<sub>1</sub>, S<sub>2</sub>, K<sub>2</sub>, L<sub>2</sub>, 2N<sub>2</sub>, MU<sub>2</sub>, NU<sub>2</sub>, Q<sub>1</sub>, and T<sub>2</sub>) based on Finite Element Solution (FES) Version 95.2 (Le Provost et al. (1998)<sup>87</sup>. Figure 3-61 shows a complete framework with step-wise methodology used for storm surge hazard assessment. The ADCIRC model requires wind forcing as an essential input parameter. For this purpose, the wind fields were computed using the dynamic storm model of Jelesnianski and Taylor. The details of the storm model are provided in the above section.

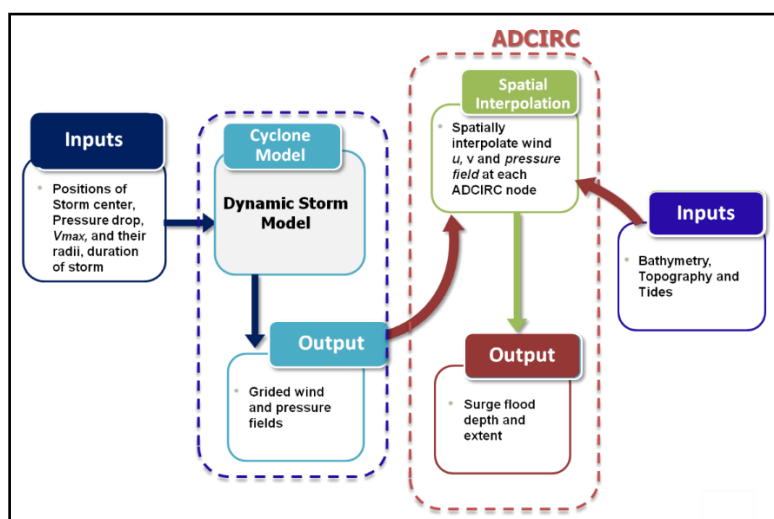


Figure 3-61: Framework of storm-surge hazard modeling

<sup>85</sup> 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.

<sup>86</sup> 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.

<sup>87</sup> Le Provost, C, Bennett, AF and Cartwright, DE (1995) Ocean tides for and from TOPEX/Poseidon, Science, 267, 639-642.

ADCIRC model was applied for historical cyclone events using both tidal and wind forcing to estimate surge amplitude, velocity, and surge flood depths and extent over the study area. The maximum surge height computed with the model was validated against observed surge heights of important cyclone events. The validated storm surge model was then applied to estimate surge flood depths for stochastic cyclone events.

The Gumbel's extreme value probability distribution was applied to the modelled surge heights at each grid point and flood depths for key return periods (10, 25, 50, 100, 250, and 500 years) were also calculated.

### 3.4.4 DETERMINATION OF FREQUENCY AND SEVERITY OF CYCLONIC DISTURBANCES

This section focuses at the frequency and severity of cyclonic disturbances passed over Kerala based on IMD best track

cyclone data and its wind intensity information for the period of 1901 to 2023. The number of cyclonic disturbances experienced over Kerala along with their probability and recurrence interval are depicted in Figure 3-62 and presented in Table 3-19. The historical event data indicates that throughout the course of the last 123 years, 10 depressions (D), 6 deep depressions (DD), 3 cyclonic storms (CS), and 1 very severe cyclonic storm (VSCS) have passed over the state of Kerala. This indicates that D and DD occur more frequently than severe cyclonic storms.

Moreover, the recurrence interval of VSCS is 123-years, but that of CS, DD, and D are 41-years, 21-years, and 12-years, respectively, according to the past cyclonic disturbances. However, the 123-year recurrence interval means that a MSW associated with VSCS has about a one percent chance of occurring in any given year.

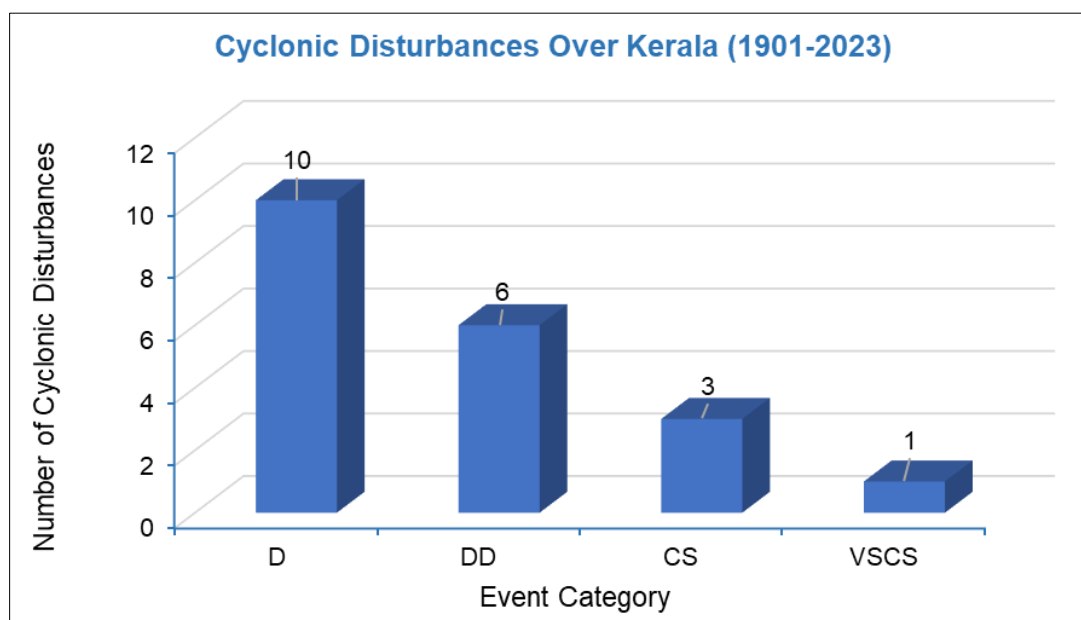


Figure 3-62: Number of Cyclonic Disturbances by Category (1901-2023)

Table 3-19: Event probability and recurrence interval of historical cyclonic disturbances over Kerala during (1901-2023)

Event Category	Number of Event (1901-2023)	Recurrence Interval (years)	Event Probability in one year
Depression	10	12	8%
Deep Depression	6	21	5%
Cyclonic Storm	3	41	2%
Very Severe Cyclonic Storm	1	123	1%

Table 3-20: Season-wise cyclonic disturbance passed over Kerala during (1901-2023)

Cyclone Category	Winter	Pre-Monsoon	Monsoon	Post-monsoon
Depression	-	1	-	9
Deep Depression	-	-	-	6
Cyclonic Storm	1	-	-	2
Very Severe Cyclonic Storm	-	-	-	1

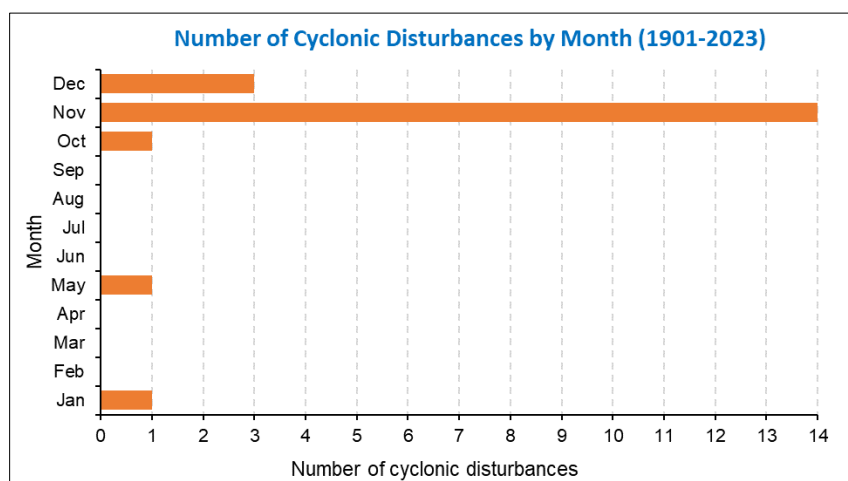


Figure 3-63: Month-wise cyclonic disturbance passed over Kerala during (1901-2023)

Table 3-20 displays cyclonic disturbances that occurred during the monsoon, post-monsoon, pre-monsoon, and winter seasons. Statistics show that just one D and one CS have passed over Kerala during the pre-monsoon and winter seasons respectively, while nine D, six DD, two CS, and one VSCS have happened during the post-monsoon season. This indicates that the frequency of cyclonic disturbances is quite low during the winter and pre-monsoon seasons, while it is negligible during winter season during the period of last 123 years.

Furthermore, Figure 3-63 depicts the frequency of cyclonic disturbances by

month, which is relatively high over Kerala during the post-monsoon season (October to December) compared to other seasons when the frequency of VSCS is lowest and depressions are highest.

In order to determine the effect of climate change on tropical cyclones, we need to investigate any changes in the intensity / frequency of cyclonic disturbances during the last 30 years that may be linked to an increase in SSTs over the course of three decades. Table 3-21 shows the probability and recurrence intervals of cyclonic disturbances from 1994 to 2023. Statistics suggest recurrence interval of D and DD over the last 30 years (1994–2023) is

increased relative to 123 years. No cyclonic activity was recorded in the 30-year period following 1993. Therefore, it appears that

currently Kerala has no substantial impact of climate change.

Table 3-21: Event probability and recurrence interval of historical cyclonic disturbances over Kerala during (1994-2023)

Event Category	Number of Event (1994-2023)	Recurrence Interval (years)	Event Probability in one year
Depression	3	10	10%
Deep Depression	2	15	7%
Cyclonic Storm	-	-	-
Very Severe Cyclonic Storm	-	-	-

### 3.4.5 STOCHASTIC CYCLONIC EVENT GENERATION

For this study, cyclone stochastic event dataset is simulated using Geoscience Australia's Tropical Cyclone Risk Model (TCRM). TCRM uses an autoregressive model to generate thousands of years of events that are statistically similar to the historical records. The model derives statistical relations for tropical cyclone behavior (genesis rate and location, intensity, speed and direction of translation) from best-track datasets, then uses these relations to create a synthetic catalogue based on stochastic sampling, representing many thousands of years of activity. TCRM has been designed to allow hazard researchers to examine the range of sensitivity to the many parameterized tropical cyclone models in use around the world.

TCRM is free and open-source software written in Python programming language with the exception of a small amount of C code used to optimize the code. It can be run on either Windows or Linux machines and includes a graphical user interface to simplify the process of preparing a simulation.

For this study, input for the TCRM model includes historical cyclone track data and their intensity information for every known tropical cyclone that passed in and around the Kerala region from 1901– 2023, recorded at 6-hours intervals. The historical cyclone tracks data set comprises of best track data of India Meteorological Department (IMD) and

International Best Track Archive for Climate Stewardship (IBTrACS).

Track Generator is the stochastic engine of the TCRM model. This module samples from the distributions of genesis location and initial parameter values to start a new Tropical Cyclone event, then steps forward in time using the autoregressive nature of Tropical Cyclone behavior. This allows users to generate thousands of random events that share the same statistical properties as the input track dataset. It is important to note that for generating the actual cyclone tracks, an acceptance-rejection method was used. After generating a storm track originating from one of the initial points, the obtained track was classified to determine whether a track has been produced, that matches the class of its initial point. If this was not the case, the track was rejected and a new track was generated, until a track with the correct classification was obtained.

The simulated stochastic event parameters include track location, central pressure, forward velocity, and location of landfall. All the stochastic cyclonic events are grouped according to their frequency and severity, i.e., Depressions, Deep Depressions, Cyclone Storms, Severe Cyclonic Storms, Very Severe Cyclonic Storms, and Extreme Severe Cyclonic Storms.

#### 3.4.5.1 Cyclonic Wind and Storm Surge Hazard Analysis

Damage from tropical cyclones is caused by strong winds as well as by

accompanying storm surge flooding. The severity of the storm surge at any location of interest is a consequence of the strength of the storm and of the complex interaction of the storm's track, pressure, and wind fields with the bathymetry (water depth offshore) near the coast. This phenomenon has been captured by making use of numerical models.

An independent sample of events has been used to calibrate and validate the wind 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 parameters (wind speed and surge height) was checked by means of relative error against observed values, expressed as percentage (%ERR):

$$\%ERR = \frac{(V_s - V_o)}{V_o} * 100$$

Where  $V_o$  and  $V_s$  are the simulated and observed parameters (e.g. wind speed and

surge height). Therefore,  $\%ERR > 0$  and  $\%ERR < 0$  indicates overestimation and underestimation by the model, respectively.

### 3.4.5.2 Calibration and validation of the cyclonic wind model

The performance of the dynamic storm model was assessed against several historical events wherever observed values were available for wind speed. In the present report, the validation of maximum sustained winds (MSW) for important historical events - SCS of November 1992, November 2017 Ockhi, and November 2018 Gaja are given in Table 3-22. The modelled maximum sustained wind speeds for these events are shown in

The percentage error between computed and observed wind speed varies between 1.0% - 3%, which exhibits a good agreement between them, indicating that the numerical solutions represent a realistic distribution of wind fields in the study region and can be used for simulation of other historical and stochastic events.

Table 3-22: Validation of wind speeds for historical cyclone events

Cyclone name and year	Observed IMD MSW (km/h)	Modelled MSW (km/h)	Error in % between Observed and Modelled MSW
SCS of November 1992	102	105	2.9
November 2017 Ockhi	157	161	2.5
November 2018 Gaja	83	84	1.2

### 3.4.5.3 Calibration and validation of the storm surge model

For the present study, simulation of storm surge heights and associated inundation were carried out by making use of the ADCIRC model. Storm surge simulations resulting from the application of wind, surface pressure and tidal constituents of K1, M2, N2, O1, P1, S2, K2, L2, 2N2, MU2, NU2, Q1, and T2 along the open ocean boundary, were consistent with the observations. The validation of maximum surge height for severe cyclonic storm of

November 1992 is given in Table 3-23. A surge height of about 0.9 m is simulated close to the coast of Tirur tehsil in Malappuram district. The reported surge height due to this cyclone was less than 1 m along the coastal regions of Kerala. This indicates a good agreement between the observed and computed maximum surge heights. No significant surges were observed in association with Ockhi and Gaja cyclonic events (IMD report, 2018).

### 3.4.6 MAPPING OF HISTORICAL AND PROBABILISTIC EVENTS FOR CYCLONIC WIND AND STORM SURGE HAZARDS

#### 3.4.6.1 Cyclonic Wind extent mapping for historical events

The dynamic storm model was used for the computation of wind fields, at each grid point of the model domain, associated with important historical cyclone events. Wind hazard maps for the historical events, SCS of November 1992, November 2017 Ockhi, and November 2018 Gaja cyclones, were prepared by integrating model results with GIS themes, as shown in Figure 3-64 to Figure 3-66, respectively.

The computed MSW associated with SCS of November 1992 of 82 kmph (

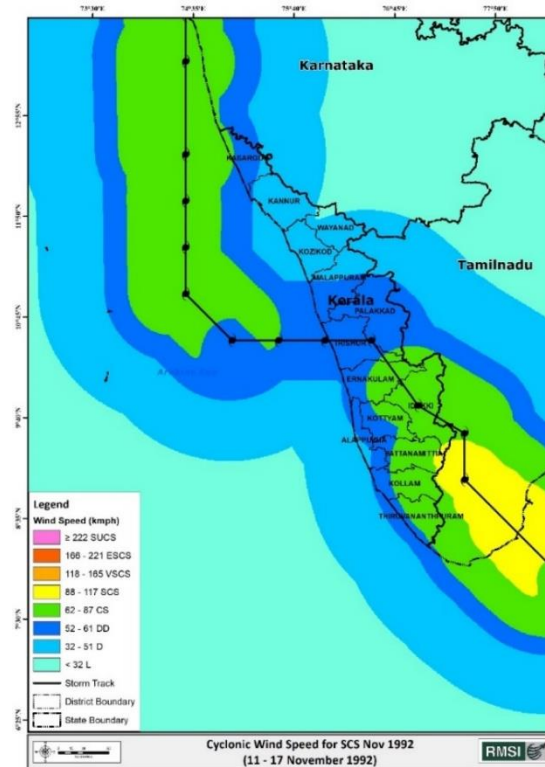


Figure 3-64) is in good agreement with IMD<sup>88</sup> provided MSW of 83 kmph over Pathanamthitta. The modelled MSW of about 65 kmph for cyclone Ockhi (Figure 3-65) over Thiruvananthapuram is in close agreement with the reported observation of 62 kmph (IMD report<sup>89</sup>). The model simulated maximum wind speed of 61 kmph over Southeast Arabian Sea associated with Gaja (Figure 3-66), which is close to the observations of 60 kmph reported by IMD report<sup>90</sup>.

Table 3-23: Validation of surge heights for SCS of November 1992 cyclone

Cyclone name and year	Observed Maximum Surge Height (m)	Modelled Maximum Surge Height (m)	Error in % between Observed and Modelled Surge Height
SCS of November 1992	<1	0.9	-

<sup>88</sup> IMD Report: 1993, Report on cyclonic disturbances over North Indian Ocean during 1992

<sup>89</sup> IMD Report: 2018, Very Severe Cyclonic Storm, 'OCKHI' over the Bay of Bengal (29 Nov.-05 Dec. 2017)

<sup>90</sup> IMD Report: 2018, Very Severe Cyclonic Storm, 'GAJA' over southeast Bay of Bengal (10 – 19 Nov. 2018)

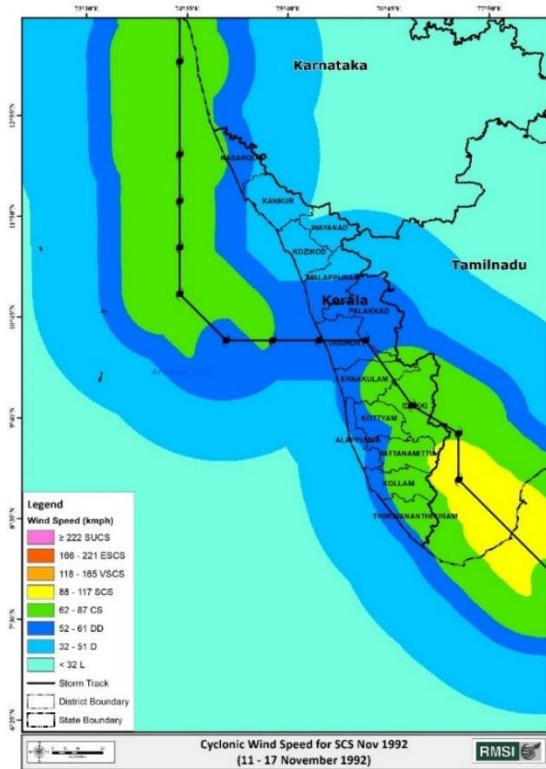


Figure 3-64: Modelled wind field of SCS of November 1992

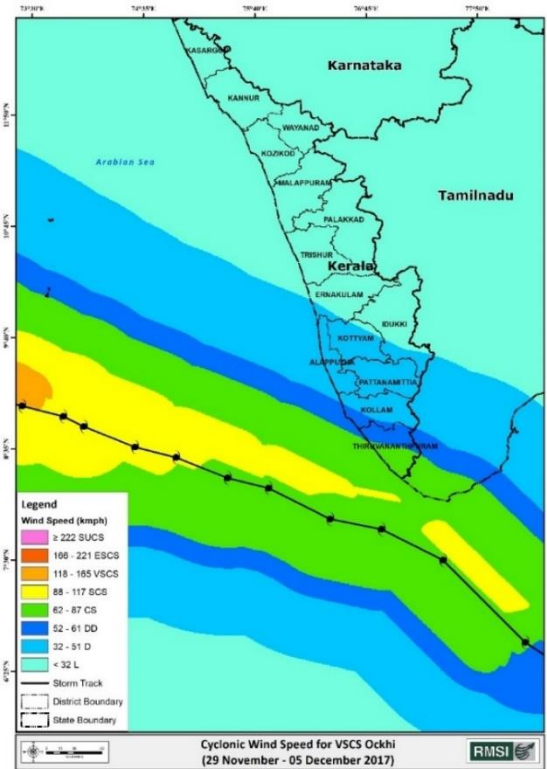


Figure 3-65: Modelled wind field of November 2017 Ockhi cyclone

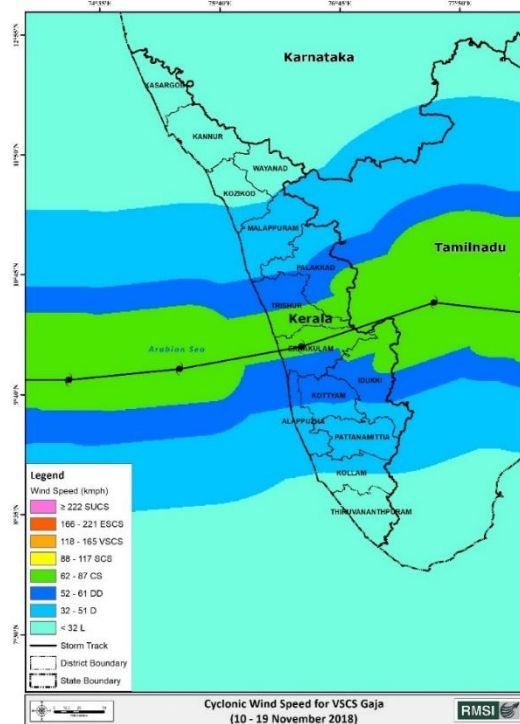


Figure 3-66: Modelled wind field of November 2018 Gaja cyclone

### **3.4.6.2 Wind extent mapping for probabilistic events**

Wind hazard assessment identifies and demarcates areas, which are likely to be exposed to various types of cyclonic events. This assessment provides information on the wind magnitude and extent throughout the areas, which are prone to high winds.

The probabilistic wind hazard extent maps at the village level involved a meticulous process of integrating modelled wind speeds, statistical methods, and GIS themes. These maps served to represent the varying wind speeds and extent of wind hazard over the study area for key return periods, including 10, 25, 50, 100, 250, and 500-years. Each map provided insights into the possible severity of wind hazard. The identification of the highest return period, which signified the worst-case scenario of wind hazard is of particular importance. By delineating village, district and state boundaries on these maps, analysts gain the ability to analyze detailed susceptibility at village level. This spatial context enhances the understanding of localized risk factors and facilitates targeted mitigation strategies.

The probabilistic cyclonic wind hazard map of Kerala for different return period events are shown in Figure 3-67 to Figure 3-72. The village-level cyclone wind hazard map of Kerala provides an extensive illustration of vulnerability to fluctuating wind speeds throughout various return periods, offering important insights into possible risks and hazards. With a 2-year return period, winds in Kerala are generally moderate, with winds of less than 50 kmph occurring throughout the state. This points to a largely quiet state scenario and a low chance of major wind-related disturbances throughout this period of time. However, as we extend the analysis to longer return periods, more nuanced patterns emerge. In a 5-year return period event, wind speeds elevate to a range of 51-65 kmph. Moving

on to a 10-year return period (), Kerala faces an escalation in wind intensity, with speeds between 65-85 kmph. Notably, the eastern part of the state, including districts such as Idukki, Pattanamittia, Kottaayam, Ernakulam, Thrissur, and Palakkad, experiences more elevated winds, while the northern part of the state exhibits lower wind speeds. In the event of a 25-year return period (Figure 3-68), Kerala encounters heightened wind hazards, with maximum sustained winds ranging from 81-102 kmph across most parts of the region, except for northern districts like Kasargod and Kannur.

In high return period events, such as the 50-year, 100-year, 250-year, and 500-year events, Kerala state faces unprecedented wind speeds that demand heightened preparedness and robust infrastructure resilience. During a 50-year return period event (Figure 3-69), state has reached wind speeds about 92-120 kmph range, the highest winds observed over Idukki district with 115 kmph and lowest over Kasargod with 92 kmph. Moving to 100-year return period event (Figure 3-70), the wind speed crossed 120 kmph over eastern part of the state with highest wind over Palakkad district with 131 kmph and Kasargod has minimum wind speed of 105 kmph over northern part of the state. In the event of 250-year return period (Figure 3-71) also having high winds at eastern part of the state with 150 kmph and low winds at northern portion of the state with 121 kmph. In the most extreme return period of 500-year event (Figure 3-72), Kerala state experienced very high winds reaching about 165 kmph over eastern part of the state and lowest winds at northern part with 134 kmph.

In essence, these wind hazard maps are invaluable tools for assessing and managing the impact of winds at the village level. Integration of scientific modeling and geographic data, together they empower stakeholders to make informed decisions to protect lives and infrastructure in vulnerable areas.

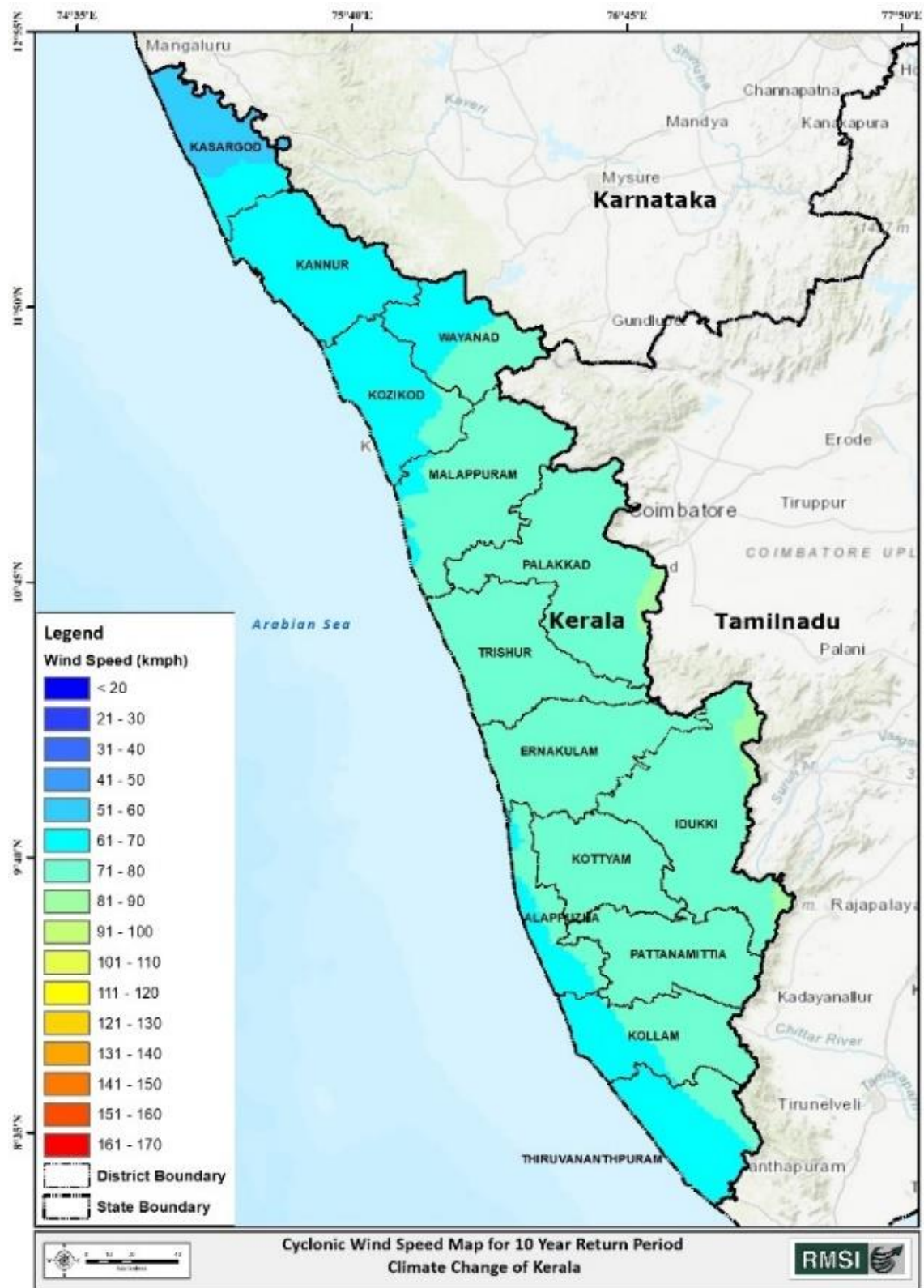


Figure 3-67: Cyclonic wind hazard map of Kerala for 10-year return period

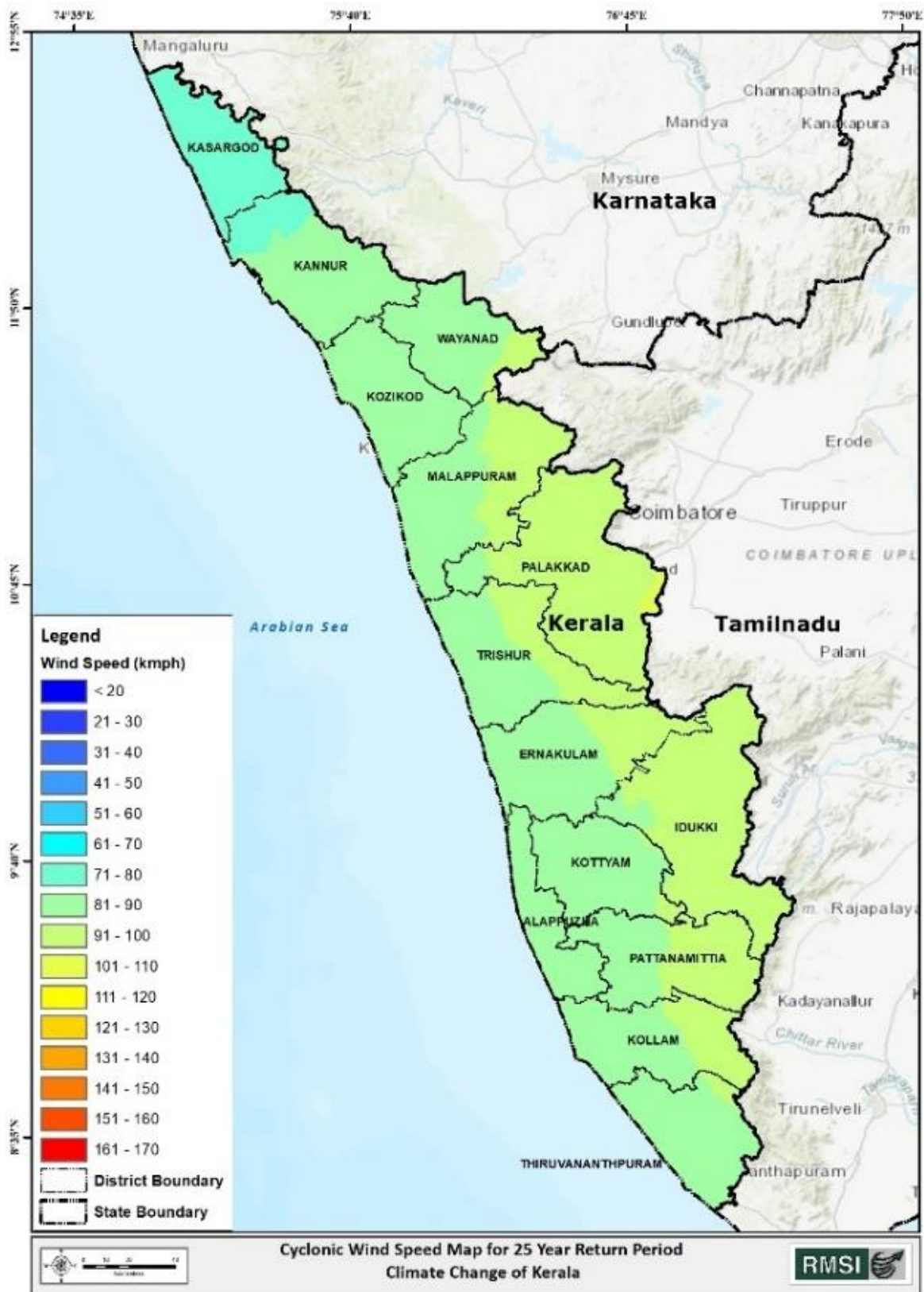


Figure 3-68: Cyclonic wind hazard map of Kerala for 25-year return period

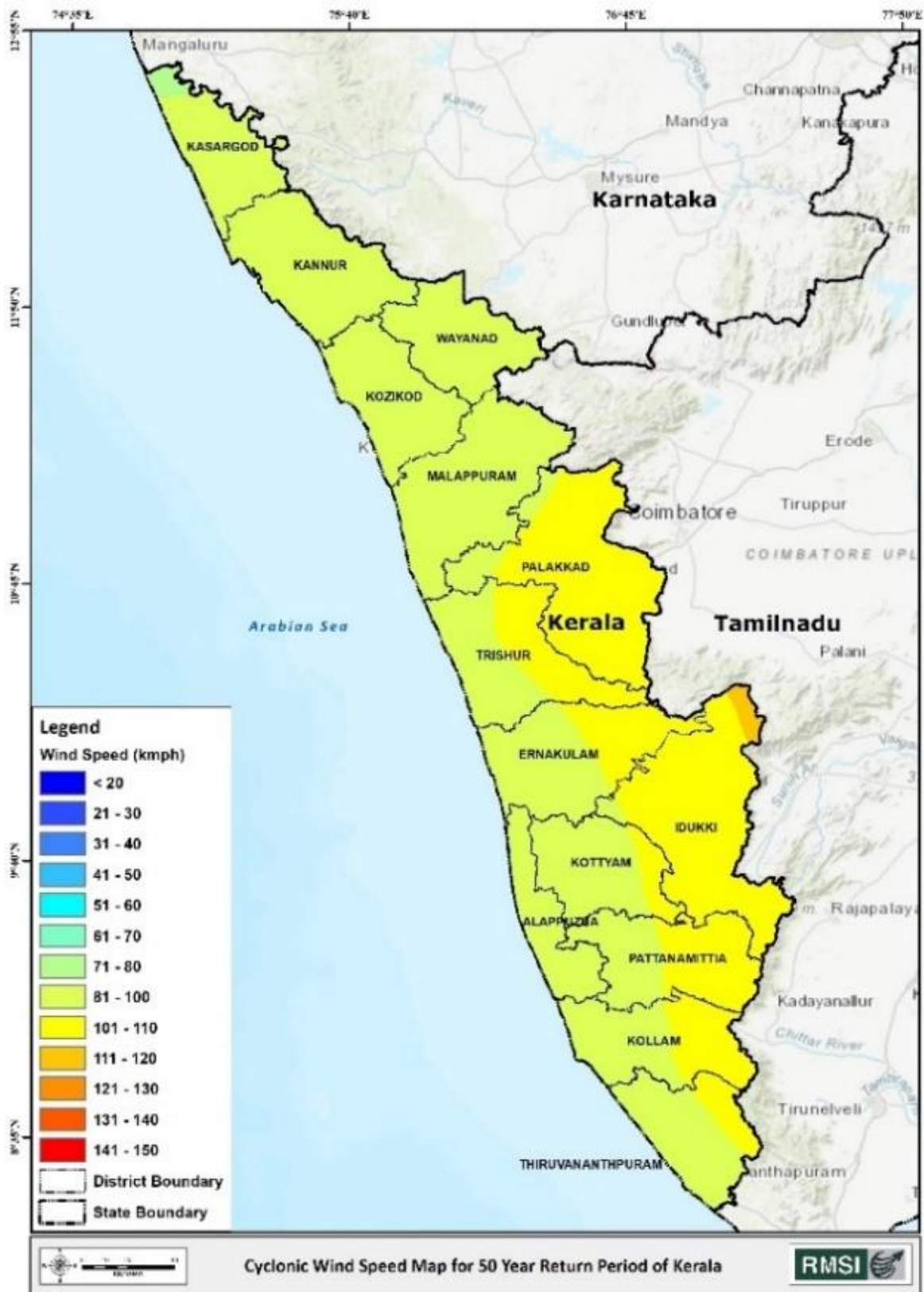


Figure 3-69: Cyclonic wind hazard map of Kerala for 50-year return period

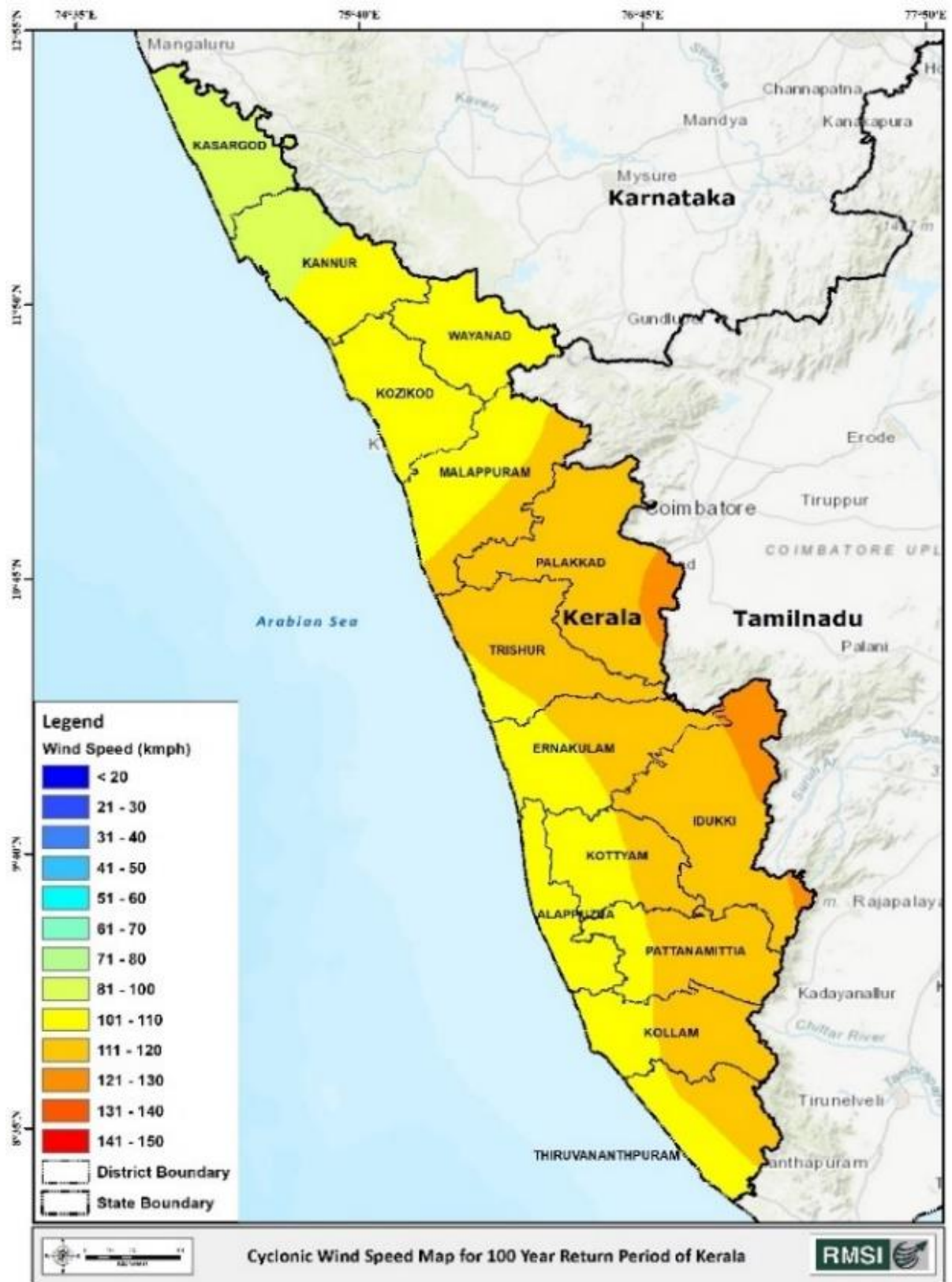


Figure 3-70: Cyclonic wind hazard map of Kerala for 100-year return period

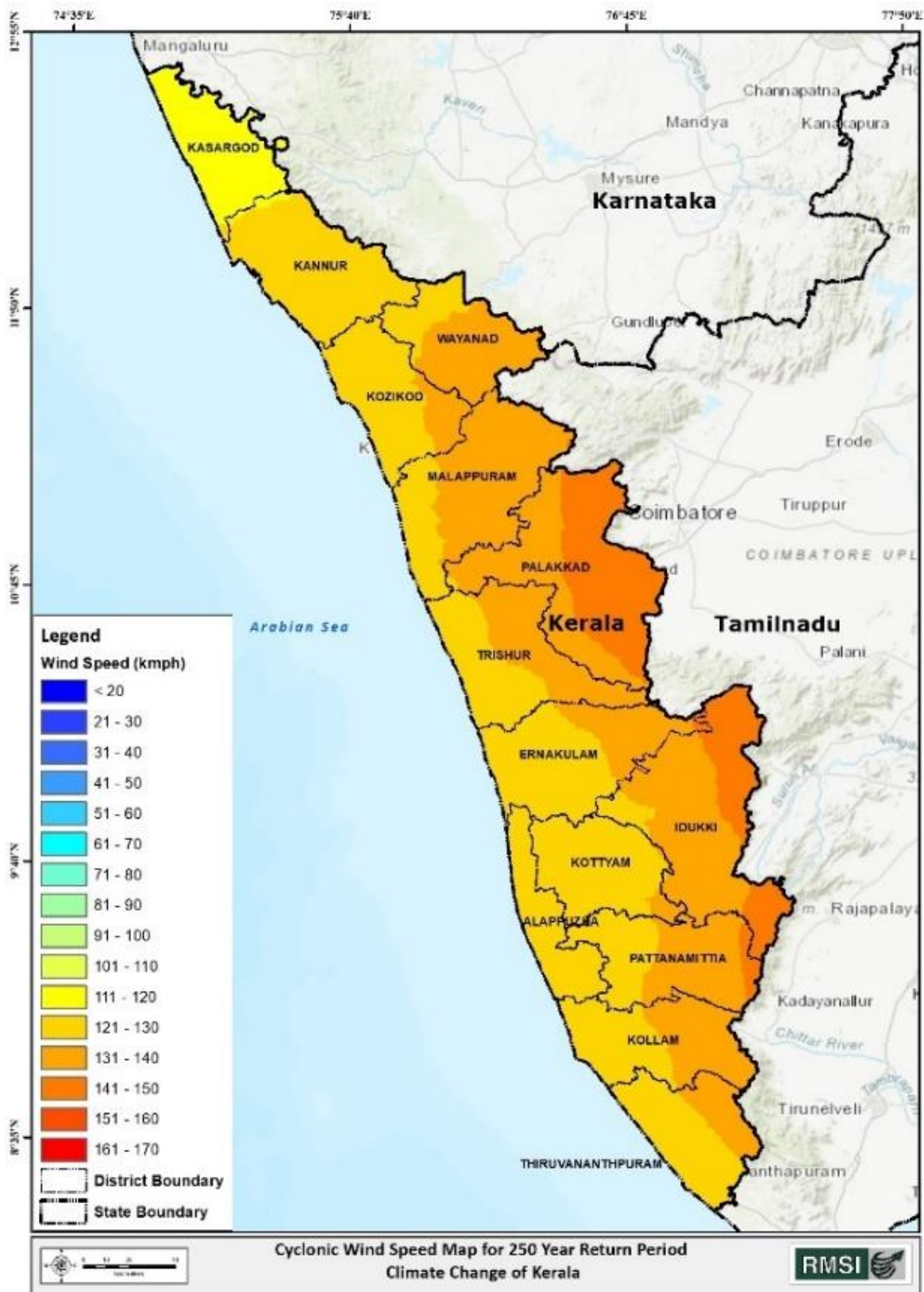


Figure 3-71: Cyclonic wind hazard map of Kerala for 250-year return period

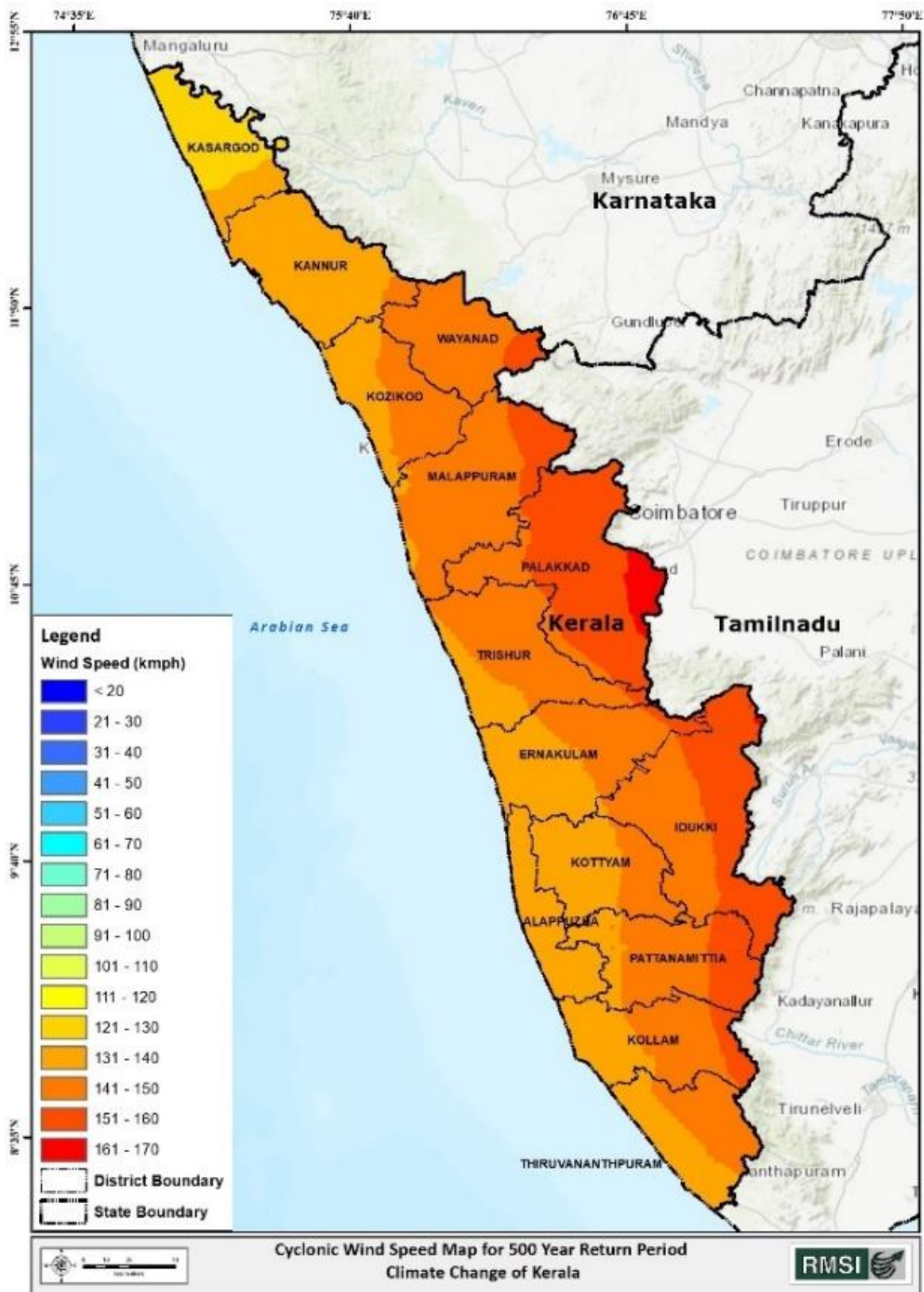


Figure 3-72: Cyclonic wind hazard map of Kerala for 500-year return period

### **3.4.6.3 Storm surge flood extent mapping for historical events**

The modeled surge flood depth and flood extent associated with severe cyclonic storm of November 1992 was insignificant in the study area. A maximum surge height of about 0.9 m was simulated near Tirur tehsil of Kerala. An extensive damage was reported in the coastal area of Tamil Nadu after the cyclone crossed the coast near Tuticorin. However, there was not considerable damage observed in Kerala due to the impact of storm surges (IMD report, 1993<sup>91</sup> and SMRC, 1998). Similarly, no significant surges were observed in association with Ockhi and Gaja cyclonic events (IMD report, 2018). After performing the validation for these events, the model was used to simulate the surge amplitude and extent of inland inundation for each identified stochastic event considered for this study to generate the probabilistic storm surge hazard maps.

### **3.4.6.4 Storm surge flood extents mapping for probabilistic events**

Storm surge hazard assessment identifies and demarcates areas, which are exposed to storm surge flooding. It provides information on the extent and depth of flooding for a range of events, which is the result of hazard assessment. This information is very useful to identify coastal stretches vulnerable to the impact of surge inundation.

The storm surge model estimated storm surge heights for key return periods were projected onto the coastal land and intersected with DEM to demarcate the horizontal extent of inundations and flood depths. As surge heights are generated above the mean sea level, the flood depths are deduced by subtracting local topographic heights from the surge heights.

Modeled surge flood depths were carefully integrated with GIS themes to create storm surge extent maps for probabilistic occurrences along the Kerala coast. These maps provide a visual depiction of the different storm surge flood depths and storm surge hazard levels throughout Kerala coast. They take into account the 2, 5, 10, 25, 50, 100, 250, and 500-year key return periods, each of which offers information on the possible severity of the surge hazards. Finding the 500-year return period is very important because it represents the highest possible level of risk.

The surge hazard map of Kerala provides an extensive illustration of vulnerability to inundated area throughout various return periods, offering important insights into possible risks and hazards. With a 2-year return period, depth of inundated area in Kerala is generally low, with maximum depth of 1.36 m in Kasargod district and average surge depth are 0.65 m for this return period in count of 11 districts. In a 5-year return period event, surge inundated depth is slightly increased to 1.54 m in Ernakulam district but not much significant relative to the 2-year return period. Moving on to a 10-year return period (Figure 3-73), slight increase in maximum inundated depth is about 1.74 m in Ernakulam District. In the event of a 25-year return period (Figure 3-74), Ernakulam district only represented with the highest surge about 1.94 m. Pattanamittia district was the least impacted, experiencing maximum storm surge depths ranging from 0.48 to 0.83 m during these return period events (2, 5, 10, and 25 years).

The surge maps for higher return periods reveal notable variations in surge depths across different return periods and districts. In the 50-year return period (Figure 3-75), Ernakulam district recorded the highest surge at 2.14 m, showcasing its vulnerability to such events. Moving to the 100-year return period (Figure 3-76), Ernakulam district experienced the most

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<sup>91</sup> IMD Report: 1993, Report on cyclonic disturbances over North Indian Ocean during 1992

significant surge, peaking at 2.54 m, while Pattanamittia district exhibited the lowest surge depth, measuring approximately 1.46 m. Interestingly, only Pattanamittia district displayed a significant surge depth during this period, highlighting its unique vulnerability compared to other districts. Ernakulam district once again emerged with the highest surge depth of 2.94 m in the 250-year return period (Figure 3-77), while Pattanamittia district recorded the lowest depth. Finally, in the 500-year return period (Figure 3-78), Ernakulam district stood out yet again, with a maximum surge depth of about 3.34 m, emphasizing its heightened risk in extreme events. These findings underscore the complex interplay

of geographical factors and return periods in determining surge depths, with Ernakulam consistently facing considerable risks, particularly in higher return periods.

These return period maps show the boundaries of states and districts, which allows analysts to evaluate the unique susceptibility in a certain area. This spatial context makes localized risk factors easier to understand and makes tailored mitigation techniques easier to implement. In essence, these maps depicting the extent of surge hazards are invaluable tools for determining and controlling the effects of surges locally.

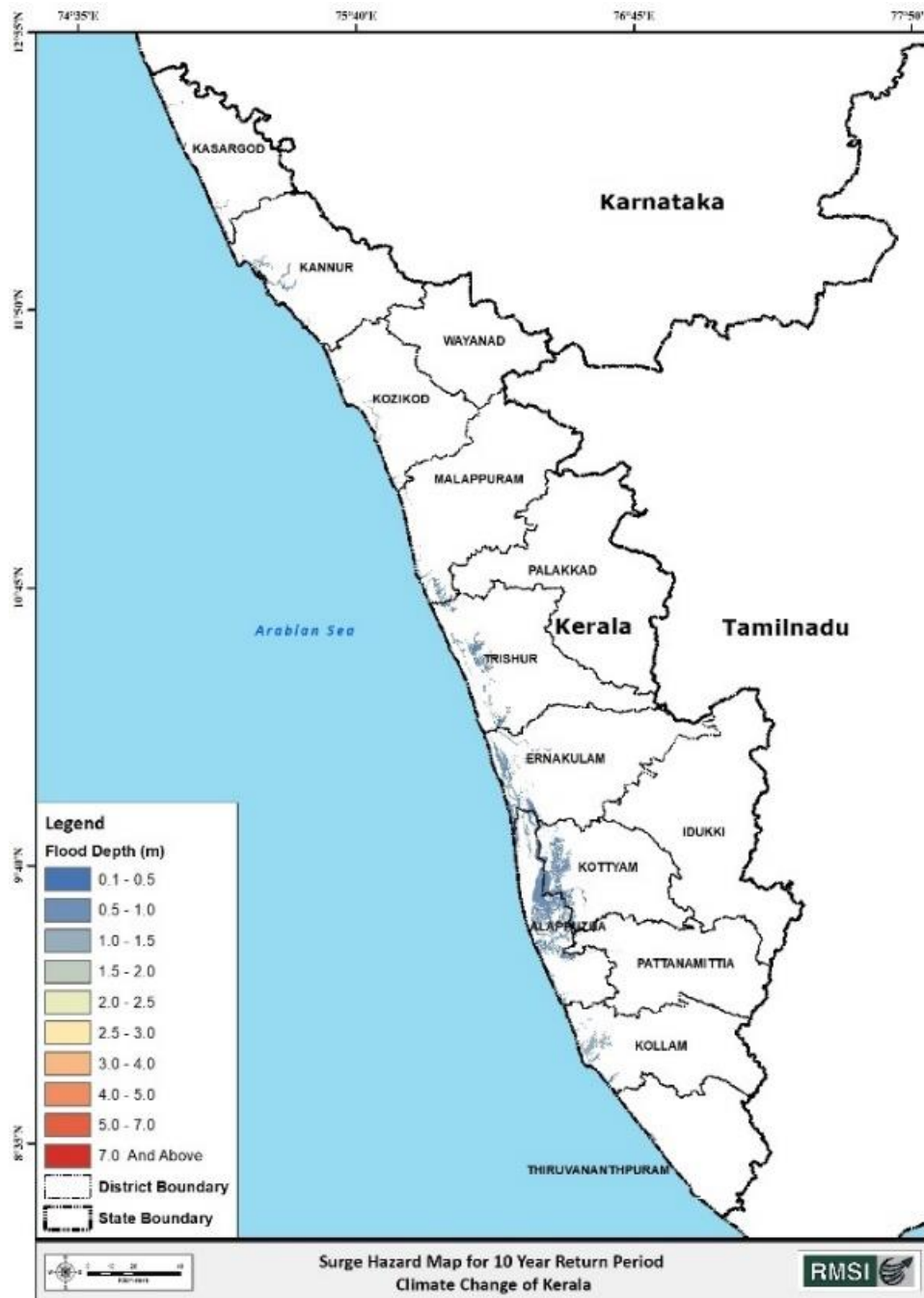


Figure 3-73: Storm surge hazard map of Kerala for 10-year return period

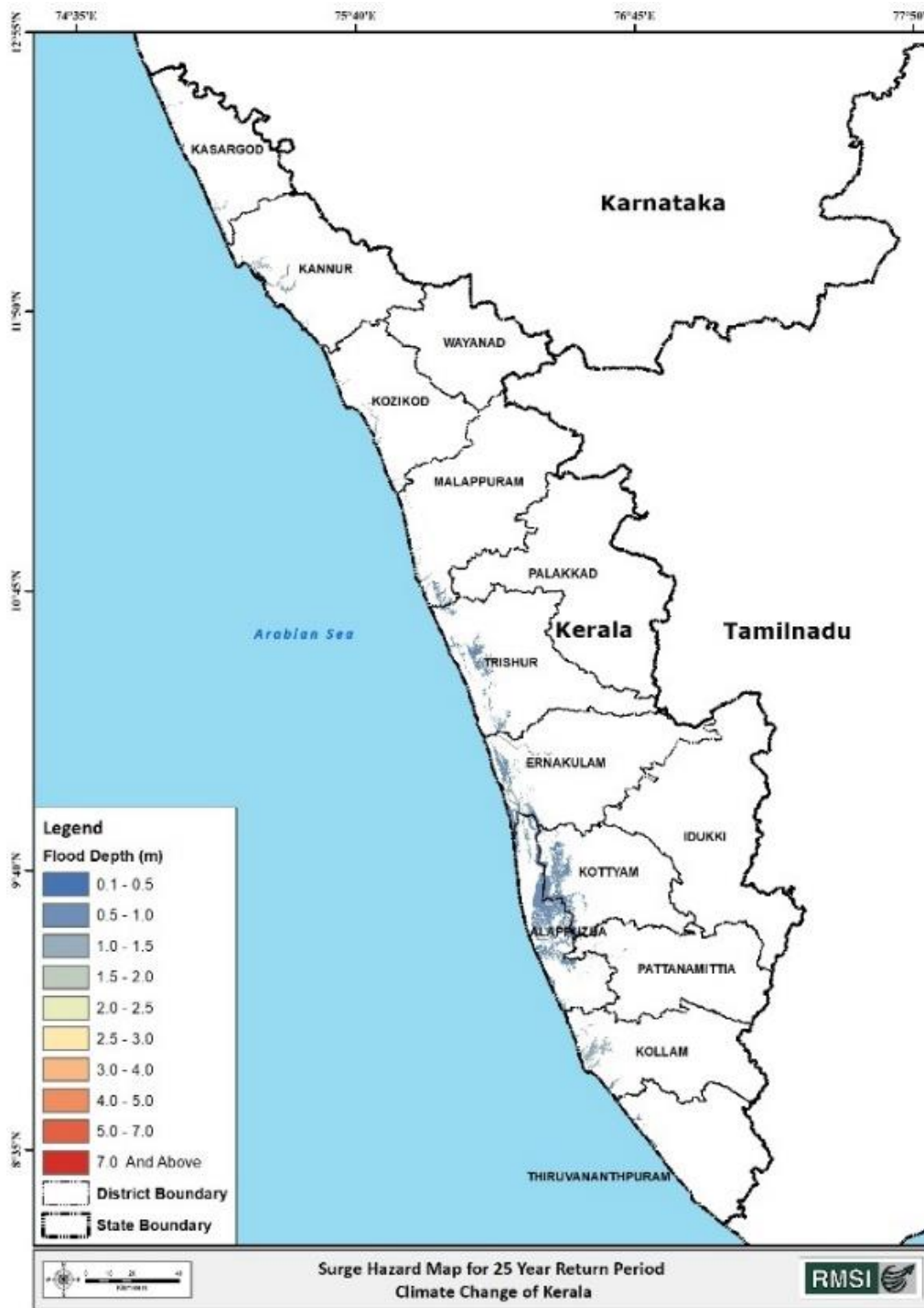


Figure 3-74: Storm surge hazard map of Kerala for 25-year return period

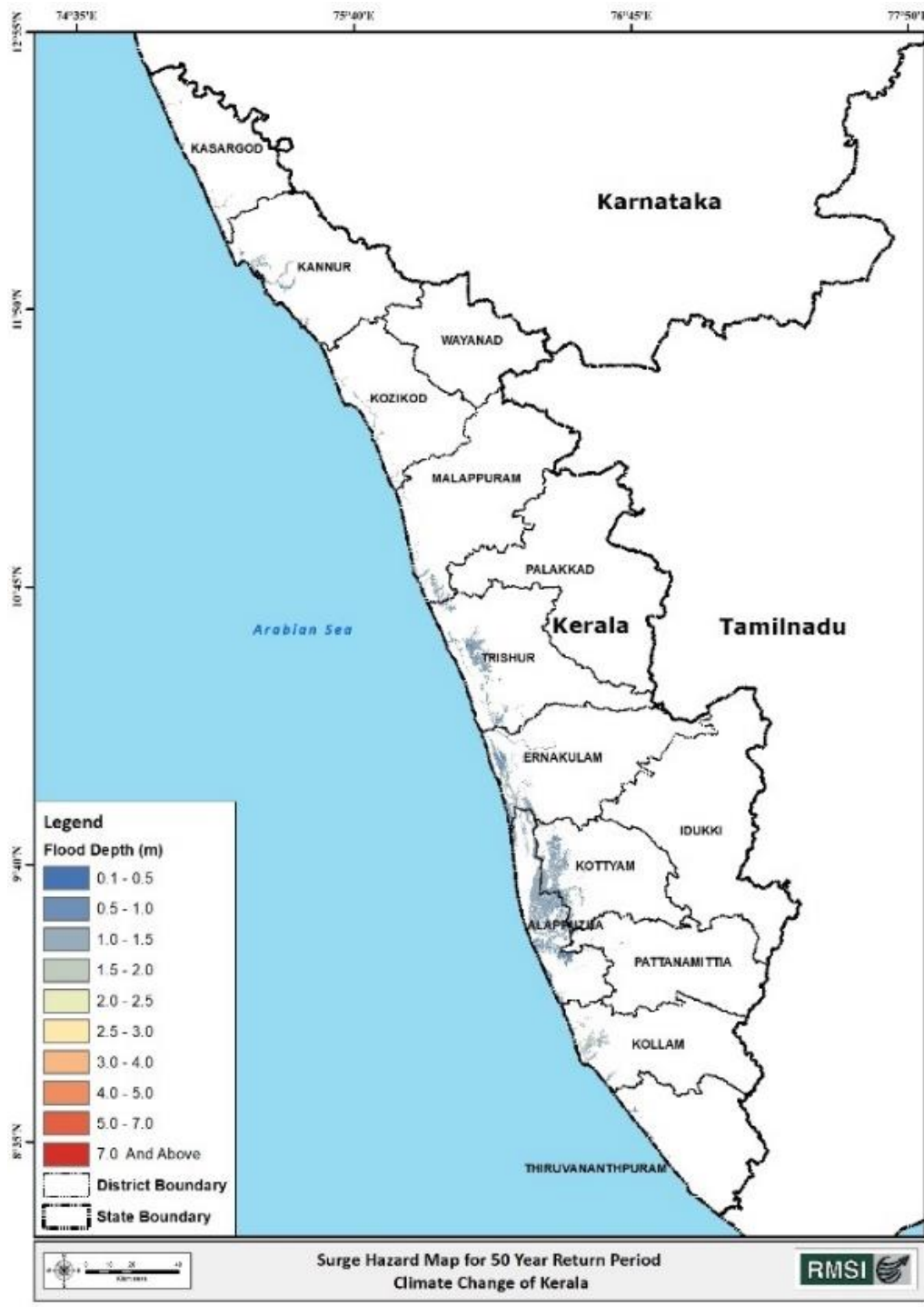


Figure 3-75: Storm surge hazard map of Kerala for 50-year return period

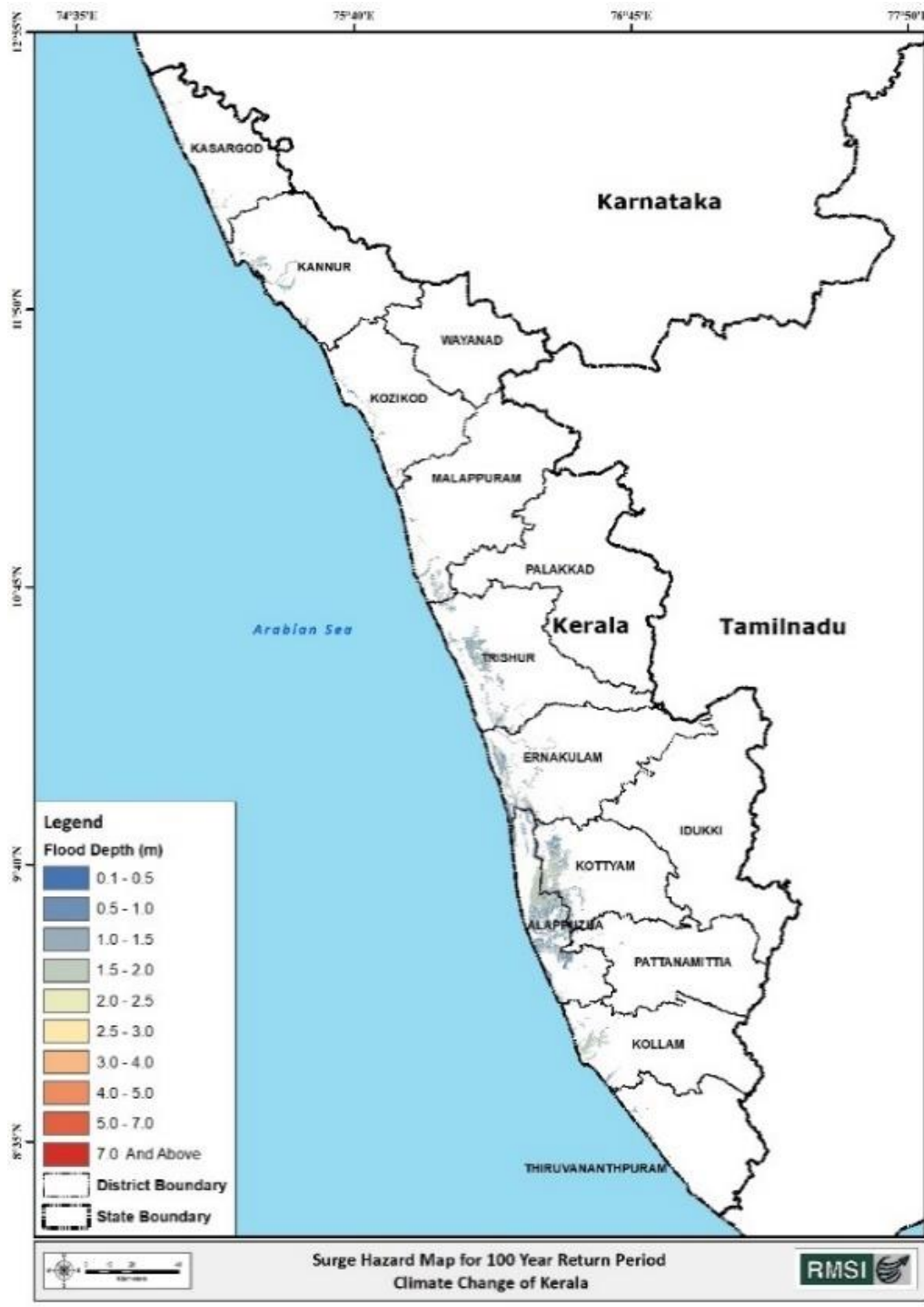


Figure 3-76: Storm surge hazard map of Kerala for 100-year return period

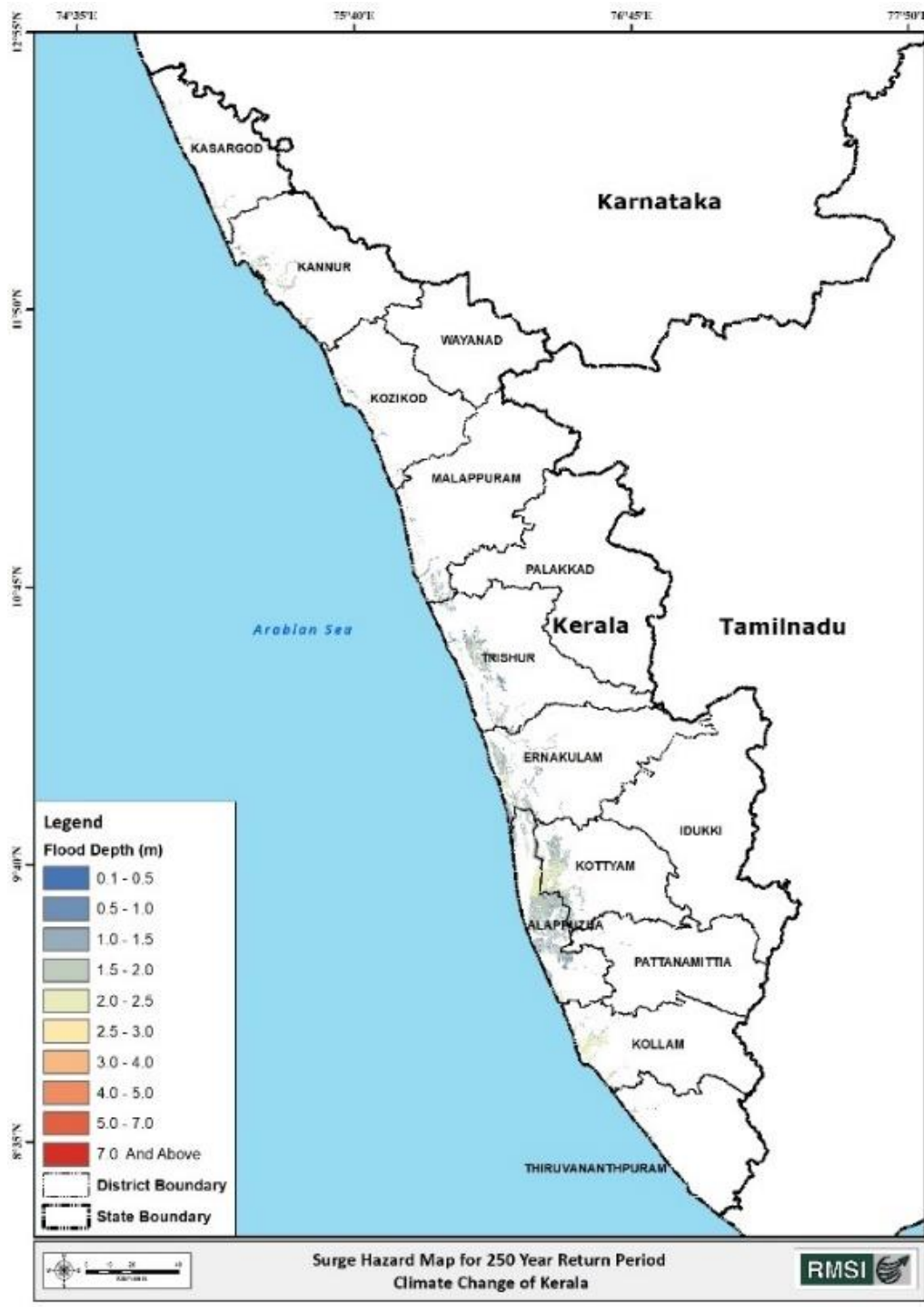


Figure 3-77: Storm surge hazard map of Kerala for 250-year return period

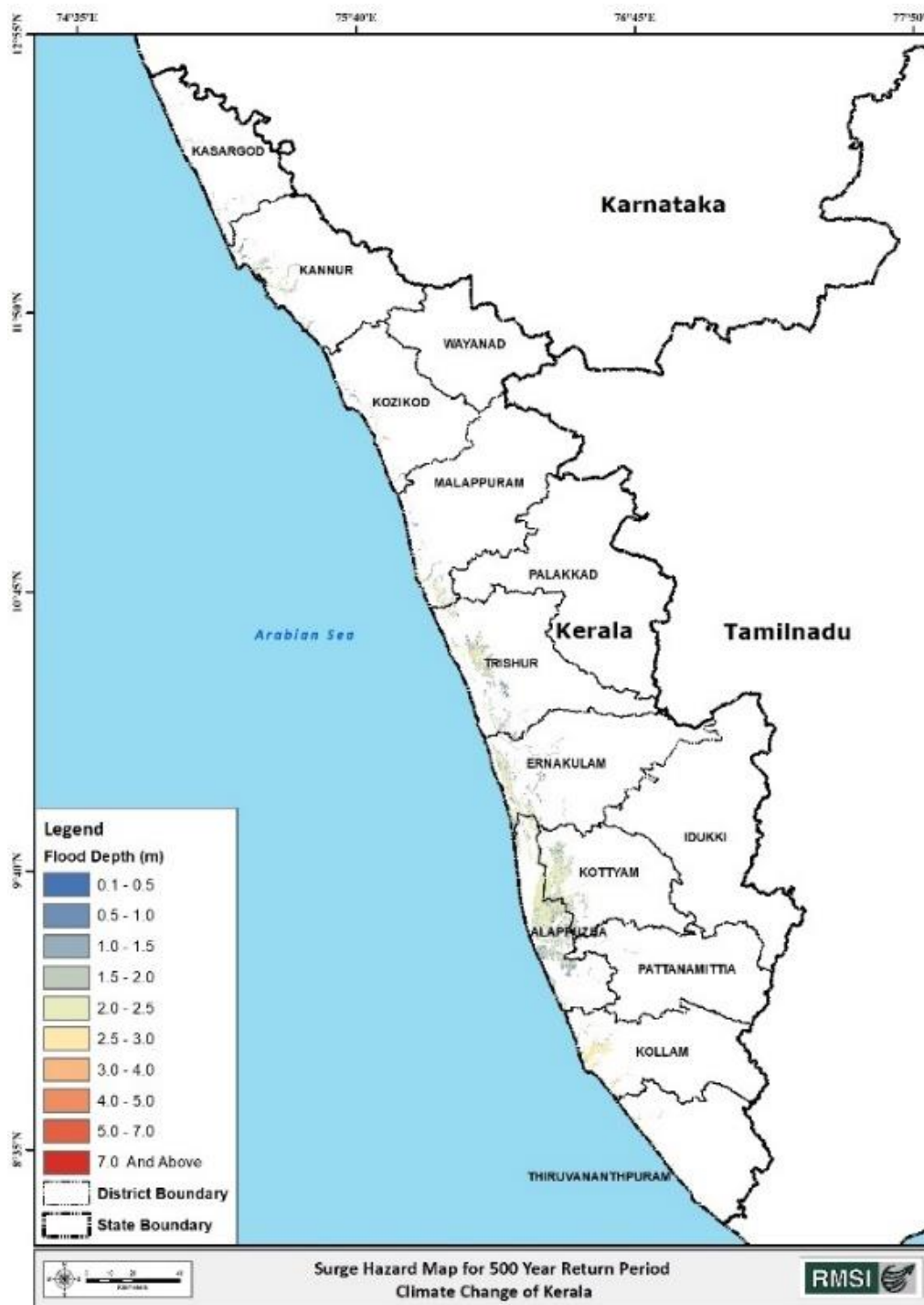


Figure 3-78: Storm surge hazard map of Kerala for 500-year return period

### 3.4.6.5 Conclusion

The development of cyclone wind hazard extent maps for key return periods ranging from 10 to 500 years offers valuable insights into the potential severity of wind disturbances in Kerala. The study highlights varying wind speeds across these return periods, ranging from 20 kmph to over 150 kmph. Of particular significance

is the observation in the 500-year return period, where high winds were estimated across Kerala state, reaching up to 165 kmph over the Palakkad district and wind speeds of 135 kmph were estimated in Kasargod. This distribution of wind intensity showcases the dynamic nature of

cyclonic events and their impact across different regions of the state.

The surge hazard maps of Kerala offer a comprehensive understanding of the region's vulnerability to inundation across various return periods. As expected, the analyses reveal distinct patterns in surge depths, with lower return periods characterized by relatively low inundation depths across the 11 districts out of 14 districts. As storm surge hazard return period increases, surge depths also increase, with coastal areas of Ernakulam consistently facing significant risks with average surge depth is 1.86 m and the maximum depth is 3.34 m, in hazard map of 500-year return period. Notably, the average surge depth in coastal areas of Kollam district is 2.43 meters and the maximum depth is about 3.14 m which stand the second highest. The non-coastal district of Pattanamittia has an average surge depth of 0.84 m, with a maximum reaching approximately 2.1 m, highlighting the diverse nature of risk distribution within the region. Overall, the analysis reveals that Kerala is a moderately vulnerable State to storm surges along the west coast of India.

### **3.5 Drought Hazard Assessment**

Drought refers to extended periods of water scarcity in a given region. Droughts are extreme hydro-climatic events that result in extended periods of water scarcity. While droughts can occur in nearly all climatic zones globally at various times, this gradual phenomenon predominantly

impacts the tropics and nearby areas (Khanday and Javed, 2008<sup>92</sup>).

Agricultural sector is the most affected sector by drought with significant drop in agricultural output and food security across the globe (Herrera and Ault, 2017<sup>93</sup>). Key factors such as reduced precipitation, diminished surface water, and lower groundwater levels contribute to the decline in crop production. Furthermore, rising atmospheric temperatures that accompany droughts exacerbate their adverse effects on agriculture, leading to decreased crop yields and higher production costs. Research shows that the growing frequency and intensity of droughts are primarily driven by climate change and human activities (Kuyawama et al, 2018<sup>94</sup>).

In India, the southwest monsoon provides the main source of water for agriculture and groundwater replenishment, contributing to 80% of the annual rainfall (Asoka et. al., 2017<sup>95</sup>). Droughts in India, which often result from a weakening southwest monsoon, are closely associated with warming in the Indian Ocean and the El Niño/Southern Oscillation (Sinha et. al., 2015<sup>96</sup>). Additionally, the country's diverse geographical features and significant variability in rainfall patterns lead to varying intensities of drought events (Rathore et. al., 2014<sup>97</sup>).

In recent decades, India has experienced an increase in the frequency, severity, and duration of droughts, a trend expected to worsen in future due to climate change (Adhar and Mishra, 2020<sup>98</sup>). The growing food demand from a rising population and urbanization will likely intensify the impact of droughts in the future (Chakraborty,

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<sup>92</sup> Khanday, M. Y., and Javed, A. (2008). Impact of climate change on land use or landcover using remote sensing and GIS in Chopal watershed, Guna, Madhya Pradesh (India). *J. Environ. Res. Dev.* 2, 568–579.

<sup>93</sup> Herrera, D. & Ault, T. (2017). Insights from a New High-Resolution Drought Atlas for the Caribbean Spanning 1950–2016. *J Clim* 30, 7801–7825.

<sup>94</sup> Kuwayama Y, Thompson A, Bernknopf R, Zaitchik B, Vail P (2018) Estimating the impact of drought on agriculture using the US drought monitor. *Am J Agr Econ* 101(1):193–210.

<sup>95</sup> Asoka, A., Gleeson, T., Wada, Y. & Mishra, V. (2017). Relative contribution of monsoon precipitation and pumping

to changes in groundwater storage in India. *Nature Geoscience* 2017 10:2 10, 109–117.

<sup>96</sup> Sinha, A. et. al. (2015). Trends and oscillations in the Indian summer monsoon rainfall over the last two millennia. *Nature Communications* 2015 6:1 6, 1–8.

<sup>97</sup> Mohan Singh Rathore, B. et al. (2014). Drought Conditions and Management Strategies in India.

<sup>98</sup> Aadhar, S. & Mishra, V. (2020). Increased Drought Risk in South Asia under Warming Climate: Implications of Uncertainty in Potential Evapotranspiration Estimates. *J Hydrometeorol* 21, 2979–2996.

2016<sup>99</sup>). Additionally, unsustainable groundwater extraction exacerbates the challenges posed by droughts, heightening future risks (Danger et. al., 2021<sup>100</sup>). The Frequency of severe and exceptional monsoon season drought over India during 1901-2021 (Chuphal et. al., 2024<sup>101</sup>) has been portrayed in Figure 3-79. Their results indicate that the states of Himachal Pradesh, Haryana, and Assam are the most susceptible to severe drought, having experienced it more than 10 times between 1901 and 2020. Punjab, Uttar Pradesh, Madhya Pradesh, Chhattisgarh, Odisha, and Gujarat have faced severe drought conditions 8-10 times during this period. Rajasthan, Karnataka, **Kerala**, and Mizoram have encountered severe drought 7-8 times in the same timeframe.

Kerala State, located in the extreme southwestern part of the Indian subcontinent, is the first region in India to experience the Southwest Monsoon. This

gives the state a moist and wet climate. The annual rainfall in Kerala ranges from 3,800 mm in the north to 1,800 mm in the extreme south. The primary rainy season is the Southwest Monsoon period, which accounts for over 80% of the state's annual rainfall.

Changes in rainfall patterns can significantly impact water resources, agriculture, and ecosystems. In this context, a probabilistic drought hazard assessment has been carried out to quantify the likelihood of drought hazard for Kerala in terms of frequency and severity. Drought hazard frequency of different severity levels has been derived using long time series (i.e., 30 years) of historical rainfall data using a standard drought index. In this study, the data collected from KSDMA, IMD, Department of Agriculture, Kerala and research publications has been used for the analysis.

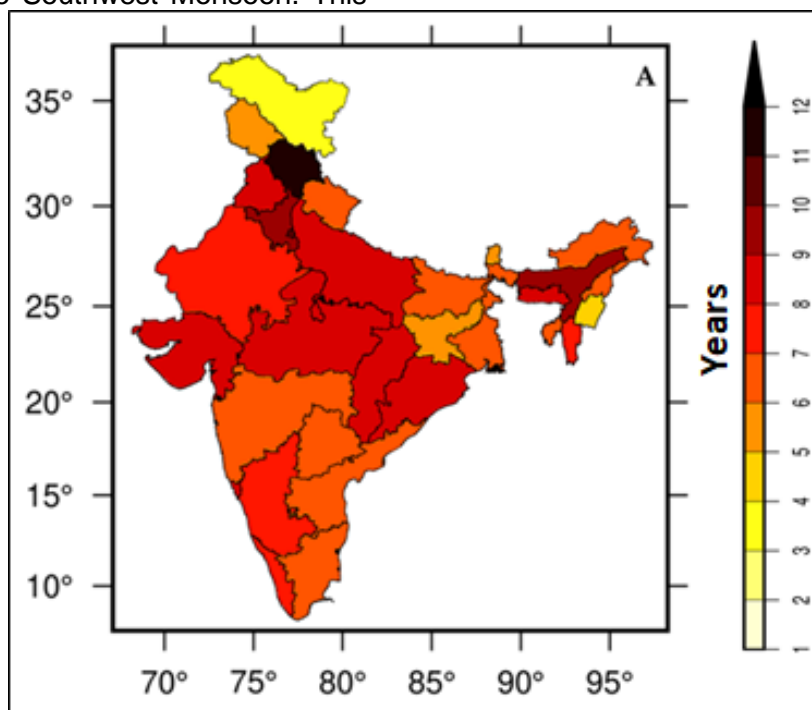


Figure 3-79: Frequency of severe and exceptional monsoon season drought over India during 1901-2021 (Source: Chuphal et. al., 2024)

<sup>99</sup> Chakrabarty, M. (2016). Climate change and food security in India. Observer Research Foundation (ORF): New Delhi, India.

<sup>100</sup> Dangar, S., Asoka, A. & Mishra, V. (2021). Causes and implications of groundwater depletion in India: A review. J Hydrol (Amst) 596,126103.

<sup>101</sup> Chuphal, D.S., Kushwaha, A.P., Aadhar, S. et. al. Drought Atlas of India, 1901–2020. (2024). Sci Data 11, 7. <https://doi.org/10.1038/s41597-023-02856-y>.

The drought risk assessment model describes the probabilistic approach designed to quantify drought-induced agricultural losses using an appropriate drought index along with historical drought losses for Kerala State. Drought risk assessment comprises of four modules, viz., hazard, exposure, vulnerability, and risk (i.e., loss) modules with the output of each preceding module processed as an input to the next module as described in the following sections.

#### ▪ **Hazard Module**

The hazard module has two parts:

1. **Historical drought hazard module:** The module estimates the geographic impact of an event in terms of physically measurable parameters. For the peril under consideration, it could be drought duration, extent, and intensity.
2. **Stochastic drought hazard module:** This module generates a set of stochastic events derived from the characteristics of historical events. The advantage of this approach is that it considers a very large population of events that includes all the potential events that can physically affect the region of interest, the historical record being a subset of this ensemble. Each stochastic event is quantified in terms of its location, size, and rate of occurrence.

#### ▪ **Exposure module**

This module describes the spatial distribution of assets (i.e., rice, banana, and tapioca crops' cultivated area and production) over the region of interest and classifies them based on their damageability potential to drought.

#### ▪ **Vulnerability module**

This module quantifies the vulnerability of the assets subjected to the hazard. In case of droughts, biological vulnerability is assessed by modelling the potential losses in the yields of the selected crops due to droughts at different phenological stages of their crop cycle. The vulnerability is expressed in terms of production losses.

#### ▪ **Risk (i.e., loss) module**

This module estimates the production losses in rice, banana, and tapioca crops. The reason for selection of three crops for this analysis is given below.

Acreage and production of major crops being grown in Kerala during Kharif season have been furnished in Figure 3-80 and Figure 3-81. It should be noted that although coconut is the predominant crop in Kerala in terms of both acreage and production but this is a perennial crop with an ability to withstand drought conditions for quite longer period than many field crops. Its deep root system enables it to extract water from deeper soil layers, and it has the capacity to store water in its trunk, enhancing its drought resistance. Hence, coconut was not considered in the present analysis. Apart from coconut, the three major crops in Kerala in terms of production are tapioca, rice, and banana, (Figure 3-81) and these crops were considered for this analysis. These crops are critical to the region's agricultural landscape and economic livelihood of a significant portion of the local farming community. Furthermore, rice, banana, and tapioca (to some extent) are highly susceptible to drought conditions, which are becoming increasingly common due to climate change (Mahapatra et. al., 2021<sup>102</sup>, Ravi et. al., 2023<sup>103</sup>, Orek et. al., 2020<sup>104</sup>). Therefore, the present study concentrates on examining the effects of drought on the production of rice, banana, and tapioca. The analysis aims to provide a comprehensive understanding of how

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<sup>102</sup> Mahapatra, B.S., Bupenchandra, I., Devi, S.H., Kumar, A., Chongtham, S.K., Singh, R., Babu, S., Bora, S.S., Devi, E.L. and Verma, G. 2021. Aerobic rice and its significant perspective for sustainable crop production. *Indian Journal of Agronomy* 66(4): 383–392.

<sup>103</sup> Ravi, I.; Uma, S.; Vaganan, M.M.; Mustafa, M.M. Phenotyping Bananas for Drought Resistance. *Front. Physiol.* 2013, 4, 9.

<sup>104</sup> Orek, C.; Gruissem, W.; Ferguson, M.; Vanderschuren, H. Morpho-physiological and molecular evaluation of drought tolerance in cassava (*Manihot esculenta* Crantz). *Field Crops Res.* 2020, 255, 107861.

drought conditions influence the yield and growth of these selected crops.

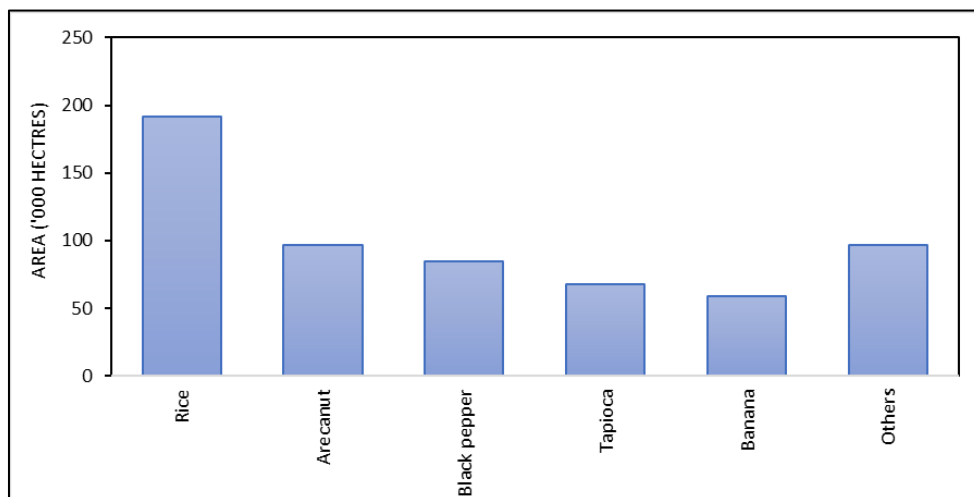


Figure 3-80: Major crops being grown in Kerala during Kharif season in terms of acreage

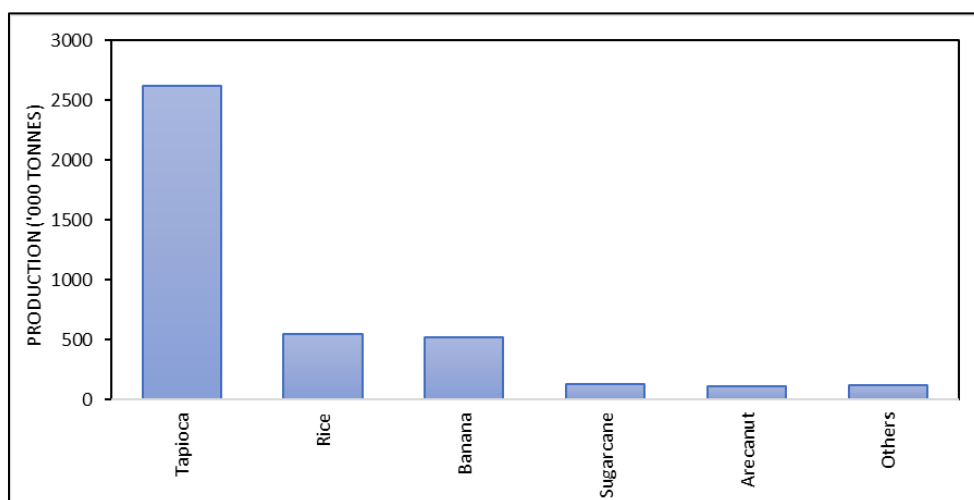


Figure 3-81: Major crops being grown in Kerala during Kharif season in terms of production

The spatial resolution of the model in this study is the administrative area of a district. The implementation of this methodology generates the following two risk metrics:

- **Loss Exceedance Curve (LEC):** After completion of the event loss analysis, the loss generated by each event as well as its rate of occurrence is determined. Using a probabilistic model, the probability for different specific losses that may be exceeded in a given period is estimated. The losses are presented for all the assets combined or for each type individually.
- **Average Annual Loss (AAL):** AAL represents the probability of a loss of any specified amount being exceeded in a given year. It represents the losses averaged over a long period of time, rather than considering the yearly variations in historical records. It is calculated by multiplying each event loss by its rate of occurrence and adding it up over all the events.

The modules in the framework of drought probabilistic risk assessment are shown in Figure 3-82.

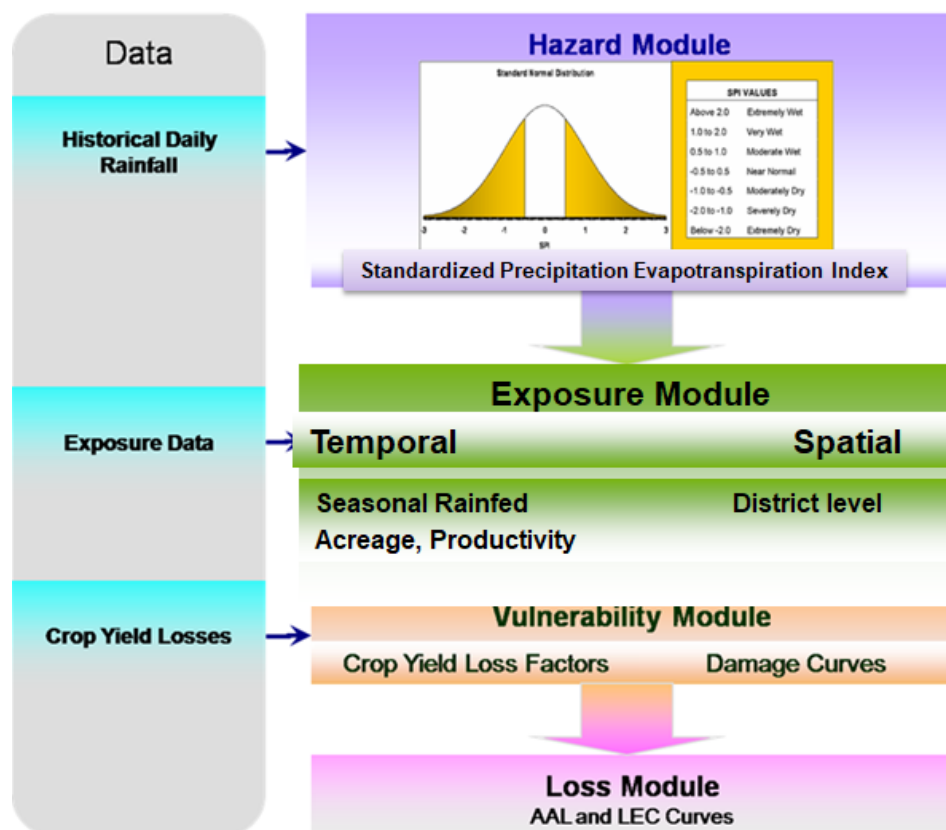


Figure 3-82: Methodological framework for probabilistic drought risk assessment.

Details of the hazard, exposure, vulnerability, and loss modules have been provided in the below given sub-sections.

### 3.5.1 DROUGHT HAZARD MODULE

#### 3.5.1.1 Methodology to assess drought hazard

The quantification of drought hazard, in terms of its severity, is normally achieved with a standard index such as the Percent of Normal Rainfall (PNRF) Indices, Rainfall Extreme Index (REI), and others using Deciles, Palmer Drought Severity Index (PDSI), Moisture Availability Index (MAI), Standardized Precipitation Index (SPI), and Standardized Precipitation Evapotranspiration Index (SPEI). However, RMSI team chose to use SPEI as the drought hazard index (*as it is more advanced index than SPI index, details given below*) for the present study to

quantify the drought in Kerala and provide GIS compatible drought hazard layers for various return periods (10, 25, 50, 100 years). Details of selected SPEI has been discussed in the below sub-section.

#### 3.5.1.2 Standardized Precipitation Evapotranspiration Index (SPEI)

The SPEI is based on a criterion for determining the beginning and end of drought or wet period spell. This index is designed to take into account both precipitation and potential evapotranspiration (PET)<sup>105</sup> in determining the drought. SPEI captures the main impact of increased temperatures on water demand and can be calculated for time steps from 1 month up to 48 months or more. It is a simple water balance model at a given time scale (e.g., week/dekad/month), which requires

<sup>105</sup> Potential evapotranspiration (PET) is the process of water transfer from the soil to the atmosphere, either

directly or through the plants when the water required for such process is fully available.

rainfall, temperature, and sunshine hour as input parameters, and can give various categories of drought severity. Furthermore, in this study, we have used Hargreaves method (Hargreaves, 1985<sup>106</sup>) for the estimation of PET as this method is one of the accurate methods to estimate PET (Junior et al, 2019<sup>107</sup>). The main attractive point to use this method being the limited data requirements to produce the PET estimates as only rainfall, maximum and minimum temperatures are required as input to derive PET. Following are the advantages of using this index:

- All that is needed is rainfall, maximum temperature, and minimum temperature.
- SPEI is a good measure for determining long-term drought.
- In addition to drought, SPEI provides information about wet spells.
- The advantage of this index is that it facilitates comparison of different stations in different climatic regions regardless, of the fact that they may have different normal rainfalls. Therefore, the rainfall of two areas with different rainfall characteristics can be compared in terms of how badly they are experiencing drought conditions.
- The inclusion of temperature along with precipitation data allows SPEI to account for the impact of temperature in a drought situation. The output is applicable for all climate regimes, with the results being comparable because they are standardized.
- Moreover, Keyantash and Dracup (2002)<sup>108</sup> indicated that drought indices must be statistically robust and easily calculated, and have a clear and comprehensible calculation procedure. All these requirements are met by the

SPEI. Furthermore, a crucial advantage of the SPEI over other widely used drought indices is that it considers the effect of PET on drought severity level. Besides, its multi-scalar characteristics enable identification of different drought types and impacts in the context of global warming. Mathematically SPEI is computed using following algorithm:

$$D_i(\text{Climatic water balance}) = P_i - PET_i$$

Where,  $D_i$  = water surplus or deficit for the analyzed time scale " $i$ " (e.g., week/dekad/month);  $P_i$  = precipitation for the analyzed time scale " $i$ "; and  $PET_i$  = Potential Evapotranspiration for the analyzed time scale " $i$ ". The long-term calculated  $D_i$  values are then fitted to a gamma probability distribution as the gamma distribution has been found to fit the  $P$ ,  $PET$ , and  $(P - PET)$  quite well. This is done through a process of maximum likelihood estimation of the gamma distribution parameters,  $\alpha$  (shape parameter) and  $\beta$  (scale parameter). Subsequently, it is then transformed into a standard normal distribution, which, by definition, has zero mean and unit variance (Edwards and McKee, 1997<sup>109</sup>). Positive SPEI values indicate greater than mean  $(P - PET)$ , while negative values indicate less than mean  $(P - PET)$ . Because SPEI is normalized, wetter and drier climates can be represented in the same way, and dry periods can be monitored using SPEI.

Table 3-24 presents how various droughts are categorized based on SPEI values.

<sup>106</sup> Hargreaves, G.L., Hargreaves, G.H. and Riley, J.P. 1985. Agricultural benefits for Senegal River Basin. J. Irrigation and Drainage Engr., ASCE., 111: 113-124.

<sup>107</sup> R. S. Nia Jnior, C. W. Fraisse, V. A. Cerbaro, M. A. Z. Karrei, N. Guindin. (2019). Evaluation of the Hargreaves-Samani method for estimating reference evapotranspiration with ground and gridded weather data sources. Applied Engineering in Agriculture. 35(5): 823-835.

<sup>108</sup> Keyantash, J. and J. Dracup., 2002: The quantification of drought: an evaluation of drought indices. Bulletin of the American Meteorological Society 83, 1167-1180.

<sup>109</sup> Edwards, D. C.; and T. B. McKee. 1997. "Characteristics of 20th century drought in the United States at multiple timescales." Climatology Rep. 97-2, Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado.

Table 3-24: Categorization of drought based on SPEI

Drought classification	SPEI
Extreme Drought	< -2.0
Severe Drought	-2.0 to -1.5
Moderate Drought	-1.5 to -1.0
Mild Drought	-1.0 to -0.5
Normal Condition	-0.5 to 0.5
Wet Condition	> 0.5

### 3.5.1.3 Generation of stochastic weather data using Stochastic Weather Generator

Stochastic weather data was generated using Stochastic Weather Generator embedded in DSSAT (Decision Support System for Agrotechnology Transfer) model (Jones et. al., 2003<sup>110</sup>) based on 30 years (1994 - 2023) of historical rainfall and temperature data set for longer time series (100 years) to generate larger number of extreme events (drought) and subsequently get long-term probabilities of occurrences of extreme events. This will help the policy makers, who are involved in water resource and agricultural sector, to make the plan for the longer term to manage the extreme drought events in the long run. Stochastic weather generator is a statistical model used to create synthetic long-term weather data by employing statistical properties from historical data (Hutchinson, 1986<sup>111</sup>).

### 3.5.1.4 Approach to derive drought hazard return period

Steps to derive drought hazard return period are as followed:

**Step 1:** To compute year-wise (i.e., 30 years for historical rainfall and temperature data set and 100 years for stochastic rainfall and temperature data set) SPEI for

the Southwest Monsoon season (i.e., June - September)

**Step 2:** To segregate all years' SPEIs in which values are  $\leq -0.5$ .

**Step 3:** To make four series of segregated SPEIs (i.e., Minor Drought, Moderate Drought, Severe Drought, and Extreme Drought).

**Step 4:** To count total number of SPEIs in each series.

**Step 5:** To divide 30 years<sup>112</sup> (when SPEI was computed using historical rainfall and temperature data set) by total number of SPEIs in each series and by 100 years<sup>113</sup> SPEI was computed using stochastic rainfall and temperature data set. Outcome of this division is called probabilities (i.e., return periods) of drought hazard event of a particular severity level. For example, if total numbers of SPEIs in each series are 10, 8, 5, and 3 (in the case of historical rainfall data set) then return period against each series will be 3 (i.e.,  $=30/10$ ), 4 (i.e.,  $=30/8$ ), 6 (i.e.,  $=30/5$ ), and 10 (i.e.,  $=30/3$ ) respectively. The interpretation of this result is that there is probability of occurrences of minor, moderate, severe, and extreme drought hazard event are 3-year, 4-year, 6-year, and 10-year respectively for a particular Taluka.

<sup>110</sup>Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.G., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T. (2003). The DSSAT cropping system model. *Eur. J. Agron.* 18, 235-265.

<sup>111</sup>Hutchinson MF (1986). Methods of generation of weather sequences. In: Bunting AH (ed) *Agricultural environments*. CAB International, Wallingford, p 149-157.

<sup>112</sup> It is to note that the reason for mentioning 30 is that we used 30 years rainfall data for the drought hazard analysis in this project.

<sup>113</sup> The reason for mentioning 100 is that we generated 100 years stochastic rainfall data using weather generator.

**Step 6:** To derive return period values for all Talukas of Kerala using above-mentioned approach.

**Step 7:** To generate spatial distribution maps of different severity level of drought hazard based on the return period values. These maps have been provided in the below given sections.

### 3.5.1.5 Data Availability

#### 3.5.1.5.1 Weather data

Long-term (ideally for 30 years) rainfall and temperature data are the primary input for drought hazard analysis as longer the available data better the outputs. Hence, in this study we used 30 years' rainfall and temperature data (i.e., from 1994 to 2023). Daily data on maximum temperature and minimum temperature at 1°x1° (Srivastava et al., 2009<sup>114</sup>), and rainfall at 0.25° x 0.25° (Pai et al., 2014<sup>115</sup>) resolution for the period 1994-2023 are sourced from National Data Center (NDC), India Meteorological Department (IMD), Pune.

#### 3.5.1.5.2 Preparation of Taluka level weather data

The conversion of gridded rainfall and temperature data to taluka level of Kerala has been done using Thiessen polygon method (Thiessen, 1911<sup>116</sup>). In this method, the influence of grid on each taluka has been quantified and can be a best possible way for spatial averaging of weather data. The steps for creating Thiessen polygon network are, first locate all the grid points over the taluka map of Kerala and connect each one with their nearby ones with imaginary straight lines. Second bisect each of these imaginary lines perpendicularly and draw line linking each one of these mid points. Third extend

these bisecting lines until it intersects another bisecting line or basin boundary. So, the polygons are formed by the perpendicular bisectors of the lines joining nearby grid points. The area of each polygon is used to weigh the station in the centre of the polygon. The area weighted value of the weather parameter ( $\bar{X}$ ) of a particular taluka is calculated as,

$$\begin{aligned}\bar{X} &= \frac{X_1A_1 + X_2A_2 + X_3A_3 + \dots + X_nA_n}{A_1 + A_2 + A_3 + \dots + A_n} \\ &= \frac{\sum_{i=1}^n X_iA_i}{\sum_{i=1}^n A_i}\end{aligned}$$

Where X is the measurement and A is the area of each polygon.

#### 3.5.1.6 Drought hazard analysis

Spatial distribution pattern of normal rainfall (i.e., 30 years average total rainfall for seasonal) across Kerala state is given in Figure 3-83. It has been observed that, the extreme northern parts of the state receive highest amount of rainfall during annual and southwest (Jun-Sep) season. Except for the extreme southern and central regions, the majority of the state receives over 3,000 mm of annual rainfall. Major parts of southernmost district of Thiruvananthapuram and parts of the Palakkad district receive less than 2,000 mm of annual rainfall. In the context of Southwest monsoon rainfall (Jun-Sep), major parts of Northern and Central Kerala receive more than 2,000 mm of total rainfall. The extreme Northern parts of the state receive more than 3,000 mm during Southwest Monsoon (Jun-Sep) season. The extreme southern parts of the state viz., Thiruvananthapuram and Kollam districts and parts of Palakkad district receive less than 1,500 mm of total rainfall during this season.

<sup>114</sup> Srivastava, A.K., Rajeevan, M. and Kshirsagar, S.R. (2009). Development of a high resolution daily gridded temperature data set (1969–2005) for the Indian region. Atmospheric Science Letters, DOI:10.1002/asl.232.

<sup>115</sup> Pai, D.S., Latha, S., Rajeevan, M., Sreejith, O.P., Satbhai, N.S. and Mukhopadhyay, B. (2014). Development

of a new high spatial resolution (0.25° x 0.25°) long period (1901-2010) daily gridded rainfall data set over India and its comparison with existing data sets over the region. Mausam, 65: 1-18

<sup>116</sup> Thiessen, A.H. (1911). Precipitation for large areas. Monthly Weather Review, 39: 1082–1084.

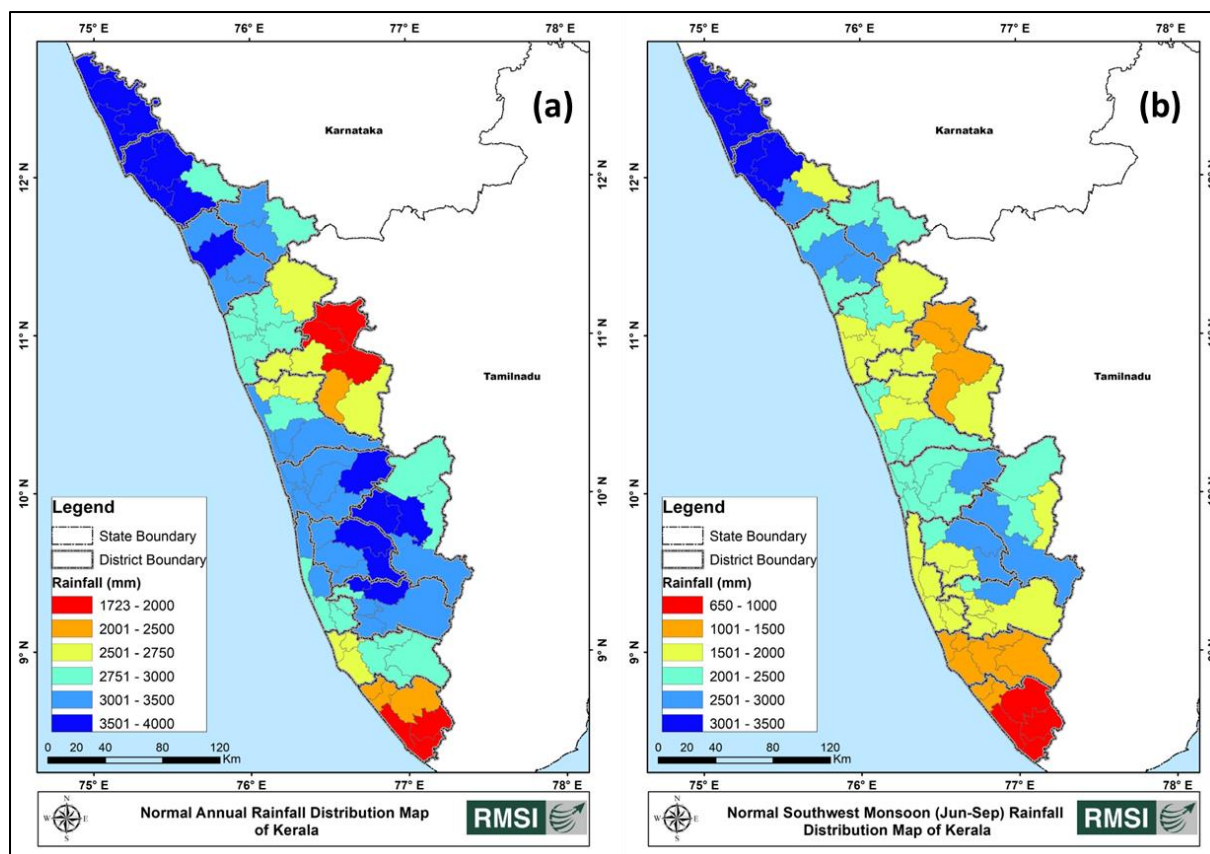


Figure 3-83: Normal rainfall distribution map of Kerala (a) Annual Rainfall, (b) Southwest (Jun-Sep) Monsoon Rainfall

Spatial distribution pattern of normal maximum and minimum temperatures (i.e., 30 years average total rainfall for seasonal) across Kerala state is given in Figure 3-84 and Figure 3-85, respectively. It has been observed that, pockets of Southern and Central parts of the state receive highest

maximum temperature during annual and southwest (Jun-Sep) season. The mountainous parts of the state (Idukki and Wayanad districts) experience a cooler temperature in comparison with the other regions.

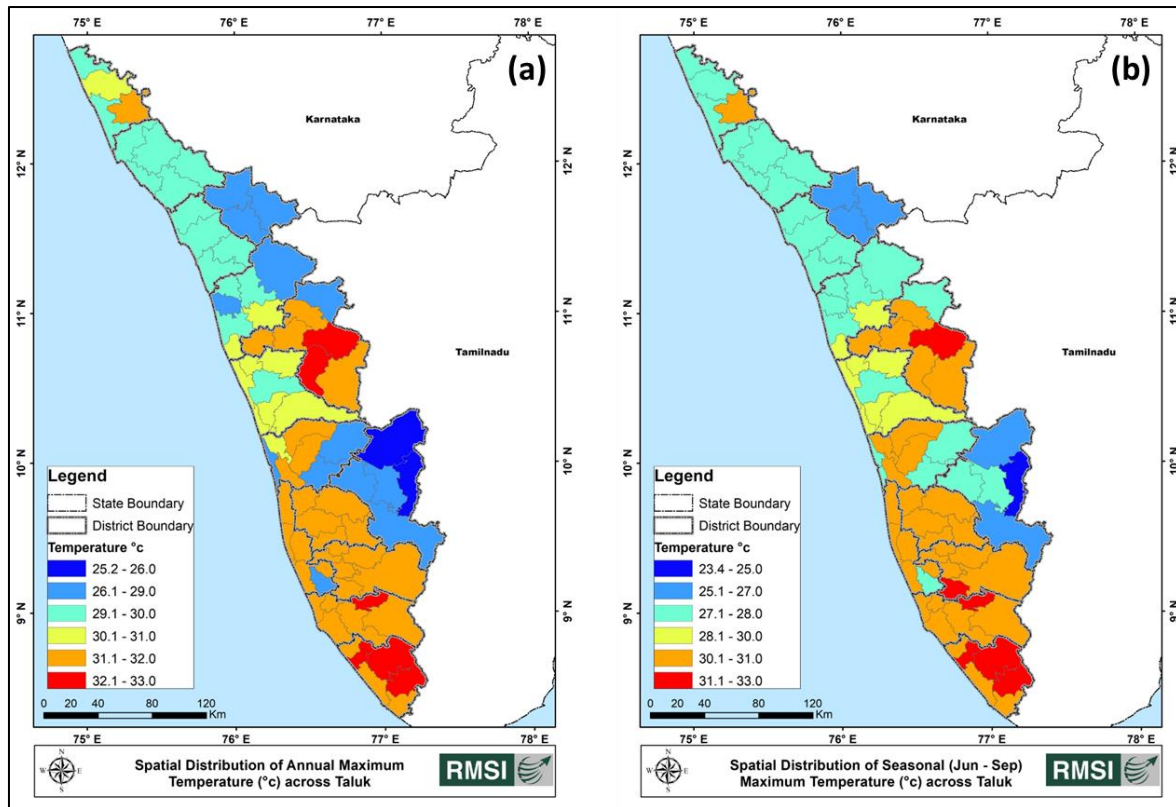


Figure 3-84: Normal maximum temperature distribution map of Kerala (a) Annual, (b) Southwest (Jun-Sep) Monsoon season

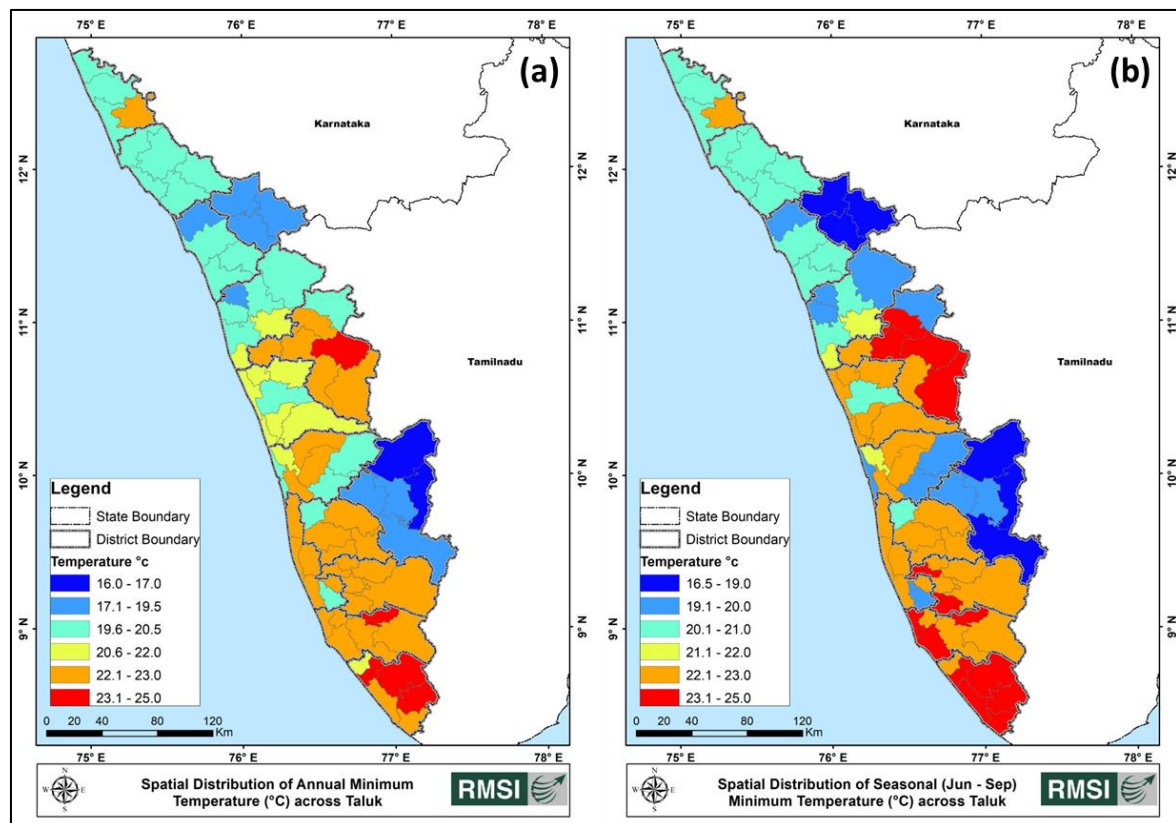


Figure 3-85: Normal minimum temperature distribution map of Kerala (a) Annual, (b) Southwest (Jun-Sep) Monsoon season

### 3.5.1.7 Drought events analysis for Southwest Monsoon (Jun-Sep) season

The present drought hazard assessment for Kerala has been conducted with the taluka level spatial resolution. As mentioned earlier, long-term rainfall data

(i.e., 30 years) was used to analyse Taluka level historical drought events in Kerala. A Taluka is considered to be affected by drought if the SPEI (Jun - Sep) for that Taluka falls below its drought threshold value. This section explains how the severity, frequency, and spatial extent of drought based on long-term rainfall data were arrived at.

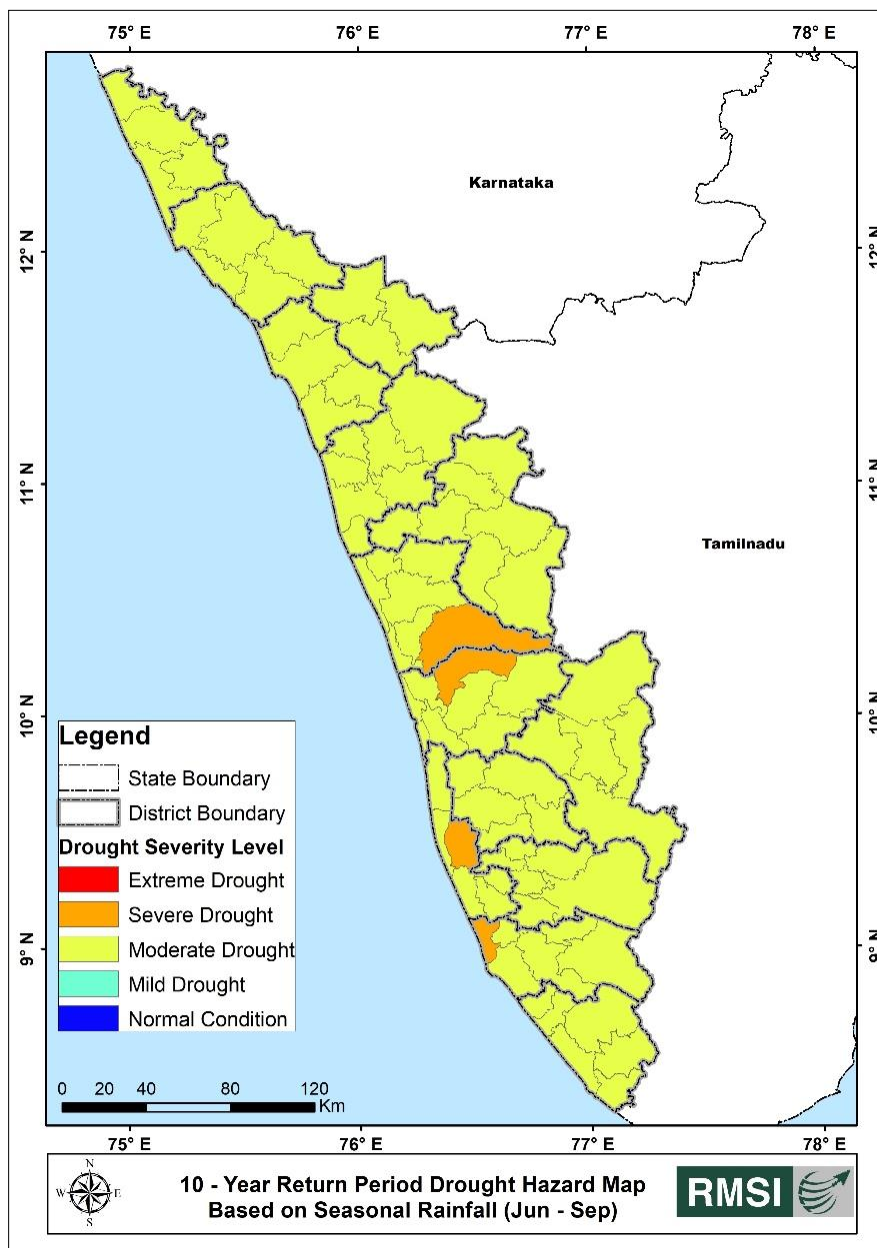


Figure 3-86: Spatial distribution pattern of drought of different intensities that are likely to occur once in 10 – year period based on historical kharif southwest monsoon rainfall and temperature

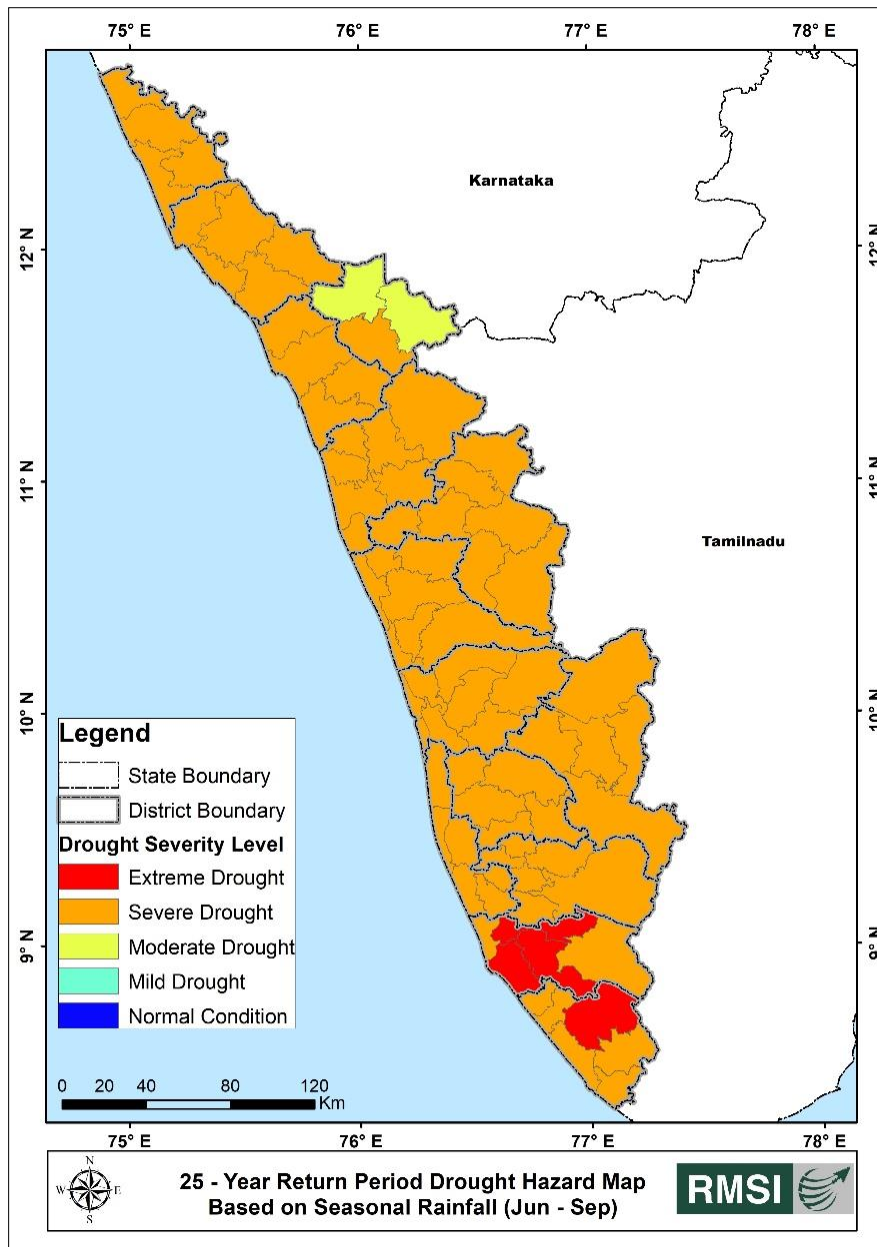


Figure 3-87: Spatial distribution pattern of drought of different intensities that are likely to occur once in 25 – year period based on historical kharif southwest monsoon rainfall and temperature

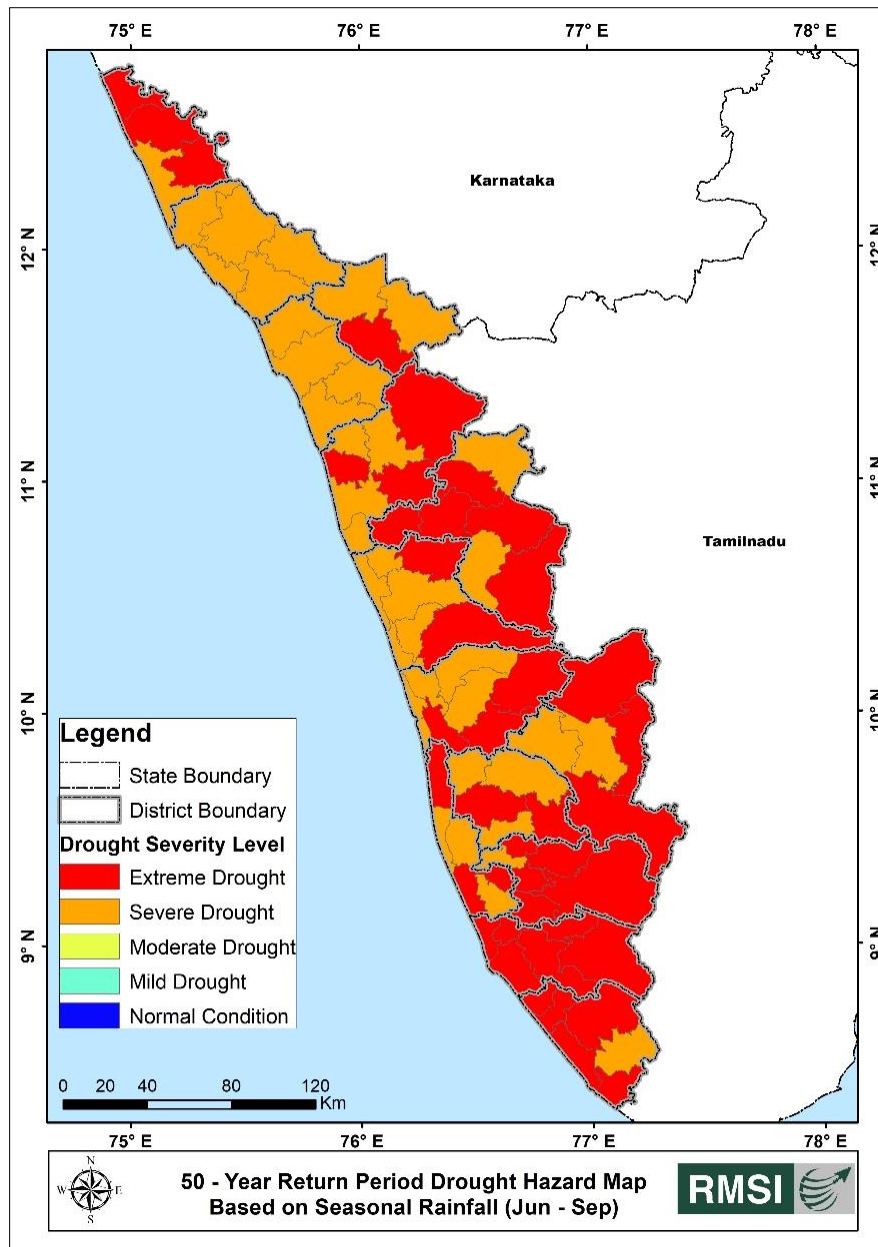


Figure 3-88: Spatial distribution pattern of drought of different intensities that are likely to occur once in 50 – year period based on historical southwest monsoon season rainfall and temperature

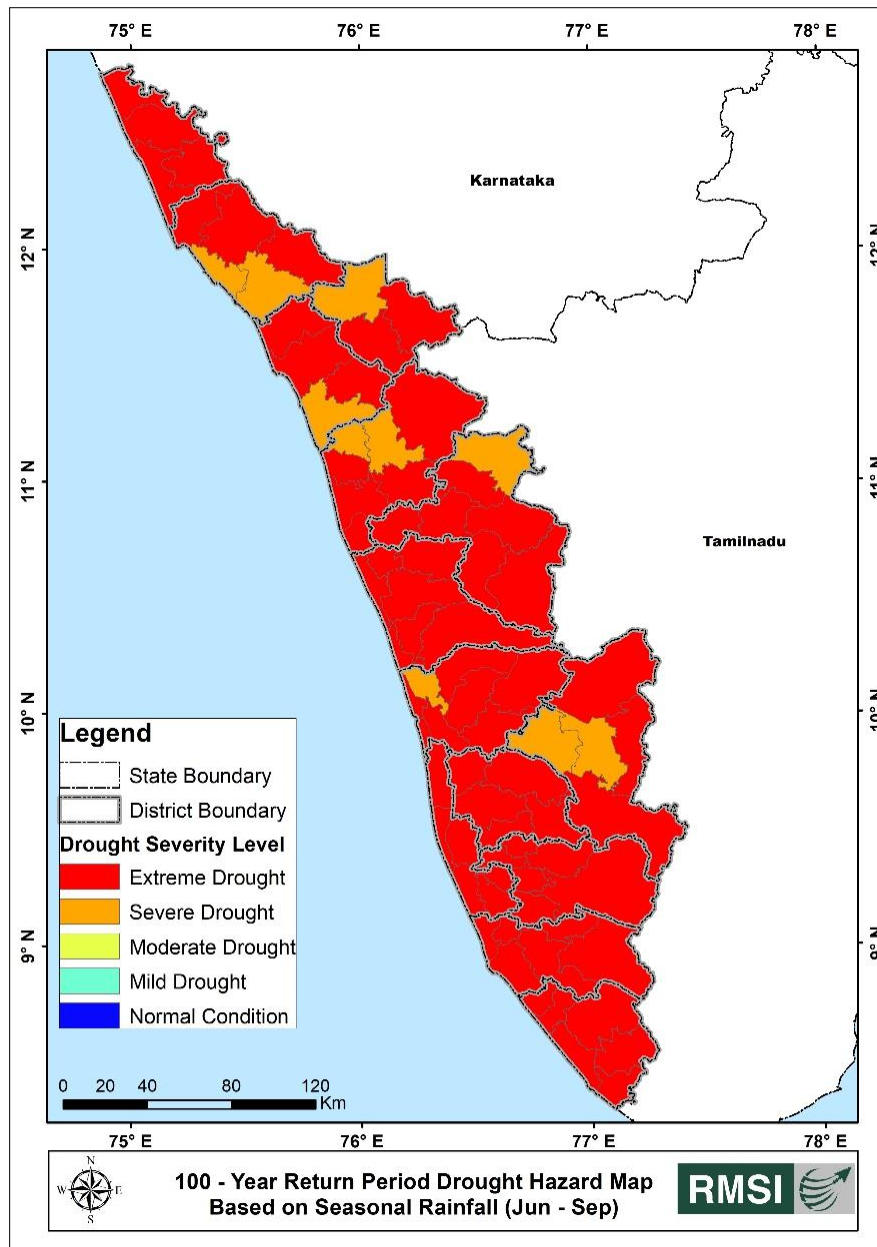


Figure 3-89: Spatial distribution pattern of drought of different intensities that are likely to occur once in 100 – year period based on historical southwest monsoon season rainfall and temperature

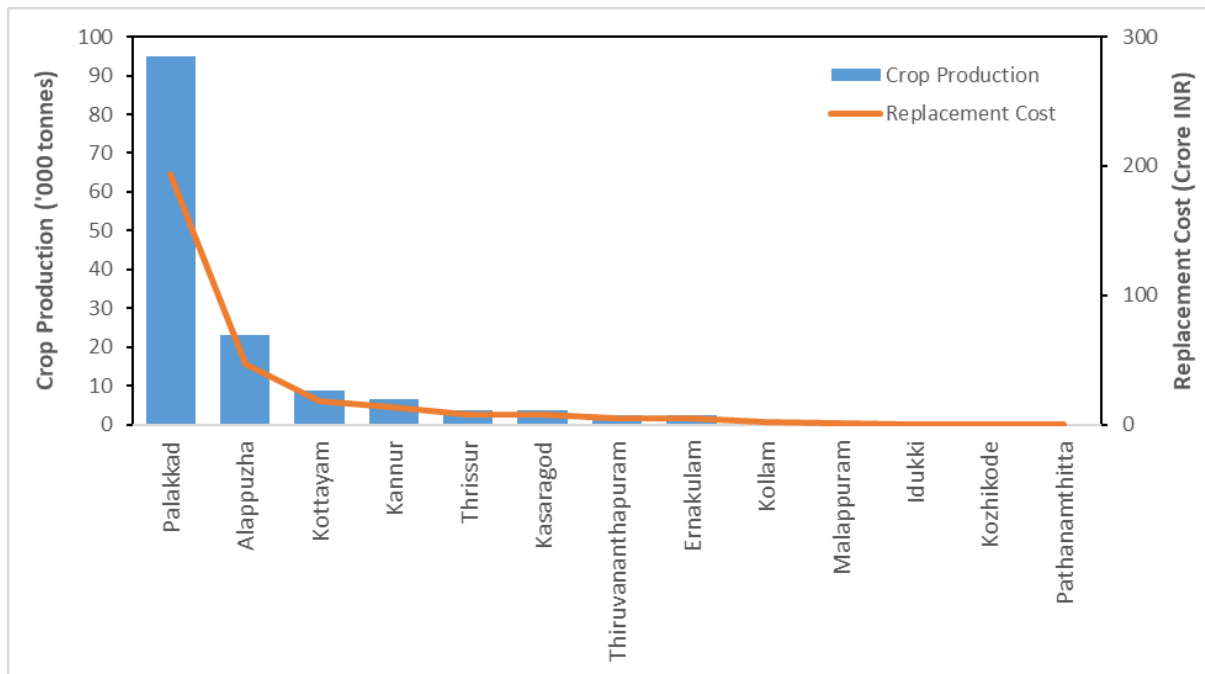


Figure 3-90: Normal production of rice crop and its replacement costs across different districts in Kerala

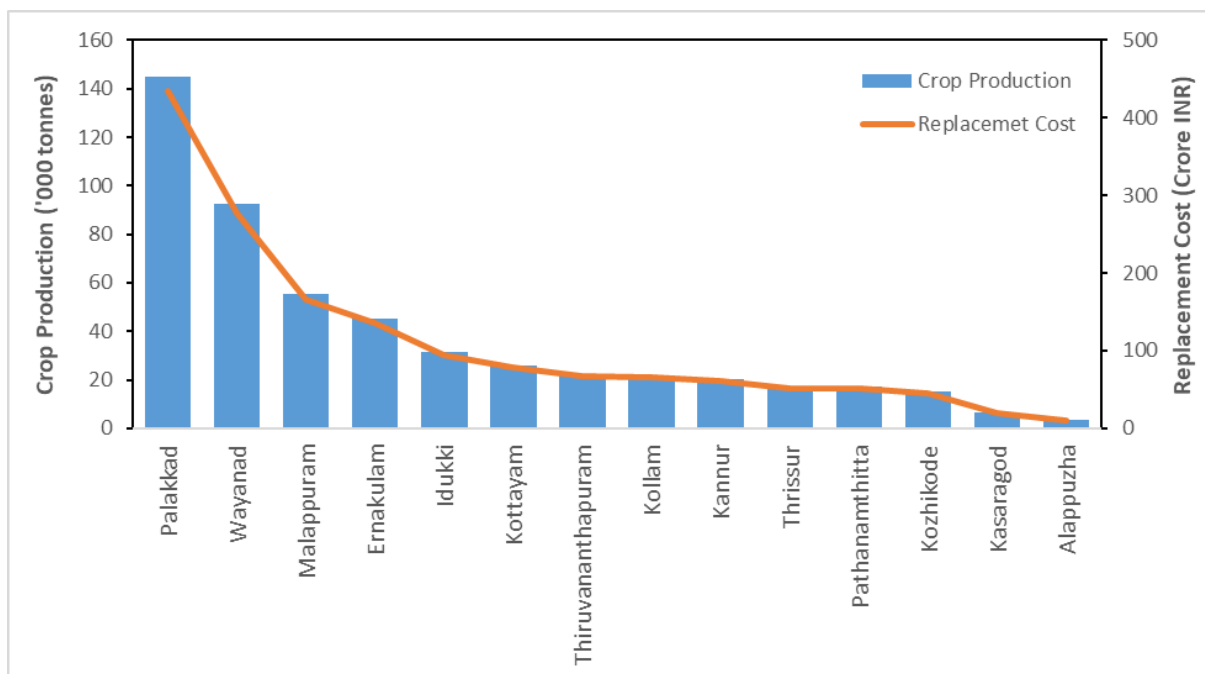


Figure 3-91: Normal production of banana crop and its replacement costs across different districts in Kerala

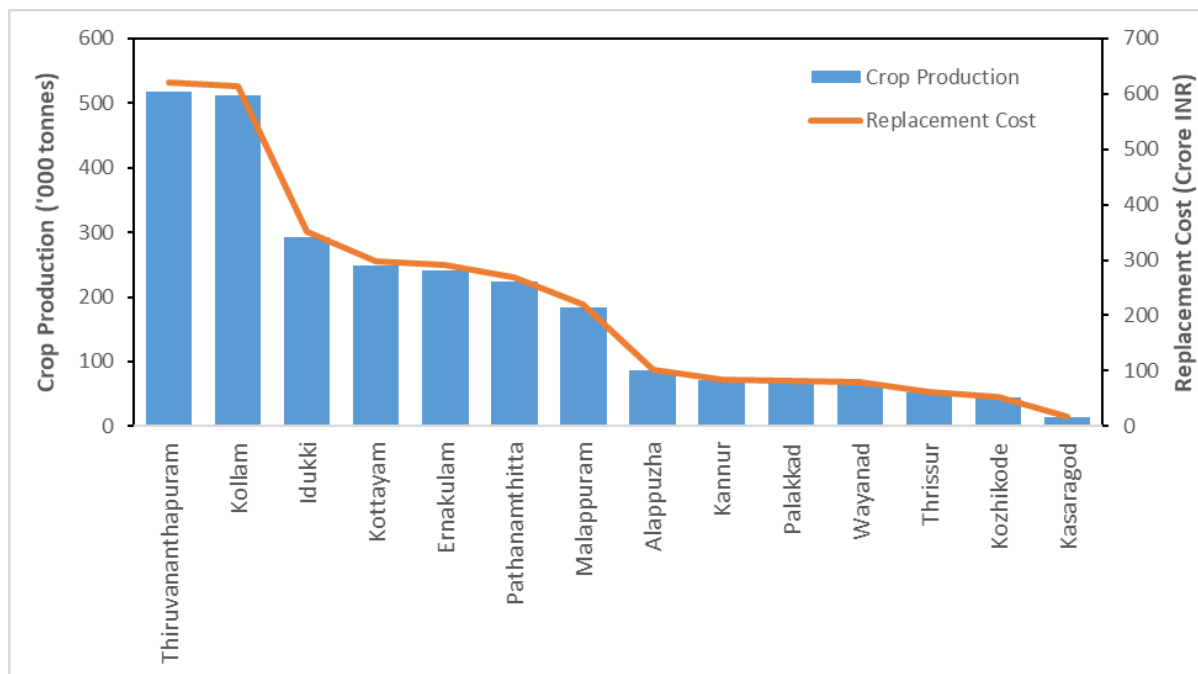


Figure 3-92: Normal production of tapioca crop and its replacement costs across different districts in Kerala

**Spatial coverage of drought:** SPEI values were computed for all the Talukas of Kerala. A spatial variability map of drought frequency was generated by using individual Taluka level SPEI value onto a surface to study the spread of drought across Kerala. Drought events based on SPEI values were computed using historical rainfall and temperature data to generate different drought Return Period (RP) maps. The severity of drought across Kerala in 100, 50, 25, 10, 5 and two years return periods have been depicted Figure 3-86 to Figure 3-89. Observations indicate that over a 100-year return period, the majority of the state is likely to experience extreme drought, while a few areas in the central and southern regions may face severe drought (Figure 3-89). Over a 50-year return period, the southern and south-central parts of Kerala are expected to experience extreme drought, whereas the northern and north-central regions are likely to face severe drought (Figure 3-88).

In a 25-year return period, over 90% of the state is expected to experience severe drought. Specifically, some areas in

southern Kerala (Thiruvananthapuram and Kollam districts) are likely to face extreme drought, while a few pockets in northern Kerala (Wayanad district) may experience moderate drought (Figure 3-87). In a 10-year return period, certain areas in central Kerala are expected to experience severe drought, with the remaining parts of the state likely facing moderate drought (Figure 3-86).

The number of talukas in Kerala at different drought severity levels has been presented in Table 3-25. It has been observed that almost the entire state is susceptible to normal conditions in a 2-year return period. For a 10-year return period, the state faces mild drought conditions, it experiences moderate drought. During a 25-year return period, the state encounters severe drought. In a 50-year return period, about half of the state is susceptible to severe drought, while the remaining parts are susceptible to extreme drought. In a 100-year return period, the majority of the state is susceptible to extreme drought, with a few pockets are likely to experience severe drought.

Table 3-25: Number of Talukas in Kerala at different drought severity levels

Return Period (RP)	No. of Talukas at different drought severity level				
	Normal Condition	Mild Drought	Moderate Drought	Severe Drought	Extreme Drought
10-years	-	-	72	4	-
25-years	-	-	2	71	5
50-years	-	-	-	37	41
100-years	-	-	-	10	68

### 3.5.1.8 Key findings of the drought hazard analysis

- The extreme northern parts of Kerala receive the highest rainfall annually and during the southwest monsoon (June-September).
- Majority of the state, excluding extreme southern and central regions, receives over 3,000 mm of annual rainfall.
- Major parts of Thiruvananthapuram (southernmost district) and parts of Palakkad district receive less than 2,000 mm of annual rainfall.
- Extreme southern regions (Thiruvananthapuram, Kollam, and parts of Palakkad) receive less than 1,500 mm during southwest monsoon season.
- Southern and central pockets experience the highest maximum temperatures annually and during the southwest monsoon season. The mountainous regions (Idukki and Wayanad districts) are cooler compared to other areas.
- Majority of the state likely to experience extreme drought; central and southern regions may face severe drought in 100-Year Return Period.
- Southern and south-central parts expected to experience extreme drought; northern and north-central regions likely to face severe drought in 50-Year Return Period.
- Over 90% of the state expected to experience severe drought in 25-Year Return Period. Extreme drought likely in southern areas (Thiruvananthapuram and Kollam), moderate drought in northern pockets (Wayanad).
- Central Kerala expected to experience severe drought, with the rest of the state facing moderate drought in 10-Year Return Period.

## 4 Exposure data Development

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### 4.1 Introduction

Exposure represents the people and assets that are exposed to natural or man-made hazard events. It covers people and households; buildings and built structures including public facilities and infrastructure assets; agricultural commodities; environmental assets; and business activities.

Disaster risk signifies the possibility of adverse effects in the future. It is derived from the combination of physical hazards and the vulnerabilities of exposed elements. Risk is determined not only by the climate and weather events (the hazards) but also by the exposure and its vulnerability to these hazards. Therefore, disaster risk reduction plans, and strategies depend on understanding the dimensions of exposure and their vulnerability, as well as proper assessment of changes in those dimensions.

As risk assessment is a function of hazard, exposure, and vulnerability, it is critical to assess exposure and its vulnerability.

The present section explains the exposure database development of the physical assets in terms of both quantity and spatial distribution.

### 4.2 Understanding of exposure

Exposure refers to the inventory of elements in an area in which hazard events may occur<sup>117</sup>. As per Global Assessment Report on Disaster Risk Assessment (2015)<sup>118</sup> exposure corresponds to assets such as people, houses, factories, offices, agricultural land, etc. located in the hazard-prone areas and thereby subjected to

potential losses. Hence, if population and economic resources are not located in (exposed to) potentially dangerous settings, no disaster risk would exist. Exposure is a necessary, but not sufficient, determinant of assessing risk. It is possible to be exposed but not vulnerable (for example, living in a floodplain but having sufficient means to modify building structure and behavior to mitigate potential losses). However, to be vulnerable to an extreme event, it is necessary to be exposed.

Kerala exposure database has been developed using inputs from the stakeholders in the State, desk research, secondary studies, RMSI in-house data and national and global open data sources. This database includes estimation of the economic value of the exposed assets, as well as their physical characteristics (for example, for buildings structure type and its primary attributes, such as number of stories, wall material, roof material) in the study area. This information is of vital importance to assess the potential damages from different hazards to each of the exposed elements. The comprehensive exposure database is developed for the state covering an area of 38,861 sq. km comprising of 14 districts. These districts are further divided into 78 talukas, 87 municipalities, and 6 municipal corporations.

In this study, exposure database comprises of demographic data, housing sector (residential building stocks), critical facilities (schools, hospitals, fire stations, police stations, cyclone shelters); government buildings (revenue offices, panchayat offices, municipality offices,

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117 Cardona, O.D., M.K. van Aalst, J. Birkmann, M. Fordham, G. McGregor, R. Perez, R.S. Pulwarty, E.L.F. Schipper, and B.T. Sinh, 2012: Determinants of risk: exposure and vulnerability. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M.

Tignor, and P.M. Midgley (eds.)]. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 65-108

118 GAR-Global Assessment Report on Disaster Risk Reduction: Data, Methodology, Source and Usage, 2015

municipal corporation offices, district and tehsil headquarter offices, and other govt. offices); transport network (roads and bridges, railway lines, railway stations, bus stand and airports); and agricultural major crops and plantations.

### **4.3 Administrative divisions**

Kerala, located in the southwestern part of India, is a distinctive state renowned for its rich cultural heritage and stunning natural beauty. Despite its relatively small size of about 1.18% of India's total land area, the state enjoys a varied landscape that includes serene backwaters, lush green hills, and vibrant coastal regions, stretching along the Malabar Coast for approximately 590 kilometers. Kerala State is bordered by Karnataka to the north, Tamil Nadu to the east, and the Arabian Sea to the south and west. The state also envelops Mahe, a small enclave of Puducherry Union Territory (UT). The capital city, Thiruvananthapuram (also known as Trivandrum), serves as the administrative and political center of Kerala. The location of the state and its districts are shown in Figure 4-1.

The state's coastline has historically been a conduit for various foreign influences, enriching its cultural tapestry. This blend of traditions is reflected in Kerala's diverse religious practices, festivals, and art forms. Malayalam, the state's official language, is an integral part of its cultural expression.

Kerala can be divided into 3 geographical regions. 1) Highlands, 2) Midlands and 3) Lowlands. The Highlands slope down from the Western Ghats which rise to an average height of 900 m, with a number of peaks well over 1,800 m in height. This is the area of major plantations like tea, coffee, rubber, cardamom, etc. The midlands lying between the mountains and the lowlands, is made up of undulating hills and valleys. This area involves intensive cultivation of cashew, coconut, arecanut, cassava (tapioca), banana, rice, ginger, pepper, sugar-cane and also vegetables of different varieties are grown in this area.

The lowlands or the coastal area, which is made up of the river deltas, backwaters and shores of Arabian sea, is essentially a land of coconuts and rice. Fisheries and coir industry constitute the major industries in this area.

Kerala is a land of rivers and backwaters, forty-four rivers (41 west-flowing and 3 east-flowing) cut across Kerala with their innumerable tributaries and branches but these rivers are comparatively small and being entirely monsoon fed, practically turn into rivulets in summer, majorly in the upper areas. Districts and number of talukas falling under each district are shown in Table 4-1.

### **4.4 Approach for Database Development**

As detailed earlier, the exposure database comprises of population, housing sector (residential buildings), critical facilities, government buildings, transport network, and major agricultural crops at risk from natural catastrophes.

Exposure quantification of buildings also includes building contents along with their structural values. The content values have been assumed at a certain percentage of the structural values. Characterization of assets based on their vulnerability to the effects of specific natural events is an important step in the exposure database preparation. Classification of assets, valuation (replacement cost) and aggregation by administrative units are also part of the process of exposure database development.

Exposure data development in Kerala involves comprehensive identification, categorization, and mapping of assets and infrastructure susceptible to various hazards prevalent in that particular region. Exposure data development integrates various sources, including satellite imagery, land use maps, census data, administrative records, and field surveys, to create a comprehensive database for elements at risk.

Figure 4-2 shows the broad categories of assets that are considered for this study. Since assets are potentially exposed to

various hazards, these are together called exposure datasets in modeling terminology.

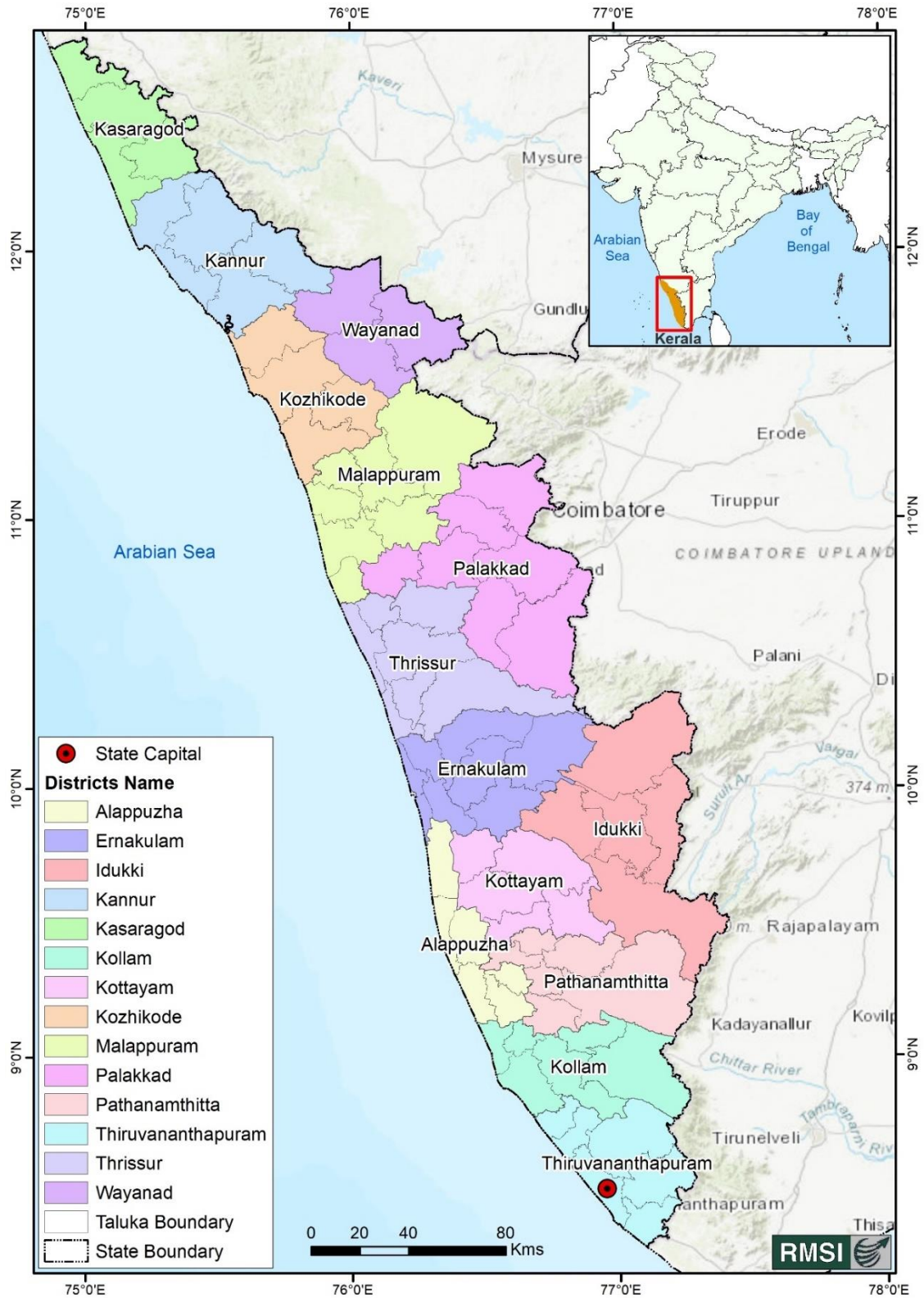


Figure 4-1: District-wise administrative boundaries of Kerala

Table 4-1: Area and number of Taluka's falling under each district in Kerala

S. No	District	No. of Taluka's	Area (in Sq. km)
1	Alappuzha	6	1,410.20
2	Ernakulam	7	2,911.79
3	Idukki	5	4,512.60
4	Kannur	5	2,969.52
5	Kasaragod	4	1,990.17
6	Kollam	6	2,488.74
7	Kottayam	5	2,201.82
8	Kozhikode	4	2,345.46
9	Malappuram	7	3,553.71
10	Palakkad	7	4,476.39
11	Pathanamthitta	6	2,654.07
12	Thiruvananthapuram	6	2,189.00
13	Thrissur	7	3,028.97
14	Wayanad	3	2,129.16
	<b>Total</b>	<b>78</b>	<b>38,861.59</b>

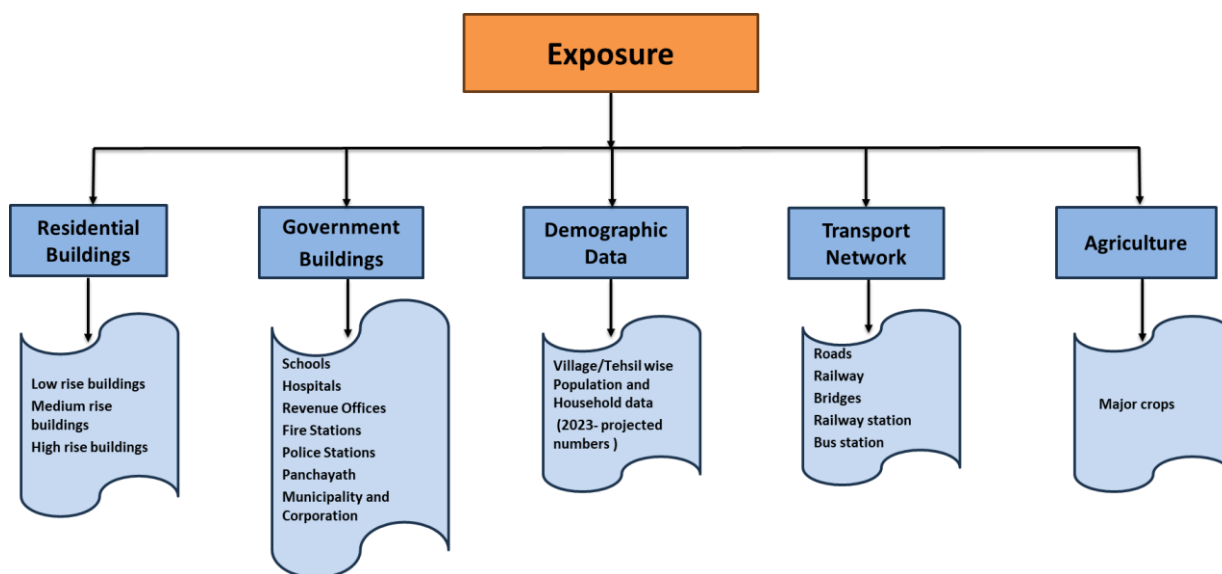


Figure 4-2: Categories of assets for exposure database development

Table 4-2: Data sources for development of exposure database

Main Category	Sub Category	Source
Administrative Boundary	District Boundary	KSDMA
	Taluka Boundary	
	LSG Boundary	
	Village Boundary	
	Ward Boundary	
	Municipality Boundary	
	Corporation ward Thrissur	
	Corporation ward Trivandrum	
	Corporation ward Kannur	
	Corporation ward Kochi	
	Corporation ward Kollam	
Corporation ward Kozhikode		
Housing sector (residential buildings)	Building Footprints	RMSI in-house building polygon foot-print data, OSM and high-resolution satellite imagery
Critical Facilities	Govt. Schools	KSDMA
	Private Schools	
	Technical Schools	
	Hospitals	
	Fire Stations	
	Police Stations	
	Cyclone Centers	
Government Building	Revenue Offices	KSDMA
	Panchayat offices	
	Municipality and Corporation offices	
	Govt. Offices (District HQ, Taluka HQ)	
Transport Network	Airports	KSDMA
	Roads	
	Railway Lines	
	Bridges	
	Railway Stations	
	Bus Station	
Agriculture	Major Crops area and yield	Ministry of Agriculture
Demographics at LSG Level	Total Population	Census 2011
	Male	
	Female	
	Households	

Main Category	Sub Category	Source
Agriculture	Area and Production	Ministry of Agriculture
Land use /Landcover	LULC (2015-2016)	KSDMA/ KSREC
	LULC 2020	

## 4.5 Data Collection and Validation

### 4.5.1 DATA SOURCE

The exposure database has been created in the GIS environment. The essential components of exposure data and their sources considered in the present study are given in Table 4-2.

#### 4.5.1.1 Data review and gap analysis

The available exposure data has been reviewed considering:

- **Population: Population distribution based on gender, and age, buildings, and critical facilities: Site-specific, vintage, structure type, occupancy type, replacement costs, etc.**
- **Transport Network: Site-specific poly-line (spatial data), road surface type, length-width, type of transport network (national highway, state highway, district road, railway line, etc.), replacement costs; bridges: site-specific, structure type, type, replacement costs, etc.**

Due to limited availability of data from various sources for this study, the RMSI team enhanced the databases of various exposure elements mentioned above and made best use of available data for modeling of various hazards and risk assessment analysis.

### 4.5.2 FIELD SURVEYS

Field survey was conducted in Trivandrum and Kollam cities for building structure analysis. It was limited to the building types and the population type surveys particularly for these two areas only. The surveyed sample images are shown in Figure 4-3.

### 4.5.3 DATA VALIDATION

The exposure data was collected, reviewed, data gaps were identified, filled the data gaps were filled to the extent possible, QA/QC was done for these datasets and results were summarized in the form of a report. An analysis of the existing processes at the macro (process) and micro (sub-process) levels was conducted in order to identify gaps and enhancement.

Gaps were assessed on the following dimensions:

- **Missing location information.**
- **Missing structure, height, or classification information.**
- **Missing replacement cost.**
- **No data available/ obtained.**

Data validation plays a vital role in exposure data development. Accuracy for the majority of data received has been validated with Google Earth, Open Street Maps (OSM), Satellite imagery, published reports, research papers and field-information and updated accordingly. For data sets such as bridges and airports, inputs received in point format was not useful from risk assessment perspective. To improve data quality, we have captured inputs in polygon format using Google Earth for better results. However, few of the datasets did not have full coverage, so we captured the missing data and their attributes with the same procedure.

Figure 4-4 and Figure 4-5 present observations on village data. Here, smallpolygons are represented as villagesbecause of topological errors. The area of such a small polygon is also represented in All these errors have been corrected during data validation process.



Figure 4-3: Building type photographs from field survey



Figure 4-4: Administrative data validation and updation

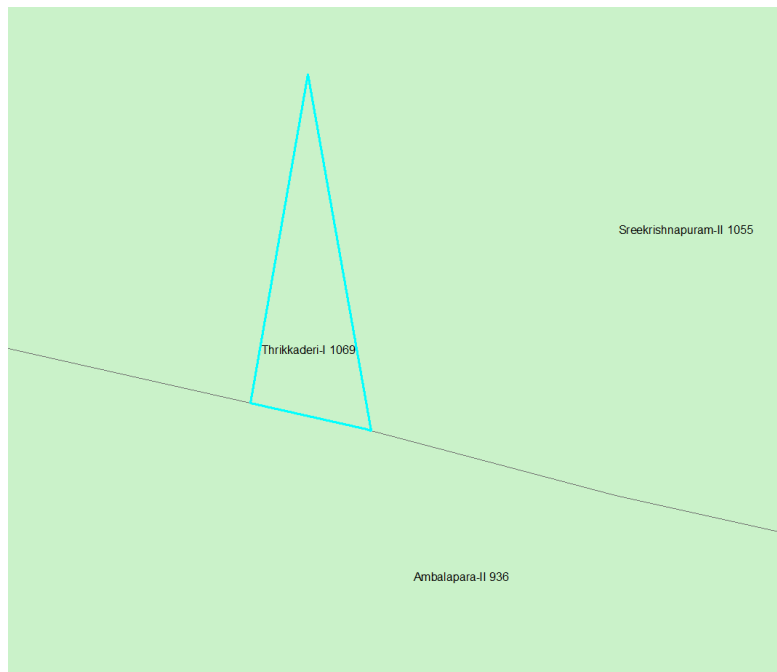


Figure 4-5: Village boundary validation and update

A comparison between Google Earth images and photographs collected during the field survey has been carried out for different types of building .



Figure 4-6 shows the sample of surveyed buildings.

RMSI team adopted following approaches mentioned in Table 4-3 to fill the data gaps in the collected, compiled and processed datasets.





Figure 4-6: A few photographs of different type of buildings

Table 4-3: Approach to fill data gaps

Approaches to fill the gaps	
Field Survey	Outcome of vulnerability survey, interaction with Public Works Engineers, Govt. Contractors, builders, and/or infrastructure developers, geo-tagged photos from surveys to fill the gaps of structural types and replacement costs
Secondary data	Using Google Earth Images for missing information updation, Open Street Maps (OSM) to fill the location information gaps, Literature surveys, historical event damage reports, technical papers, review of web sites and other government resources like annual reports, DPRs, etc. to get the information.

## 4.6 Exposure Analysis

The exposure development focused on capturing and developing all exposure/asset layers (spatial and tabular information) relevant to risk assessment. A comprehensive methodology was adopted for development of exposure data, namely demography, building occupancy and structure type, critical infrastructure, transport infrastructure (roads and bridges) and agriculture. Detailed demographic analysis has been presented in the following sub-sections.

### 4.6.1 DEMOGRAPHY

As of 2011, according to the Census of India, the population in Kerala was 3,26,02,902 with a population density of 839 persons/sq. km. Under this study, we have projected the state's population for 2023 based on Census 2011. The

estimated projected population for 2023 is 3,46,88,375 with Malappuram and Ernakulam districts with the highest population of 47,88,769 and 34,87,361 persons, respectively. Wayanad district has been estimated to have the lowest population with 8,64,734 persons. Kerala is renowned for having one of the most favorable male-to-female ratios in India, reflecting its progressive social, education and health indicators. As per the projected data, Kerala's overall sex ratio stands at 1,085 females per 1,000 males, significantly higher than the national average. Kannur district has the highest male-to-female ratio at 1,135, followed by Pathanamthitta with 1,132 and Kollam with 1,114, respectively.

Figure 4-6 indicates the distribution of the population percentage based on gender. It can be observed that Kannur and Pathanamthitta districts show the highest male-to-female percentage difference, with

Kannur at 46.85% males to 53.15% females, and Pathanamthitta at 46.91% males to 53.09% females. In contrast, Idukki has an almost equal gender ratio, with 49.85% males to 50.15% females.

#### **4.6.2 POPULATION DENSITY**

Population density is another key parameter looked upon while understanding a state's demography. Population density (number of people per sq km) has been calculated district wise. Table 4-5 summarizes the population

density of the 14 districts. It indicates that Alappuzha district has the highest population density of 1,525 persons/sq km, followed by Thiruvananthapuram with 1,442 persons/sq. km. Amongst all the districts, Idukki and Wayanad are sparsely populated with 241 and 406 persons residing per sq. km area. The total number of projected households in Kerala state are 9,424,863. The highest households are in Malappuram district with 11,19,461 and lowest in Wayanad district with 2,26,623, respectively.

Table 4-4: Area, count, Census 2011 and projected population (2023) in districts of Kerala

S. No	District	Area (Sq. Km)	No. of Taluka's	Population in 2011	Projected Population in 2023	Male Population in 2023	Female Population in 2023
1	Alappuzha	1,410.20	6	2,127,582	2,150,676	1,024,046	1,126,628
2	Ernakulam	2,911.79	7	3,257,433	3,487,361	1,721,137	1,766,217
3	Idukki	4,512.60	5	1,110,627	1,086,876	541,787	545,086
4	Kannur	2,969.52	5	2,333,254	2,468,303	1,156,295	1,312,006
5	Kasaragod	1,990.17	4	1,307,375	1,448,864	696,642	752,221
6	Kollam	2,488.74	6	2,721,061	2,783,757	1,317,038	1,466,722
7	Kottayam	2,201.82	5	1,891,486	1,916,606	940,173	976,433
8	Kozhikode	2,345.46	4	2,909,350	3,170,913	1,511,149	1,659,764
9	Malappuram	3,553.71	7	4,081,815	4,788,769	2,281,586	2,507,187
10	Palakkad	4,476.39	7	2,847,048	3,110,417	1,505,321	1,605,097
11	Pathanamthitta	2,654.07	6	1,197,285	1,154,886	541,769	613,119
12	Thiruvananthapuram	2,189.00	6	3,078,262	3,156,736	1,510,091	1,646,650
13	Thrissur	3,028.97	7	2,922,904	3,099,477	1,470,212	1,629,262
14	Wayanad	2,129.16	3	817,420	864,734	424,931	439,798
Grand Total		38,861.59	78	32,602,902	34,688,375	16,642,177	18,046,190

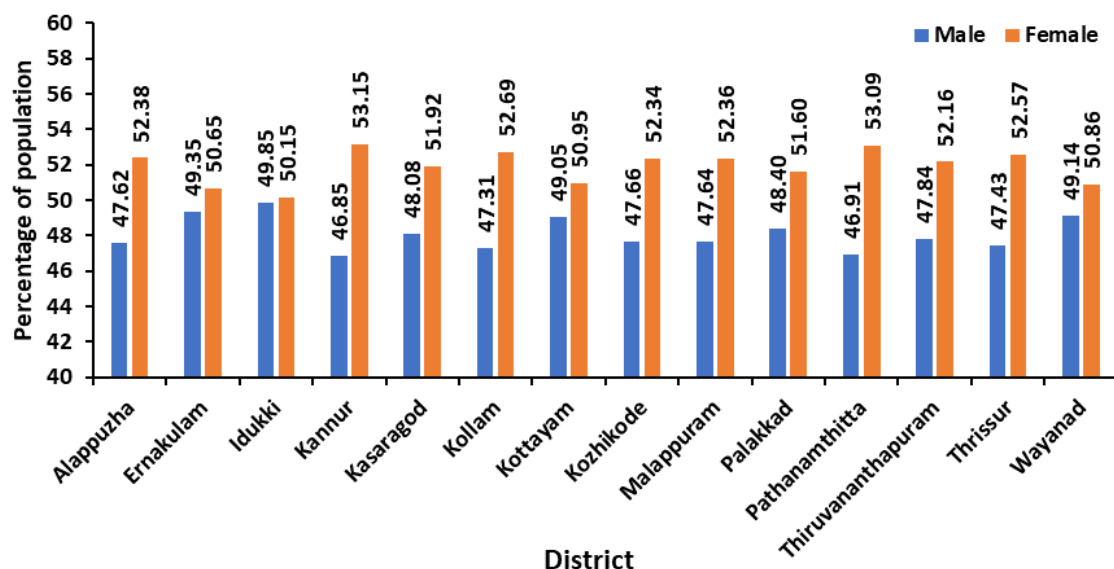


Figure 4-6: District-wise population distribution based on gender

Table 4-5: Population density in different districts

S. No	District	Area (Sq. Km)	Projected Population in 2023	Population Density (Persons/Sq. km)	No. of Households in 2023
1	Alappuzha	1,410.20	21,50,676	1525	6,08,912
2	Ernakulam	2,911.79	34,87,361	1198	9,93,058
3	Idukki	4,512.60	10,86,876	241	2,98,958
4	Kannur	2,969.52	24,68,303	831	6,63,190
5	Kasaragod	1,990.17	14,48,864	728	3,52,095
6	Kollam	2,488.74	27,83,757	1119	8,05,439
7	Kottayam	2,201.82	19,16,606	870	5,38,993
8	Kozhikode	2,345.46	31,70,913	1352	8,69,295
9	Malappuram	3,553.71	47,88,769	1348	11,19,461
10	Palakkad	4,476.39	31,10,417	695	8,19,552
11	Pathanamthitta	2,654.07	11,54,886	435	3,57,147
12	Thiruvananthapuram	2,189.00	31,56,736	1442	8,84,911
13	Thrissur	3,028.97	30,99,477	1023	8,87,229
14	Wayanad	2,129.16	8,64,734	406	2,26,623
Grand Total		38,861.59	3,46,88,375	893	94,24,863

Table 4-6 presents district wise population density in Kerala. Interestingly Idukki and Pathanamthitta districts were observed with the decadal decline in the population in recent years' compared to the 2011 population data. The decline rate is about 1.79 in Idukki and 2.97 in Pathanamthitta

district. In contrast, the highest decadal growth rate is observed in Malappuram district with 13.45 followed by Kasargod with 8.58.

### 4.6.3 BUILDING POLYGON STOCK DATABASE

In Kerala, the total number of building polygons stand at 1,47,92,886, encompassing various types of occupancies such as housing sector (residential buildings), government, critical facilities (schools, hospitals, fire station, police station and cyclone shelters). The total built-up area in Kerala is 1,244.83 sq. km out of 38,861.59 sq. km. Residential buildings dominate the landscape, constituting a significant 95.91% of the total building stock. The detailed distribution of these buildings is illustrated in Figure 4-8.

### 4.6.3.1 Building Typology for various occupancies

There is a total of 4 types of building structures for various occupancies identified in Kerala based on roof and wall materials. All the exposure elements mapped under the study are classified under each structure type. This structure type information is very critical in determining the building's vulnerability to various hazards. Table 4-6 shows the summary of each structure type considered in the study. Various building footprint polygons were collected, those samples are presented in Figure 4-9.

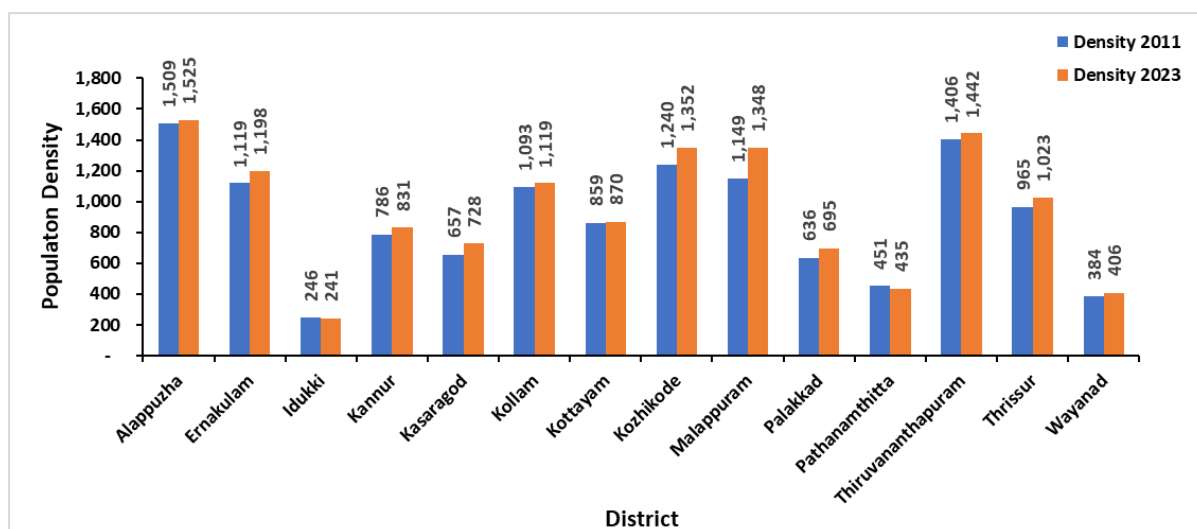


Figure 4-7: District-wise population density distribution of Kerala

### Distribution of Buildings

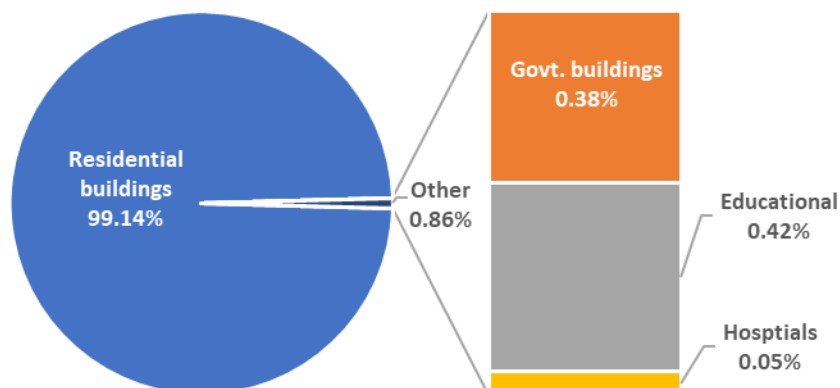


Figure 4-8: Distribution of occupancy type in Kerala

Table 4-6: Structure types considered for Kerala

S. No	Building Structure type	Percentage
1	Adobe Masonry / Rubble stone masonry	56.4%
2	Unreinforced masonry bearing wall	0.6%
3	Reinforced masonry	42.9%
4	Reinforced concrete	0.1%



Figure 4-9: Building type foot print sample in Kozhikode.

#### 4.6.3.2 Residential Building polygons

Kerala has 14,666,217 residential building polygons which represent about 95.91% of total building polygons. Most of the residential building polygons are Adobe Masonry / Rubble stone masonry (56.4 %), Reinforced masonry packed with flat roof at low rise (42.9%), Unreinforced masonry

bearing wall packed with mortar with slopy roof (0.6%) structures and Reinforced concrete (0.1 %). Distribution of residential buildings in dominant structure type is presented in Figure 4-10 and district wise distribution of residential building polygons are shown in Figure 4-11.

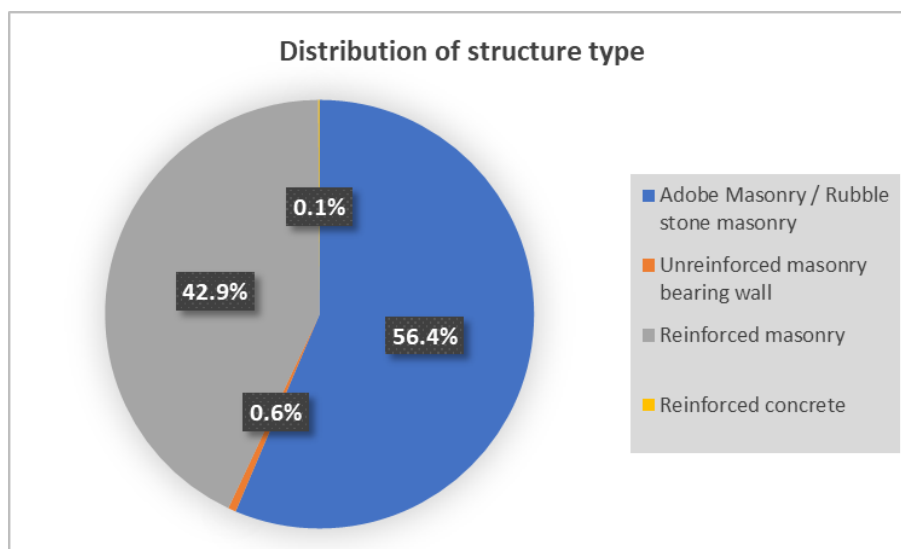


Figure 4-10: Distribution of residential buildings in dominant structure type

Malappuram district has the highest number of residential building polygons in Kerala, with a built-up area of 130.85 sq. km, encompassing approximately 17,69,218 building polygons. In contrast, Wayanad district has the smallest built-up area, measuring 29.05 square kilometers and about 3,05,069 residential building polygons. This stark contrast highlights the significant variation in residential density and infrastructure across the districts of Kerala.

Built-up area of residential building polygons has been multiplied with its per unit replacement cost to get the total exposure value of residential building polygons. Based on this, the total exposure value for residential buildings was estimated. Table 4-7 represents projected household number for 2023 using Census 2011 data.

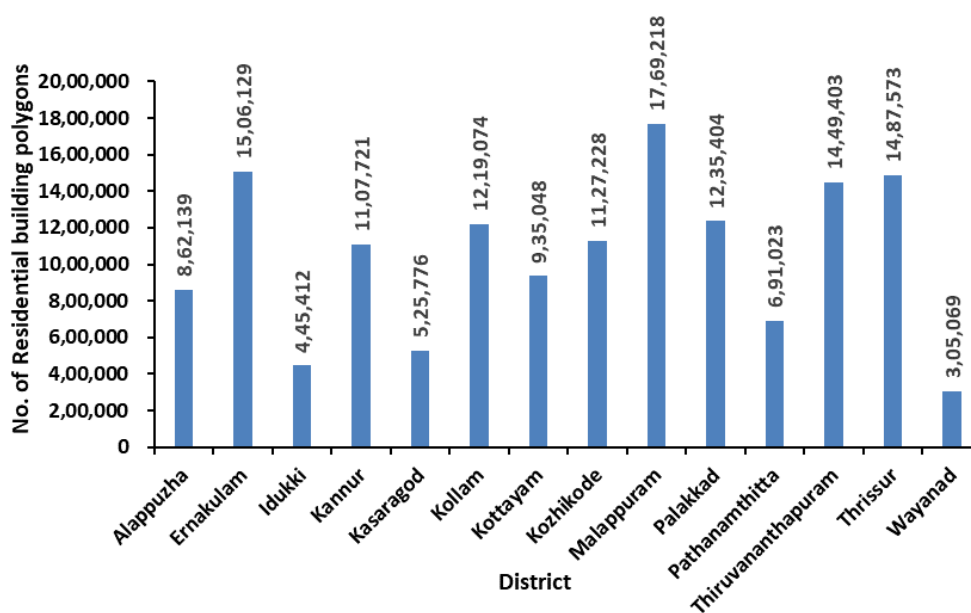


Figure 4-11: District-wise distribution of residential building polygons

Table 4-7: Projected Census household 2023

S. No.	District	Area Sq.Km	Number of Household 2023
1	Alappuzha	1,410.20	6,08,912
2	Ernakulam	2,911.79	9,93,058
3	Idukki	4,512.60	2,98,958
4	Kannur	2,969.52	6,63,190
5	Kasaragod	1,990.17	3,52,095
6	Kollam	2,488.74	8,05,439
7	Kottayam	2,201.82	5,38,993
8	Kozhikode	2,345.46	8,69,295
9	Malappuram	3,553.71	11,19,461
10	Palakkad	4,476.39	8,19,552
11	Pathanamthitta	2,654.07	3,57,147
12	Thiruvananthapuram	2,189.00	8,84,911
13	Thrissur	3,028.97	8,87,229
14	Wayanad	2,129.16	2,26,623
	<b>Grand Total</b>	<b>38,861.60</b>	<b>94,24,863</b>

#### 4.6.4 CRITICAL FACILITIES

Schools, hospitals, fire stations, police stations and cyclone shelters are included under critical facilities. These play a critical role in mitigation, response, and recovery operations before, during, and after a disaster. The following sections discuss the quantification of exposure values for these essential facilities.

##### 4.6.4.1 Schools

The state has a total of 62,458 school building polygons, which are categorized into three main types: government schools building polygons (45,773), private schools building polygons (16,442), and technical

schools (243). It is important to note that technical schools are included within the infrastructure designated for government schools according to KSDMA. Collectively, these institutions occupy a built-up area of approximately 12.13 square kilometers. In terms of distribution across districts, Malappuram stands out with the highest number of schools building polygons, totaling 9,983, while Wayanad has the fewest, with 1,103. This distribution reflects the varying concentration of schools throughout the state and provides insight into regional differences in school infrastructure (Figure 4-12 and Figure 4-13). The district-wise distribution of schools is presented in Figure 4-13.

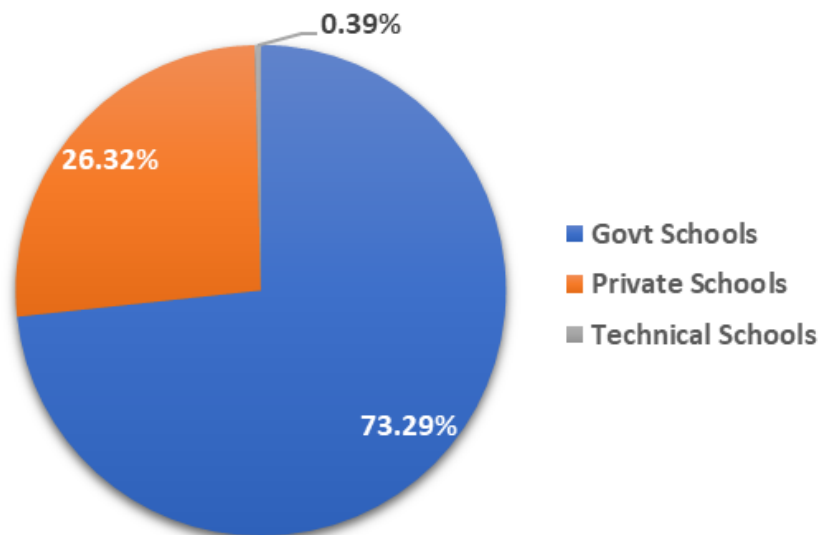


Figure 4-12: Categorization of school building polygons

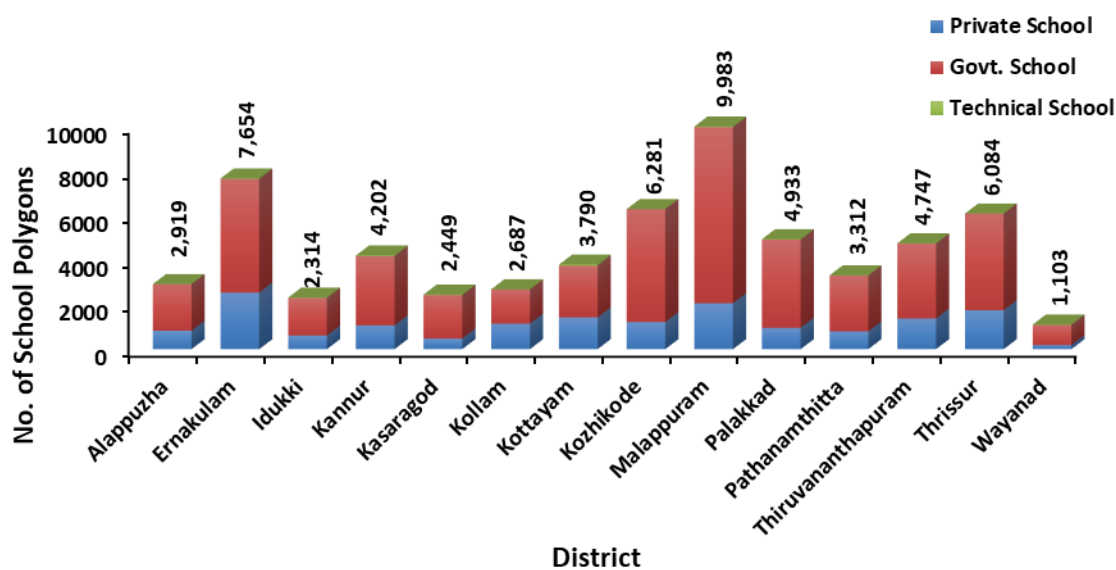


Figure 4-13: District-wise distribution of school polygons

Table 4-8: District-wise distribution of schools

S. No	District	Govt. School	Private School	Technical School
1	Alappuzha	532	103	3
2	Ernakulam	749	309	7
3	Idukki	316	87	4
4	Kannur	814	163	3
5	Kasaragod	450	87	2
6	Kollam	200	146	2

S. No	District	Govt. School	Private School	Technical School
7	Kottayam	527	159	7
8	Kozhikode	907	150	1
9	Malappuram	1049	252	5
10	Palakkad	667	153	3
11	Pathanamthitta	523	87	2
12	Thiruvananthapuram	701	242	4
13	Thrissur	767	214	1
14	Wayanad	234	48	2
	Grand Total	8436	2200	46

#### 4.6.4.2 Hospitals

KSDMA has provided a comprehensive dataset of 7,726 hospitals building polygon points across Kerala. This data is divided into two main categories: government hospitals building polygons, totaling 2,909, and private hospital building polygons, totaling 4,817. The district wise distribution of these hospital building polygons is illustrated in Figure 4-15. Notably,

Ernakulam district stands out with the highest concentration of hospitals, boasting a remarkable total of 1,010 facilities, which includes both government and private institutions. Following closely is Thrissur district, with 987 hospital building polygons. However, Wayanad district has the lowest number of 167 hospital building polygons. Table 4-9 represents district-wise distribution of hospitals.

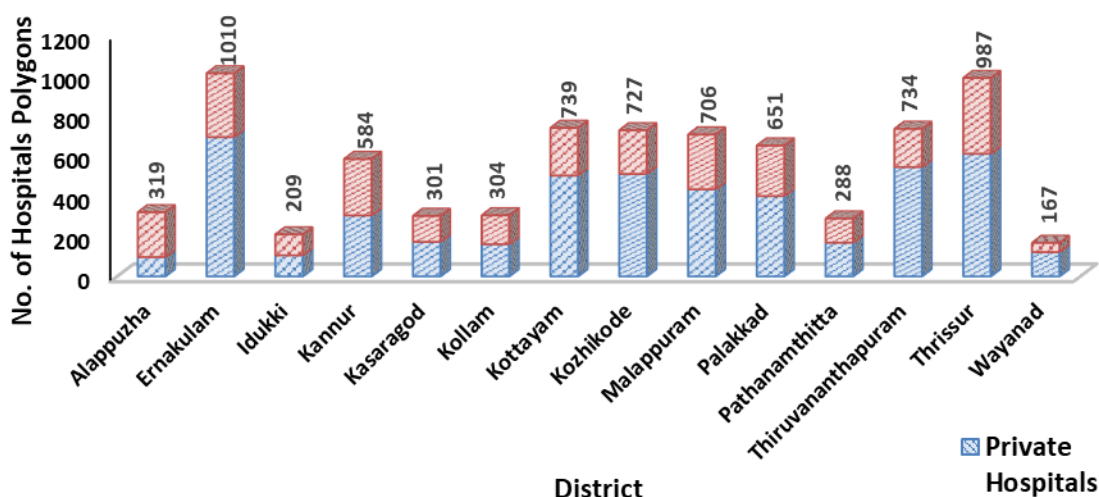


Figure 4-14: District-wise distribution of hospital polygons

Table 4-9: District-wise distribution of hospital

S. No.	District	Govt. Hospital	Private Hospital
1	Alappuzha	24	20
2	Ernakulam	41	82
3	Idukki	23	6
4	Kannur	39	52
5	Kasaragod	13	28
6	Kollam	24	28
7	Kottayam	22	25
8	Kozhikode	18	55
9	Malappuram	25	79
10	Palakkad	24	38
11	Pathanamthitta	14	19
12	Thiruvananthapuram	38	157
13	Thrissur	33	67
14	Wayanad	19	27
	<b>Grand Total</b>	<b>357</b>	<b>683</b>

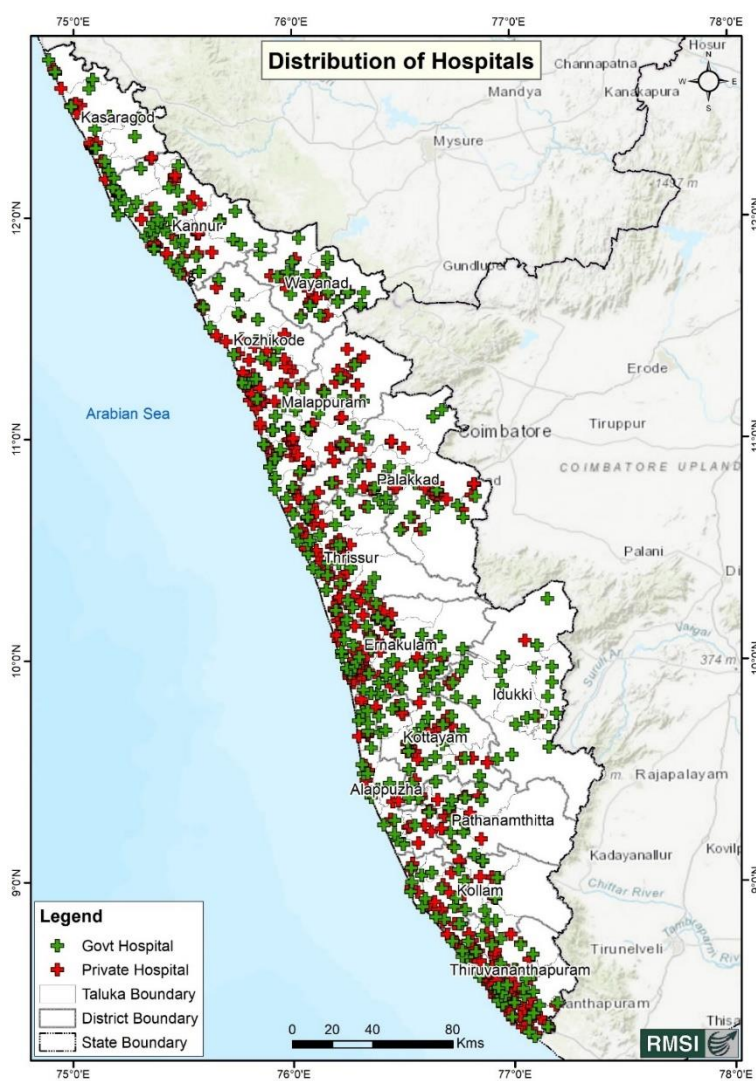


Figure 4-15: District-wise distribution of hospitals

#### 4.6.4.3 Fire stations

Kerala has a total of 208 fire station buildings distributed across its districts. The distribution varies significantly, with Kollam district having the highest number of fire stations, i.e. 29, ensuring extensive coverage for fire safety and emergency response in the area. Interestingly, the

Wayanad district has only 3 fire-stations. and Figure 4-16, respectively, which provide a detailed view of the locations and number of fire station buildings across the state. Table 4-10 represents the district-wise distribution of fire stations

Table 4-10: District-wise distribution of fire stations

S. No.	District	Fire Station
1	Alappuzha	7
2	Ernakulam	14
3	Idukki	5
4	Kannur	7
5	Kasaragod	4
6	Kollam	8
7	Kottayam	7
8	Kozhikode	6
9	Malappuram	7
10	Palakkad	3
11	Pathanamthitta	5
12	Thiruvananthapuram	9
13	Thrissur	10
14	Wayanad	3
	<b>Grand Total</b>	<b>95</b>

#### 4.6.4.4 Police Stations

Kerala has a total of 941 police station building polygons distributed across its districts. The distribution varies significantly, with Ernakulam district having the highest number of police station buildings at 124, and Wayanad district has the least number of police stations at 19.

This district-wise distribution is illustrated in Figure 4-17, which provide a detailed view of the locations and number of fire station buildings throughout the state. Table 4-11 represents district-wise distribution of police stations.

Table 4-11: District wise distribution of police station

S..No	District	Police Station
1	Alappuzha	27
2	Ernakulam	47
3	Idukki	26
4	Kannur	37
5	Kasaragod	16
6	Kollam	30
7	Kottayam	25
8	Kozhikode	30
9	Malappuram	33
10	Palakkad	27

S.No	District	Police Station
11	Pathanamthitta	18
12	Thiruvananthapuram	29
13	Thrissur	38
14	Wayanad	15
	<b>Grand Total</b>	<b>398</b>

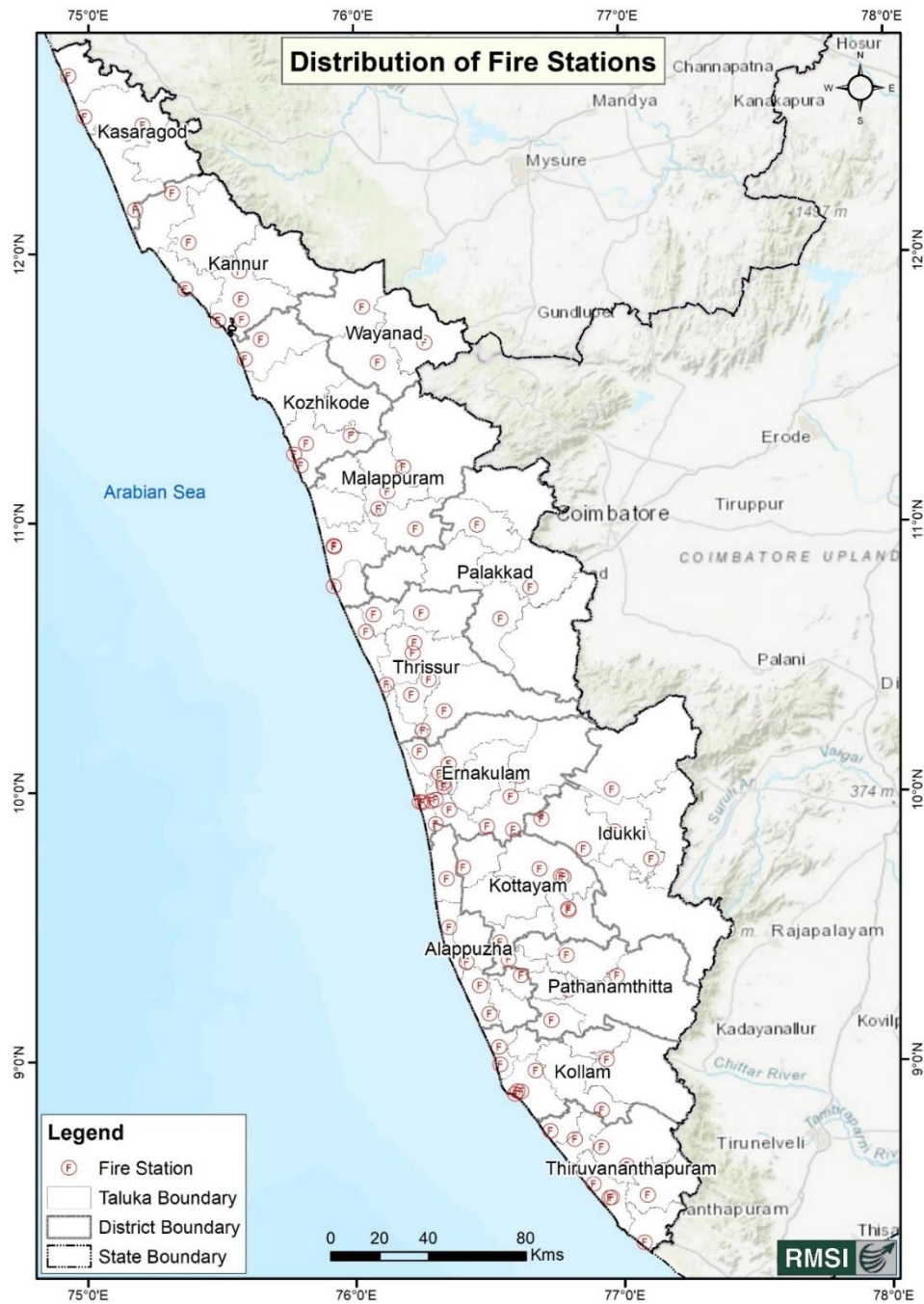


Figure 4-16: District-wise distribution of fire stations

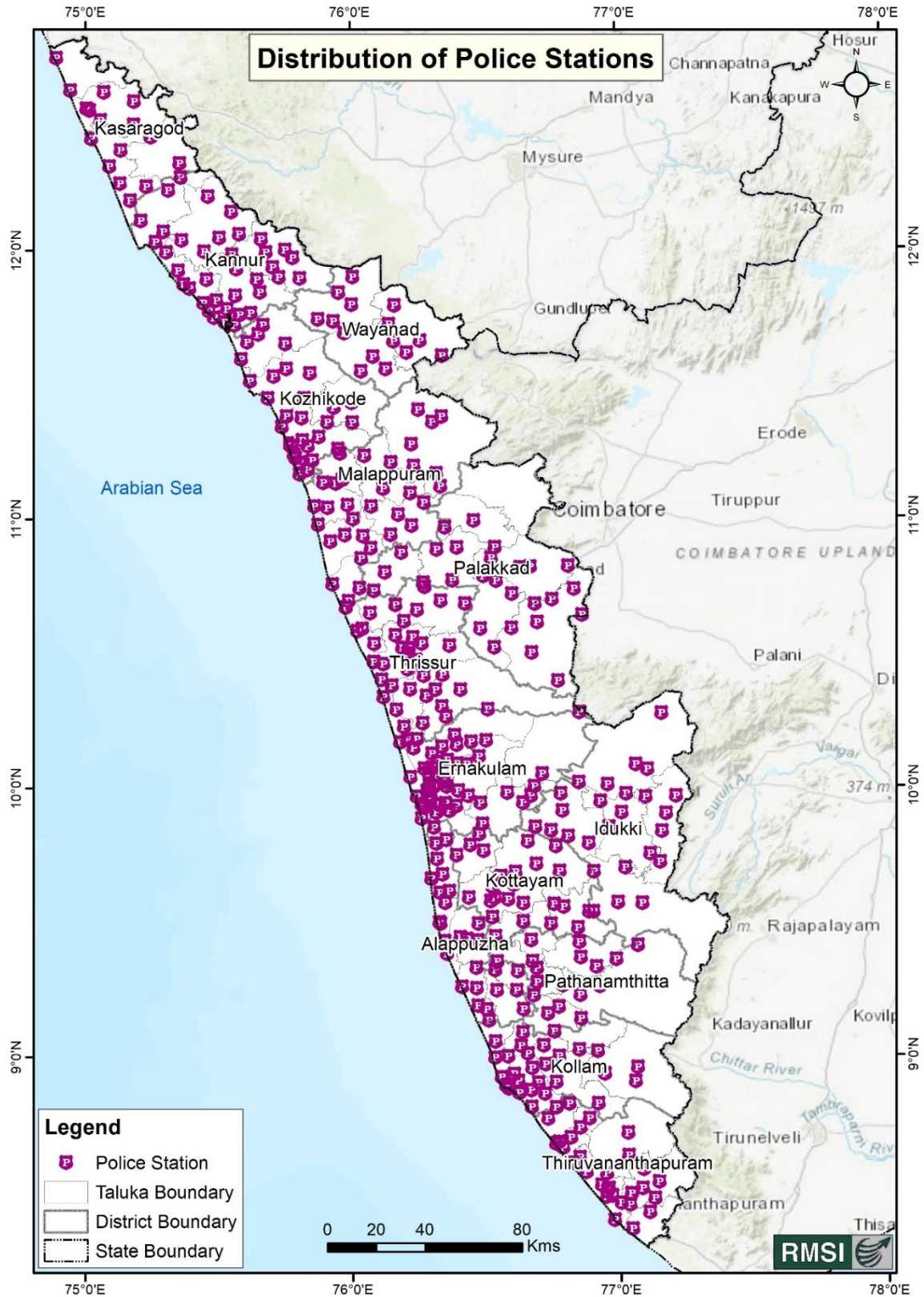


Figure 4-17: District-wise distribution of police stations

#### **4.6.4.5 Cyclone shelters**

Cyclone shelters are the most critical buildings pre, during, and post disaster. Cyclone shelters are used to provide shelter to the people during any disaster, like cyclone, flood, landslide, tsunami or any other disaster. As per database available with us, there are 40 cyclone

shelter building polygons located in different parts of the state.

Table 4-12 shows the district-wise distribution of cyclone shelter numbers in the state; and Figure 4-18 shows the spatial distribution of cyclone shelters in the study area.

Table 4-12: District-wise distribution of cyclone shelter

<b>S.No</b>	<b>District</b>	<b>Cyclone Shelter</b>
1	Alappuzha	2
2	Ernakulam	2
3	Idukki	
4	Kannur	1
5	Kasaragod	3
6	Kollam	1
7	Kottayam	
8	Kozhikode	1
9	Malappuram	1
10	Palakkad	
11	Pathanamthitta	
12	Thiruvananthapuram	1
13	Thrissur	2
14	Wayanad	
	<b>Grand Total</b>	<b>14</b>

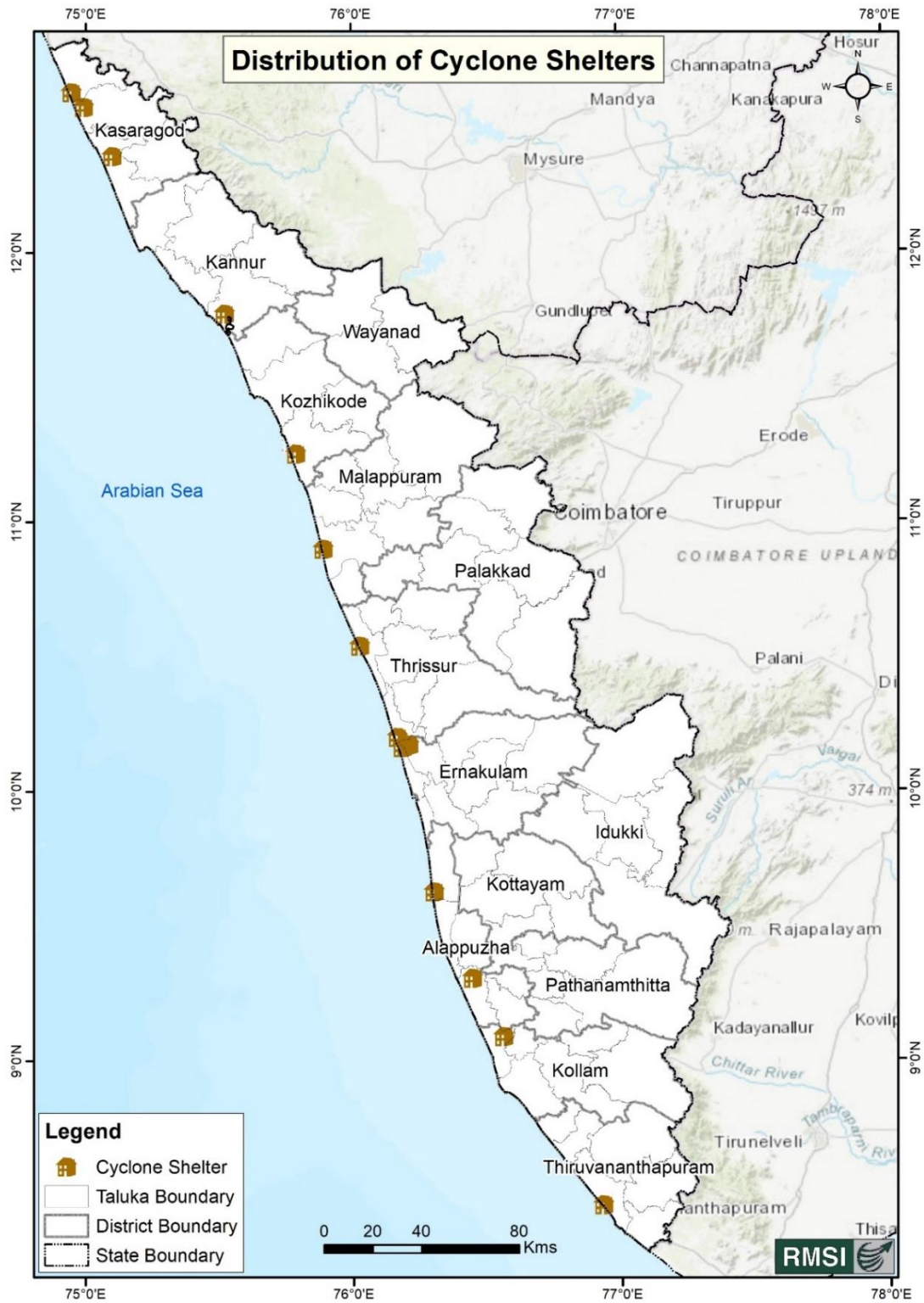


Figure 4-18: District-wise distribution of Cyclone shelters

## 4.6.5 PUBLIC BUILDINGS

### 4.6.5.1 Government offices

Kerala has a total of 684 govt. office building polygons distributed across its districts. The distribution varies significantly, with Kannur district having the highest number of govt. offices at 124, in contrast, Wayanad and Kasargod districts

have 12 govt office buildings each. This district-wise distribution is illustrated in Figure 4-19, which provide a detailed view of the locations and number of govt. office buildings throughout the state.

Table 4-13: District-wise distribution of government office

S.No	District	District HQ	Govt. Office	Municipal Corporation Office	Municipality Office	Panchayat Office	Revenue Office	Tehsil HQ
1	Alappuzha	1	38		6	51	2	6
2	Ernakulam	1	80	1	13	68	6	6
3	Idukki	1	27		2	74	1	5
4	Kannur	1	123	1	9	60	1	5
5	Kasaragod	1	3		3	34	2	5
6	Kollam	1	25	1	4	59	1	6
7	Kottayam	1	9		6	53		5
8	Kozhikode	1	48	1	7	96	1	4
9	Malappuram	1	5		12	55	2	7
10	Palakkad	1	27		7	65	1	6
11	Pathanamthitta	1	10		4	29	1	6
12	Thiruvananthapuram	1	13	1	4	75	4	6
13	Thrissur	1	12	1	7	53	4	7
14	Wayanad	1	5		3	21		3
	Grand Total	14	425	6	87	793	26	77

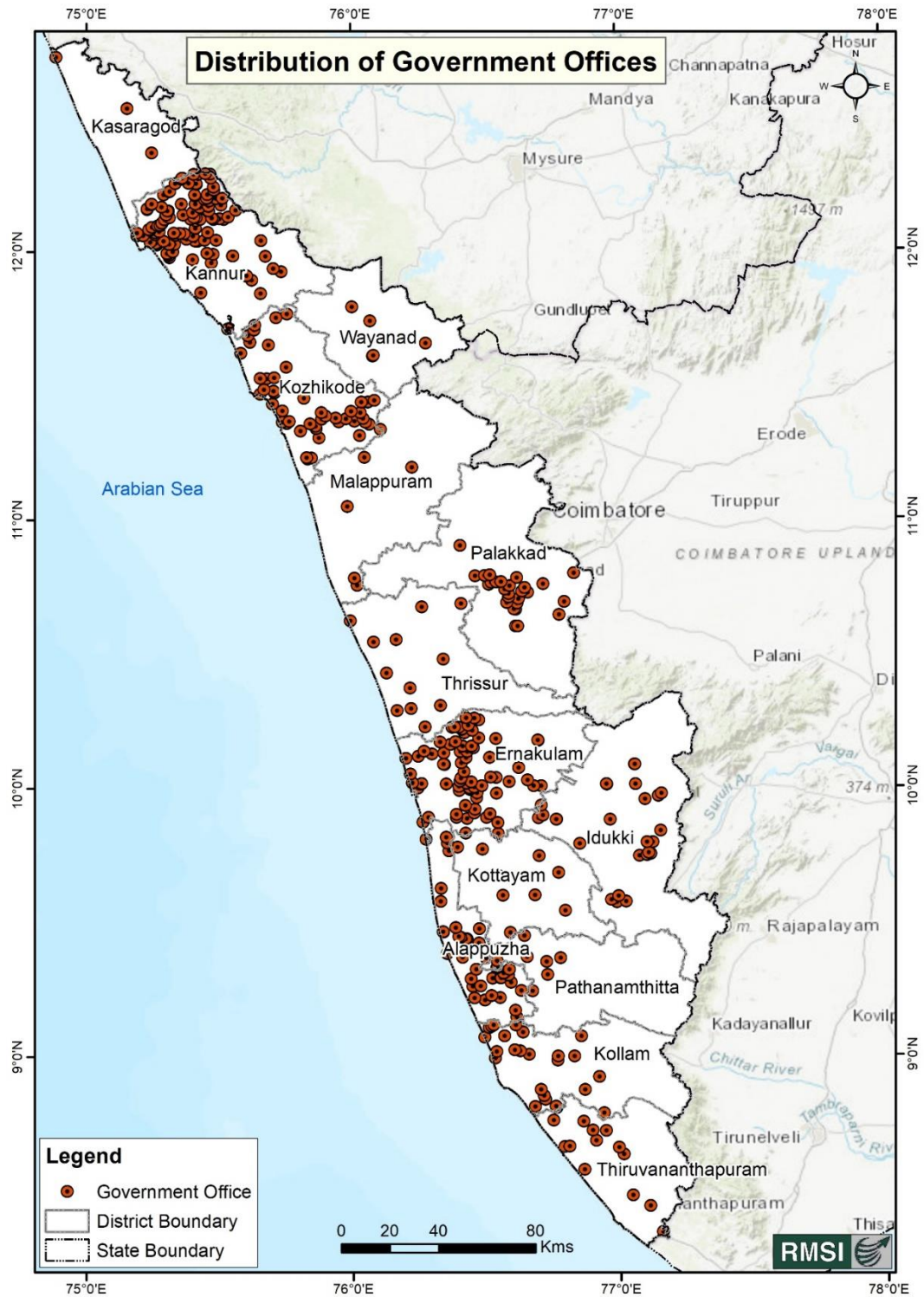


Figure 4-19: District-wise distribution of government offices

### 4.6.6 TRANSPORT

Transport network plays an important role in pre, during, and post disaster throughout the year. For developing exposure, roads and bridges, railway line and railway stations, and airports are considered for exposure analysis and are presented below.

#### 4.6.6.1 Roads

The data on the road network was collected from KSDMA in this study. This data is enhanced and validated further using high-resolution satellite imagery, OSM, RMSI in-house data and published reports. The data provides information regarding the various types of roads as well as their

respective lengths. The available data classified roads into 6 categories, namely, national highways (NH), state highways (SH), district roads (DR), city roads (CR), village roads (VR), and footpaths (FP). Depending on the road typologies, information of road width (center line basis) was added to the data attribute.

A total road length of 54,996km was mapped under various categories. Total length of various categories of roads were calculated to compute the exposure values. Unit replacement cost of different type of roads were collected through local consultant and were used in estimating total exposure value for the road network Figure 4-20.

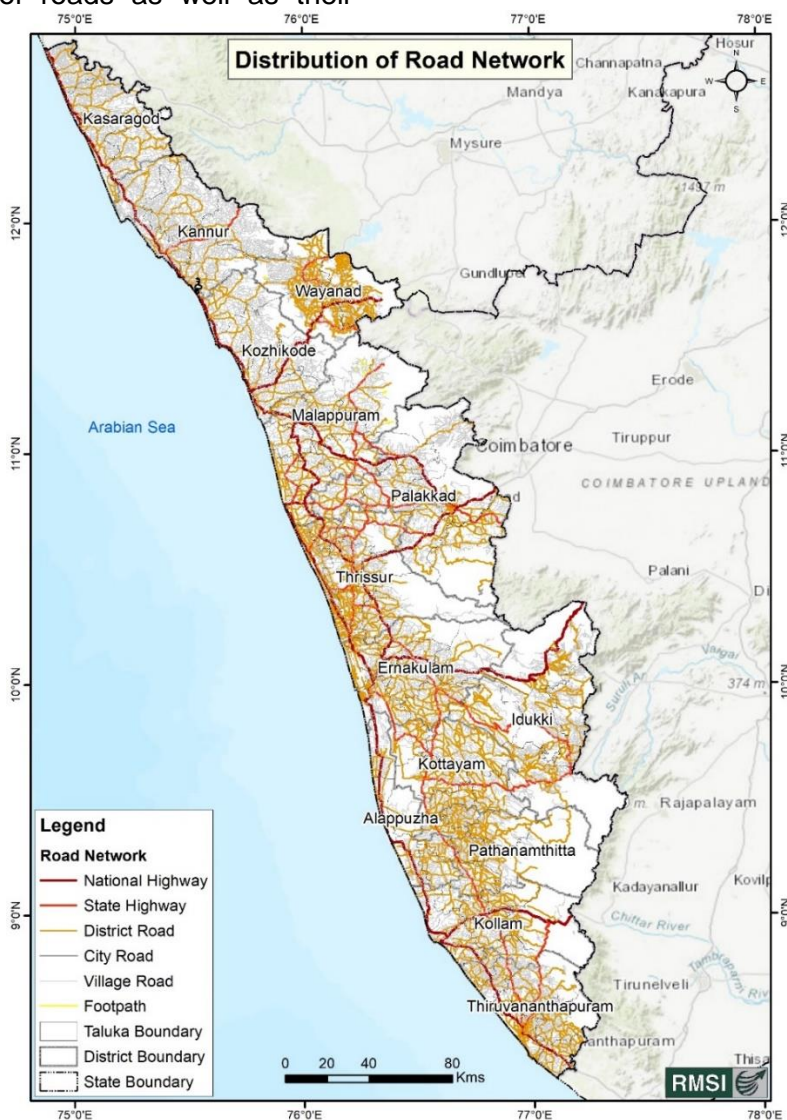


Figure 4-20: District-wise road network

The analysis of road network of the State reveals a diverse infrastructure comprising various categories. National highways extend over 1,298 km, while state highways cover 1,207km. District roads span a substantial 13,096 km, with village roads emerging as the most extensive category at 39,340 km, respectively. Additionally, city roads and footpaths collectively amount to about 55km. Notably, village roads contribute the longest length within road network. In terms of road surface types, about 113 km are kuccha roads, while pucca roads dominate at about 54,883 km. District-wise, Kannur exhibits the highest length of roads network at 5,980 km, contrasting with Alappuzha's

lowest figure of 1,842 km district wise road length and the percentage of road types are shown in the following Figure 4-21 and Figure 4-22.

Bus stand data has been provided by the KSDMA for the entire Kerala state. The data received from the KSDMA includes 304 bus stand and 884 buildings for the entire state. Figure 4-23 shows the locations of bus stand. Thiruvananthapuram is having the highest number of bus stand buildings about 209 while Kasargod is having only 10 bus stand buildings. Table 4-14 represents district-wise distribution of bus stand.

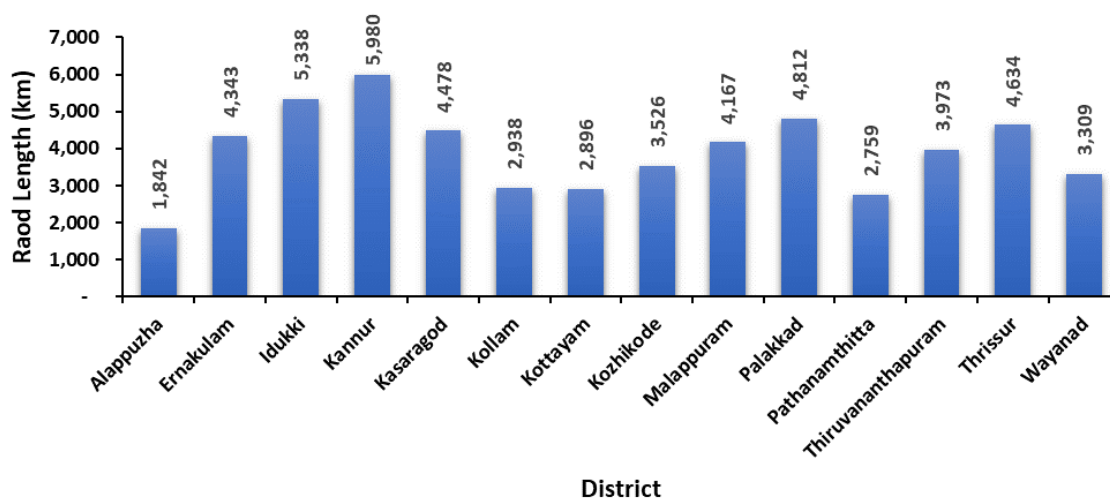


Figure 4-21: District-wise road length in Kerala

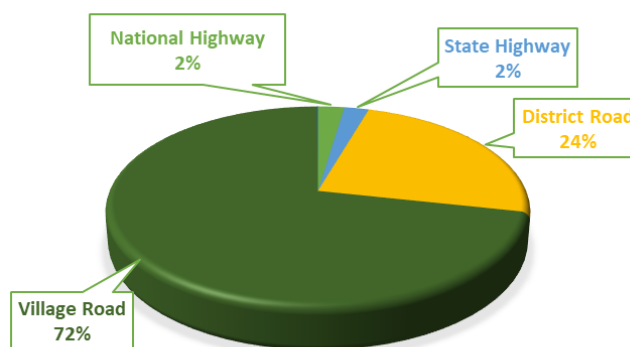


Figure 4-22: Distribution of road network in Kerala

Table 4-14: District-wise distribution of bus stands in Kerala

S. No	District	Bus Stand
1	Alappuzha	12
2	Ernakulam	16
3	Idukki	12
4	Kannur	34
5	Kasaragod	15
6	Kollam	9
7	Kottayam	28
8	Kozhikode	24
9	Malappuram	16
10	Palakkad	10
11	Pathanamthitta	12
12	Thiruvananthapuram	23
13	Thrissur	15
14	Wayanad	4
	<b>Grand Total</b>	<b>230</b>

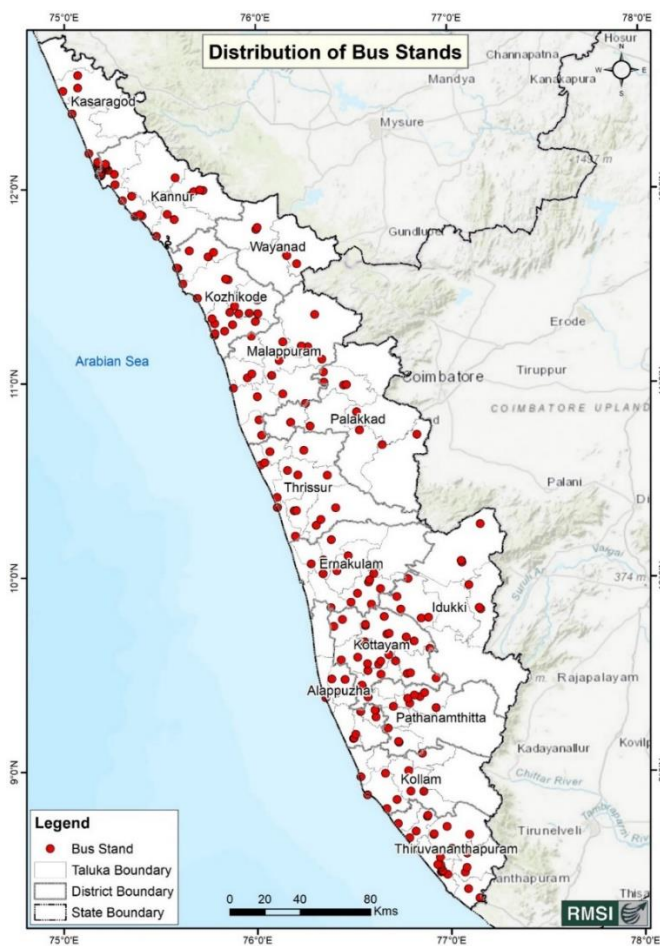


Figure 4-23: District-wise distribution of bus stands

### 4.6.6.2 Railways

The data on the railway network was collected from KSDMA for this study. This data was improved and validated further using high-resolution satellite images. As per this database, the railway line of 1,063 km in total has been laid in the state with 160 railway stations (Figure 4-24 to Figure

4-26). In Kerala, the district of Palakkad leads the longest railway line, extending about 160.25 km. Conversely, Pathanamthitta district has the shortest railway line length, measuring about 9 km. Notably, two districts, Wayanad and Idukki, do not have any railway networks. Distribution of railway line length and railway stations at the district level is presented in Table 4-15.

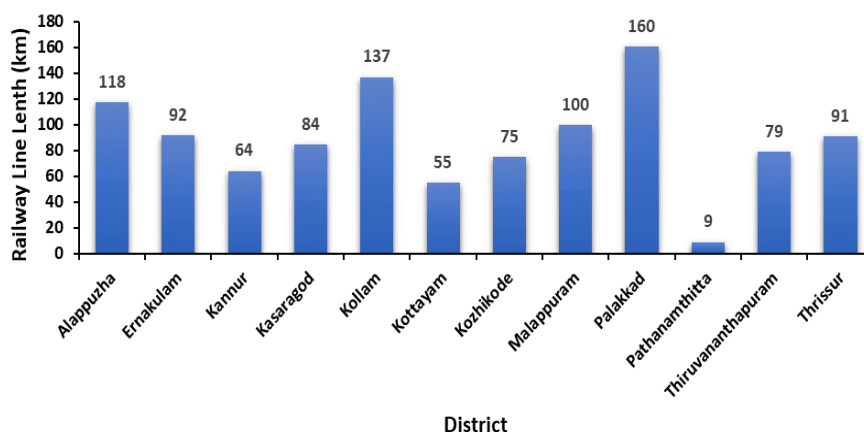


Figure 4-24: District-wise length (km) of Railway line

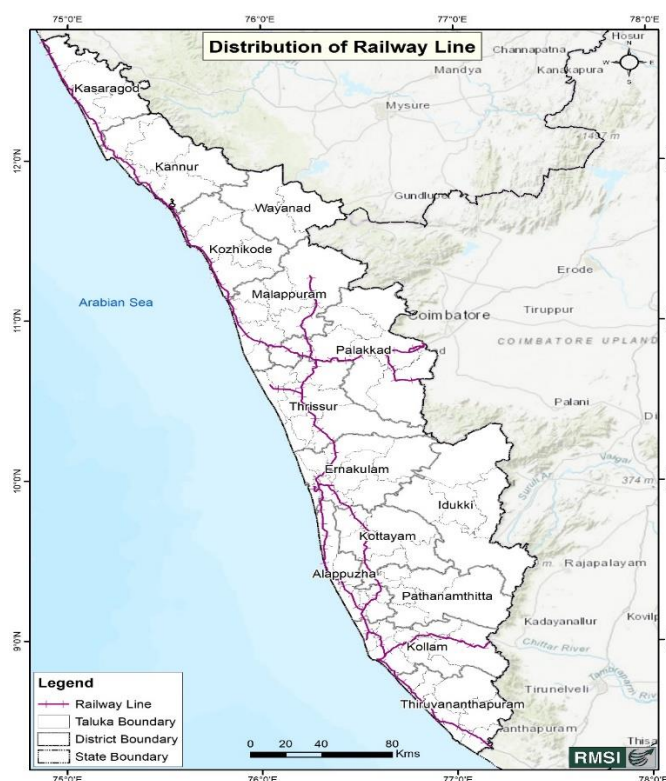


Figure 4-25: District-wise rail network

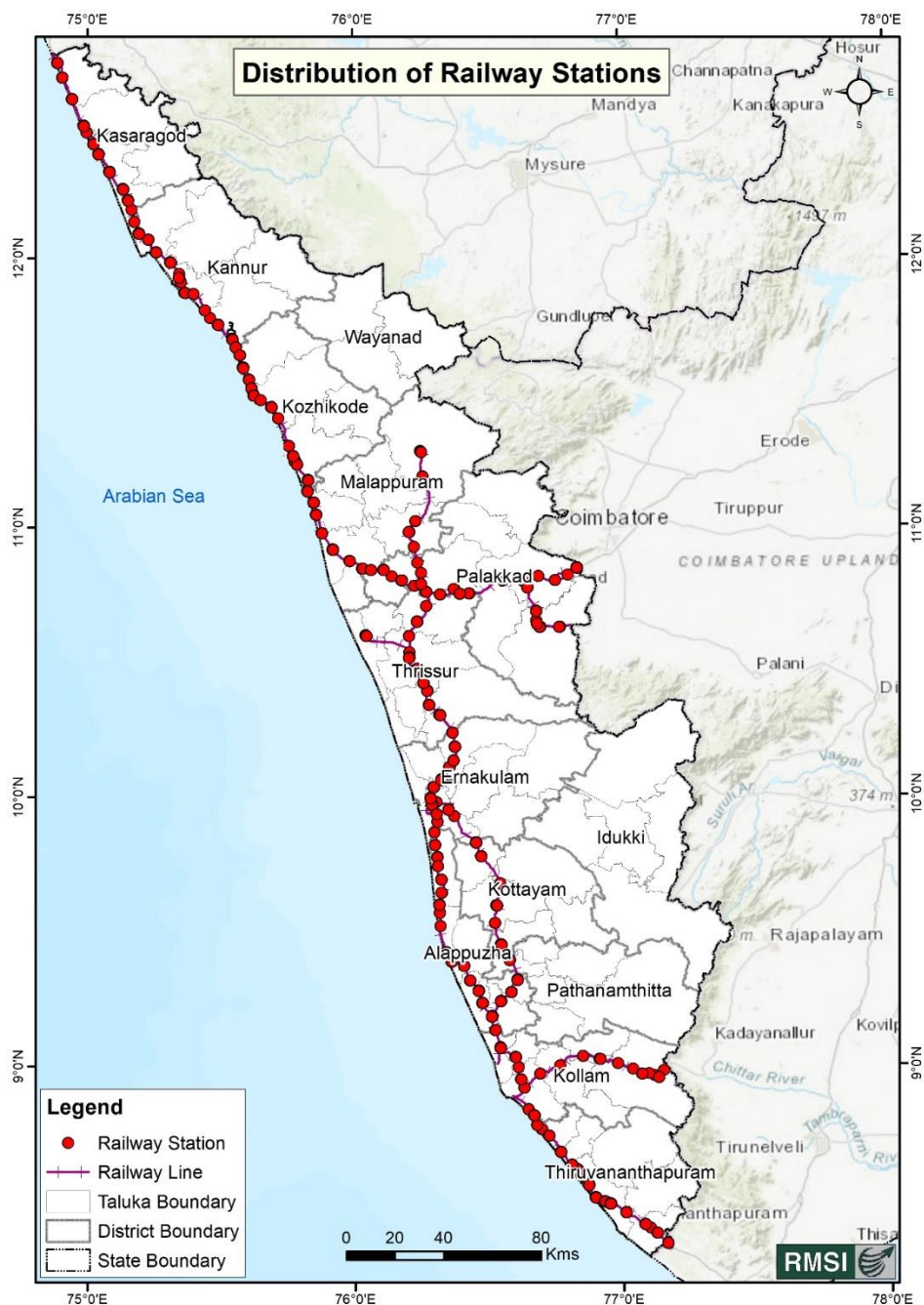


Figure 4-26: District-wise railway stations

Table 4-15: Distribution of Railway line length and Railway stations at the district level.

S. No.	District	Railway line length in km	No. of Railway Stations
1	Alappuzha	117.54	19

S. No.	District	Railway line length in km	No. of Railway Stations
2	Ernakulam	91.58	13
3	Kannur	64.08	12
4	Kasaragod	84.44	12
5	Kollam	136.89	19
6	Kottayam	54.96	6
7	Kozhikode	74.76	16
8	Malappuram	99.81	12
9	Palakkad	160.25	23
10	Pathanamthitta	8.97	1
11	Thiruvananthapuram	78.67	16
12	Thrissur	91.06	11
<b>Total</b>		<b>1,063.02</b>	<b>160</b>

#### 4.6.6.3 Bridges

Data for bridges have been obtained from KSDMA, which contains point locations. Bridges are essential component of transport network throughout the year and become critical, during response and relief activities as they often connect across the river and if damaged, can severely affect the plan of action during response and relief activities. Thus, it is imperative to maintain a detailed database of bridges including bridge type, year of construction, last maintenance date and type, etc. The bridge inventory database will also help the administration to have alternate routes/plans for emergency situations. The scanty bridge data received was further enhanced using RMSI in-house data, OSM

data, and high-resolution satellite data. These open-source data had limitations providing name of bridge, construction years and type. About 284 km of bridges length data has been mapped by the RMSI team under this study. Figure 4-27 presents the distribution of bridges length in different districts of Kerala. In Kerala, the district of Ernakulam stands out for having the highest cumulative length of bridges, totaling 62.65 km, and boasts a substantial number of 846 bridges. In contrast, Kasargod district has the least number of bridges, with a total count of just 101. Meanwhile, Wayanad district records the shortest total bridge length, measuring about 4 km with a total count of 136 bridges. This data highlights significant variations in bridge infrastructure across different districts of Kerala.

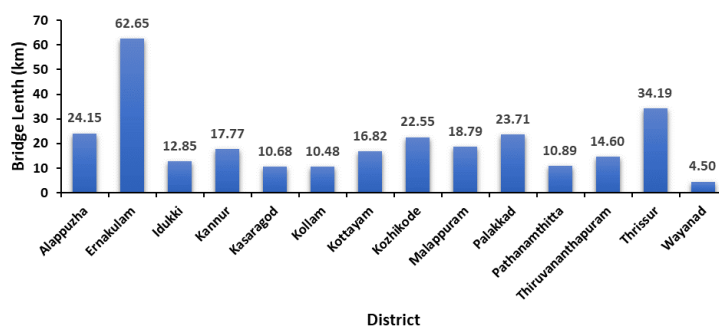


Figure 4-27: District-wise distribution of bridges length

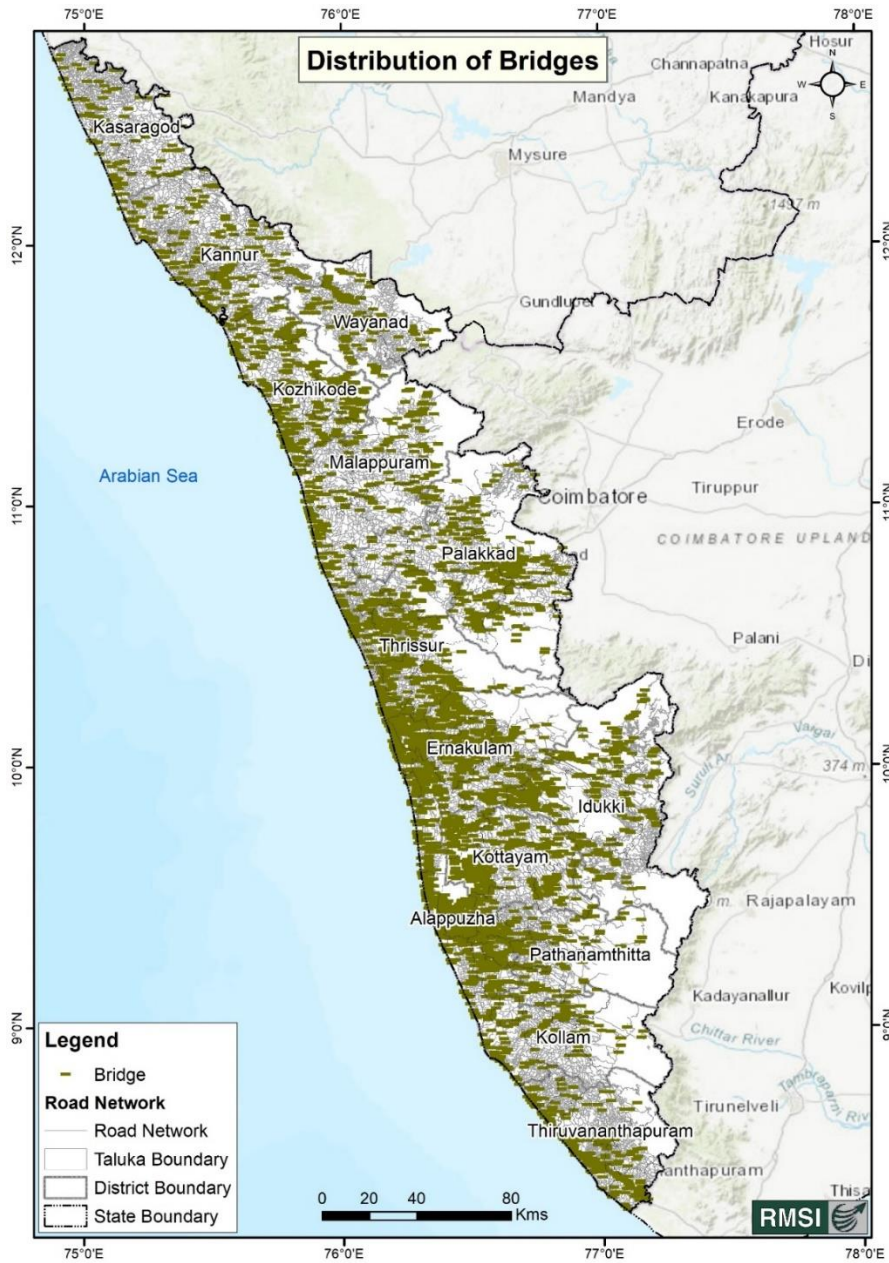


Figure 4-28: District-wise location of Bridges

#### 4.6.6.4 Airports

There are six airports mapped in Kerala. Four out of six are international airports, namely Calicut, Cochin, Kannur, and Trivandrum airports. Among these airports Trivandrum airport is the largest and Calicut airport is the smallest. Airport data was collected from KSDMA and open-

source data and information related to the covered built-up area and the length of the runway was captured using high-resolution satellite data in Table 4-16. Figure 4-29 shows the location of airports and represents names, location and category type of airports in Kerala.

Table 4-16: District-wise airport name and category

S. No	Name	Category	District
1	Kannur International Airport	International Airport	Kannur
2	Calicut International Airport	International Airport	Malappuram
3	Cochin International Airport	International Airport	Ernakulam
4	INS Garuda Defence Airport	Defence Airport	Ernakulam
5	INS Venduruthy Defence Airport	Defence Airport	Ernakulam
6	Trivandrum International Airport	International Airport	Thiruvananthapuram

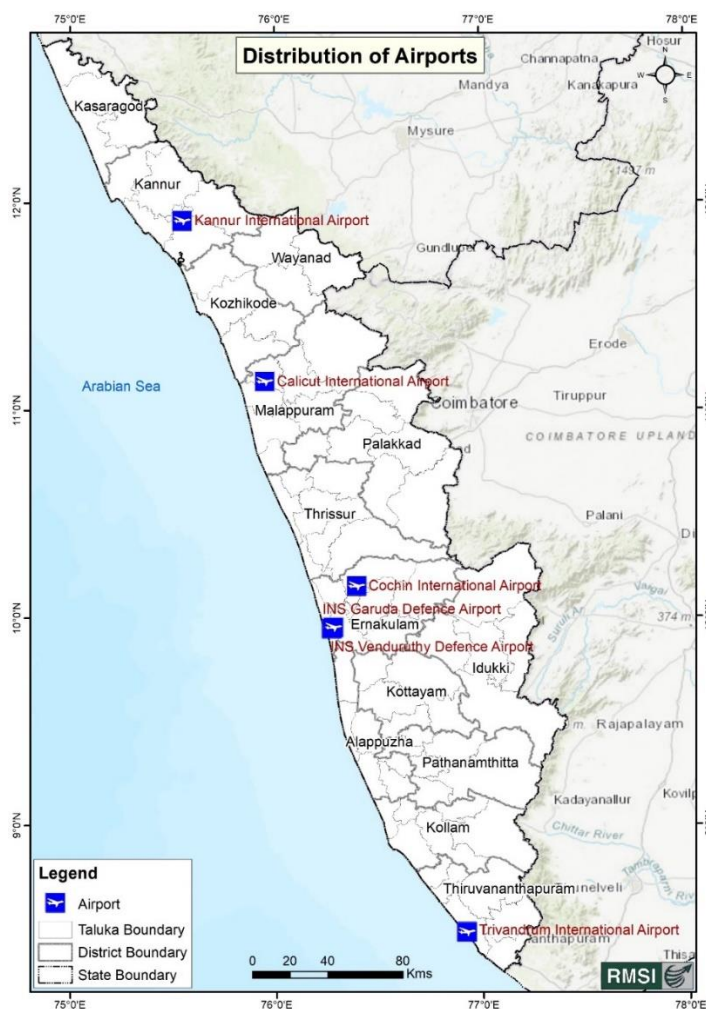


Figure 4-29: District-wise airport locations

#### 4.6.7 AGRICULTURE

The agriculture sector contributes 8.5% of the GSVA of Kerala (KSPB, 2023<sup>119</sup>). Kerala's agriculture is shaped by the state's tropical climate, varied topography, and rich biodiversity. The state benefits from significant annual rainfall, and diverse landscapes ranging from coastal plains to highland areas. This climate and topography support a wide array of crops. Rice is a staple crop grown primarily in lowland paddy fields, while spices like black pepper and cardamom thrive in the Western Ghats and nutmeg is widely grown over midlands. The banana, tapioca and arecanut crops are extensively grown over midlands and highlands of Kerala. Tea and coffee plantations are prominent in the highland regions, and Kerala is a leading producer of rubber, with extensive plantations in midland and highland areas. Cash crops such as cashew has been cultivated across low and mid lands and cocoa has been prominent across mid and high lands of Kerala. Coconut palms are abundant throughout the state, providing a range of products from water to oil. Additionally, various fruits and vegetables are cultivated for both commercial and subsistence purposes.

In Kerala, approximately 65% of the state's land is dedicated to agricultural purposes (KSPB, 2023<sup>99</sup>). Among these, agricultural plantations occupy the largest area. According to data from the Department of Economics and Statistics, Government of Kerala (2023<sup>120</sup>), horticultural crops including cash crops such as coconut, rubber, arecanut, banana, black pepper, coffee, cardamom, cashew nut, tea, nutmeg, and cocoa, as well as fruit crops like jackfruit, mango, pineapple, and papaya, account for 86% of the total

agricultural area in Kerala. The field crops, including rice and tapioca, occupy the remaining 14% of the state's agricultural land. Among the 14 districts of Kerala, Palakkad district has the largest field crop area, with 81,418 hectares, followed by Alappuzha district with 43,706 hectares. Four districts namely Thrissur, Kottayam, Kollam, and Thiruvananthapuram, have more than 20,000 hectares of field crop area. Kasargod district has the smallest field crop area at 5,173 hectares, followed by Kozhikode with 6,925 hectares. The field crop area in Idukki and Kannur districts ranges between 7,500 and 10,000 hectares, while in Wayanad, Malappuram, Ernakulam, and Pathanamthitta districts, it falls between 10,000 and 20,000 hectares.

In terms of horticultural crops, including plantation and fruit crops, the area ranges from 51,000 hectares in Alappuzha district to 199,119 hectares in Idukki district. The horticultural crop area exceeds 180,000 hectares in both Kannur and Malappuram districts, while it is less than 100,000 hectares in Pathanamthitta district. Kozhikode and Kottayam districts have between 160,000 and 180,000 hectares of horticultural crops, while the remaining districts have horticultural crop areas between 100,000 and 160,000 hectares.

The fraction of field crop and horticulture area at district level is presented in Figure 4-31. Alappuzha district has the highest proportion of field crop area relative to the total agricultural area, accounting for 46%, followed by Palakkad district at 37%. The proportion of field crop area in the total agricultural area ranges between 10% and 20% in Ernakulam, Kollam, Kottayam, Pathanamthitta, Thiruvananthapuram, and Thrissur districts. In all remaining districts, the proportion is less than 10%.

<sup>119</sup> KSPB(2023).  
[https://spb.kerala.gov.in/sites/default/files/2024-02/ER\\_English\\_Vol\\_1\\_2023.pdf](https://spb.kerala.gov.in/sites/default/files/2024-02/ER_English_Vol_1_2023.pdf).

<sup>120</sup> <https://ecostat.kerala.gov.in/dataset/28?page=86>

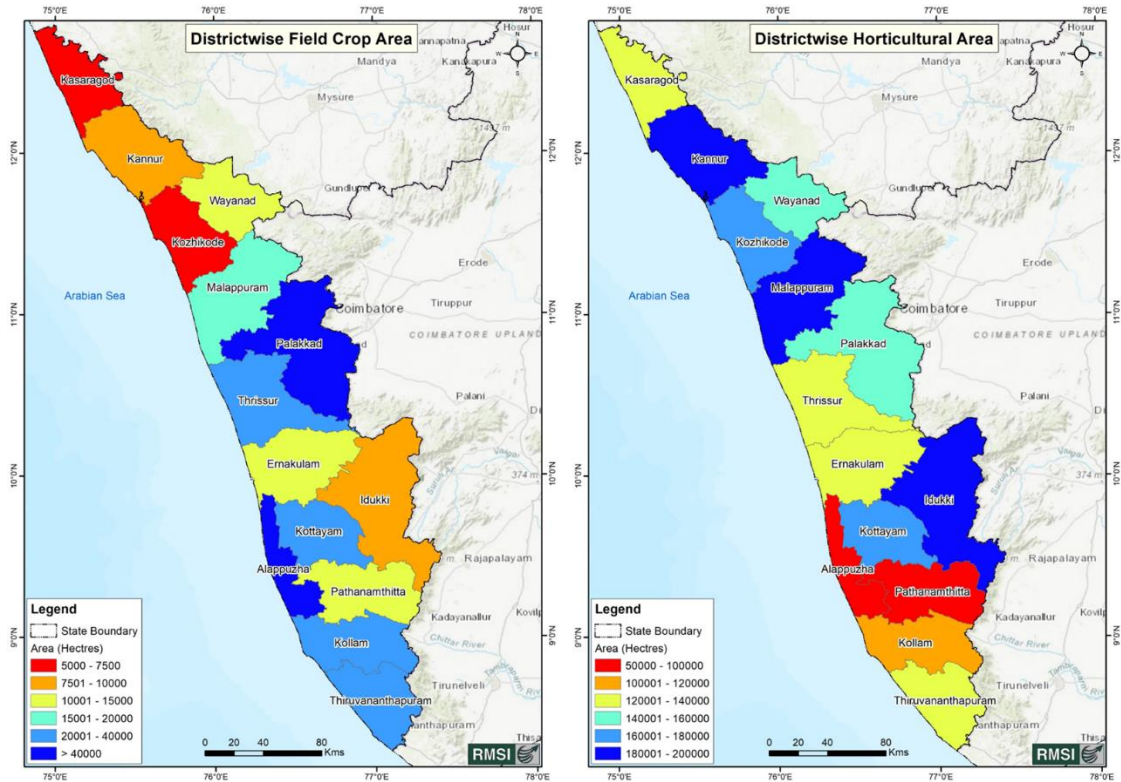


Figure 4-30: District wise field crop (left pane) and horticulture (right pane) area in Kerala

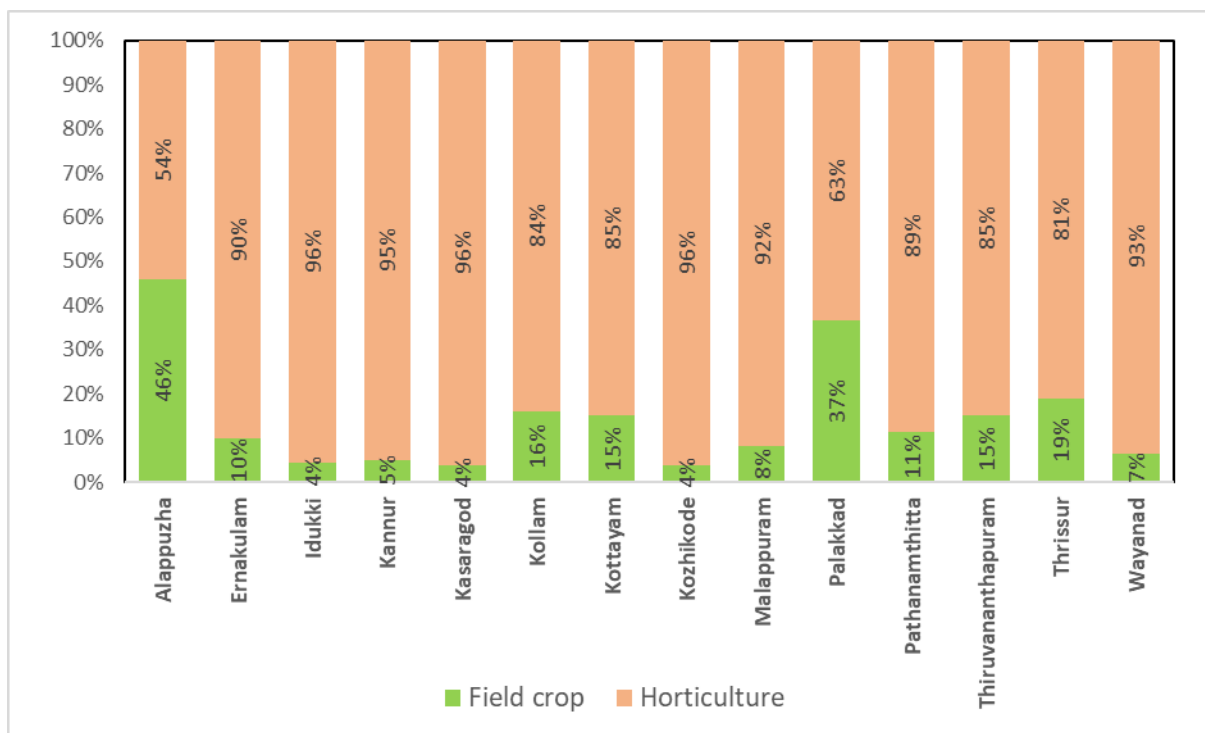


Figure 4-31: Fraction of agricultural area across the districts of Kerala

Table 4-17: Area and production of key crops at district level across Kerala

District	Arecanut		Coconut		Rice		Banana		Tapioca	
	Area (Hectres )	Production (Tonnes)	Area (Hectres )	Production (Numbers)	Area (Hectres )	Production (Tonnes)	Area (Hectres )	Production (Tonnes)	Area (Hectres )	Production (Tonnes)
ALAPPUZHA	1,586	433	34,205	20,00,000	39,685	116,253	453	3,380	2,417	85,606
ERNAKULAM	4,033	2,919	40,580	15,90,000	4,757	10,976	5,139	45,327	5,341	2,41,787
IDUKKI	1,696	592	13,613	5,60,000	595	1,363	3,430	31,293	6,655	2,93,307
KANNUR	9,612	7,699	86,877	41,20,000	5,456	11,573	2,198	20,221	1,806	70,967
KASARAGOD	21,074	44,814	63,303	54,30,000	2,609	5,609	660	6,412	449	14,702
KOLLAM	1,570	818	45,348	29,10,000	2,133	4,561	3,065	21,698	14,506	5,12,137
KOTTAYAM	1,350	641	25,221	10,20,000	19,648	55,750	3,012	26,005	5,915	2,48,963
KOZHIKODE	9,735	6,170	1,14,865	74,10,000	2,099	2,747	1,750	15,031	1,523	44,174
MALAPPURAM	19,018	12,565	1,05,381	77,80,000	9,223	30,193	6,786	55,341	5,111	1,84,187
PALAKKAD	7,619	5,706	57,428	45,40,000	76,193	237,755	15,165	1,44,983	2,048	69,283
PATHANAMTHITTA	1,032	571	16,056	7,60,000	3,520	10,944	2,164	16,988	5,037	2,23,785
THIRUVANANTHAPURAM	859	342	70,373	42,40,000	1,922	4,822	2,886	22,542	14,244	5,18,030
THRISSUR	5,479	4,157	77,785	52,50,000	23,075	76,950	2,126	17,212	1,181	51,524
WAYANAD	12,258	5,328	9,741	5,30,000	7,799	21,909	10,268	92,602	1,716	66,751

### 4.6.8 EXPOSURE VALUE

Total exposure values for all the assets/ exposure layers considered in this study were estimated. Table 4-18 shows total exposure values for different types of exposure categories in Kerala. Total exposure

value for the buildings, critical infrastructure, public buildings and transport mapped in the study has been estimated to be about 32,30,385.60 INR in crores.

Table 4-18: Exposure value for each exposure type (INR in Crores)

S. No.	Exposure Category	Exposure	Feature Type	Area/Length(meter)	Feature Count	Exposure Value (INR in crores)
1	Buildings	Residential Buildings	Polygon	1,14,17,23,222	1,45,75,698	33,63,107.81
2	Critical Facilities	Cyclone Shelters	Polygon	6,373	40	24.45
		Schools	Polygon	1,24,31,944	62,513	36,639.22
		Fire Stations	Polygon	36,501	208	271.11
		Health Centres	Polygon	16,85,230	7,526	12677
		Police Stations	Polygon	1,10,038	942	319.4
3	Public Buildings	Government Buildings	Polygon	4,41,678	3,429	3,458.30
4	Transport Infrastructure	Airports	Polygon	22,96,604	404	18,478
		Bridges	Line	2,60,347	5,757	2,146
		Railway Lines	Line	10,62,751	278	11,951
		Railway Stations	Polygon	4,34,562	2,000	442.82
		Road Network	Line	5,49,24,593	74,961	2,26,877
		Bus Stations	Polygon	1,06,490	883	437.11

## 4.7 Vulnerability Assessment

In general, vulnerability describes the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard. There are many aspects of vulnerability, arising from various physical, social, economic, and environmental factors. This section describes the physical vulnerability functions of identified assets – buildings, critical facilities, and infrastructure - to the various levels of natural hazards intensity (wind speed, flood depth, peak ground acceleration, etc.). The outputs of this analysis are a set of vulnerability functions for each hazard, for each structure class. The vulnerability functions help in calculating the probable economic losses that will occur for different levels of hazard intensity.

### 4.7.1 DEFINITION

A vulnerability function defines the level of damage as a function of an intensity measure of hazard. Once the physical characteristics for each building class are defined, it is possible to establish and assign the likely damage, and subsequently losses to that specific building class subjected to various levels of specific hazard intensity. This is done by defining relationships between a measured parameter of the hazard intensity (e.g. water depth in case of flooding or the peak ground acceleration in the case of earthquakes) to the likely damage level of the particular building class. The damage is expressed in relative terms to their replacement value. These relationships are also called “vulnerability curves” (or “damage functions”).

For each hazard and each building typology, one vulnerability curve is defined. Each point of the curve links a characteristic of the hazard to a mean damage value and in order to consider the fact there is an uncertainty in how a building performs, the curve also includes the variance, representing the probability distribution of the damage that are likely to occur following the given hazard intensity (Figure 4-32). So, each point on the

vulnerability curve is itself a probability distribution.

Vulnerability curves allow losses can be calculated for each building typology throughout the geographical area for each defined hazard event using assets replacement values and its content.

### 4.7.2 RMSI VULNERABILITY MODULE

The vulnerability module for India in the RMSI Risk Platform contains hazard-specific large datasets of vulnerability curves which takes into account building type (construction material) and occupancy class (residential, commercial, industrial), height and secondary characteristics such as presence/ absence of basement, plinth height, first floor height etc. When such characteristics attributes are missing, a default vulnerability curve is used. These vulnerability curves are regularly updated as and when more damage data is available from any disaster event.

The Kerala State-specific vulnerability curves for the major agriculture crops and plantation are developed, which are further improved at the district level as detailed below:

The drought vulnerability model for Paddy, Banana, and Tapioca consists of establishing relationships between crop yield loss and meteorological hazards, focusing on drought intensity measured by SPEI. This study developed vulnerability functions using historical weather data and district-level crop statistics. The vulnerability function estimates the crop production losses due to drought conditions, using a statistical regression approach guided by expert knowledge of crop responses. Critical growth stages of each crop were identified to quantify drought hazards using SPEI, integrated with a Drought Damage Matrix that assigns weights based on crop sensitivity at different stages. Integrated SPEI (ISPEI) was computed by assigning weightage for different crop stages on the basis of drought sensitivity. District-specific vulnerability functions were then derived

for each crop using the ISPEI and Mean Damage Ratio (MDR), representing the ratio of drought induced crop yield loss to normal yield.

Drought vulnerability functions were developed for rice, banana, and tapioca crops on each district. Southern districts such as Thiruvananthapuram and Alappuzha exhibit higher vulnerability due

to lower monsoon rainfall, whereas northern districts like Kasargod are less vulnerable with higher rainfall. A non-linear (logarithmic) relationship was identified as best fitting for drought-induced rice yield loss, with similar vulnerability patterns observed for banana and tapioca. Rice emerges as the most vulnerable crop due to its intensive water requirements, followed by banana and tapioca.

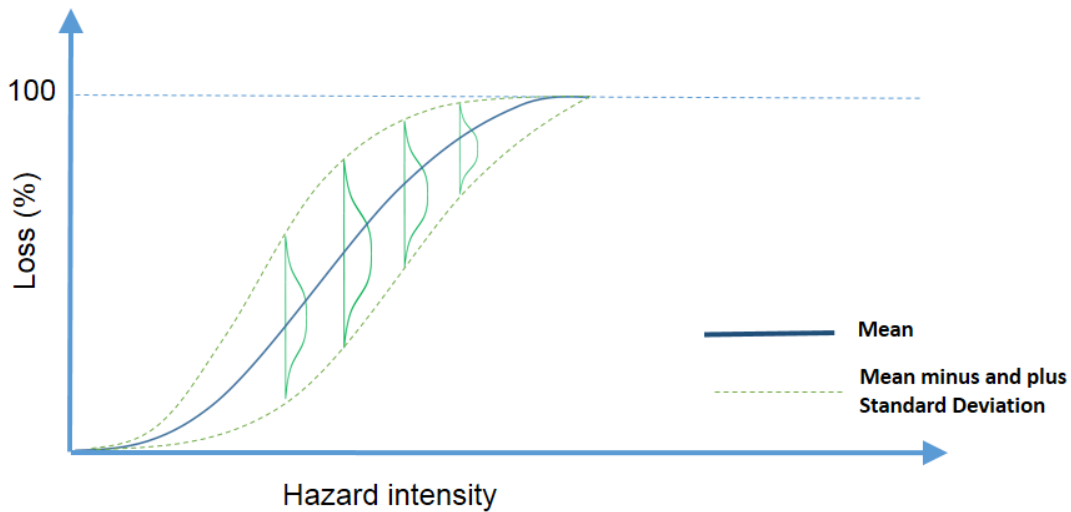


Figure 4-32: Example of Vulnerability Curve

## 5 Risk Assessment

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Risk information, being an important component for Disaster Risk Reduction (DRR), provides a critical foundation for managing disaster risks across a wide range of sectors.

Risk is the uncertainty of future losses – if we perfectly knew a future loss, it would simply be a cost, not a risk. Risk is uncertain with regard to the causative hazard event, its location, date and time of occurrence, and the degree or amount of damage to assets caused by the hazard event, and what losses accrue due to the damage.

This report deals with probabilistic risk assessment for flood, landslide, cyclonic wind, storm surge, and drought hazards on key assets such as buildings, government buildings, critical facilities, transport infrastructure, agriculture in Kerala at the state, district, taluka and LSG levels have been carried out. The outputs from these modelling studies were used to estimate key return periods probable maximum losses (PML) and average annual losses (AAL) for each category of exposure elements using OASIS Loss Modelling Framework.

The total losses at the state, district, taluka levels were presented by aggregating at Local Self Government (LSG) level across various sectors considered in this study (residential building, critical facilities (Schools, Hospitals, Fire stations, Police stations, Cyclone shelters); government buildings (Revenue Offices, Panchayat offices, Municipality offices, Municipal Corporation Offices, District and Tehsil

headquarters offices, and other Govt. offices); transport networks (Roads and Bridges, Railway lines, Railway stations, Bus stations and Airports); and agriculture major crops and plantations).

For flood, cyclonic wind, and storm surge risk assessment, vulnerability functions for buildings, critical facilities, transport infrastructure and agriculture developed by RMSI were used. These functions, proprietary to RMSI, were employed to estimate the losses. The estimated PML and AAL for residential buildings and various sectors, as well as their contributions to total losses in the state due to these hazards are provided in the sections below.

### 5.1 Risk assessment and its components

The components for assessing risk to assets caused by the hazard event, and the resulting losses are depicted in Figure 5-1. Risk assessment provides insight into potential losses, the interaction of a single or multiple hazards with the exposure, and all dimensions of vulnerability. Risk assessment determines the nature and extent of risk by analysing potential hazards and evaluating existing conditions of vulnerability that together could potentially harm exposed people, property, services, livelihoods, and the environment on which they depend.

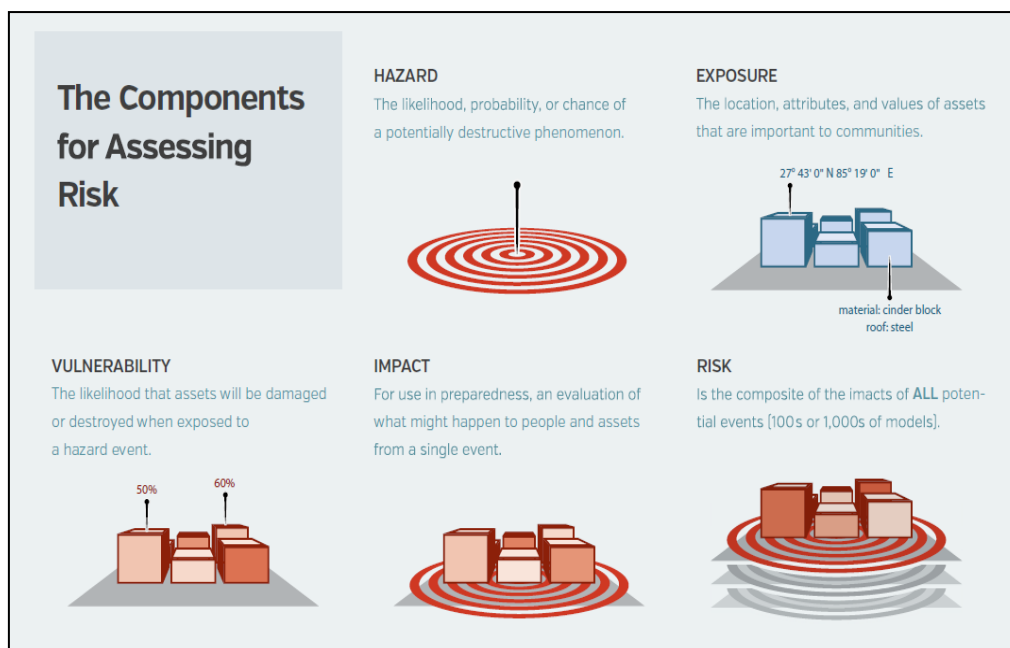


Figure 5-1: Components of risk assessment<sup>121</sup>

$$\text{RISK} = \text{HAZARD} \times \text{EXPOSURE} \times \text{VULNERABILITY}$$

Hence, risk is a combination of hazard, exposure, and vulnerability and has been estimated for various exposure elements (point, line, and polygon). This study employed a probabilistic model-based risk assessment.

As mentioned above, the hazards considered for the study mainly includes floods, cyclonic winds, landslide, storm surge and drought. For these hazards, the team used a probabilistic modelling approach. Probabilistic modelling generates hazard and risk scenarios for various return periods. For instance, the 100-year return period flood means that a flood of this magnitude has a 1% chance of occurring in any given year. In other words, the chances that a river will flow as high as the 100-year flood this year are 1 in 100. It does not mean that a flood of this magnitude will occur once in 100 years only.

In the present study, economic losses are calculated for every probabilistic scenario and for all types of assets at risk, e.g., residential buildings, critical facilities, transport infrastructure, and agriculture. This information helps government and district administrators take intervention measures and prioritize them.

The resulting economic losses are presented as PML as well as AAL for each hazard. Both metrics are useful in disaster risk reduction and planning. For example, AAL provides an indication of average sector wise losses, helping to allocate budgets for risk reduction and take proactive measures to mainstream DRR into development planning, while return period scenarios and PML are useful for mitigation planning.

The following is a description of risk assessment methodology and key definitions:

<sup>121</sup> GFDRR report "Understanding Risk in an Evolving World", 2014

<p><b>Average Annual Loss (AAL):</b> Annual average loss (AAL) is the average of the annual aggregate losses.</p>
<p><b>Exceeding Probability:</b> It is the probability of exceeding specified loss thresholds. In risk analysis, this probability relationship is commonly represented as a curve (the EP curve) which defines the probability of various levels of potential loss for a defined structure or portfolio of assets at risk of loss from natural hazards.</p>
<p><b>Exposure cost:</b> The total value or replacement cost of assets that are at risk from a loss-causing event.</p>
<p><b>Hazard:</b> A potentially damaging physical event, phenomenon or human activity that may cause the loss of life or injury, damage to property, social and economic disruption, and environmental degradation.</p>
<p><b>Return period (RP):</b> The expected length of time between recurrences of two events with similar characteristics. For instance, a 100year RP means the probability of occurrence of a particular severity of an event is 1/100 in a given year</p>
<p><b>Risk:</b> The probability of harmful consequences or expected loss (loss of human life, property, livelihoods, disrupted economic activity, or environmental damage) resulting from interactions between natural or human induced hazards and vulnerable conditions.</p>
<p><b>Vulnerability:</b> Degree of loss to a system or structure resulting from exposure to a hazard of a given severity</p>

## 5.2 Methodology for Risk Assessment

Hazards with adequate historical event data are considered for probabilistic risk modeling - flood, cyclonic wind, and storm surge hazards were analyzed at the state and district levels. The estimation of losses to various exposure elements were expressed in terms of AAL and PML for various return periods as described below:

The assessment of risk starts with the estimation of losses to various exposure elements for every historical and probabilistic event for which the hazard was assessed. The probabilistic scenarios were used to estimate AAL (Figure 5-2) for every exposure type and for different

hazards (flood, cyclonic wind, and storm surge).

The probability weighted average of all possible losses is termed as AAL. In the present risk assessment exercise, losses are presented in terms of AAL and PMLs for various key return periods. The term “25-year loss” means a loss that can occur about once every 25 years on an average, given what we know about the hazard occurrence. Such a “25-year loss” in actuality has a  $1/25 = 0.04$  probability of occurrence in any one year. Similarly, a “100-year loss” has a probability per year (or “per annum”, pa) of  $1/100 = 0.001$ .



Figure 5-2: Sample of AAL

### 5.3 Estimation of economic/financial loss and damage

Economic loss has two main components; i) Direct loss which occurs due to the direct impact of the hazard on assets, and ii) Social loss which refers to the consequential impact of the hazard on people and their livelihoods.

Direct loss typically is quantified as the replacement or repair cost, and the content values of the assets are also considered. Direct loss is a function of the damage ratio derived in the vulnerability module, translated into currency loss by multiplying the damage ratio by the value at risk.

*Direct loss is calculated for every probabilistic scenario and for all types of exposure at risk like residential, commercial, and industrial buildings, essential facilities, and transport infrastructure. This is done for each asset class at each location where the treatment of location differs for different hazards and asset classes. Losses are then aggregated at ward-level.*

### 5.4 Determining risk for different exposure elements

Based on the above approach, losses were computed for all the exposure elements discussed in the Exposure and Vulnerability Report submitted earlier. These elements are categorized into two broad categories - aggregated exposure and site-specific exposure.

**Site-specific exposure:** Site-specific exposure was further divided into two types – point location type exposure like schools, hospitals, police stations, fire stations, etc. and line type exposure like roads, railway lines, electric transmission lines, pipelines, etc.

**Point Type Exposure:** For point type exposure elements, the loss computation was conducted at the point location level based on the hazard intensity estimated at the location for various stochastic events. The Average Annual Loss (AAL) was computed for every location of the exposure element. Consequently, the loss for these elements was available at the location level and aggregated at various administrative levels.

**Line Type Exposure:** The treatment for line type exposure differs from that of point type exposure. Since line type exposure elements are spread over a long area, a single hazard value cannot be used to estimate the losses. Instead, a line type exposure element is made into a set of smaller segments, and the loss is estimated at the centroid of each segment. The losses of all the segments are then summed up to estimate the total losses for the line-type exposure elements. shows an example of the segments for railway lines where the losses were estimated.

The estimated PML and AAL to residential buildings and various sectors, as well as their contributions to the total losses in the state due to cyclonic wind, storm surge, and flood hazards are provided in the sections below.

## 5.5 Risk Assessment - Flood Hazard

In the risk assessment, RMSI NatCAT modelling team was considered following exposure types such as residential buildings (housing sector), critical facilities (school, hospital, police station, fire station and cyclone shelter), govt. buildings, transport infrastructure (State and below level roads, bridges and bus station/ Bus depos) and agriculture (rice, banana, tapioca, coconut and arecanut).

### 5.5.1 PROBABLE MAXIMUM LOSSES FOR FLOOD

The state level losses for key exposure elements for Kerala for key return periods (10, 25, 50, 100, 250 and 500)-years is provided in Table 5-1. The analysis shows that economic losses to residential buildings are the highest, followed by Transport Infrastructures.

Table 5-1: State-level flood losses for key return periods for all considered exposure types

Category	Total Flood Loss (INR Crores)					
	10 RP	25 RP	50 RP	100 RP	250 RP	500 RP
Residential Buildings	3,029.0	5,667.1	6,285.5	10,395.1	17,679.7	19,371.6
Transport Infrastructure	427.8	753.0	977.4	1,529.7	2,492.1	3,054.5
Agriculture	269.7	291.7	313.6	335.1	356.9	374.3
Critical Facilities	24.2	45.1	112.6	188.9	354.5	424.5
Government Buildings	1.8	3.6	28.7	48.7	118.9	129.8

### 5.5.2 DISTRICT-WISE PROBABLE MAXIMUM LOSS FOR FLOOD

The summary of flood losses for the key return periods (10, 25, 50, 100, 250 and 500 years) for all the districts of Kerala are provided in Table 5-2.

. The total losses have been calculated by aggregating the PML to various exposure elements considered for this study (residential buildings, critical facilities, government buildings, transport infrastructure, and agriculture).

The flood risk assessment carried out show that for a 500-year return period, the highest economic loss of INR 4,470 /- Crores may occur in the Alappuzha district.

The distribution of PML due to flood hazard for a 100-year return period among key sectors for Kerala is presented in Figure 5-3. It can be seen from the figure that residential buildings contribute about 83.20 % of the total losses, followed by the Transport Infrastructure that contributes about 12.20% of the total losses.

Spatial distribution of the total PML at district-level due to various exposure elements considered in this study for a 100-year return period flood hazard is shown in Figure 5-4. These exposure elements include residential buildings, critical facilities, government buildings, transport infrastructure, and the agriculture sector.

Table 5-2: District-wise key return periods losses for flood hazard

District Name	Total wind residential, Govt. buildings, critical facilities, transport and agriculture Loss (INR Crores) for various return periods					
	10	25	50	100	250	500
Alappuzha	726.3	1,336.8	1,514.4	2,452.7	4,067.1	4,469.7
Ernakulam	713.2	1,300.8	1,455.7	2,306.9	3,791.5	4,183.8
Idukki	264.0	487.8	591.7	1,036.8	2,022.5	2,357.4
Kannur	58.4	91.5	105.6	147.5	212.7	239.7
Kasaragod	36.8	63.3	75.3	120.2	204.4	250.7
Kollam	79.3	142.3	181.9	343.0	695.7	923.3
Kottayam	296.7	543.8	611.4	984.2	1,586.0	1,691.0
Kozhikode	95.1	167.5	200.0	322.1	551.4	643.7
Malappuram	97.1	179.8	213.0	356.0	585.4	632.3
Palakkad	257.5	449.6	507.4	804.7	1,301.1	1,422.5
Pathanamthitta	317.7	529.9	606.6	941.0	1,522.0	1,678.1
Thiruvananthapuram	78.8	141.9	153.8	243.2	385.8	424.8
Thrissur	504.6	901.6	1,015.9	1,658.0	2,801.3	3,059.0
Wayanad	227.0	423.8	485.1	781.2	1,275.4	1,378.6

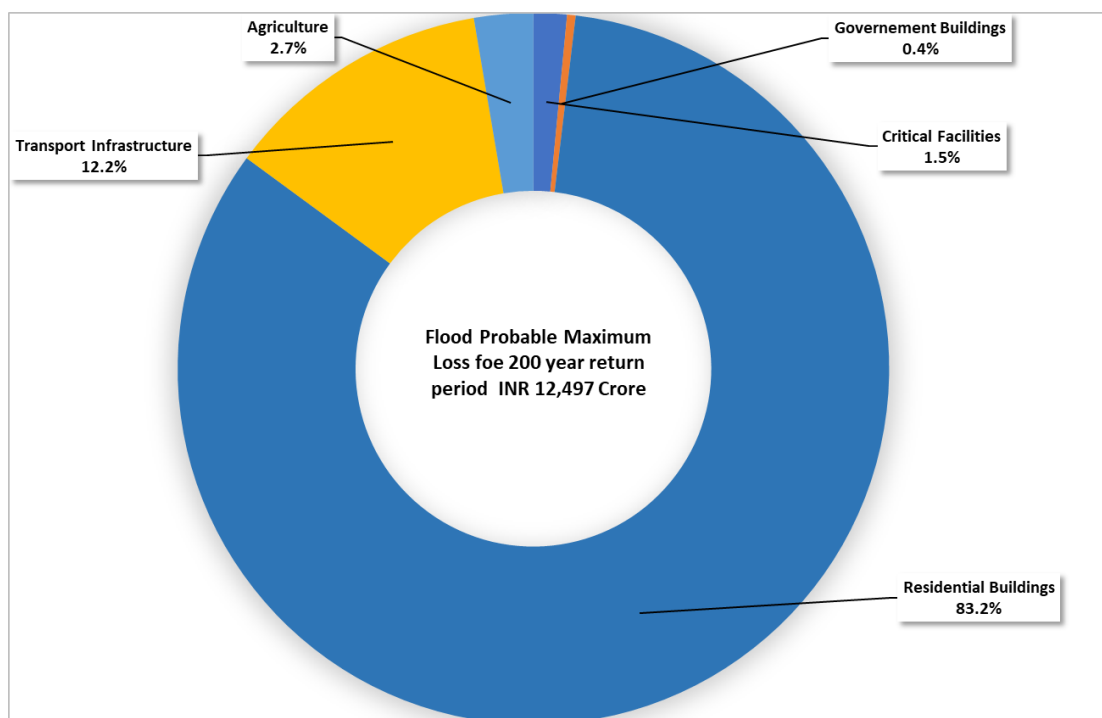


Figure 5-3: Flood losses with sector contribution to total losses for a 100-year return period

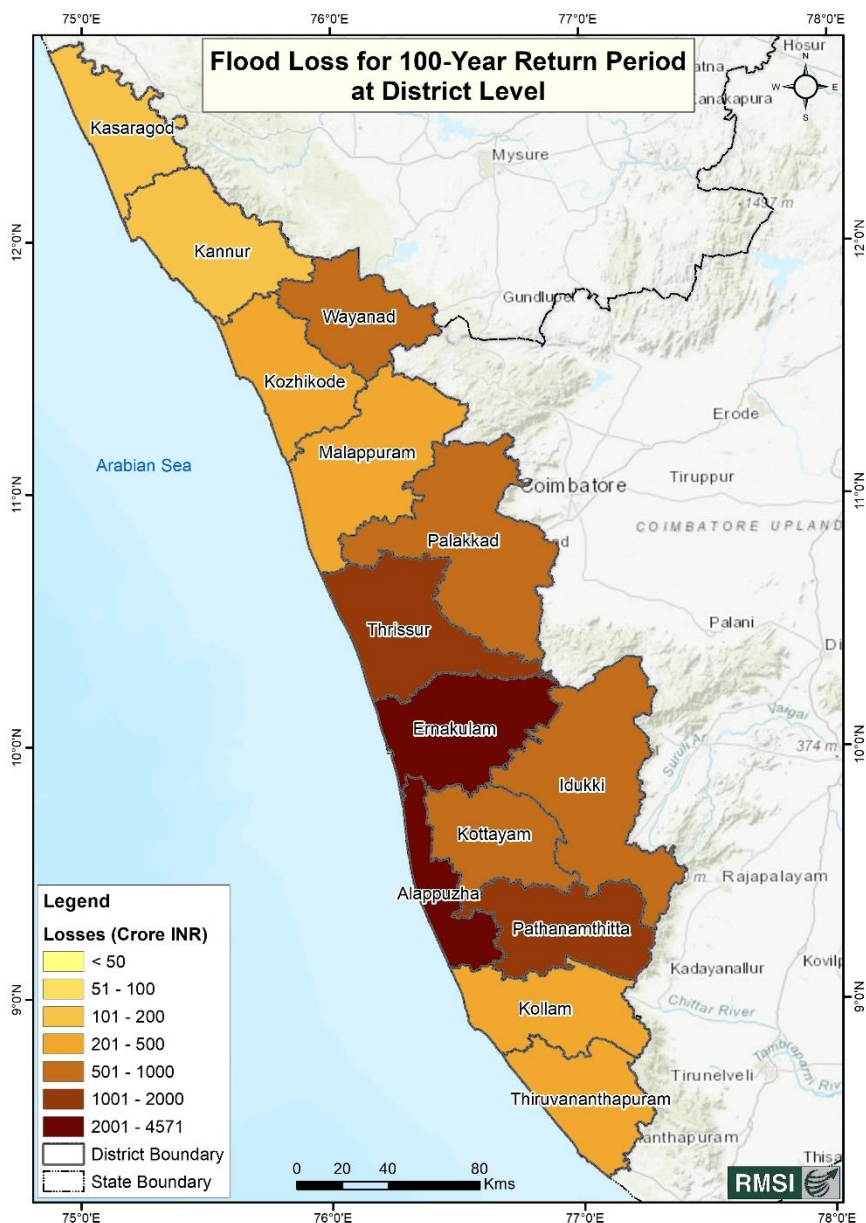


Figure 5-4: Flood PML map of 100-year return period

### 5.5.3 AVERAGE ANNUAL LOSS FOR FLOOD

The AAL due to flood hazard has been estimated at the LSG level, which are summarized at Taluka and District level and presented here at the district-level for various sectors. A summary is presented in Table 5-3, which presents the total value of assets (exposure) in the state, the total AAL (estimated to be INR 1,331.6 Crores), and the percentage of this loss compared to the total exposure value. The estimated AAL accounts for approximately 0.036% of the total exposure value of various exposure elements considered in this study

in the state. The distribution of AAL among key sectors due to flood hazard is shown in Table 5-4. The total value of assets exposed to flood and the total AAL for residential buildings and various other exposure elements in Kerala is provided in Figure 5-5. It is clearly evident from the figure that the AAL contribution is highest for residential buildings, which account for 79.2 % of the total losses. The Transport Infrastructure is another significant contributor to losses due to flood (10.5 %).

Table 5-3: Total AAL loss due to the flood hazard

State	Total Exposure Value, INR Crores (Structure + Content + Agriculture)	Total AAL, INR Crores (Buildings +Transport + Agriculture)	% AAL with respect to Total Exposure
Kerala	36,27,962	1,331.6	0.036%

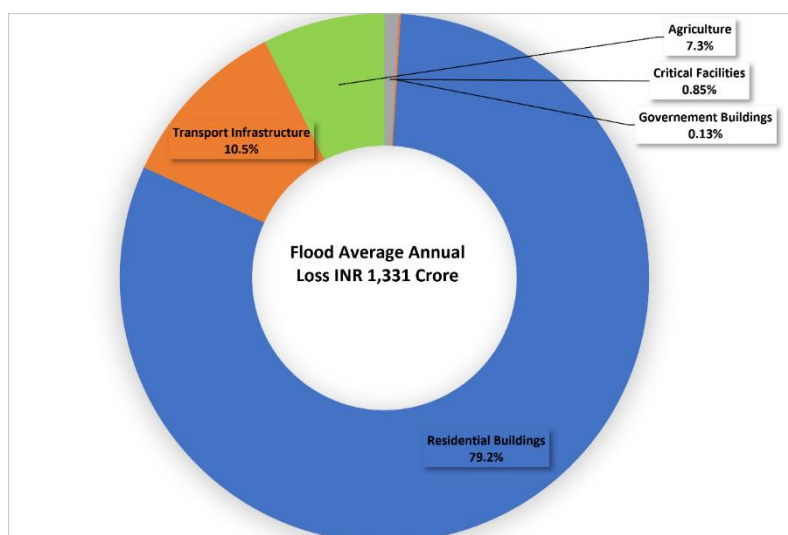


Figure 5-5: Sector wise distribution of flood average annual loss

Table 5-4: Flood AAL for various exposure types

Category	Total AAL, INR Crores (Buildings +Transport + Agriculture)	AAL (%) w.r.t Total AAL
Residential Buildings	1,081.9	79.22%
Transport Infrastructure	139.4	10.47%
Agriculture	97.3	7.31%
Critical Facilities	11.3	0.85%
Government Buildings	1.7	0.13%

#### 5.5.4 DISTRICT-WISE AVERAGE ANNUAL LOSS FOR FLOOD

The district-wise total AALs due to flood for residential buildings, critical facilities, government buildings, transport sector, and agriculture exposure is given in Table 5-5. The AAL numbers indicate that 3 districts are highly vulnerable, and 5 districts are moderately vulnerable, while 6 districts are low in vulnerability to flood hazard. Analysis shows that Ernakulam

district has the highest AAL of INR 265.3 Crores, followed by Alappuzha, and Thrissur district. Therefore, from AAL perspective, these three districts need more attention due to flood hazard.

Spatial distribution of the district-level AAL for the considered exposure elements of Kerala is also depicted in Figure 5-6.

Table 5-5: District-wise total AAL due to flood hazard

Kerala Districts	Total AAL, INR Crores (Structure + Content+ Agriculture)	AAL (%) w.r.t Total AAL
Alappuzha	250.0	18.8%
Ernakulam	265.3	19.9%
Idukki	93.6	7.0%
Kannur	19.4	1.5%
Kasaragod	13.0	1.0%
Kollam	28.8	2.2%
Kottayam	101.3	7.6%
Kozhikode	31.8	2.4%
Malappuram	32.0	2.4%
Palakkad	93.2	7.0%
Pathanamthitta	117.4	8.8%
Thiruvananthapuram	26.1	2.0%
Thrissur	184.5	13.9%
Wayanad	75.3	5.7%
<b>Grand Total</b>	<b>1331.6</b>	<b>100%</b>

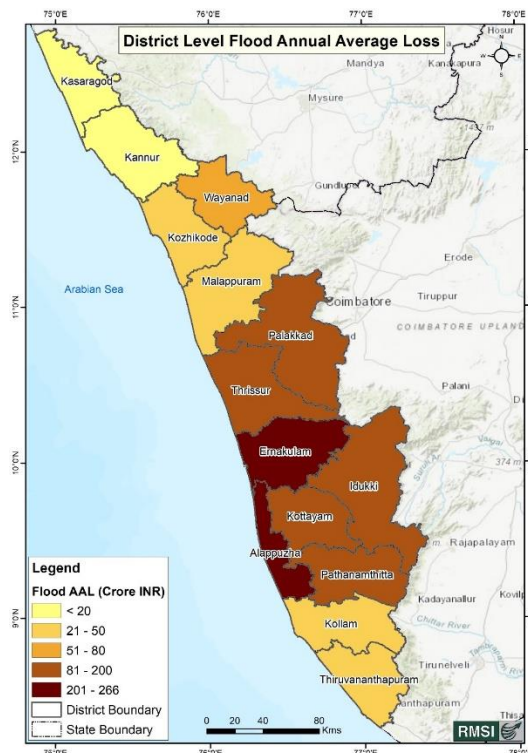


Figure 5-6: District level spatial distribution of AAL due to flood hazard

### **5.5.5 SUMMARY**

The AAL due to flood hazard for Kerala is INR 1331 Crores. Residential buildings are the major contributor to economic losses, followed by the Transport Infrastructure. The highest estimated AAL is around INR 265.3 Crores for Ernakulam district, followed by Alappuzha district with an estimated AAL of about INR 250 Crores. The estimated losses of residential buildings for a 100-year return period hazard are highest for Alappuzha district followed by Ernakulum district with estimated losses of INR 2,479 Crores and INR 2,357 Crores, respectively. From the AAL perspective, Ernakulum, Alappuzha and Thrissur, districts are at the highest risk of flood hazard.

## 5.6 Risk Assessment - Cyclonic Wind

### 5.6.1 PROBABLE MAXIMUM LOSSES FOR CYCLONIC WIND

The state-level losses for key exposure elements for Kerala for key return periods (10, 25, 50, 100, 250, and 500-years) are provided in Table 5-6. The analysis shows that economic losses to residential buildings are the highest, followed by agriculture sector.

### 5.6.2 DISTRICT-WISE PROBABLE MAXIMUM LOSS FOR CYCLONIC WIND

The summary of cyclonic wind losses for the key return periods (10, 25, 50, 100, 250

and 500 years) for all the districts of Kerala are provided in Figure 5-7. The total losses have been calculated by aggregating the PML to various exposure elements considered for this study (residential buildings, critical facilities, government buildings, transport infrastructure (bus station / bus depo), and agriculture).

The estimated losses show that for a 500-year return period, the highest loss occurred for Palakkad district followed by Malappuram with an estimated loss of about INR 1,293.67 Crores and 1,074.69 Crores, respectively.

Table 5-6: State-level cyclonic wind losses for key return periods for all exposure types considered

Category	Total Cyclonic Wind Loss (INR Crores)					
	10 RP	25 RP	50 RP	100 RP	250 RP	500 RP
Residential Buildings	22.27	136.46	661.34	1,603.32	4,229.19	7,863.96
Agriculture	138.90	353.61	609.10	960.65	1,443.21	1,896.66
Critical Facilities	0.17	1.99	9.69	23.37	62.38	115.40
Government Buildings	0.01	0.09	0.45	1.14	3.11	5.81
Transport Infrastructure	0.00	0.03	0.15	0.38	1.00	1.86

Table 5-7: District-wise key return periods losses for cyclonic wind hazard

District Name	Total Cyclonic Wind Loss (INR Crores) for Various Return Periods					
	10 RP	25 RP	50 RP	100 RP	250 RP	500 RP
Palakkad	34.42	93.97	202.16	366.07	758.84	1,293.67
Malappuram	17.84	65.03	159.73	306.77	638.19	1,074.69
Ernakulam	16.64	52.05	146.53	274.79	597.89	1,037.19
Thrissur	15.74	34.96	118.01	227.43	519.15	899.87
Kozhikode	4.89	24.42	91.46	202.46	468.70	817.79
Kannur	3.94	17.06	47.73	152.72	411.40	728.55
Thiruvananthapuram	4.58	17.09	56.03	159.13	404.63	726.83
Kollam	6.13	20.68	70.83	156.46	375.66	664.65
Kottayam	15.64	41.02	91.20	163.98	337.65	591.40
Idukki	9.62	32.00	76.74	145.57	309.61	518.36

District Name	Total Cyclonic Wind Loss (INR Crores) for Various Return Periods					
	10 RP	25 RP	50 RP	100 RP	250 RP	500 RP
Wayanad	17.51	53.03	102.71	169.84	303.17	470.66
Alappuzha	8.70	16.18	50.47	110.35	260.46	440.92
Pathanamthitta	4.74	17.43	48.39	90.55	195.87	337.07
Kasaragod	0.94	7.25	18.74	62.74	157.66	282.04

The distribution of PML due to cyclonic wind hazard for a 250-year return period among key sectors in Kerala is presented in Figure 5-7. It can be seen from the figure that residential buildings contribute about 73.69% of the total losses, followed by the agriculture sector which contributes about 25.15%.

Spatial distribution of the total losses at district-level due to cyclonic wind for all exposure types for a 250-year return period is shown in Figure 5-8. These exposure elements include residential buildings, critical facilities, government buildings, transport infrastructure, and the agriculture sector.

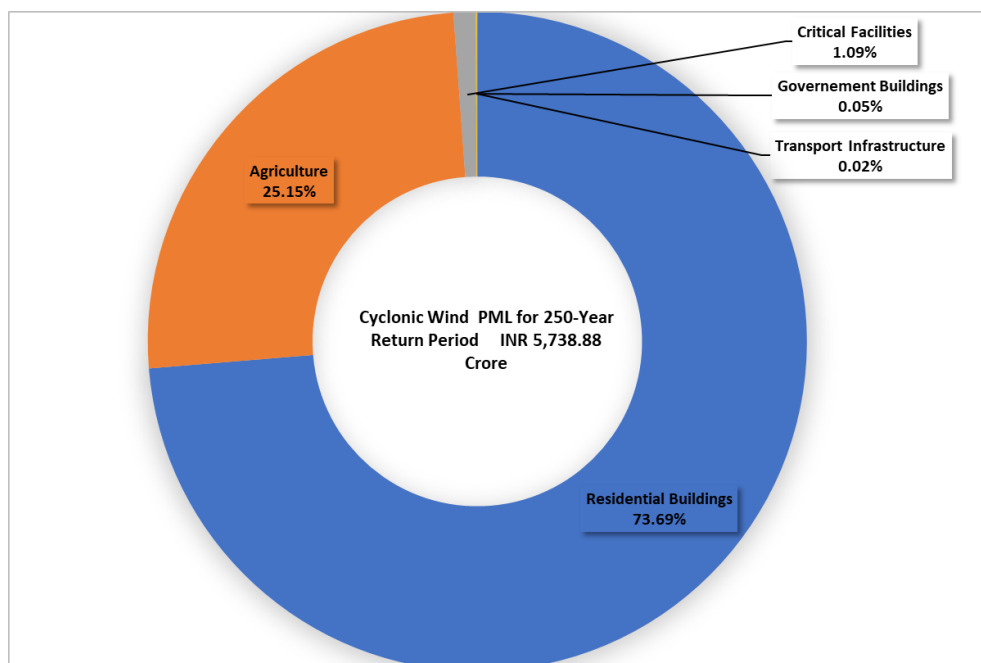


Figure 5-7: Cyclonic wind losses with sector contribution to total PML for a 250-year return period

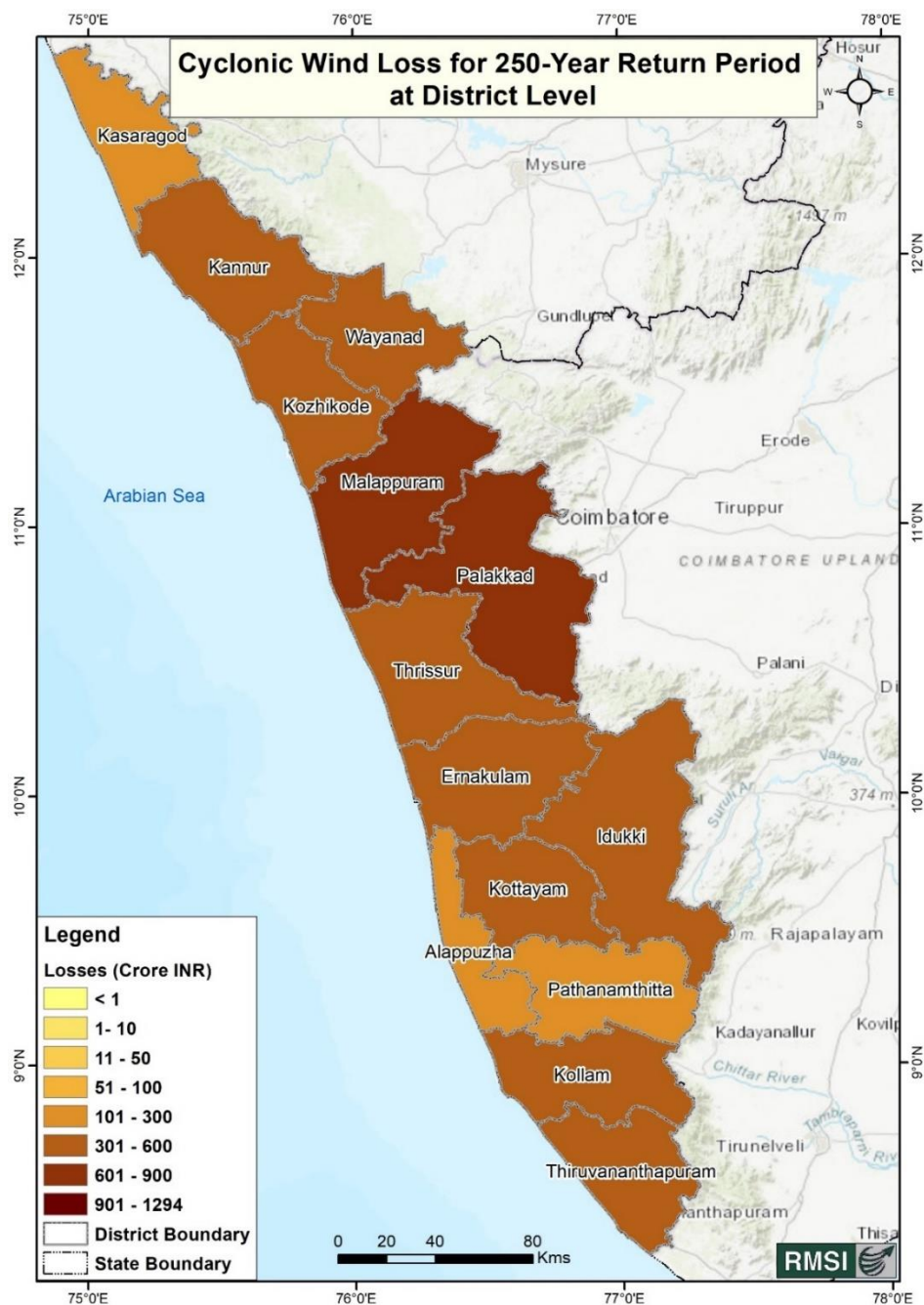


Figure 5-8: Cyclonic wind loss map of 250-year return period for Kerala

### 5.6.3 AVERAGE ANNUAL LOSS FOR CYCLONIC WIND

The AAL due to cyclonic wind hazard has been estimated at the district-level for various sectors. A summary is presented in Table 5-8.

which presents the total value of assets in the state, the total AAL (estimated to be INR 83.66 Crores), and the percentage of this loss compared to the total exposure value. This accounts for approximately

0.0023% of the total exposure value on the state.

The distribution of AAL among key sectors due to cyclonic wind hazard is shown in Figure 5-9. It is clearly evident from the figure that the AAL contribution is highest for residential buildings, which accounts for 53.17% of the total losses followed by the agriculture sector (46.01%).

Table 5-8: Total AAL loss due to the cyclonic wind hazard

State	Total Exposure Value (INR Crores)	Total AAL (INR Crores)	% AAL with respect to Total Exposure
Kerala	36,27,962	83.66	0.0023

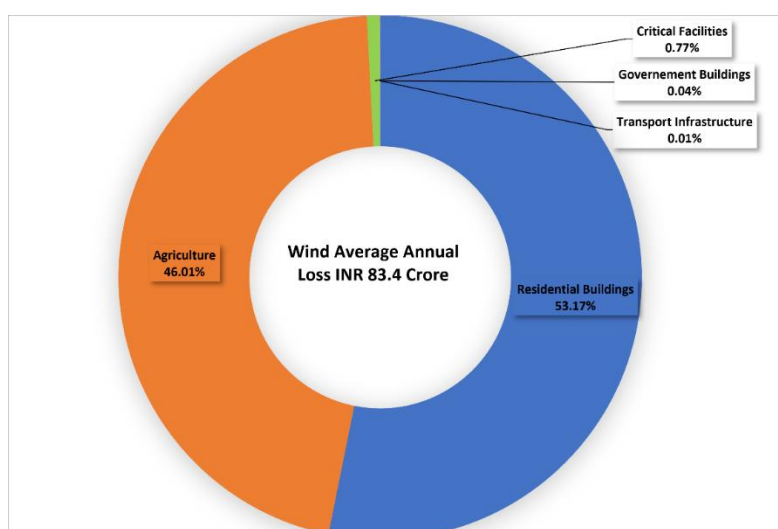


Figure 5-9: Sector-wise distribution of cyclonic wind average annual losses

Table 5-9: AAL for various exposure types due to cyclonic wind

Category	Total AAL (INR Crores)	AAL (%) w.r.t Total Loss
Residential Buildings	44.49	53.17
Agriculture	38.49	46.01
Critical Facilities	0.64	0.77
Government Buildings	0.03	0.04
Transport Infrastructure	0.01	0.01

#### 5.6.4 DISTRICT-WISE AVERAGE ANNUAL LOSS FOR CYCLONIC WIND

The district-wise total AALs due to cyclonic wind for residential buildings, critical facilities, government buildings, transport infrastructure, and agriculture exposure is given in Table 5-10. Analysis shows that Palakkad district has the highest AALs, followed by Malappuram district. These two districts need more attention with regard to cyclonic winds. Analysis also indicates that

the non-coastal district Wayanad is also moderately vulnerable to cyclonic winds.

Spatial distribution of district-level AAL for all considered exposure elements of Kerala is depicted in Figure 5-10. The AAL contribution indicate that 7 districts are moderately vulnerable (Palakkad, Malappuram, Ernakulam, Thrissur, Wayanad, Kottayam, and Kozhikode),

while remaining 7 districts (Idukki, Kollam, Thiruvananthapuram, Kannur, Alappuzha, Pathanamthitta, and Kasaragod) are low in vulnerability to cyclonic wind hazard. Thus,

districts Palakkad, Malappuram, and Ernakulam require more attention with regard to cyclonic wind hazard.

Table 5-10: District-wise total AAL due to cyclonic wind hazard

Kerala Districts	AAL (INR Crores)	AAL (%) w.r.t Total Loss
Palakkad	13.50	16.14
Malappuram	9.66	11.54
Ernakulam	8.87	10.60
Thrissur	7.40	8.84
Wayanad	6.05	7.23
Kottayam	5.93	7.08
Kozhikode	5.55	6.64
Idukki	4.88	5.83
Kollam	4.67	5.58
Thiruvananthapuram	4.53	5.41
Kannur	4.32	5.16
Alappuzha	3.80	4.54
Pathanamthitta	2.86	3.42
Kasaragod	1.65	1.98

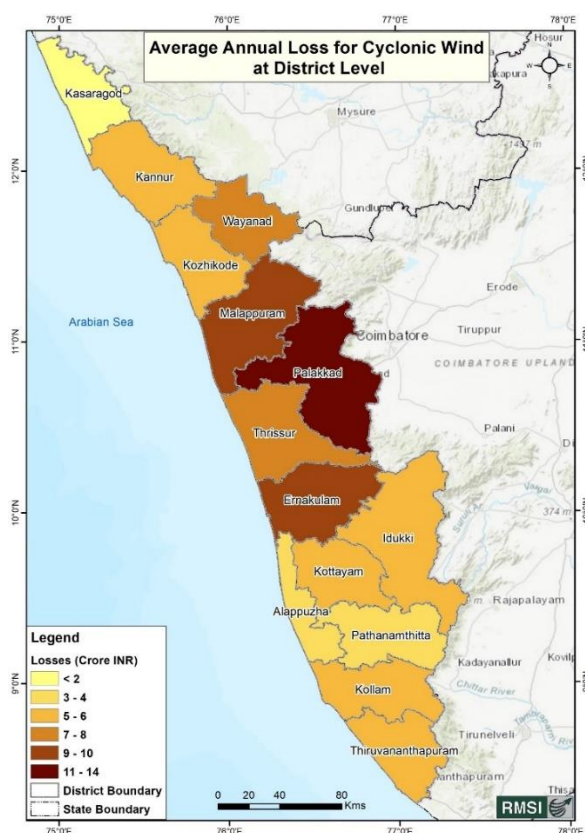


Figure 5-10: District-level AAL distribution of cyclonic wind

The district-wise AALs due to cyclonic wind for residential buildings is given in Table 5-11. Analysis shows that Palakkad district has the highest AAL (INR 13.5 Crores), followed by Malappuram (INR 9.66 Crores)

and Ernakulam (INR 8.87 Crores) districts. These three districts need more attention of residential buildings due to cyclonic wind hazard.

Table 5-11: District-wise cyclonic wind AAL for all exposure

Kerala Districts	Total AAL (INR Crores)	AAL (%) w.r.t Total Loss
Alappuzha	3.80	4.5%
Ernakulam	8.87	10.6%
Idukki	4.88	5.8%
Kannur	4.32	5.2%
Kasaragod	1.65	2.0%
Kollam	4.67	5.6%
Kottayam	5.93	7.1%
Kozhikode	5.55	6.6%
Malappuram	9.66	11.5%
Palakkad	13.50	16.1%
Pathanamthitta	2.86	3.4%
Thiruvananthapuram	4.53	5.4%
Thrissur	7.40	8.8%
Wayanad	6.05	7.2%

### 5.6.5 SUMMARY

The AAL due to cyclonic wind hazard for Kerala is INR 83.66 Crores. Residential buildings are the major contributor to economic losses, followed by agriculture sector. The highest estimated AAL is for Palakkad district, which is about INR 13.5 Crores followed by Malappuram and Ernakulam districts with an estimated AAL of about INR 9.66 Crores and 8.87 Crores, respectively. However, the estimated losses for a 250-year return period are highest for Palakkad district followed by Malappuram district, with estimated losses of INR 758.84 Crores and INR 638.19 Crores, respectively.

## 5.7 Risk Assessment-Storm Surge

### 5.7.1 PROBABLE MAXIMUM LOSSES FOR STORM SURGE

The state-level losses due to storm surge for key exposure elements for Kerala for key return periods (10, 25, 50, 100, 250, and 500-years) is provided in Table 5-12. The analysis shows that economic losses to residential buildings are the highest, followed by transport Infrastructure.

#### 5.7.1.1 District-wise Probable Maximum Loss for Storm Surge

The summary of storm surge losses for the key return periods (10, 25, 50, 100, 250 and 500 years) for all the districts of Kerala area provided in Table 5-13. The total losses have been calculated by aggregating the PML to various exposure elements considered for this study (residential buildings, critical facilities, government buildings, transport infrastructure, and agriculture).

The estimated losses show that for a 500-year return period, the highest loss

occurred for Alappuzha district followed by Ernakulam district with an estimated loss of about INR 81.8 Crores and INR 46.3 Crores, respectively.

The distribution of PML due to storm surge hazard for a 250-year return period among key sectors for Kerala is presented in

Figure 5-11: Storm surge losses with sector contribution to total PML for a 250-year return period

It can be seen from the figure that residential buildings contribute about 52.66% of the total losses, followed by the Transport Infrastructure that contributes about 31.46% of the total losses.

Spatial distribution of the total PML at LSG-level due to storm surge for all exposure types for a 250-year return period is shown in Figure 5-12. These exposure elements include residential buildings, critical facilities, transport infrastructure, and the agriculture sector.

Table 5-12: State-level storm surge losses for key return periods for all considered exposure types

Category	Total Cyclonic Wind Loss (INR Crores)					
	10 RP	25 RP	50 RP	100 RP	250 RP	500 RP
Residential Buildings	30.5	33.8	53.6	79.1	122.7	157.1
Transport Infrastructure	15.5	20.7	32.8	50.7	73.3	95.1
Agriculture loss	4.5	6.8	15.0	24.6	35.3	41.0
Critical Facilities	0.2	0.2	0.7	1.0	1.5	2.2
Government Buildings	0.03	0.03	0.07	0.10	0.17	0.21

Table 5-13: District-wise key return periods losses for storm surge hazard

District Name	Total surge residential, Govt. buildings, critical facilities, transport and agriculture Loss (INR Crores) for various return periods					
	10	25	50	100	250	500
Alappuzha	13.4	18.2	30.9	45.9	67.3	81.8
Ernakulam	8.4	9.7	14.2	21.4	34.8	46.3
Idukki	-	-	-	-	-	-
Kannur	3.8	4.2	7.0	10.9	16.0	21.5

Kasaragod	3.1	3.2	4.8	6.9	9.4	11.9
Kollam	6.5	7.5	9.4	13.1	19.1	21.9
Kottayam	6.0	7.5	14.8	22.7	35.6	44.3
Kozhikode	3.1	3.4	5.6	7.8	10.4	13.6
Malappuram	1.9	2.2	3.1	4.6	6.3	8.3
Palakkad	-	-	-	-	-	-
Pathanamthitta	0.8	1.1	1.8	2.9	4.5	5.5
Thiruvananthapuram	1.7	2.0	3.5	5.6	7.8	9.8
Thrissur	2.0	2.8	7.0	13.7	21.7	30.6
Wayanad	-	-	-	-	-	-

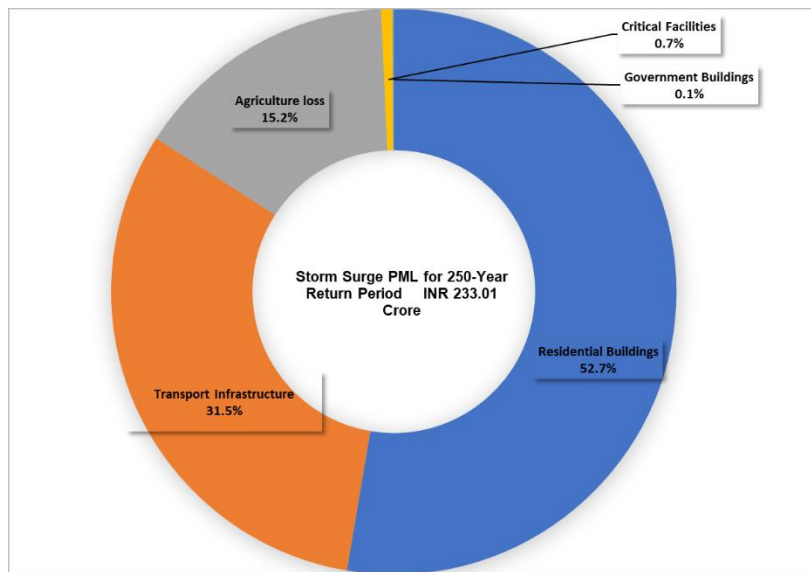


Figure 5-11: Storm surge losses with sector contribution to total PML for a 250-year return period

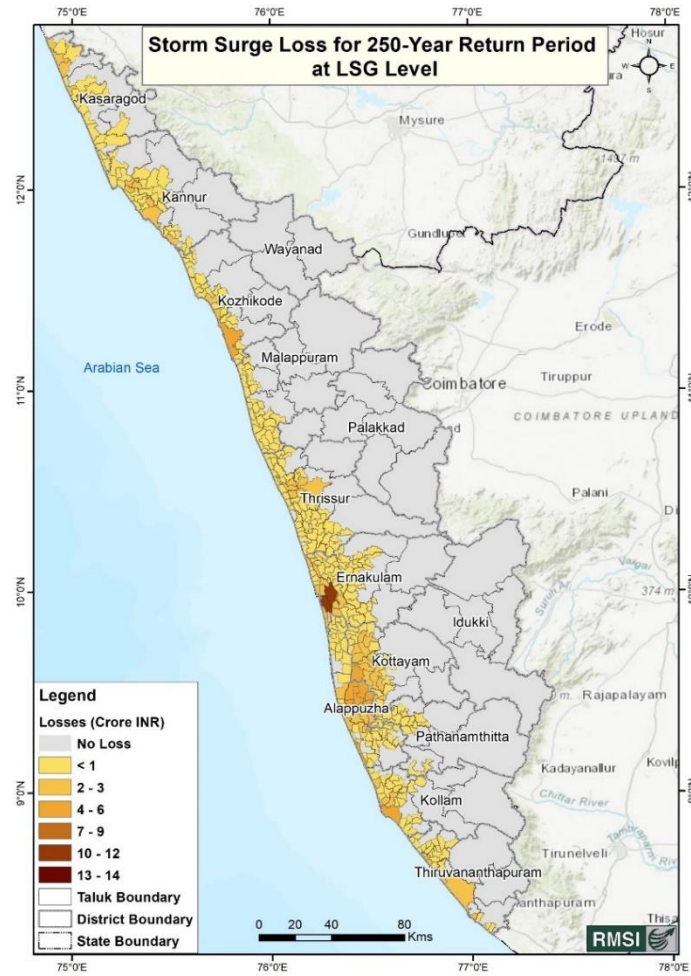


Figure 5-12: storm surge loss map of 250-year return period for Kerala

### 5.7.2 AVERAGE ANNUAL LOSS FOR STORM SURGE

The total AAL due to storm surge hazard has been estimated at the district-level for various sectors. A summary is presented in Table 5-14, which presents the total value of assets in the state, the total AAL (estimated to be INR 14.96 Crores), and the percentage of this loss compared to the total exposure value. This accounts for approximately 0.0004% of the total exposure value in the state.

The distribution of AAL among key sectors due to storm surge hazard is shown in

Figure 5-13. The total value of assets exposed to storm surge and the total AAL for residential buildings and various other exposure elements in Kerala is provided in Table 5-15. It is clearly evident from the figure that the AAL contribution is highest for residential buildings, which account for 51.7% of the total losses. The transport infrastructure is another significant contributor to losses due to storm surge (36.76%).

Table 5-14: Total AAL loss due to the storm surge hazard

State	Total Exposure Value, INR Crores	Total AAL, INR Crores	AAL (%) w.r.t Total AAL
Kerala	36,27,962	14.96	0.0004

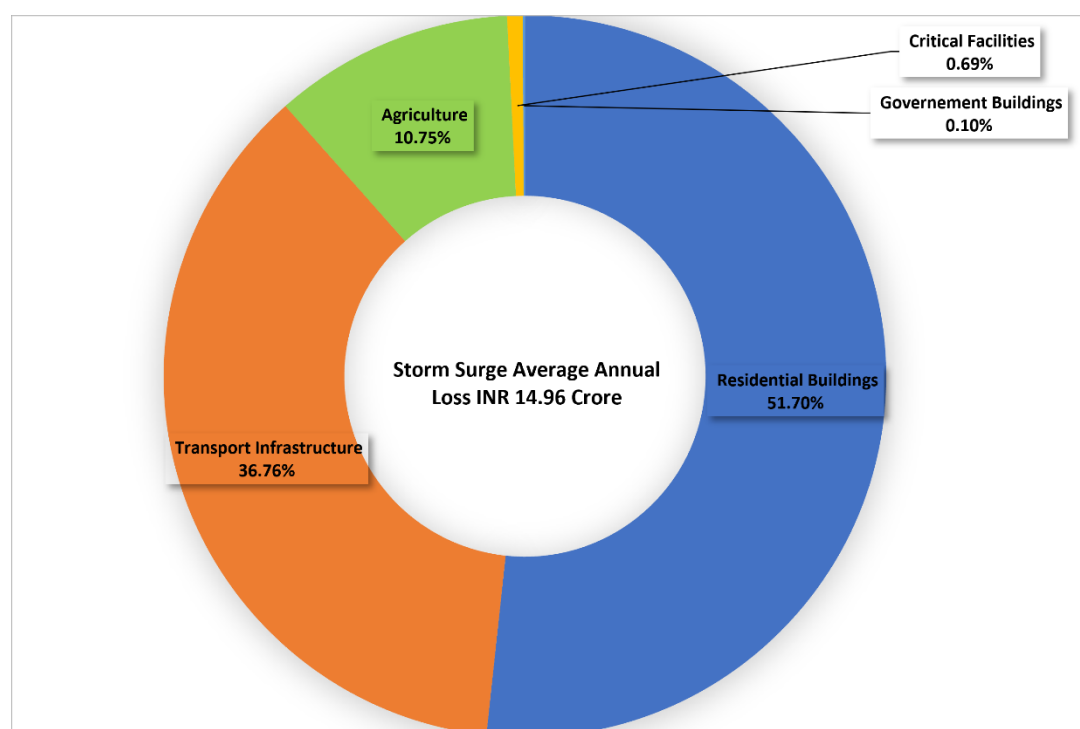


Figure 5-13: Sector-wise distribution of storm surge average annual loss

Table 5-15: AAL for various exposure types due to storm surge

Category	Total AAL (INR Crores)	AAL (%) w.r.t Total Loss
Residential Buildings	7.74	51.70
Transport Infrastructure	5.5	36.76
Agriculture	1.61	10.75
Critical Facilities	0.10	0.69
Government Buildings	0.01	0.10

### 5.7.3 DISTRICT-WISE AVERAGE ANNUAL LOSS FOR STORM SURGE

The district-wise total AALs due to storm surge for residential buildings, critical facilities, government buildings, transport sector, and agriculture exposure is given in Table 5-16. The analysis shows that Alappuzha district has the highest AAL, followed by Ernakulam and Kollam districts. The AAL contribution indicate that coastal district Alappuzha is moderately vulnerable, while remaining 10 districts (Ernakulam, Kollam, Kottayam, Kannur, Kasaragod, Kozhikode, Malappuram, Thrissur, Thiruvananthapuram, and Pathanamthitta) are low in vulnerability to storm surge hazard. Thus, district Alappuzha require more attention with regard to storm surge hazard. These two districts need more attention with regard to storm surges.

Spatial distribution of LSG-level AAL for all considered exposure elements of Kerala is depicted in Figure 5-14.

### 5.7.4 SUMMARY

The AAL due to storm surge hazard for Kerala is INR 14.96 Crores. Residential buildings are the major contributor to economic losses, followed by the transport infrastructure and agriculture sector. The highest estimated AAL is around INR 3.4 Crores for Alappuzha district, followed by Ernakulam district with an estimated AAL of about INR 2.5 Crores. However, the estimated losses for a 250-year return period are highest for Alappuzha district followed by Ernakulam district with estimated losses of INR 67.3 Crores and INR 34.8 Crores, respectively.

Table 5-16: District-wise total AAL due to storm surge hazard

Kerala Districts	AAL (INR Crores)	AAL (%) w.r.t Total AAL
Alappuzha	3.4	22.4%
Ernakulam	2.5	17.0%
Idukki	-	0.0%
Kannur	1.4	9.4%
Kasaragod	1.0	6.6%
Kollam	1.9	12.7%
Kottayam	1.8	11.9%
Kozhikode	1.0	6.6%
Malappuram	0.7	4.5%
Palakkad	-	0.0%
Pathanamthitta	0.2	1.3%
Thiruvananthapuram	0.5	3.3%
Thrissur	0.7	4.4%
Wayanad	-	0.0%

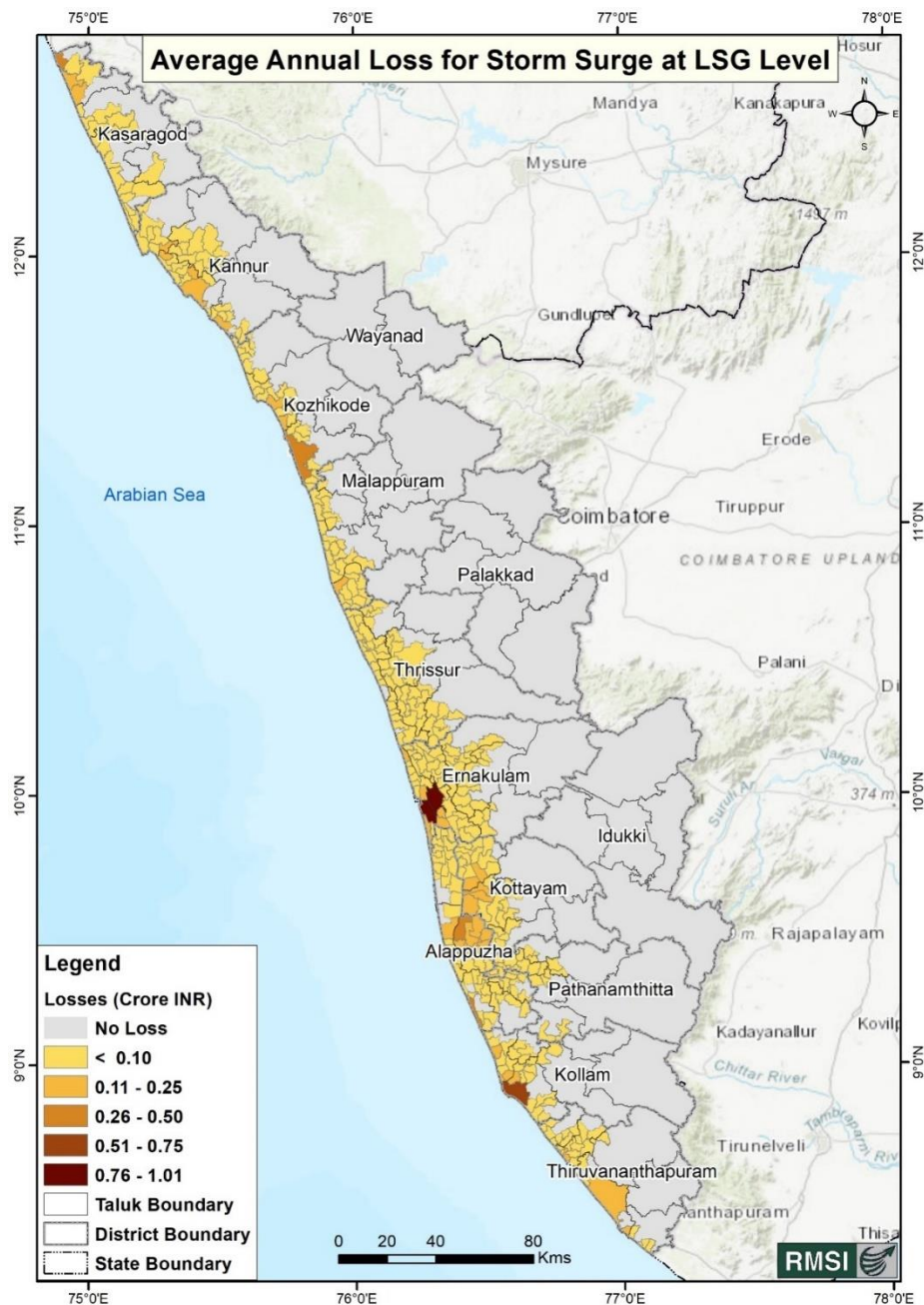


Figure 5-14: LSG-level AAL distribution for storm surge hazard

## 5.8 Risk Assessment - Landslide

### 5.8.1 PROBABLE MAXIMUM LOSSES FOR LANDSLIDE

The state-level losses for key building exposure elements including residential buildings, critical facilities (schools, hospitals) Govt offices, roads, and major agriculture crops including (Coconut, Arecanut, Rice & Banana) for Kerala for key return periods (10, 25, 50, 100, 250, 500, and 1000-years) is provided in Table

5-17. The analysis shows that economic losses to residential buildings are the highest, followed by transport infrastructure.

### 5.8.2 DISTRICT-WISE PROBABLE MAXIMUM LOSS FOR LANDSLIDE

The summary of landslide losses for the key return periods (10, 25, 50, 100, 250, 500 and 1000 years) for all the districts of Kerala are provided in Table 5-18. The total losses have been calculated by aggregating the PML to residential buildings, critical facilities, Govt offices, transport infrastructure and agriculture crops including (Coconut, Arecanut, Rice & Banana). exposure elements considered in this study.

The estimated losses show that for a 1000-year return period, the highest loss

occurred for Idukki district followed by Palakkad with an estimated loss of about INR 23,996 Crores and INR 2538.2 Crores, respectively.

The distribution of PML due to landslide hazard for a 1000-year return period among various sectors in Kerala is presented in Figure 5-15. It can be seen from the figure that residential buildings contribute about 84.68% of the total losses, followed by the Transport Infrastructure that contributes about 14.61% of the total losses.

Table 5-17: State-level Landslide losses for key return periods for all considered exposure types

Category	Total Landslide Loss (INR Crores)						
	10 RP	25 RP	50 RP	100 RP	250 RP	500 RP	1000 RP
Residential Buildings	226.4	375.7	525.1	768.0	2,072.3	4,376.5	26,960.2
Transport Infrastructure	125.6	200.4	262.2	310.4	995.0	2,091.4	4,650.1
Agriculture loss	18.5	20.6	21.8	25.0	30.2	33.0	39.5
Critical Facilities	1.6	2.6	3.7	5.4	14.4	30.3	187.0
Government Buildings	0.007	0.012	0.017	0.025	0.07	0.14	0.9

Table 5-18: District-wise key return periods losses for Landslide hazard

District Name	Total landslide residential, Govt. buildings, critical facilities, transport and agriculture Loss (INR Crores) for various return periods						
	10	25	50	100	250	500	1000
Alappuzha	-	-	-	-	-	-	-
Ernakulam	3.2	4.1	4.4	5.5	8.6	11.6	32.4
Idukki	286.1	465.0	633.1	883.1	2,433.4	5,104.9	23,996.0
Kannur	7.1	11.9	16.2	22.7	60.7	125.6	751.0
Kasaragod	1.1	1.9	2.7	3.8	10.6	22.2	128.0
Kollam	1.0	1.3	1.4	1.8	3.8	7.6	39.5
Kottayam	3.9	6.5	9.0	13.0	35.3	74.5	450.4
Kozhikode	7.8	11.0	14.1	18.3	44.3	88.5	514.0
Malappuram	3.2	4.8	6.3	8.2	24.2	51.3	303.4
Palakkad	30.6	45.9	59.9	64.8	233.5	499.6	2,538.2
Pathanamthitta	8.6	14.4	19.6	28.9	79.2	168.3	1,023.8
Thiruvananthapuram	0.1	0.1	0.2	0.3	0.9	1.9	11.6
Thrissur	0.8	1.2	1.5	2.1	5.4	11.4	68.5
Wayanad	18.6	31.4	44.6	56.5	171.8	364.0	1,980.6
<b>Grand Total</b>	<b>372.1</b>	<b>599.3</b>	<b>813.0</b>	<b>1,108.8</b>	<b>3,111.8</b>	<b>6,531.3</b>	<b>31,837.6</b>

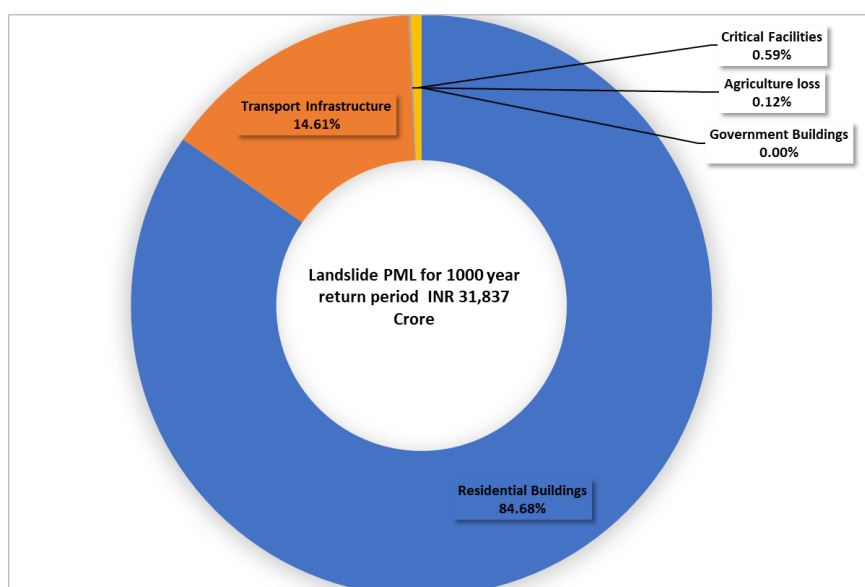


Figure 5-15: Landslide losses with sector contribution to total losses for a 1000-year return period

### 5.8.3 AVERAGE ANNUAL LOSS FOR LANDSLIDE

The total AAL due to landslide hazard has been estimated at the district-level for residential buildings, critical facilities, Govt offices, transport infrastructure and agriculture crops including (Coconut, Arecanut, Rice & Banana). A summary is presented in Table 5-19, which presents the total value of assets in the state, the total AAL (estimated to be INR 143.4 Crores), and the percentage of this loss compared to the total exposure value.

The distribution of AAL among key sectors due to landslide hazard is shown in Figure 5-16. The total value of assets exposed to storm surge and the total AAL for residential buildings and various other exposure elements in Kerala is provided in Table 5-20. It is clearly evident from the figure that the AAL contribution is highest for residential buildings, which account for 55.9% of the total AALs. The transport infrastructure is another significant contributor to losses due to storm surge (37.4%).

Table 5-19: Total AAL loss due to the Landslide hazard

State	Total Exposure Value	Total AAL, INR Crores	AAL (%) w.r.t Total AAL
Kerala	36,27,962	143.4	0.0039

Table 5-20: Flood AAL for various exposure types

Category	Total AAL, INR Crores	AAL (%) w.r.t Total AAL Loss
Residential Buildings	80.2	55.9%
Transport Infrastructure	53.6	37.4%
Agriculture loss	9	6.3%
Critical Facilities	0.6	0.4%
Government Buildings	0.003	0.002%

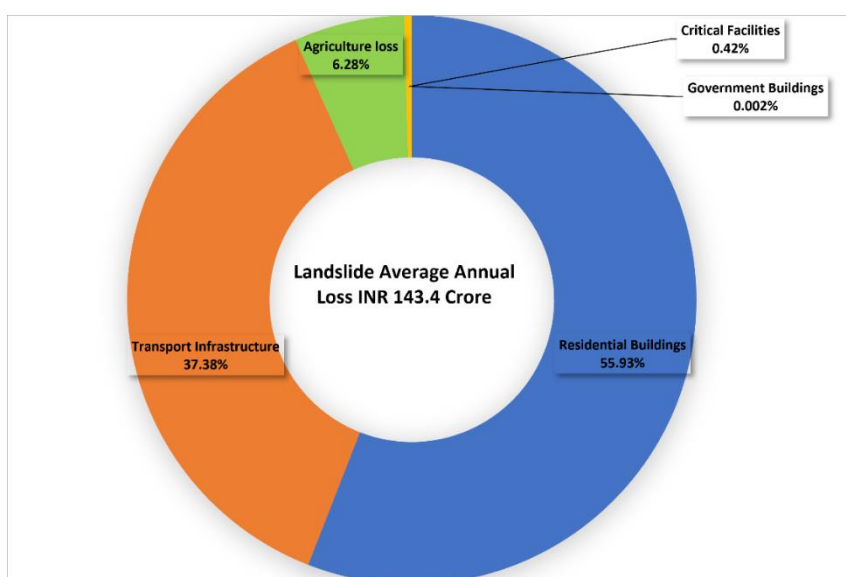


Figure 5-16: Sector-wise distribution of landslide average annual loss

#### 5.8.4 DISTRICT-WISE AVERAGE ANNUAL LOSS FOR LANDSLIDE

The district-wise total AALs due to landslide for residential buildings, critical facilities, government buildings, transport sector, and agriculture exposure is given in Table 5-21. Analysis shows that Idukki district has the highest losses, followed by Palakkad and Wayanad district. These three districts need more attention with regard to landslide.

#### 5.8.5 SUMMARY

The AAL due to hazard for Kerala is INR 143.4 Crores. Residential buildings are the major contributor to economic losses, followed by the transport infrastructure and agriculture. The highest estimated AAL is around INR 108.5 Crores for Idukki district, followed by Palakkad district with an estimated AAL of about INR 13.3 Crores.

Table 5-21: District-wise total AAL due to Landslide hazard

District Name	AAL (INR Crores)	AAL (%) w.r.t Total AAL
Idukki	108.5	76%
Palakkad	13.3	9%
Wayanad	6.9	5%
Kozhikode	3.2	2%

District Name	AAL (INR Crores)	AAL (%) w.r.t Total AAL
Pathanamthitta	3.2	2%
Kannur	2.5	2%
Ernakulam	1.6	1%
Kottayam	1.5	1%
Malappuram	1.3	1%
Kollam	0.5	0.4%
Kasaragod	0.4	0.3%
Thrissur	0.3	0.2%
Thiruvananthapuram	0.04	0.03%
Alappuzha	-	0%

## 5.9 Risk Assessment - Drought

### 5.9.1 PROBABILISTIC RISK ASSESSMENT OF THE CROPS TO DROUGHT HAZARD

Drought hazard vulnerability models were used to assess the risk of the crops to the drought hazard of different severity levels using the following steps:

**Step 1:** Computed year-wise integrated SPEI (ISPEI) for 100 years for every district and every crop separately and subsequently segregated all negative ISPEI values.

**Step 2:** Calculated crop yield loss using Step 1 derived IRFD values in conjunction with the district and crop-specific drought vulnerability model as discussed in the section 3.5.

**Step 3:** Calculated crop production loss in absolute terms (i.e., in tons) by multiplying Step 2 results with the normal acreage of the corresponding district's crop.

**Step 4:** Calculated crop production loss in monetary terms (i.e., in Rupees) by multiplying Step 3 result with the Minimum Support Price (MSP for 2022-23) of the respective crops.

**Step 5:** Arranged all crop-specific losses of the respective district in descending order

and subsequently assigned a return period against each loss value. For example, after arranging in descending order first value represents the crop loss value for a 100-year return period, second value represents the loss value for a 50-year return period, so on and so forth.

**Step 6:** Computed Average Annual Loss (AAL) for every crop at taluka level in every district separately.

As explained in the earlier section, crop-wise total exposure values (i.e., total production value as per the current market price) and associated loss at different return periods have been summarized in Table 5-22 and Table 5-23, respectively for selected crops,.

It should be noted that it is not necessary that districts shown under each return period will experience such conditions simultaneously. In other words, districts suffering loss due to drought may experience the loss at different times within the time bands they are expected to occur. For example, areas prone to suffer loss once-in-25-year (i.e., 25-year return period) may experience them at different times within a 25 years' period.

Table 5-22: Replacement costs of the agricultural exposure calculated by using normal production and Minimum Support Price (MSP) of 2022-23

District	Crop	Normal Area (Hectares)	Normal Production (Tonnes)	MSP (INR/Ton) for 2022-23	Replacement cost (Crore INR) = Production * MSP
Alappuzha	Rice	10,020	23,052	20,400	47.0
	Banana	453	3,380	30,000	10.1
	Tapioca	2,417	85,606	12,000	102.7
	Rubber	4,047	4,609	18,000	8.3
Ernakulam	Rice	1,336	2,387	20,400	4.9
	Banana	5,139	45,327	30,000	136
	Tapioca	5,341	2,41,787	12,000	290.1
	Rubber	58,492	68,644	18,000	123.6
Idukki	Rice	95	203	20,400	0.4
	Banana	3,430	31,293	30,000	93.9
	Tapioca	6,655	2,93,307	12,000	352
	Rubber	39,027	44,149	18,000	79.5
Kannur	Rice	2,846	6,586	20,400	13.4
	Banana	2,198	20,221	30,000	60.7
	Tapioca	1,806	70,967	12,000	85.2
	Rubber	39,497	45,304	18,000	81.5
Kasaragod	Rice	1,539	3,671	20,400	7.5
	Banana	660	6,412	30,000	19.2
	Tapioca	449	14,702	12,000	17.6
	Rubber	27,271	29,271	18,000	52.7
Kollam	Rice	373	881	20,400	1.8
	Banana	3,065	21,698	30,000	65.1
	Tapioca	14,506	5,12,137	12,000	614.6
	Rubber	37,533	44,150	18,000	79.5
Kottayam	Rice	3,999	8,833	20,400	18
	Banana	3,012	26,005	30,000	78
	Tapioca	5,915	2,48,963	12,000	298.8
	Rubber	112,262	130,796	18,000	235.4

Kozhikode	Rice	91	141	20,400	0.3
	Banana	1,750	15,031	30,000	45.1
	Tapioca	1,523	44,174	12,000	53
	Rubber	19,277	23,239	18,000	41.8
Malappuram	Rice	363	730	20,400	1.5
	Banana	6,786	55,341	30,000	166
	Tapioca	5,111	1,84,187	12,000	221
	Rubber	34,693	38,555	18,000	69.4
Palakkad	Rice	35,805	94,862	20,400	193.5
	Banana	15,165	1,44,983	30,000	435
	Tapioca	2,048	69,283	12,000	83.1
	Rubber	33,215	36,041	18,000	64.9
Pathanamthitta	Rice	44	57	20,400	0.1
	Banana	2,164	16,988	30,000	51
	Tapioca	5,037	2,23,785	12,000	268.5
	Rubber	49,225	60,269	18,000	108.5
Thiruvananthapuram	Rice	909	2,432	20,400	5
	Banana	2,886	22,542	30,000	67.6
	Tapioca	14,244	5,18,030	12,000	621.6
	Rubber	29,559	33,988	18,000	61.2
Thrissur	Rice	1,895	3,747	20,400	7.6
	Banana	2,126	17,212	30,000	51.6
	Tapioca	1,181	51,524	12,000	61.8
	Rubber	13,970	18,270	18,000	32.9
Wayanad	Banana	10,268	92,602	30,000	277.8
	Tapioca	1,716	66,751	12,000	80.1
	Rubber	8,378	6,104	18,000	11.0

Table 5-23: Drought induced losses for selected return periods for agricultural crops

District	Exposure Type	Exposure Value (Crores INR)	Losses (Crore INR) at different return periods (years)			
			10	25	50	100
Alappuzha	Banana	10.14	0.83	0.94	0.97	0.99
	Rice	47.03	6.33	7.24	7.57	7.74
	Tapioca	102.73	9.03	10.13	10.54	10.74
	Rubber	8.3	0.83	0.88	0.9	0.91
	<b>Total</b>	<b>168.2</b>	<b>17.02</b>	<b>19.19</b>	<b>19.98</b>	<b>20.38</b>
Ernakulam	Banana	135.98	10.22	11.76	12.33	12.63
	Rice	4.87	0.4	0.44	0.46	0.47
	Tapioca	290.14	19.36	22.13	23.13	23.64
	Rubber	123.56	17.3	18.53	18.9	19.03
	<b>Total</b>	<b>554.55</b>	<b>47.28</b>	<b>52.86</b>	<b>54.82</b>	<b>55.77</b>
Idukki	Banana	93.88	9.08	10.26	10.69	10.91
	Rice	0.41	0.04	0.05	0.05	0.05
	Tapioca	351.97	34.07	38.97	40.72	41.63
	Rubber	79.47	15.81	16.93	17.24	17.4
	<b>Total</b>	<b>525.73</b>	<b>59</b>	<b>66.21</b>	<b>68.7</b>	<b>69.99</b>
Kannur	Banana	60.66	5.24	5.92	6.17	6.3
	Rice	13.43	0.95	1.07	1.11	1.14
	Tapioca	85.16	7.18	8.18	8.55	8.76
	Rubber	81.55	10.68	11.34	11.58	11.74
	<b>Total</b>	<b>240.8</b>	<b>24.05</b>	<b>26.51</b>	<b>27.41</b>	<b>27.94</b>
Kasaragod	Banana	19.24	2.09	2.35	2.45	2.49
	Rice	7.49	0.51	0.58	0.61	0.62
	Tapioca	17.64	1.52	1.72	1.79	1.83
	Rubber	52.69	8.43	8.43	8.96	8.96
	<b>Total</b>	<b>97.06</b>	<b>12.55</b>	<b>13.08</b>	<b>13.81</b>	<b>13.9</b>
Kollam	Banana	65.1	4.36	5.03	5.28	5.42
	Rice	1.8	0.16	0.19	0.19	0.2
	Tapioca	614.57	42.61	49	51.51	52.91
	Rubber	79.47	17.96	19.15	19.55	19.71
	<b>Total</b>	<b>760.94</b>	<b>65.09</b>	<b>73.37</b>	<b>76.53</b>	<b>78.24</b>
Kottayam	Banana	78.02	5.49	6.17	6.42	6.54
	Rice	18.02	2.63	2.99	3.12	3.18
	Tapioca	298.76	15.19	17.27	18.01	18.39
	Rubber	235.43	37.43	39.79	40.73	41.2
	<b>Total</b>	<b>630.23</b>	<b>60.74</b>	<b>66.22</b>	<b>68.28</b>	<b>69.31</b>
Kozhikode	Banana	45.09	2.89	3.23	3.35	3.42
	Rice	0.29	0.03	0.03	0.03	0.03
	Tapioca	53.01	4.68	5.3	5.52	5.63

	Rubber	41.83	4.22	4.52	4.6	4.64
	<b>Total</b>	<b>140.22</b>	<b>11.82</b>	<b>13.08</b>	<b>13.5</b>	<b>13.72</b>
Malappuram	Banana	166.02	11.54	12.96	13.47	13.74
	Rice	1.49	0.15	0.16	0.17	0.17
	Tapioca	221.02	18.46	20.75	21.57	21.98
	Rubber	69.4	8.54	9.09	9.3	9.37
	<b>Total</b>	<b>457.93</b>	<b>38.69</b>	<b>42.96</b>	<b>44.51</b>	<b>45.26</b>
Palakkad	Banana	434.95	22.12	24.76	25.72	26.21
	Rice	193.52	16.54	18.48	19.75	20.2
	Tapioca	83.14	7.07	7.94	8.26	8.42
	Rubber	64.87	7.85	8.37	8.56	8.63
	<b>Total</b>	<b>776.48</b>	<b>53.58</b>	<b>59.55</b>	<b>62.29</b>	<b>63.46</b>
Pathanamthitta	Banana	50.97	3.87	4.35	4.52	4.6
	Rice	0.12	0.02	0.02	0.02	0.02
	Tapioca	268.54	18.75	21.1	21.94	22.39
	Rubber	108.48	13.67	14.54	14.86	14.97
	<b>Total</b>	<b>428.11</b>	<b>36.31</b>	<b>40.01</b>	<b>41.34</b>	<b>41.98</b>
Thiruvananthapuram	Banana	67.63	5.18	5.85	6.09	6.22
	Rice	4.96	0.73	0.84	0.88	0.9
	Tapioca	621.64	42.79	49.33	51.8	53.14
	Rubber	61.18	8.75	9.3	9.54	9.61
	<b>Total</b>	<b>755.41</b>	<b>57.45</b>	<b>65.32</b>	<b>68.31</b>	<b>69.87</b>
Thrissur	Banana	51.64	6.68	7.64	8	8.19
	Rice	7.64	0.88	1	1.04	1.06
	Tapioca	61.83	4.76	5.49	5.76	5.9
	Rubber	32.89	4.11	4.37	4.47	4.51
	<b>Total</b>	<b>154</b>	<b>16.43</b>	<b>18.5</b>	<b>19.27</b>	<b>19.66</b>
Wayanad	Banana	277.81	26.73	30.24	31.51	32.25
	Tapioca	80.1	6.06	6.96	7.3	7.51
	Rubber	10.99	1.55	1.65	1.68	1.7
	<b>Total</b>	<b>368.9</b>	<b>34.34</b>	<b>38.85</b>	<b>40.49</b>	<b>41.46</b>
<b>Grand Total</b>		<b>6,058.55</b>	<b>534.36</b>	<b>595.7</b>	<b>619.26</b>	<b>630.94</b>

### 5.9.2 TALUKA WISE PROBABLE MAXIMUM LOSS (PML) DUE TO DROUGHT IN KERALA FOR ALL THE CROPS AT VARIOUS RETURN PERIODS

Finally, district level PML has been distributed among the Talukas of Kerala using remote sensing technique, results of which have been presented in this section. Taluka wise loss due to drought at key return periods (10, 25, 50 and 100 years)

have been depicted in Figure 5-17 to Figure 5-20.

**10-Year Return Period:** The combined 10-year return period loss map has been classified in to five classes as shown in Figure 5-17. As per these classification, maximum loss of around 18.01 – 29.00 crores expected to be at four talukas (2 in Kottayam and one each in Idukki and Kollam). Between 10.01 – 18.00 observed at fifteen talukas (3 in Palakkad and 2 each in Wayanad, Ernakulam, Idukki,

Pathanamthitta and Thiruvananthapuram and one each in Alappuzha and Kollam). Between 5.01 – 10.00 crores at twenty-two talukas (4 in Malappuram and Kollam, 3 each in Thiruvananthapuram, 2 in Kannur, Palakkad and one in Kasaragod, Wayanad, Thrissur, Ernakulam, Idukki, Kottayam and Pathanamthitta) and in remaining talukas observed to be below 5 crores.

**25-Year Return Period:** The combined 25-year return period loss map has been classified in to five classes as shown in **Error! Reference source not found..** As per these classification, maximum loss of around 20.01 – 32.00 crores at 25-year return period expected to be at five talukas (2 in Kottayam and one each in Idukki, Thiruvananthapuram and Kollam). Between 11.01 – 20.00 observed at fifteen talukas (3 in Palakkad and 2 each in Wayanad, Ernakulam, Idukki, Pathanamthitta and Kollam and one each in Alappuzha and Thiruvananthapuram). Between 5.01 – 11.00 crores at twenty-four talukas (4 in Malappuram, 3 each in Kannur, Ernakulam, Kollam and Thiruvananthapuram, 2 in Palakkad and one in Kasaragod, Wayanad, Thrissur, Idukki, Kottayam and Pathanamthitta) and in remaining talukas observed to be below 5 crores.

**50-Year Return Period:** The combined 50-year return period loss map has been classified in to five classes as shown in **Error! Reference source not found..** As per these classification, maximum loss of

around 21.01 – 33.00 crores at 50-year return period expected to be at five talukas (2 in Kottayam and one each in Idukki, Thiruvananthapuram and Kollam). Between 11.01 – 21.00 observed at fifteen talukas (3 in Palakkad and 2 each in Wayanad, Ernakulam, Idukki, Pathanamthitta and Kollam and one each in Alappuzha and Thiruvananthapuram). Between 5.01 – 11.00 crores at twenty-one talukas (4 in Malappuram, 3 each in Kollam and Thiruvananthapuram, 2 in Kannur, Palakkad and one in Kasaragod, Wayanad, Thrissur, Idukki, Kottayam and Pathanamthitta) and in remaining talukas observed to be below 6 crores.

**100-Year Return Periods:** The combined 100-year return period loss map has been classified in to five classes as shown in *Figure 5-20*. As per these classification, maximum loss of around 18.01 – 34.00 crores at 100-year return period expected to be at six talukas (2 in Kottayam, Thiruvananthapuram and one each in Idukki and Kollam). Between 10.01 – 18.00 observed at seventeen talukas (3 in Palakkad, Wayanad and 2 each in Ernakulam, Idukki, Pathanamthitta and Kollam and one each in Alappuzha and Thiruvananthapuram). Between 6.01 – 10.00 crores at twenty-one talukas (4 in Malappuram, 3 each in Kollam and Thiruvananthapuram, 2 in Kannur, Palakkad, Kollam and one in Kasaragod, Thrissur, Ernakulam, Idukki, Kottayam and Pathanamthitta) and in remaining talukas observed to be below 6 crores.



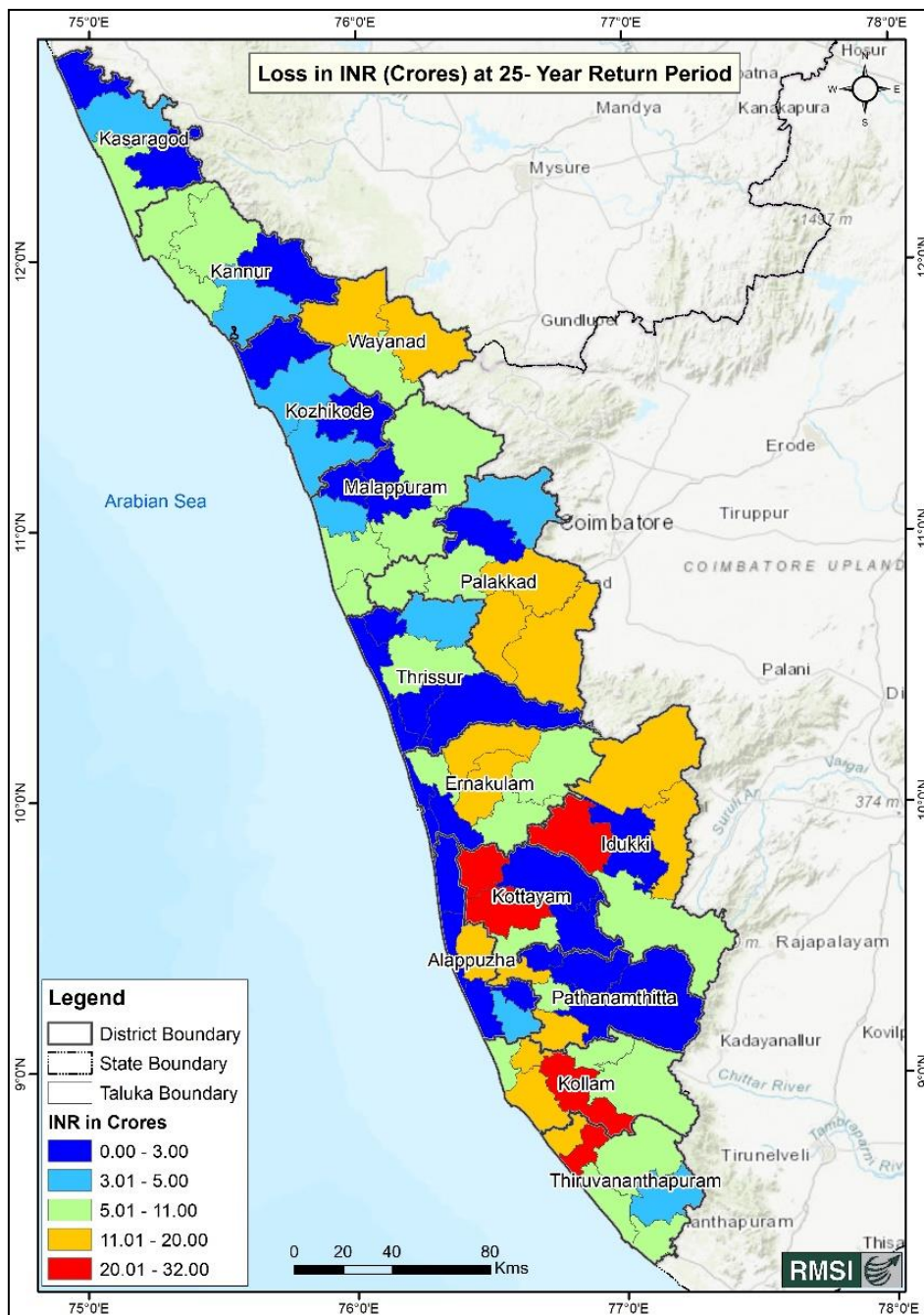


Figure 5-18: Loss in INR (Crores) at 25-year return period

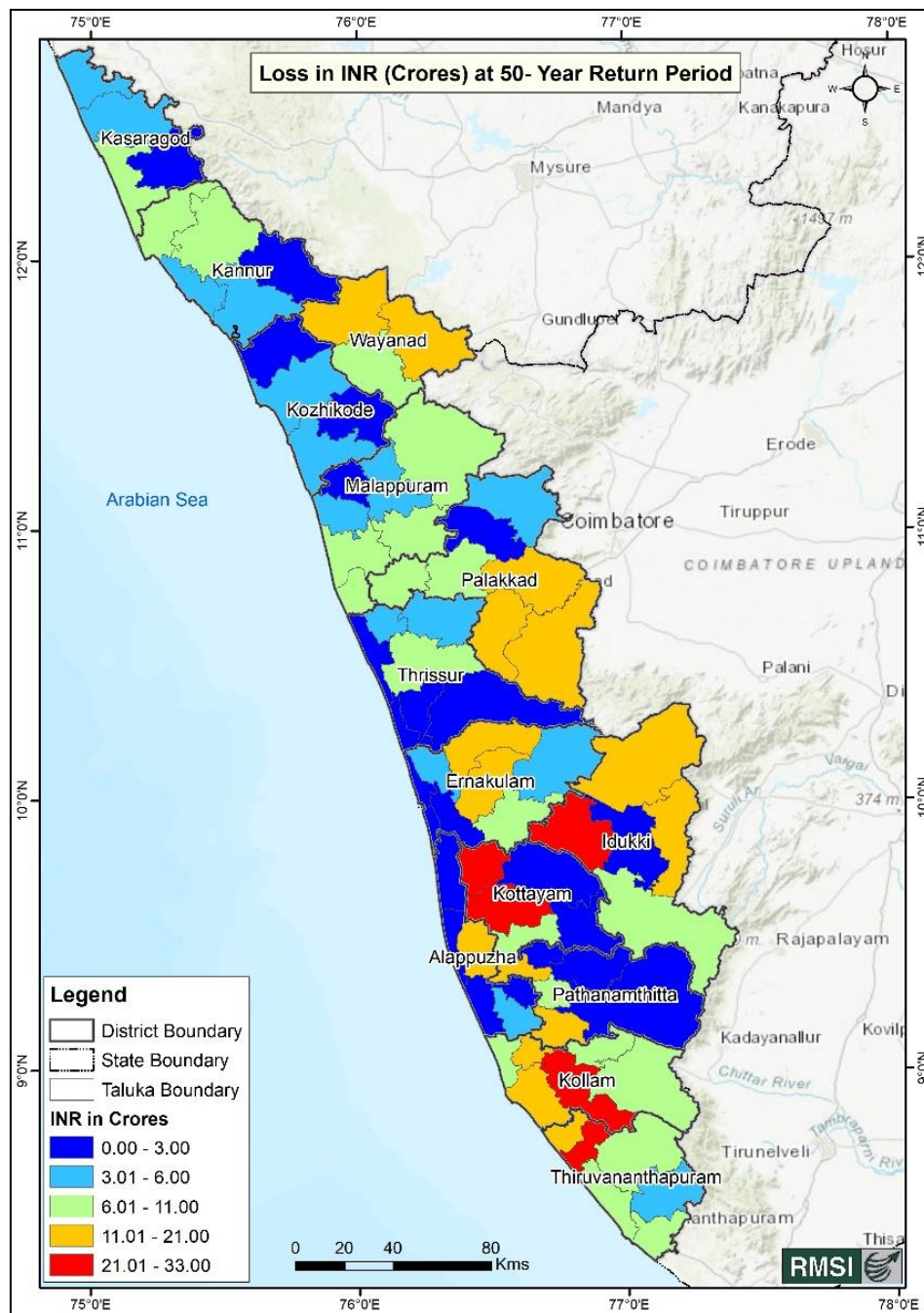


Figure 5-19: Loss in INR (Crores) at 50-year return period

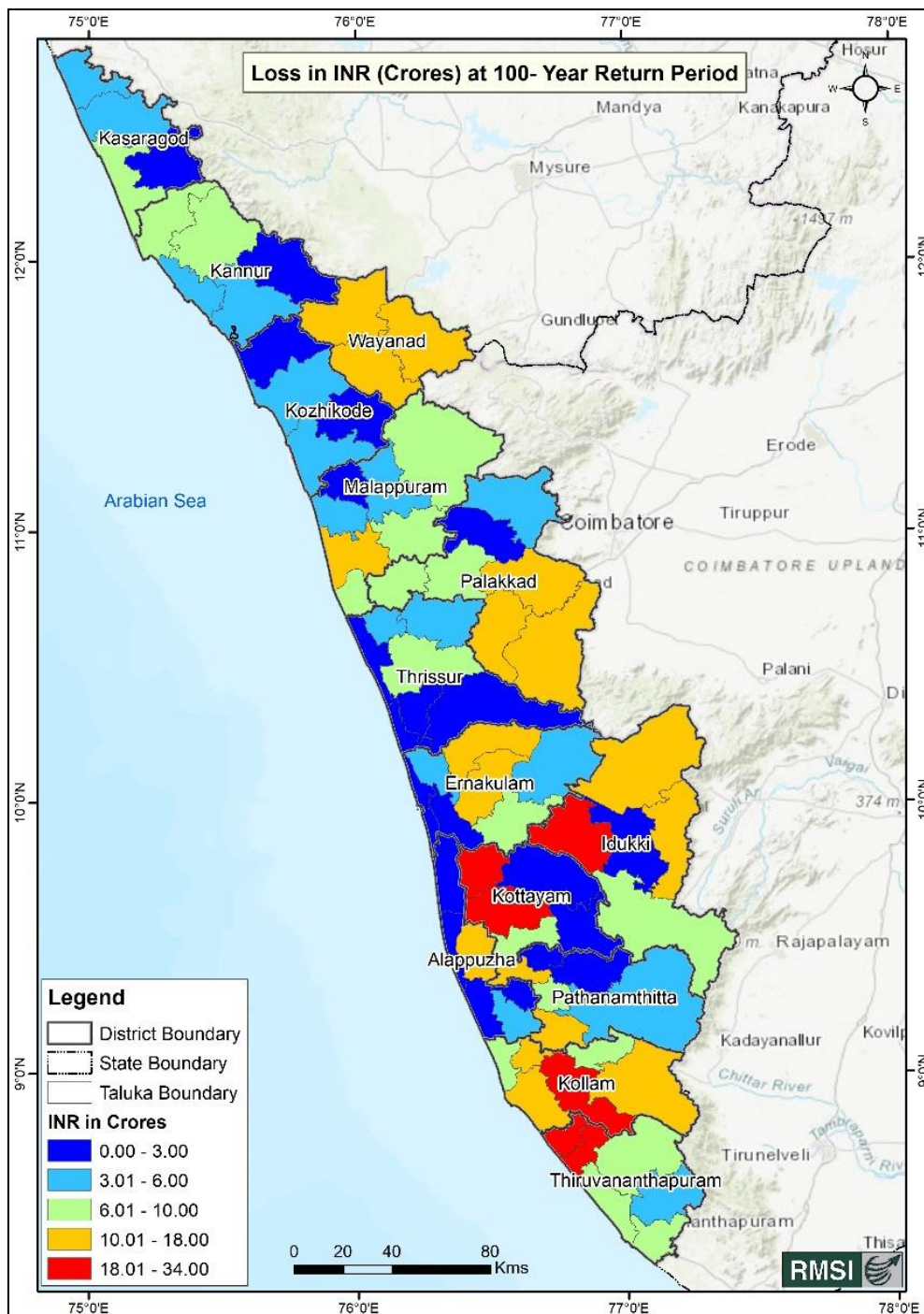


Figure 5-20: Loss in INR (Crores) at 100-year return period

### 5.9.3 AGGREGATED LOSS IN KERALA DUE TO DROUGHT ON VARIOUS CROPS AT DIFFERENT RETURN PERIODS

Furthermore, aggregated level return period loss curves for the Rice, Banana and

Tapioca, Rubber and all crops combined have been shown in Figure 5-21 to Figure 5-25. These curves show the extent of aggregated loss, which a particular crop suffers at a certain return period (say at 10, 25, 50 and 100 years return period) due to drought hazard.

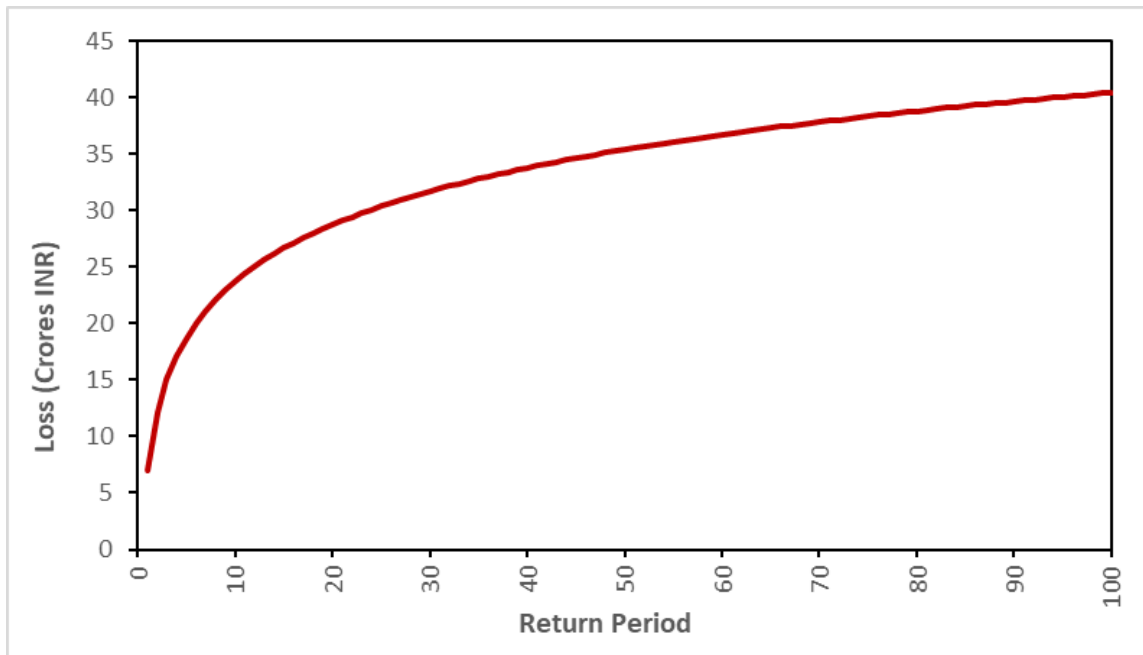


Figure 5-21: Rice crop loss at different return periods for drought

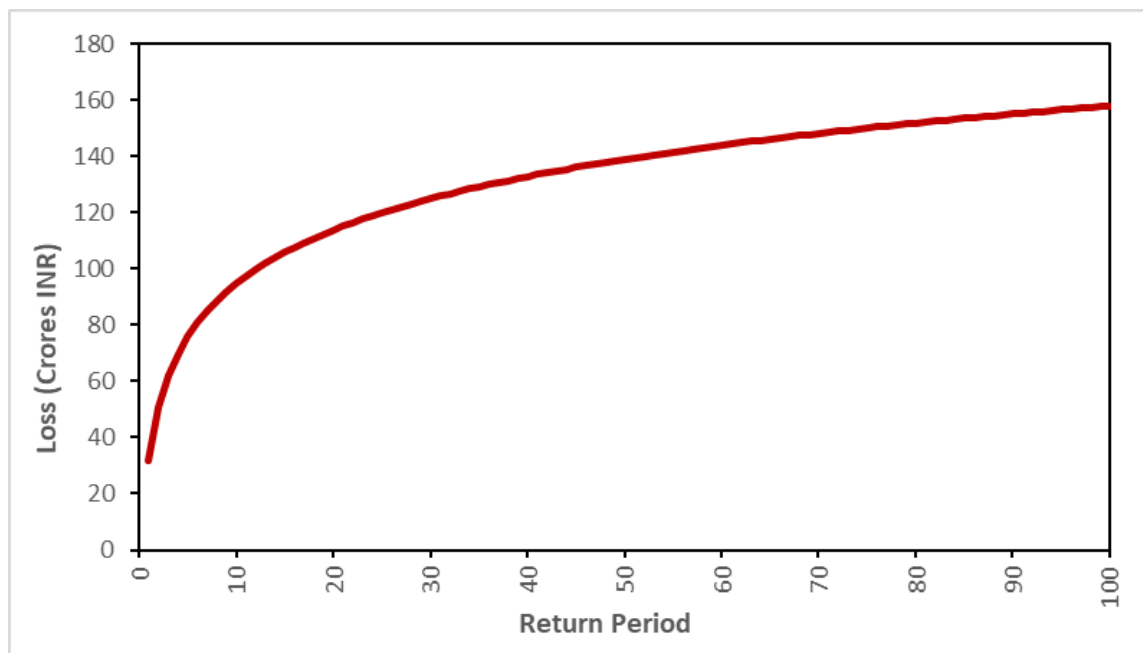


Figure 5-22: Banana crop loss at different return periods for drought

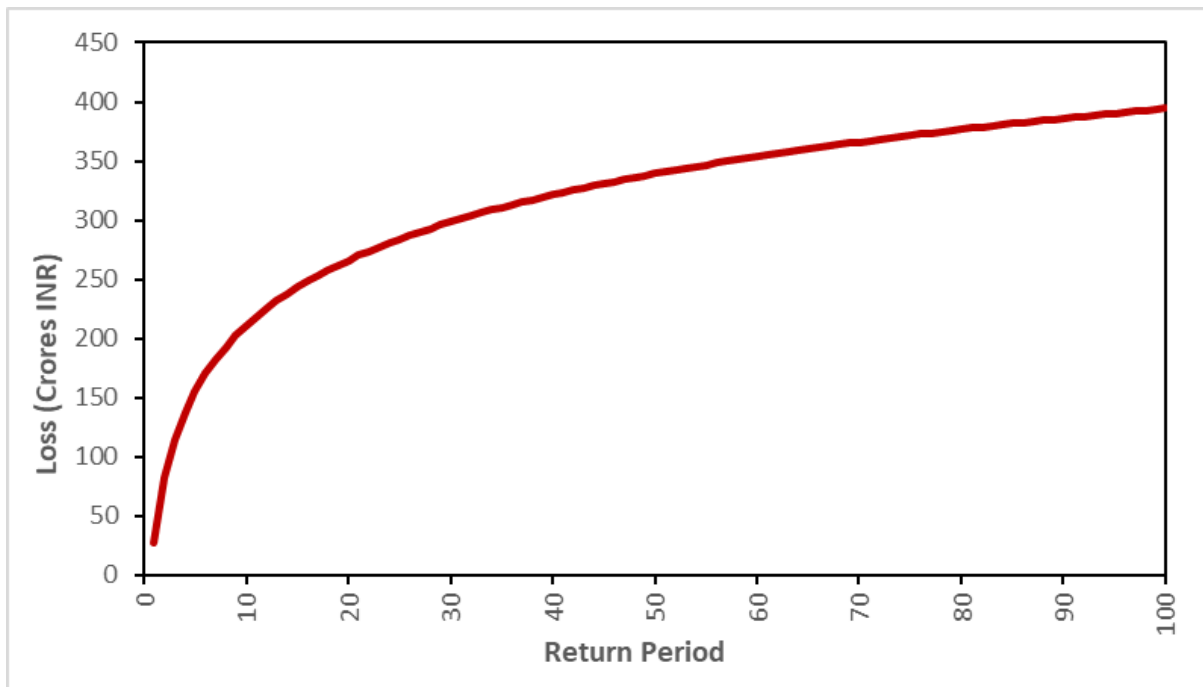


Figure 5-23: Tapioca crop loss at different return periods for drought

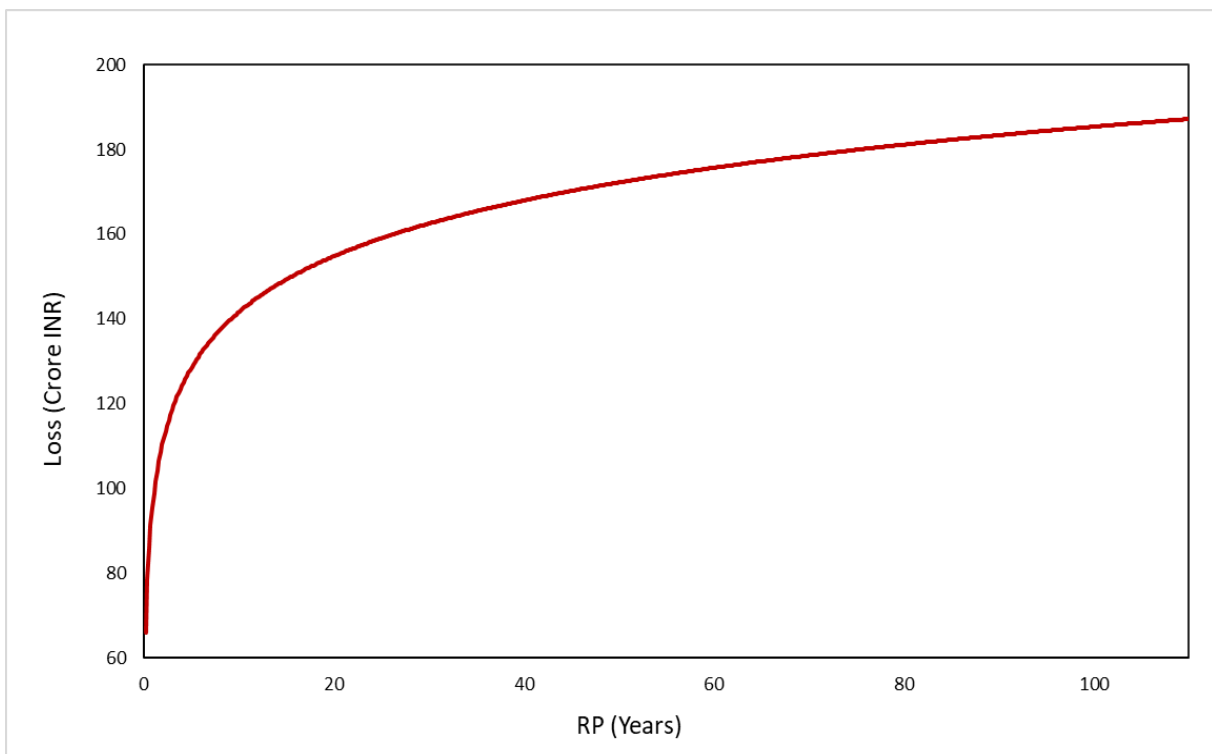


Figure 5-24: Rubber crop loss at different return periods for drought

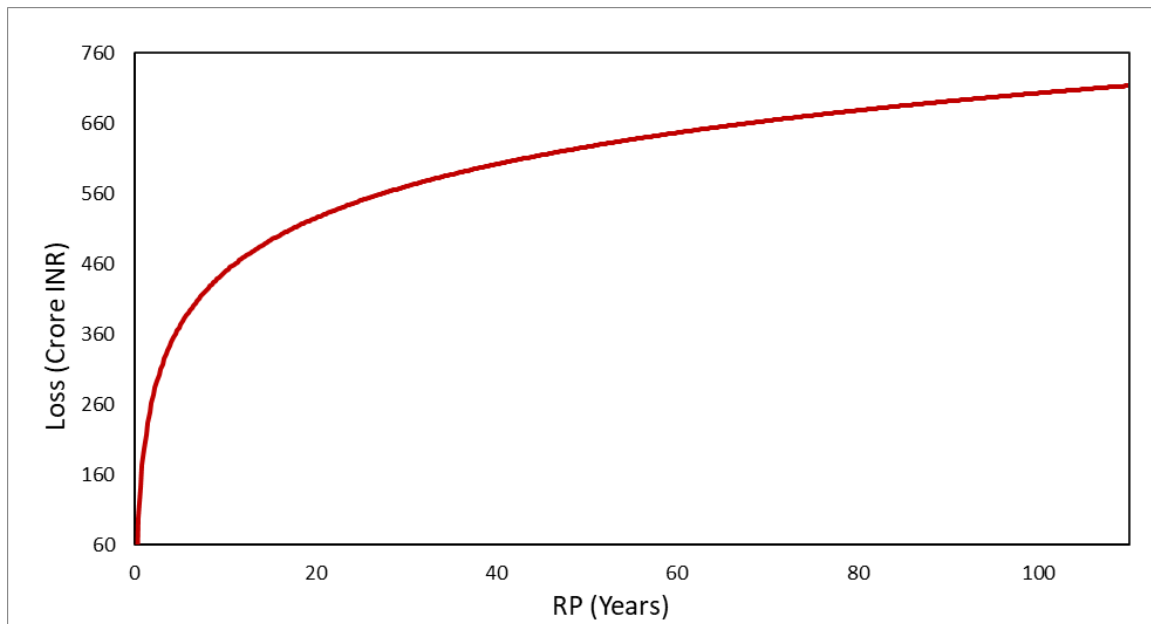


Figure 5-25: All crops (Rice, Banana, Tapioca and Rubber) aggregated losses crop loss at different return periods for drought

#### 5.9.4 LOSS EXCEEDANCE PROBABILITIES (EP) FOR THE DROUGHT RISK ASSESSMENT

Loss Exceedance Probability (EP) curves for Banana, Rice, Tapioca and all crops combined have been depicted in Figure

5-26. These curves give the likelihood of having the potential loss for a particular crop in excess of a given amount (also referred to as Loss Exceedance Curve, LEC).

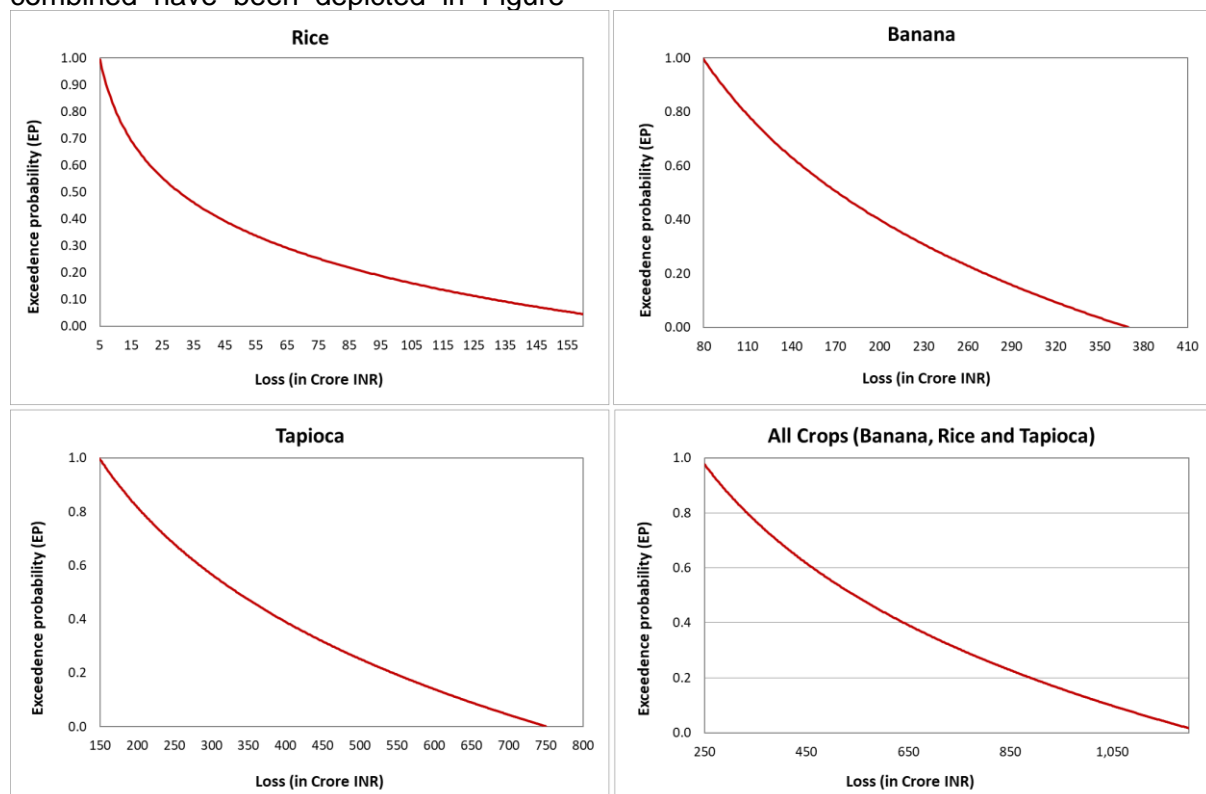


Figure 5-26: Loss Exceedance Probability (EP) curve for drought the drought risk assessment

### 5.9.5 AVERAGE ANNUAL LOSS (AAL) FOR THE DROUGHT RISK ASSESSMENT

District-wise Average Annual Loss (AAL) for the crops and the cumulative loss for the state have been summarized in Table 5-24 and Table 5-25. Low AAL of the crops can be attributed to the fact that drought is not a frequent phenomenon. The districts have been ranked on the basis of AAL (Crore INR) from highest to lowest. In terms of AAL (Crore INR), Kottayam district was ranked first followed by Kollam district. The lowest AAL was observed in Northern most district of Kozhikode. The AAL in

percentage was found highest in Kasaragod (6.47%) and Idukki district (3.07%), which is followed by Kottayam (3.04%) and Kannur (2.95%). The AAL (%) hovered between 2-1% across all the remaining districts of Kerala. Furthermore, AAL value for rice crop is highest as compared to banana and tapioca which can be attributed to the fact that rice is more sensitive to water stress as compared to other crops due to the fact that rice is a drought stress sensitive crop (Zhang, et. al., 2013<sup>122</sup>). The total AAL of the state due to drought was found to be 149.43 crores INR which was around 2.5% of the exposure value.

Table 5-24: Drought induced Average Annual Loss (AAL) for agricultural crops

S.No.	District	Crop	Exposure Value (Crores INR)	AAL (crore INR)	AAL (%)
1	Alappuzha	Banana	10.14	0.21	2.02%
		Rice	47.03	1.47	3.12%
		Tapioca	102.73	2.26	2.20%
		Rubber	8.3	0.3	3.60%
		<b>Total</b>	<b>168.197</b>	<b>4.23869</b>	<b>2.52%</b>
2	Ernakulam	Banana	135.98	2.31	1.70%
		Rice	4.87	0.1	2.01%
		Tapioca	290.14	4.51	1.55%
		Rubber	123.56	6.3	5.10%
		<b>Total</b>	<b>554.549</b>	<b>13.2215</b>	<b>2.38%</b>
3	Idukki	Banana	93.88	2.23	2.37%
		Rice	0.41	0.01	2.50%
		Tapioca	351.97	8.2	2.33%
		Rubber	79.47	5.72	7.20%
		<b>Total</b>	<b>525.729</b>	<b>16.1618</b>	<b>3.07%</b>
4	Kannur	Banana	60.66	1.3	2.14%
		Rice	13.43	0.24	1.75%
		Tapioca	85.16	1.73	2.03%
		Rubber	81.54778	3.832746	4.70%
		<b>Total</b>	<b>240.798</b>	<b>7.10275</b>	<b>2.95%</b>
5	Kasaragod	Banana	19.23	0.52	2.71%

<sup>122</sup> Zhang, L., Gao, M., Zhang, L., Li, B., Han, M., Alva, A. K., & Ashraf, M. (2013). Role of exogenous glycinebetaine and humic acid in mitigating drought stress induced adverse

effects in *Malus robusta* seedlings. Turkish Journal of Botany, 37(5), 920-929. <https://doi.org/10.3906/bot-1212-21>.

		Rice	7.49	0.12	1.65%
		Tapioca	17.64	0.38	2.13%
		Rubber	52.68693	5.263424	9.99%
		<b>Total</b>	<b>97.0469</b>	<b>6.28342</b>	<b>6.47%</b>
6	Kollam	Banana	65.09	1.03	1.58%
		Rice	1.8	0.04	2.21%
		Tapioca	614.56	9.9	1.61%
		Rubber	79.4693	6.437014	8.10%
		<b>Total</b>	<b>760.919</b>	<b>17.407</b>	<b>2.29%</b>
7	Kottayam	Banana	78.02	1.38	1.77%
		Rice	18.02	0.63	3.51%
		Tapioca	298.76	3.71	1.24%
		Rubber	235.4327	13.41967	5.70%
		<b>Total</b>	<b>630.233</b>	<b>19.1397</b>	<b>3.04%</b>
8	Kozhikode	Banana	45.09	0.73	1.61%
		Rice	0.29	0.01	2.36%
		Tapioca	53.01	1.15	2.17%
		Rubber	41.82997	1.547709	3.70%
		<b>Total</b>	<b>140.22</b>	<b>3.43771</b>	<b>2.45%</b>
9	Malappuram	Banana	166.02	2.86	1.72%
		Rice	1.49	0.04	2.41%
		Tapioca	221.02	4.6	2.08%
		Rubber	69.39842	3.05353	4.40%
		<b>Total</b>	<b>457.928</b>	<b>10.5535</b>	<b>2.30%</b>
10	Palakkad	Banana	434.95	5.51	1.27%
		Rice	193.52	3.83	1.98%
		Tapioca	83.14	1.74	2.09%
		Rubber	64.8745	2.854478	4.40%
		<b>Total</b>	<b>776.484</b>	<b>13.9345</b>	<b>1.79%</b>
11	Pathanamthitta	Banana	50.97	0.98	1.91%
		Rice	0.12	0	3.97%
		Tapioca	268.54	4.69	1.75%
		Rubber	108.48	4.88	4.50%
		<b>Total</b>	<b>428.114</b>	<b>10.5518</b>	<b>2.46%</b>
12	Thiruvananthapuram	Banana	67.63	1.28	1.90%
		Rice	4.96	0.17	3.46%
		Tapioca	621.64	10	1.61%
		Rubber	61.17892	3.181304	5.20%
		<b>Total</b>	<b>755.409</b>	<b>14.6313</b>	<b>1.94%</b>
13	Thrissur	Banana	51.64	1.57	3.04%
		Rice	7.64	0.21	2.78%
		Tapioca	61.83	1.1	1.78%
		Rubber	32.88635	1.479886	4.50%
		<b>Total</b>	<b>153.996</b>	<b>4.35989</b>	<b>2.83%</b>
14	Wayanad	Banana	277.81	6.47	2.33%
		Tapioca	80.1	1.4	1.75%

		Rubber	10.98645	0.560309	5.10%
		<b>Total</b>	<b>368.896</b>	<b>8.43031</b>	<b>2.29%</b>
	<b>Grand Total</b>		<b>6058.52</b>	<b>149.454</b>	<b>2.47%</b>

Table 5-25: District wise PML and AAL for the selected crops (Rice, Banana and Tapioca) in Kerala

<b>Total drought (Rice+Banana+Tapioca+Rubber) Loss (INR Crores) for Various Return Periods</b>					
<b>Kerala Districts</b>	<b>10 RP</b>	<b>25 RP</b>	<b>50 RP</b>	<b>100 RP</b>	<b>AAL</b>
Kollam	65.09	73.37	76.53	78.24	17.41
Idukki	59	66.21	68.71	69.99	16.16
Thiruvananthapuram	57.45	65.32	68.31	69.86	14.64
Kottayam	60.75	66.22	68.27	69.31	19.14
Palakkad	53.58	59.55	62.29	63.46	13.94
Ernakulam	47.28	52.87	54.82	55.77	13.22
Malappuram	38.68	42.96	44.51	45.27	10.55
Pathanamthitta	36.3	40	41.34	41.99	10.55
Wayanad	34.34	38.85	40.49	41.46	8.43
Kannur	24.05	26.5	27.42	27.94	7.09
Alappuzha	17.02	19.18	19.97	20.38	4.23
Thrissur	16.43	18.5	19.27	19.65	4.36
Kasaragod	12.56	13.08	13.8	13.9	6.28
Kozhikode	11.82	13.08	13.5	13.72	3.43
<b>Grand Total</b>	<b>534.36</b>	<b>595.69</b>	<b>619.23</b>	<b>630.94</b>	<b>149.43</b>

### 5.9.6 TALUKA WISE AVERAGE ANNUAL LOSS (AAL) IN KERALA FOR THE CROPS

The rice crop in Kerala is primarily cultivated during the Winter (Mundakan) and Summer (Puncha) seasons. The winter crop (Mundakan) surpasses the other two crops (Summer and Autumn) both in terms of area and production. During the Kharif (Autumn) season, rice cultivation is limited to a few regions, especially in Palakkad and parts of Kuttanad (Alappuzha and Kottayam

districts). In other regions, rice cultivation is marginal.

Taluk-wise AAL analysis for rice during the Kharif season in Kerala shows that the AAL due to drought exceeds INR 1.00 crores in four taluks (three in Palakkad and one in Alappuzha). The AAL for rice during the Kharif season ranges between INR 0.31 to 0.50 crores in three taluks from Palakkad. In the remaining taluks, the AAL was below INR 0.30 crores.

The AAL distribution across the taluks of Kerala for banana crop shows highest loss of range 1.81 to 2.50 crores across two

taluks from Wayanad and between INR 1.21 to 1.80 crores in three taluks (one in Wayanad and two in Palakkad). The AAL between INR 0.41 to 0.80 crores found in sixteen taluks (four in Malappuram and three from Palakkad and Two in each Ernakulam, Idukki, Kottayam and Thrissur and one from Kannur). In the remaining taluks, it was found to be below INR 0.40 crores.

For Tapioca, the AAL was found to be between INR 2.01 to 4.00 crores in four taluks (two in Thiruvananthapuram and one in Idukki and Kollam district) and between 1.16 to 2.00 in twelve taluks (three from Kollam and two taluks each in Idukki, Kottayam and Pathanamthitta and one taluk each in Alappuzha, Ernakulam and Thiruvananthapuram). The AAL was between INR 0.61 to 1.15 crores in twelve taluks (four in Malappuram, two each in Ernakulam, Thiruvananthapuram and Kollam and one each in Idukki and Pathanamthitta districts). In the remaining taluks, it was below INR 0.60 crores. It was observed that the AAL was higher in the southern districts compared to the northern districts of Kerala.

For Rubber, the AAL was found to be between INR 2.76 to 6.50 crores in two taluks (two in Kottayam district) and between 1.76 to 2.75 in five taluks (one each in Kollam, Pathanamthitta, Idukki, Ernakulam and Kasaragod). The AAL was between INR 1.01 to 1.75 crores in ten taluks (two each in Kasaragod, Ernakulam and Idukki and one each in Kannur, Kottayam, Pathanamthitta and Kollam districts). In the remaining taluks, it was below INR 1.00 crores.x

The combined AAL for Rice, Banana, Tapioca and Rubber crops lies between INR 4.51 to 9.00 crores in four taluks (two in Kottayam and one each in Idukki and Kollam districts). The combined AAL lies between INR 3.01 to 4.50 crores in fourteen taluks (two each in Wayanad, Palakkad, Ernakulam, Idukki, Pathanamthitta and Thiruvananthapuram districts and one each in Kasaragod and Kollam). The AAL lies between INR 2.01 to 3.00 crores in eleven taluks (one each in Kannur, Wayanad, Palakkad, Ernakulam, Idukki, Kottayam, Alappuzha and two each in Kollam and Malappuram). In the remaining taluks, it was found to be below INR 2.00 crores.

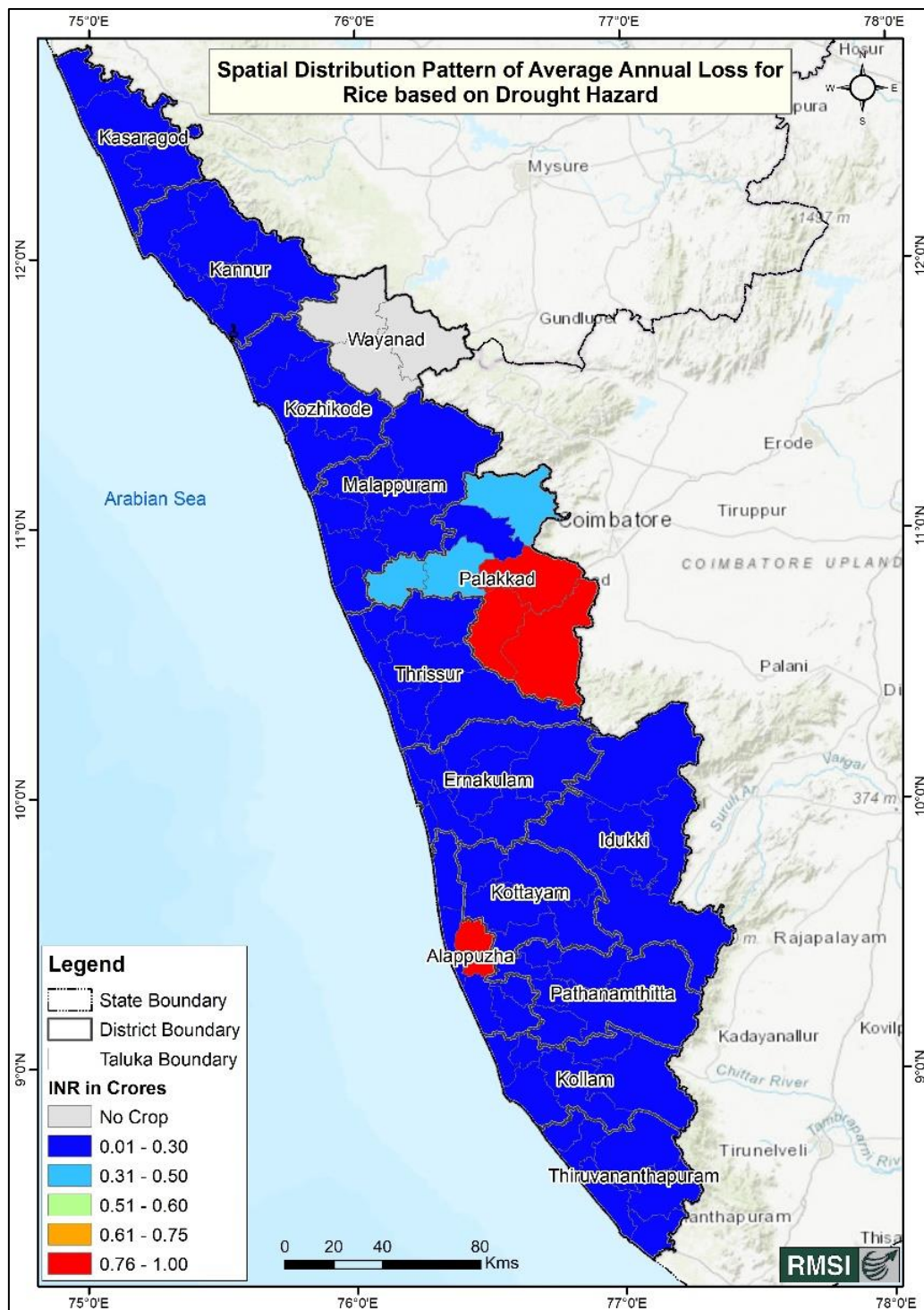


Figure 5-27: Taluka-wise Average Annual Loss in INR (Crores) for Rice in Kerala

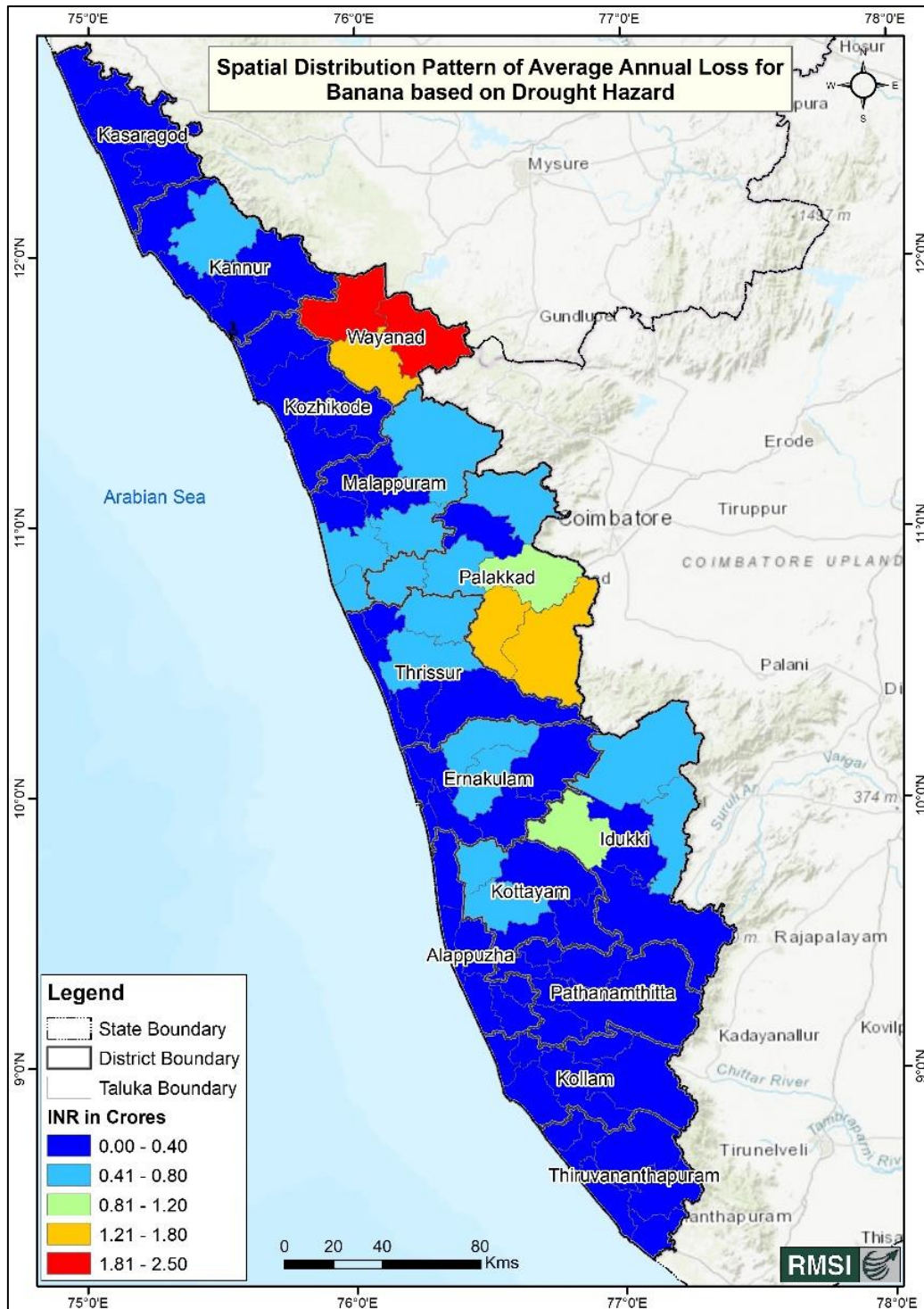


Figure 5-28: Taluka-wise Average Annual Loss in INR (Crores) for Banana in Kerala

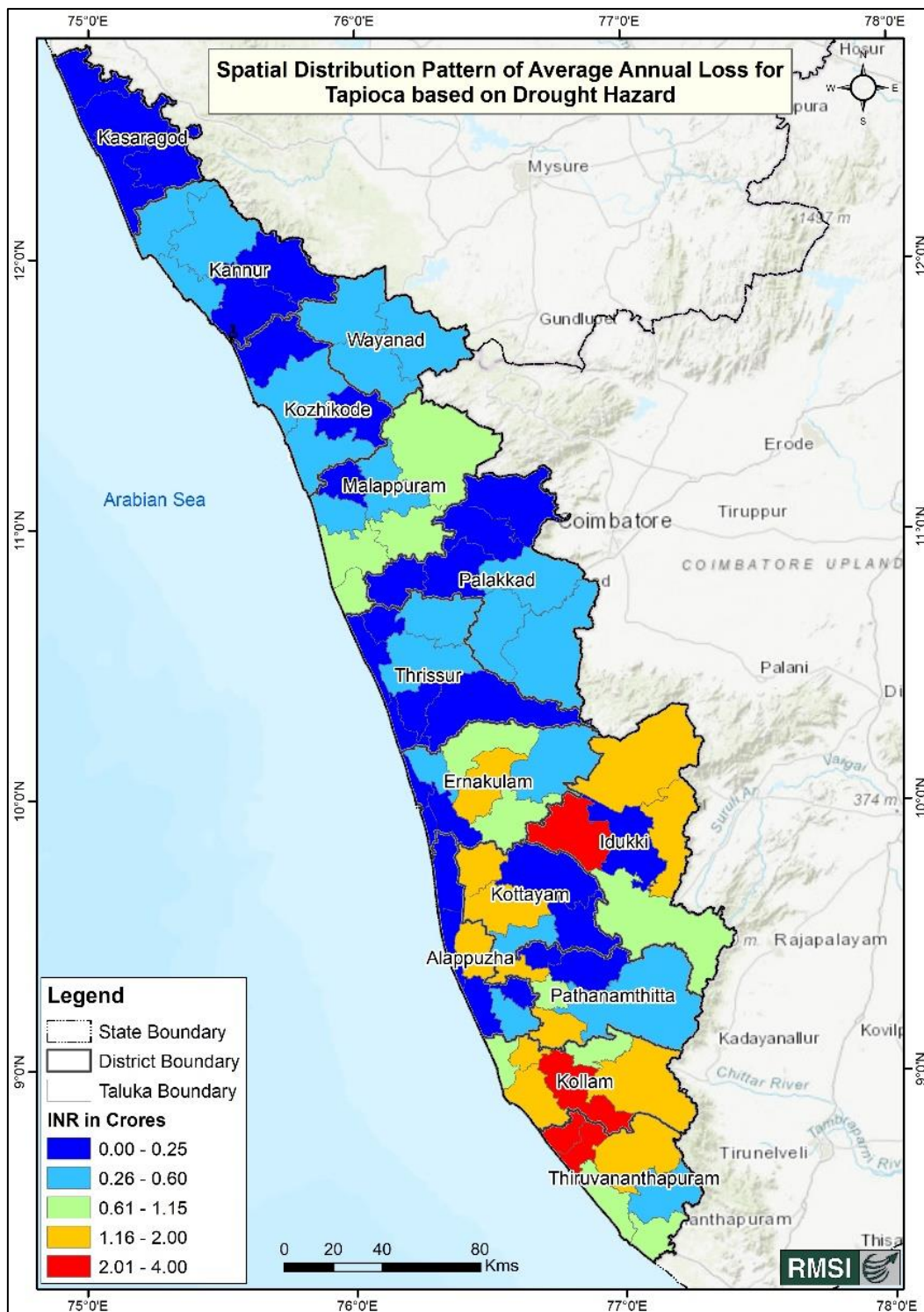


Figure 5-29: Taluka-wise Average Annual Loss in INR (Crores) for Tapioca in Kerala

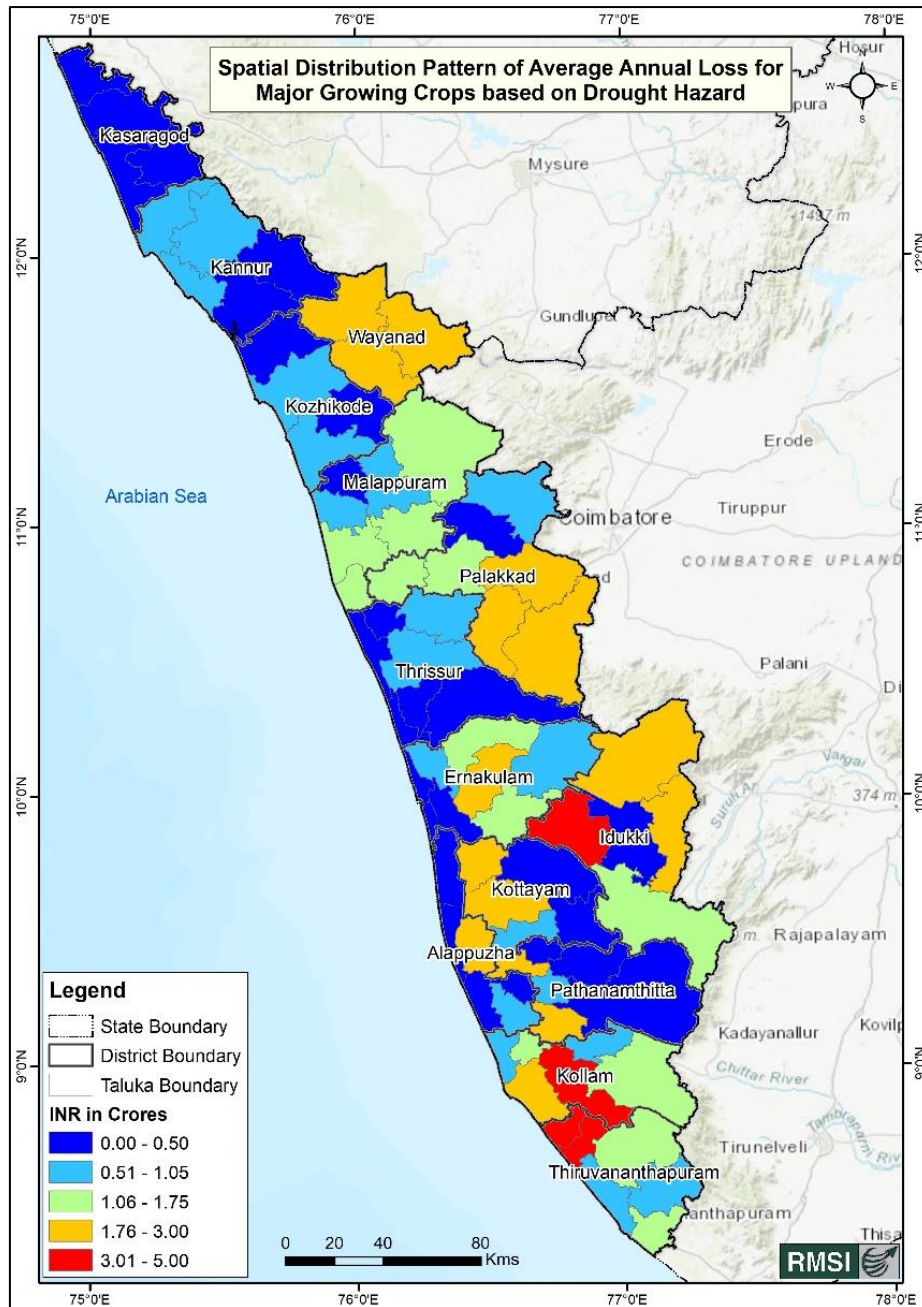


Figure 5-30: All crops (Rice, Banana and Tapioca) aggregated AAL due to drought

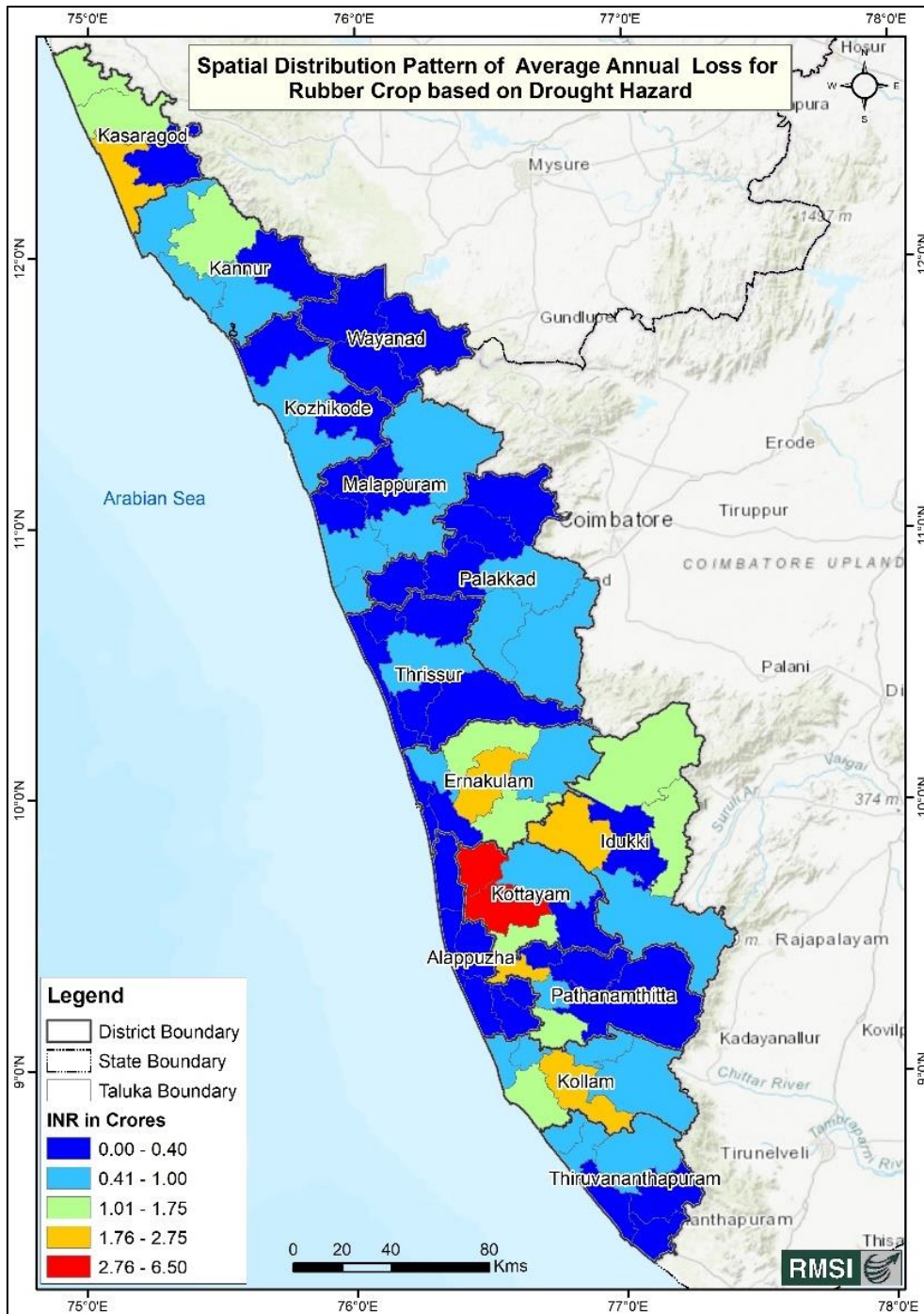


Figure 5-31: Taluk-wise Average Annual Loss in INR (Crores) for Rubber in Kerala

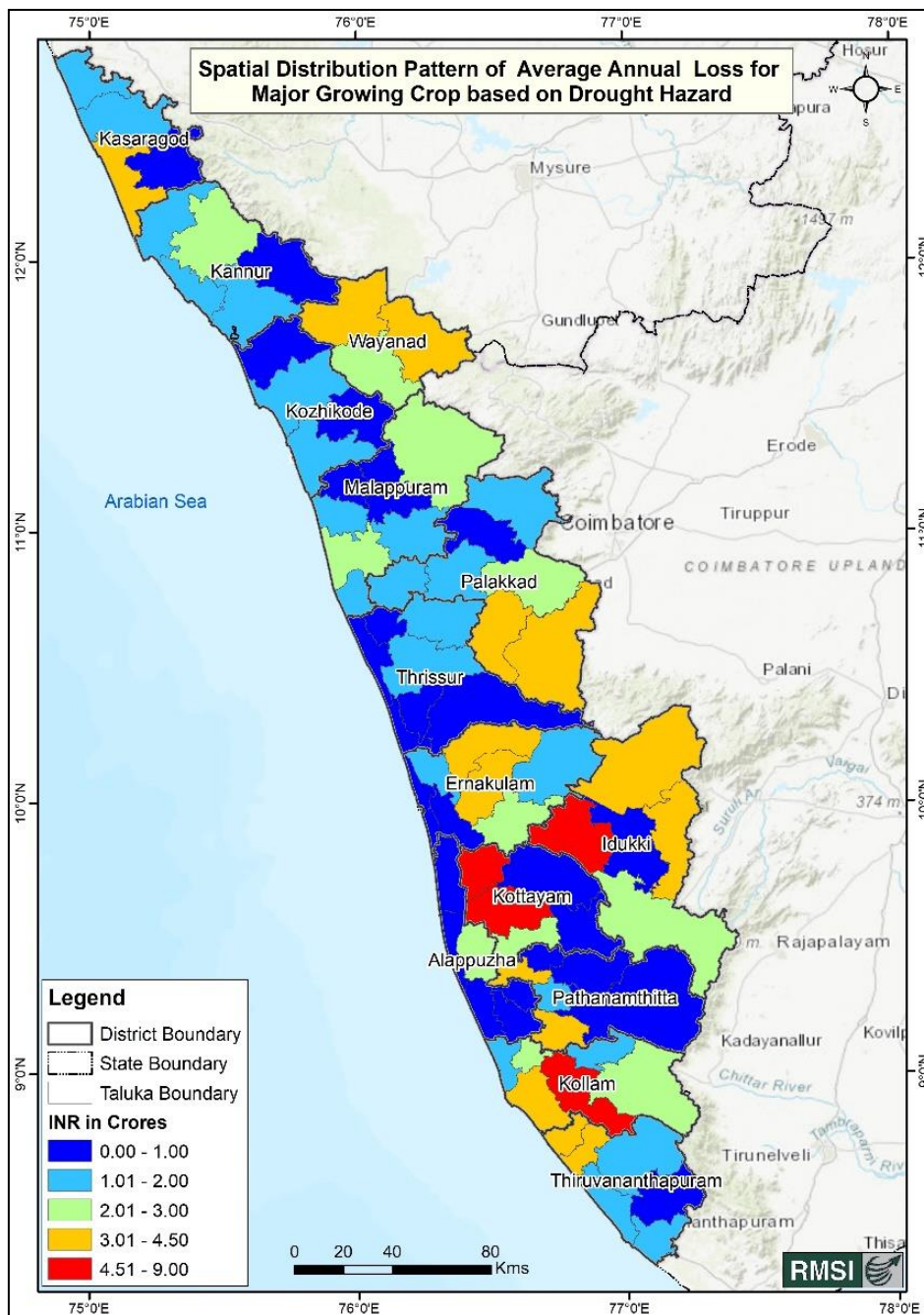


Figure 5-32: All crops (Rice, Banana, Tapioca and Rubber) aggregated AAL due to drought

### 5.9.7 DETERMINISTIC RISK ASSESSMENT OF THE CROPS TO DROUGHT HAZARD

The evaluation of the drought-induced loss estimation model was performed using observed data from the state agricultural department. The project team received data on drought-induced losses for several crops from 2020 to 2023. Among these crops, banana was the most affected,

accounting for more than 50% of the total drought-induced losses. Consequently, the project team conducted an evaluation of the current model against the observed drought-induced losses on banana crop during the 2020-2023 period.

Following are the steps followed to carry out the deterministic risk assessment (i.e., validation of the drought induced loss estimation models as furnished in Section 5.9.1) of the crops to drought hazard:

**Step 1:** As a first step for the validation of the drought induced estimated crop yield loss (i.e., modelled crop yield loss) with the observed crop yield loss, district specific past drought years (during which crops got affected due to water deficit in the respective district) were picked.

**Step 2:** Calculated drought years' crop yield loss (in terms of MDR) of all the major growing crops of each district using the RMSI platform for drought induced loss estimation models.

**Step 3:** Calculated yield loss in the monetary terms (in terms of Crore INR) using outcome of Step-2 and replacement cost of the exposure as provided in Table 5-22.

(i.e., modelled loss = MDR\*replacement cost). Replacement cost = normal production \* Minimum Support Price (MSP).

**Step 4:** Derived observed crop yield loss by computing deviation of actual crop yield w.r.t. the normal crop yield (in percentage)

for all the identified drought years and subsequently converted in the monetary terms (in INR) using replacement cost of the exposure as provided in Table 5-22.

(observed loss = % deviation in the actual crop yield w.r.t. normal crop yield in drought years\* replacement cost).

**Step 5:** Compared observed crop yield loss with the modelled crop yield loss.

**Step 6:** Plotted graph between observed and modelled crop yield loss and also calculated various statistical indices in order to validate the model.

On the basis of data availability, the deterministic risk assessment was carried out only for banana crop for all the 14 districts of Kerala.

Observed and modelled drought induced crop yield loss statistical indices has been furnished in Table 5-27. Overall analysis shows that drought hazard crop yield estimation models being developed using statistical modeling approach, in which historical weather and crop yield data were used as an input data, work very well to capture the ground reality. Hence, it can be concluded that this model can be used to estimate the crop yield loss with the good precision level in the event of drought condition.

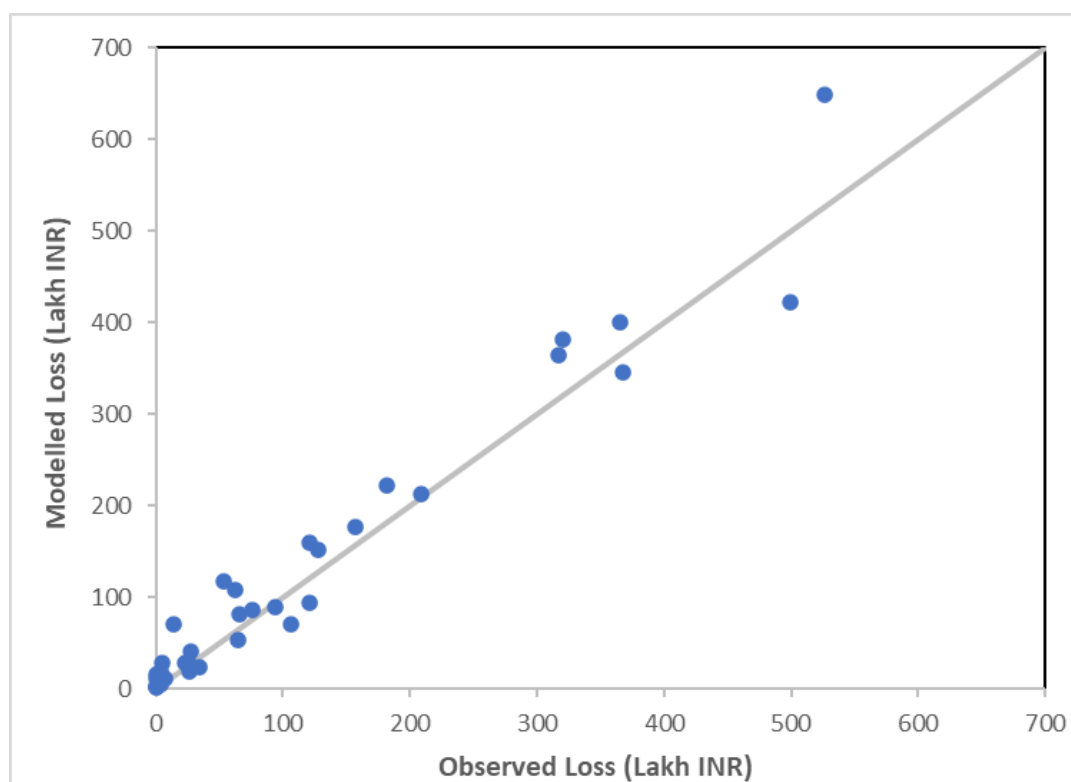


Figure 5-33: Relationship between observed and modelled drought induced loss for Banana crop

Crop and district specific drought induced observed and modelled crop yield loss has been summarized in Table 5-26.

Table 5-26: Observed and modelled loss for banana crop in the drought affected years

District	Observed Loss (Lakhs INR)				Modelled Loss (Lakhs INR)			
	2020	2021	2022	2023	2020	2021	2022	2023
Alappuzha	128.0	-	1.2	0.5	151.3	-	3.9	1.5
Kannur	-	-	-	106.6	-	-	-	70.0
Kasaragod	-	-	-	62.1	-	-	-	108.7
Kollam	499.3	27.3	94.4	53.1	422.5	40.6	89.6	116.9
Kottayam	365.3	-	26.6	120.5	399.9	-	19.1	93.9
Kozhikode	-	-	3.9	64.5	-	-	5.6	53.4
Malappuram	75.9	-	34.2	316.5	86.9	-	24.5	364.8
Pathanamthitta	525.9	-	65.5	157.0	648.3	-	81.4	176.8
Thiruvananthapuram	209.3	319.8	23.0	367.7	213.4	381.9	28.1	345.5
Thrissur	7.7	-	-	27.4	11.3	-	-	25.8
Wayanad	-	-	-	121.1	-	-	-	159.5

Table 5-27: Observed vs. modelled drought induced crop yield loss statistical indices

Statistical Index	Value
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Mean (Observed)	105.8
Mean (Simulated)	119.1
Root Mean Square Error (RMSE)	34.9
D-Index	0.99
R <sup>2</sup>	0.96

### 5.9.8 KEY FINDINGS

The key findings from the drought hazard risk assessment reveal significant trends across various return periods. Over a 100-year return period, extreme drought is projected to affect most of Kerala, particularly impacting central and southern regions with severe drought. For a 50-year return period, southern and south-central areas are likely to experience extreme drought, whereas northern and north-central regions may face severe drought. In a 25-year return period, severe drought is expected to affect over 90% of the state, with Thiruvananthapuram and Kollam districts experiencing extreme drought and Wayanad district facing moderate drought. A 10-year return period indicates severe drought in central Kerala, while the rest of the state will likely experience moderate drought. During a 5-year return period, most of Kerala is projected to encounter mild drought, with moderate drought in northern pockets. A 2-year return period suggests that normal conditions will prevail across the entire state.

The drought vulnerability analysis says that, southern districts like Thiruvananthapuram and Alappuzha exhibit higher drought vulnerability due to lower monsoon rainfall. Northern districts like Kasargod are less vulnerable with higher rainfall.

The Average Annual Loss (AAL) analysis says that, the highest AAL was observed at Palakkad district in monetary terms, followed by Kollam, while Kasargod has the lowest (Figure 1 1). In terms of percentage, the AAL is highest in Kasargod at 6.47%, with Idukki and Kottayam each at 3.0%, and other districts between 2.95% and 1.79%. Southern districts show higher AAL percentages due to lower rainfall compared to northern districts. Rice exhibits the highest AAL among crops, reflecting its

greater sensitivity to water stress. The total state AAL due to drought stands at 149.45 crores INR, around 2.47% of the exposure value. For banana crops, AAL ranges range 1.81 to 2.50 crores across two taluks from Wayanad and between .21 to 1.80 crores in three taluks (one in Wayanad and two in Palakkad). For tapioca, AAL is between INR 2.01 to 4.00 crores in four taluks (two in Thiruvananthapuram and one in Idukki and Kollam district) and between 1.16 to 2.00 in twelve taluks (three from Kollam and two taluks each in Idukki, Kottayam and Pathanamthitta and one taluk each in Alappuzha, Ernakulam and Thiruvananthapuram). For Rubber, the AAL was found to be between INR 2.76 to 6.50 crores in two taluks (two in Kottayam district) and between 1.76 to 2.75 in five taluks (one each in Kollam, Pathanamthitta, Idukki, Ernakulam and Kasaragod). Combined AAL for rice, banana, rubber and tapioca crops lies between INR 4.51 to 9.00 crores in four taluks (two in Kottayam and one each in Idukki and Kollam districts), and between 3.01 to 4.50 crores in fourteen taluks. It ranges between INR 2.01 to 3.00 crores in eleven taluks, with the remaining taluks below INR 2.00 crores.

The taluk-wise AALs for drought at different return periods show significant variability. In 2-Year Return Period, the loss may exceed INR 6.51 crores in three taluks and ranges between INR 0.75 to 2.0 crores in central and southern taluks. In 5-Year Return Period, the loss may exceed INR 14 crores in four taluks, and between INR 8 to 14 crores in fifteen taluks, with the rest ranging between INR 8 crores and below. In 10-Year Return Period, the loss may exceed INR 18 crores in four taluks, and between INR 10 to 18 crores in fifteen taluks, with others between INR 10 crores and below. In 25- and 50-Year Return

Period, the loss may exceed INR 20.01 crores in five taluks, and between INR 11.00 – 20.00 crores in fifteen taluks, with others between INR 11 crores and below. In 100-Year Return Periods, the loss may exceed INR 18 crores in six taluks, and between INR 10 to 18 crores in seventeen taluks, with others between INR 10 crores and below.

The evaluation of the drought induced crop loss model concludes that the model effectively captures real-world conditions, providing precise estimates of crop yield losses during drought events.

Based on the extensive analysis of drought impact and risk assessment for agricultural crops in Kerala, several key recommendations emerge to mitigate

adverse effects and enhance resilience. Firstly, there is a critical need to implement enhanced water management strategies, including rainwater harvesting and efficient irrigation systems, to alleviate water scarcity during drought periods. Promoting crop diversification beyond rice, banana, rubber and tapioca to include more drought-resistant crops including millets and pulses can reduce overall agricultural vulnerability. Strengthening early warning systems, supporting climate-resilient farming practices, increasing community awareness, investing in research for drought-resistant crop varieties and innovative agricultural technologies will further enhance Kerala's capacity to manage drought risks effectively.

## 6 Casualty estimation for flood and landslide, cyclonic wind and storm surge, and Drought

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As explained in Chapter 1, a comprehensive Geo-Referenced Catalogue of historical major disaster events have been developed as part of Component-1 Report. Key parameters included in this catalogue are the date, location (latitude and longitude), type of event, areas impacted including damages and losses, number of deaths (mortality), number of injured, etc.

In this chapter, we have analyzed deaths from various historical flood and landslides, as casualty from landslides in Kerala are mainly triggered from the results of heavy rainfall. Deaths in the recent Floods and landslide disasters of 2018, 2019 and recent 2024 are the stark reminders of the fragility of the State from floods and landslides. Cyclones are another disaster events, which created deaths in the State in the years 1977, 1978, 1992, 1995, 2004, 2017, and 2021. On the other hand, drought is a very slow disaster and now a days, deaths due to drought hazard is rare and no deaths have been reported from droughts in the Geo-Referenced catalogue of historical major disaster event database of Kerala State.

Casualty (deaths, injured) estimates come with lot of uncertainty as casualty due to several factors, such as:

- (a) Incompleteness of detailed historical data on casualty numbers,
- (b) Timing of the occurrence of disaster event,
- (c) Availability and effectiveness of early warning about the event, and
- (d) Effectiveness of evacuation planning etc.

For example, from Cyclonic events in India, death toll used to very high (in few

hundreds to few thousands) before 2000. Odisha Super Cyclone of 1999 is dark reminder when death toll reached to the order of 10,000. Even in Kerala State, during 1992 Severe Cyclonic events, there are 175 reported deaths. However, due to the efficient early warning and evacuation planning, these numbers have been brought down to a few or few tens. 2013 Cyclone Phailin and 2014 Cyclone Hudhud and subsequent cyclones are the example of significant reduction in the casualty numbers due to efficient cyclone early warning system in India.

On the other hand, providing early warning to landslide is challenging as installation and maintenance of dense instrumentation in high to very high landslide susceptibility areas are a costly affair and worldwide, there are limited success in landslide early warnings and effective timely evacuation of people. During day-time, it still become easy to evacuate, however, during night-time, it becomes difficult to evacuate, when people are in sleep. Wayanad, 2024 Landslide (*may be called as 2024 Flood & landslide*) is a stark reminder of heavy casualty as this event happened when people were sleeping during night.

### 6.1 Floods and Landslide

As mentioned above, we have collated a comprehensive database of floods and landslides starting from 1924. Since, number of deaths reported in this disaster is approximately reported as 1,000, and next reported major flood and landslide disaster is 1961, in which 115<sup>123</sup> deaths were reported due to floods and landslides. The next major flood events are of 1968 with the reported death of 63, and in

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<sup>123</sup> CWC (2018). Study Report Kerala Floods Of August 2018, 46 pp.

subsequent years, almost every year or other, there are reported deaths in the State except the 5 years' period of 2003 – 2007, when no deaths have been reported, which might be due to incomplete reporting. Hence, in this study, we have considered the completeness of numbers of deaths data in the catalogue from 1961 onwards for estimation of probabilistic death losses at State level from flood & landslide. The probabilistic estimates from our NatCat model provides following deaths number wrt to key return-periods (RPs) in years and Average Annual Deaths (AADs):

## 6.2 Cyclone (including Storm-Surge)

As mentioned above, we have collated a database of Cyclones (including Storm-Surge) deaths starting from 1977. The State suffered and reported deaths from the cyclones in the years 1978, 1992, 1995, 2004, 2017, and 2021. Hence, in this study, we have considered completeness of deaths data in the catalogue from 1977 onwards. The probabilistic estimates from our NatCat model provides following deaths number wrt to key return-periods (RPs) in years and average annual deaths:

Table 6-1: AADs and key Return- Period (RP) deaths from Floods and Landslides

10-Years RP	25-Years RP	50-Years RP	100-Years RP	250-Years RP	500-Years RP	Average Annual Deaths
208	295	355	413	489	548	56

Table 6-2: AADs and key Return- Period (RP) deaths from Cyclones & Storm-Surge

10-Years RP	25-Years RP	50-Years RP	100-Years RP	250-Years RP	500-Years RP	Average Annual Deaths
25	50	74	107	160	212	6

## 6.3 Drought

Historically droughts have been impacting the State periodically. However, as discussed above, drought is a very slow disaster and now a days, deaths due to drought hazard is rare and no deaths have been reported in the Geo-Referenced catalogue of historical major disaster event database of Kerala State. Hence, in this study, we could not estimate deaths numbers.

## 6.4 Summary Conclusions

The above estimated Average AADs and key return-periods deaths numbers are the best-estimate of deaths numbers. However, as discussed above, the number of deaths in a disaster depends upon several factors, and hence these estimates should be viewed with a word of caution. However, there is a need to consider high number of deaths (mortality) from floods and landslides, while updating mitigation action plans for floods and landslides in the State.

## 7 Characteristics of Risk Zones in the state

Risk zone profiles of Kerala has been prepared for flood, landslide, Cyclonic wind and surge and drought using Average Annual Losses (AAL). Based on AAL value range, state has been classified in to low, moderate and high for each hazard.

### 7.1 Floods:

#### 7.1.1 FLOOD RISK ZONES IN KERALA BASED ON AAL

The project team conducted a comprehensive analysis to identify flood risk zones in Kerala, focusing on flood induced losses in terms of monetary losses. For this study flood hazard induced

Average Annual Loss (AAL) across the LSGs in Kerala has been considered to delineate the flood hazard risk zones. Based on the AAL values, the LSGs were categorized into three risk zones: high, moderate, and low. This categorization was determined by the degree of financial losses caused by flood conditions in each area. The AAL value serves as a reliable indicator of flood impact, helping to map the region's most susceptible to economic damage from floods. The AAL (residential, govt. buildings, critical facilities, transport infrastructure and agriculture.) across the LSGs in Kerala has been classified in to four categories as shown in below Table 7-1.

Table 7-1: Categorization of drought hazard risk zone based on the AAL

AAL (INR Crores)	Flood hazard Risk Zone
>10	Very High
5-10	High
1-5	Moderate
<1	Low

Figure 7-1 illustrates the flood risk zones in Kerala, based on monetary losses attributed to flood. It has been observed that 18 talukas fall within the high-risk zone,

39 talukas fall within the moderate-risk zone, and the remaining 21 talukas fall within the low-risk zone, as determined by the Average Annual Loss (AAL).

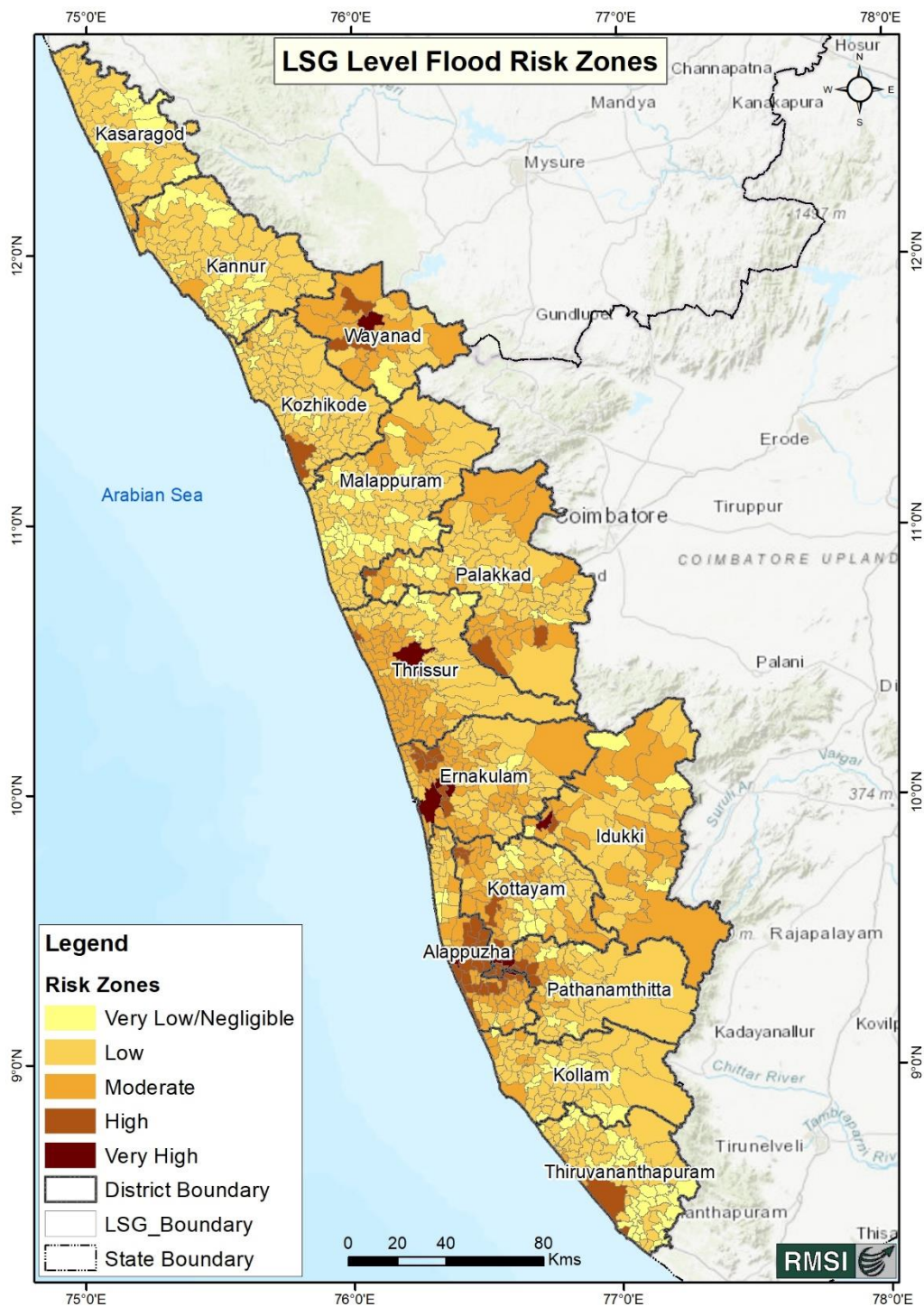


Figure 7-1: LSG wise flood risk zone over Kerala

Table 7-2: List of LSG falling in Very High-Risk zone for flood

LSG Name	Taluka Name	District Name
Ambalapuzha South	Ambalapuzha	Alappuzha
Cochin Corporation	Kochi	Ernakulam
Kalamassery Municipality	Paravur	Ernakulam
Panamaram	Mananthavady	Wayanad

Thiruvananthapuram	Chengannur	Alappuzha
Thodupuzha Municipality	Thodupuzha	Idukki
Thrissur Corporation	Thrissur	Thrissur

*Table 7-3: List of LSG falling in High-Risk zone for flood*

LSG Name	Taluka Name	District Name
Alangad	Paravur	Ernakulam
Ambalapuzha North	Ambalapuzha	Alappuzha
Anakkara	Pattambi	Palakkad
Arattupuzha	Karthikapally	Alappuzha
Budhanoor	Chengannur	Alappuzha
Changanassery Municipality	Changanassery	Kottayam
Chavakkad Municipality	Chavakkad	Thrissur
Chendamangalam	Paravur	Ernakulam
Chengannur Municipality	Chengannur	Alappuzha
Chennithala-Thrippurumthura	Mavelikkara	Alappuzha
Edathua	Kuttanad	Alappuzha
Edavetty	Thodupuzha	Idukki
Eraviperoor	Thiruvalla	Pathanamthitta
Haripad Municipality	Karthikapally	Alappuzha
Kadapra	Thiruvalla	Pathanamthitta
Karumallur	Paravur	Ernakulam
Karuvatta	Karthikapally	Alappuzha
Kizhakkencherry	Alathur	Palakkad
Kollengode	Chittur	Palakkad
Kottathara	Vythiri	Wayanad
Kottayam Municipality	Kottayam	Kottayam
Kottuvally	Paravur	Ernakulam
Kozhikode Corporation	Kozhikode	Kozhikode
Kumarapuram	Karthikapally	Alappuzha
Mananthavady Municipality	Mananthavady	Wayanad
Maravanthuruthu	Vaikom	Kottayam
Neelamperoor	Kuttanad	Alappuzha
North Paravur Municipality	Paravur	Ernakulam
Padinharathara	Vythiri	Wayanad
Pallippad	Karthikapally	Alappuzha
Pandanad	Chengannur	Alappuzha
Peringara	Thiruvalla	Pathanamthitta
Pulincunoo	Kuttanad	Alappuzha
Purakkad	Ambalapuzha	Alappuzha
Ramankary	Kuttanad	Alappuzha
Thakazhy	Kuttanad	Alappuzha
Thalavady	Kuttanad	Alappuzha
Thiruvalla Municipality	Thiruvalla	Pathanamthitta

Thiruvananthapuram Corporation	Thiruvananthapuram	Thiruvananthapuram
Thrikkakara Municipality	Kanayannur	Ernakulam
Thrikkunnappuzha	Karthikapally	Alappuzha
Tripunithura Municipality	Kanayannur	Ernakulam
Udayanapuram	Vaikkom	Kottayam
Veliyanad	Kuttanad	Alappuzha

## 7.2 Landslides:

The project team conducted a comprehensive analysis to identify landslide risk zones in Kerala, focusing on landslide-induced losses in terms of monetary losses. For this study, landslide hazard induced Average Annual Loss (AAL) across the talukas in Kerala have been considered to delineate the landslide hazard risk zones. Based on the AAL values, the talukas were categorized into four risk zones such as low, moderate, high and very high. This categorization was

determined by the degree of financial losses caused by landslide in each area. The AAL value serves as a reliable indicator of landslide impact, helping to map the region's most susceptible to economic damage from landslide. The AAL (combined for all buildings (Residential, Govt offices, Govt Schools and Govt hospitals), roads, railways and agriculture crops including (Coconut, Arecanut, Rice & Banana)) across the talukas in Kerala has been categorized as shown in Table 7-4. Landslide risk zone map of the State has depicted in Figure 7-2.

Table 7-4: Categorization of landslide hazard risk zone based on the AAL

AAL (INR Crores)	Landslide hazard Risk Zone
>1	Very High
0.25-1	High
0.01-0.25	Moderate
0-0.01	Low

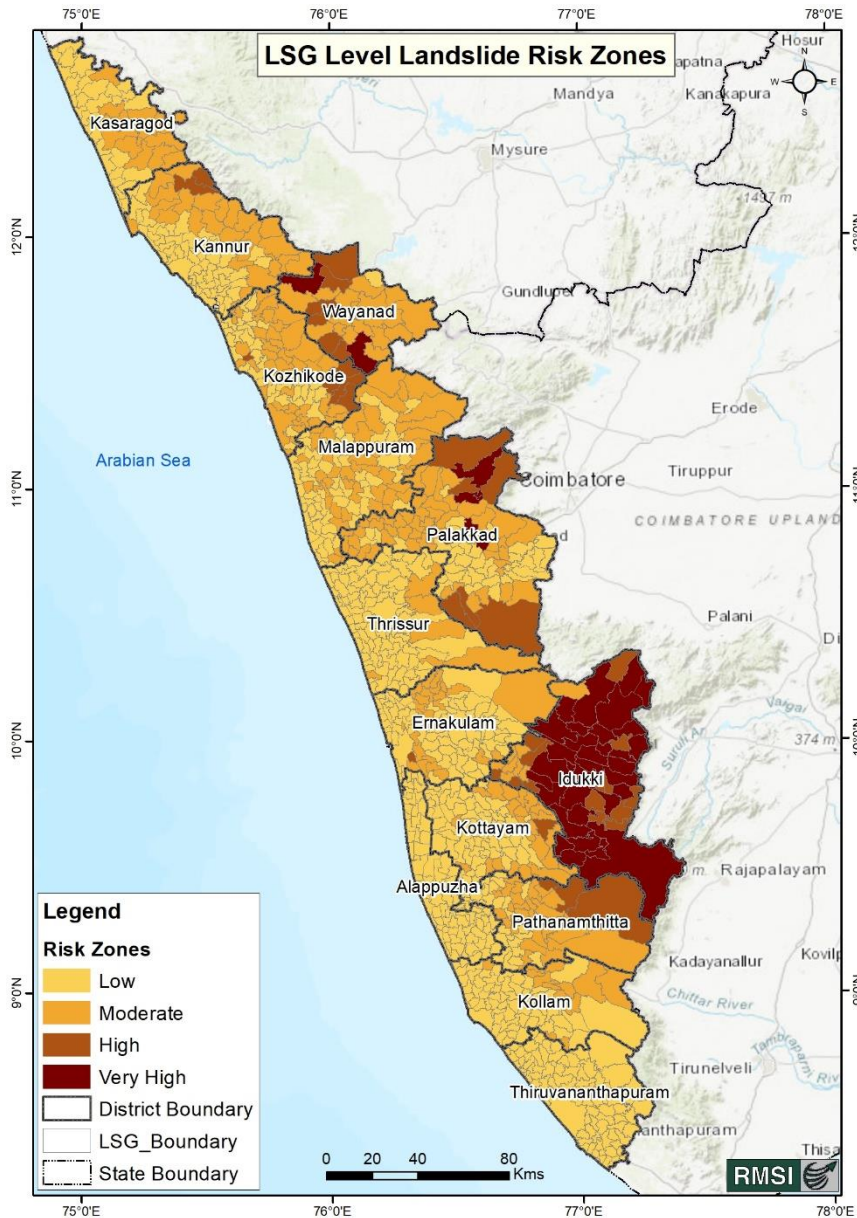


Figure 7-2: LSG-wise Landslide risk zone over Kerala

Table 7-5: List of LSG falling in Very High-Risk zone for landslide

LSG Name	Taluka Name	District Name
Adimaly	Devikulam	Idukki
Arakulam	Thodupuzha	Idukki
BysonValley	Devikulam	Idukki
Devikulam	Devikulam	Idukki
Idukki Kanjikuzhy	Idukki	Idukki
Kattappana Municipality	Idukki	Idukki
Konnathady	Idukki	Idukki
Kumily	Peermade	Idukki
Mariyapuram	Idukki	Idukki
Munnar	Devikulam	Idukki

Nedumkandam	Udumbanchola	Idukki
Udumbanoor	Thodupuzha	Idukki
Vazhathope	Idukki	Idukki
Vellathooval	Devikulam	Idukki
Agali	Attappadi	Palakkad
Meppadi	Vythiri	Wayanad
Thavinhal	Mananthavady	Wayanad
Kokkayar	Peermade	Idukki
Rajakkad	Udumbanchola	Idukki
Mundur	Palakkad	Palakkad
Chinnakanal	Udumbanchola	Idukki
Mankulam	Devikulam	Idukki
Pallivasal	Devikulam	Idukki
Pampadumpara	Udumbanchola	Idukki
Peermade	Peermade	Idukki
Peruvanthanam	Peermade	Idukki
Santhanpara	Udumbanchola	Idukki
Senapathy	Udumbanchola	Idukki
Udumbanchola	Udumbanchola	Idukki
Upputhara	Peermade	Idukki
Vandiperiyar	Peermade	Idukki
Vathikudy	Idukki	Idukki
Vattavada	Devikulam	Idukki
Velliyamattom	Thodupuzha	Idukki
Elappara	Peermade	Idukki

Table 7-6: List of LSG falling in High-Risk zone for landslide

LSG Name	Taluka Name	District Name
Amboori	Kattakada	Thiruvananthapuram
Chittar	Ranni	Pathanamthitta
Seethathodu	Konni	Pathanamthitta
Vannappuram	Thodupuzha	Idukki
Kizhakkencherry	Alathur	Palakkad
Pudur	Attappadi	Palakkad
Sholayoor	Attappadi	Palakkad
Ayancheri	Vadakara	Kozhikode
Kodanchery	Thamarassery	Kozhikode
Thiruvambadi	Thamarassery	Kozhikode
Pozhuthana	Vythiri	Wayanad
Thirunelly	Mananthavady	Wayanad
Pattiam	Thalassery	Kannur
Kayyur Cheemeni	Hosdurg	Kasaragod
Kumbadaje	Kasaragod	Kasaragod
Peringammala	Nedumangad	Thiruvananthapuram

Kulathupuzha	Punalur	Kollam
Poonjar Thekkkara	Meenachil	Kottayam
Chakkupallam	Udumbanchola	Idukki
Kanchiyar	Idukki	Idukki
Kudayathoor	Thodupuzha	Idukki
Muttom	Thodupuzha	Idukki
Purapuzha	Thodupuzha	Idukki
Tachampara	Mannarkkad	Palakkad
Vandazhy	Alathur	Palakkad
Kanhirapuzha	Mannarkkad	Palakkad
Nelliyampathy	Chittur	Palakkad
Chakkittapara	Quilandy	Kozhikode
Kavilumpara	Vadakara	Kozhikode
Koorachundu	Quilandy	Kozhikode
Koodaranhi	Thamarassery	Kozhikode
Vellamunda	Mananthavady	Wayanad
Vythiri	Vythiri	Wayanad
Mananthavady Municipality	Mananthavady	Wayanad
Padinharathara	Vythiri	Wayanad
Kottiyoor	Iritty	Kannur
Udayagiri	Taliparamba	Kannur
Alakode Knr	Taliparamba	Kannur
AyyappanCoil	Idukki	Idukki
Kamakshy	Idukki	Idukki
Kanthalloor	Devikulam	Idukki
Karimannoor	Thodupuzha	Idukki
Karunapuram	Udumbanchola	Idukki
Marayoor	Devikulam	Idukki
Rajakumary	Udumbanchola	Idukki
Vandanmedu	Udumbanchola	Idukki
Erattayar	Idukki	Idukki
Kattippara	Thamarassery	Kozhikode
Kanichar	Iritty	Kannur
Kelakam	Iritty	Kannur

## 7.3 Cyclonic Wind

### 7.3.1 CYCLONIC WIND RISK ZONES IN KERALA BASED ON THE RISK ASSESSMENT

The project team conducted a comprehensive analysis to identify cyclonic wind risk zones in Kerala, focusing on the associated monetary losses. For this study, the Average Annual Loss (AAL) due to cyclonic wind hazard across the talukas in

Kerala were analyzed to delineate risk zones. Based on the AAL values, the talukas were categorized into three risk levels: high, moderate, and low (**Error! Not a valid bookmark self-reference.**). This classification reflects the extent of financial losses caused by cyclonic wind events in each area. The AAL value serves as a reliable indicator of the economic impact of cyclonic winds, helping to map the region's most vulnerable to such damage.

The combined AAL (including residential buildings, critical facilities, government buildings, transport infrastructure, and agriculture) across the talukas in Kerala ranged from INR 0.11 crore to INR 2.93 crores.

**Error! Not a valid bookmark self-reference.** illustrates the wind risk zones in Kerala, categorized based on monetary losses attributed to cyclonic wind. The analysis indicates that all 79 talukas are in the low-risk zone, as determined by the Average Annual Loss (AAL).

Table 7-7: Categorization of cyclonic wind hazard risk zone based on the AAL

Wind Risk Zone Range (INR Crore)	
High	>0.25
Moderate	>0.10 - 0.25
Low	<0.10

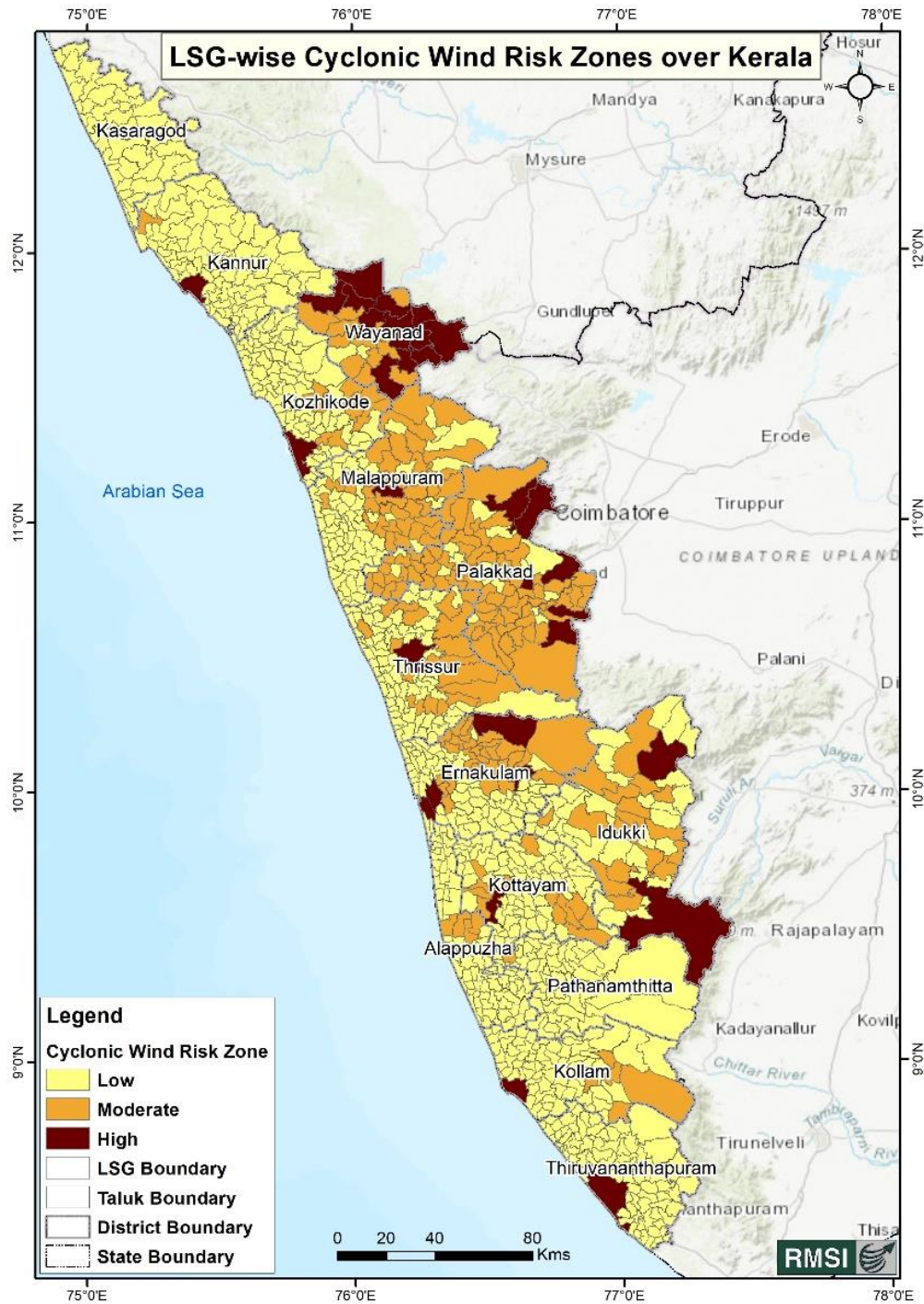


Figure 7-3: LSG-wise cyclonic wind risk zone over Kerala

Table 7-8: List of LSG falling in High-Risk zone for Cyclonic Wind

LSG Name	Taluka Name	District Name
Cochin Corporation	Kochi	Ernakulam
Kannur Corporation	Kannur	Kannur
Kollam Corporation	Kollam	Kollam
Kozhikode Corporation	Kozhikode	Kozhikode
Thiruvananthapuram Corporation	Thiruvananthapuram	Thiruvananthapuram
Thrissur Corporation	Thrissur	Thrissur

## 7.4 Storm Surge

### 7.4.1 STORM SURGE ZONES IN KERALA BASED ON THE RISK ASSESSMENT

The project team conducted a comprehensive analysis to identify storm surge risk zones in Kerala, focusing on the associated monetary losses. For this study, the Average Annual Loss (AAL) due to storm surge hazard across the talukas in Kerala were analyzed to delineate risk zones. Based on the AAL values, the talukas were categorized into three risk levels: high, moderate, and low (Table 7-9). This classification reflects the extent of financial losses caused by storm surge

events in each area. The AAL value serves as a reliable indicator of the economic impact of storm surges, helping to map the region's most vulnerable to such damage.

The combined AAL (including residential buildings, critical facilities, government buildings, transport infrastructure, and agriculture) across the talukas in Kerala ranged from INR 0.000001 crore to INR 1.84 crores. Figure 7-3 illustrates the storm surge risk zones in Kerala, categorized based on monetary losses attributed to storm surge. The analysis indicates that 50 talukas are in the low-risk zone, as determined by the Average Annual Loss (AAL)

Table 7-9: Categorization of storm surge hazard risk zone based on the AAL

Surge Risk Zone Range (INR Crore)	
High	>0.25
Moderate	>0.05 - 0.25
Low	<0.05

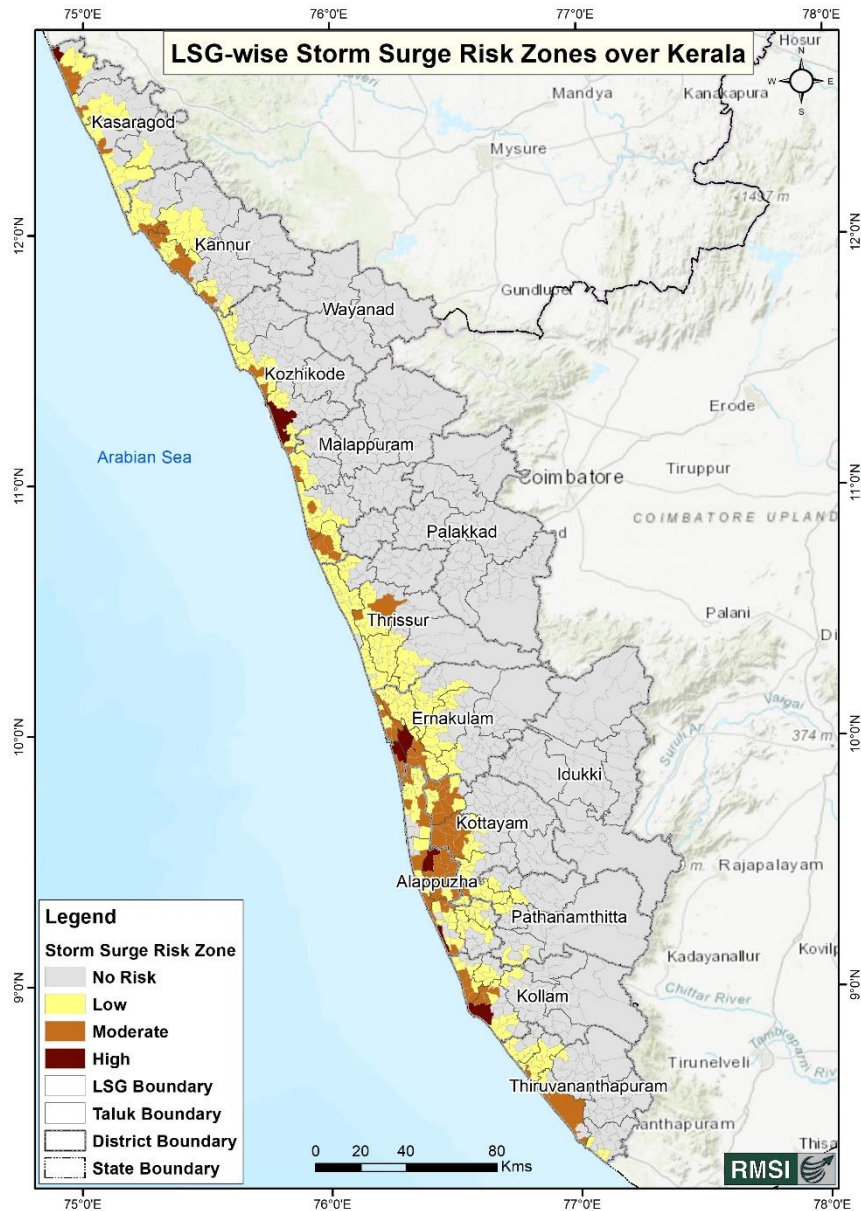


Figure 7-4: LSG-wise storm surge risk zone over Kerala

Table 7-10: List of LSG falling in High-Risk zone for Storm Surge

LSG Name	Taluka Name	District Name
Alappad	Karunagapally	Kollam
Arattupuzha	Karthikapally	Alappuzha
Cochin Corporation	Kochi	Ernakulam
Kainakary	Kuttanad	Alappuzha
Kollam Corporation	Kollam	Kollam
Kozhikode Corporation	Kozhikode	Kozhikode
Manjeshwar	Manjeswaram	Kasaragod

## 7.5 Drought:

### 7.5.1 DROUGHT RISK ZONES IN KERALA BASED ON THE RISK ASSESSMENT

The project team conducted a comprehensive analysis to identify drought risk zones in Kerala, focusing on drought-induced loss in terms of monetary loss. For this study, drought hazard induced Average Annual Loss (AAL) across the talukas in Kerala have been considered to delineate the drought hazard risk zone. Based on the AAL values, the talukas were categorized into three risk zones: high, moderate, and low. This categorization was determined by the degree of financial

loss caused by drought conditions in each area. The AAL value serves as a reliable indicator of drought impact, helping to map the region's most susceptible to economic damage from droughts. The AAL (combined for Rice, Banana, and Tapioca) across the talukas in Kerala have been categorized into three classes as given in Table 7-11. Figure 7-5 illustrates the drought risk zones in Kerala, based on monetary losses attributed to drought. It has been observed that 4 talukas fall within the high-risk zone, 25 talukas fall within the moderate-risk zone, and the remaining 49 talukas fall within the low-risk zone, as determined by the Average Annual Loss (AAL).

Table 7-11: Categorization of drought hazard risk zone based on the AAL

AAL (Crore INR)	Drought Risk
>5	High
2 - 5	Moderate
< 2	Low

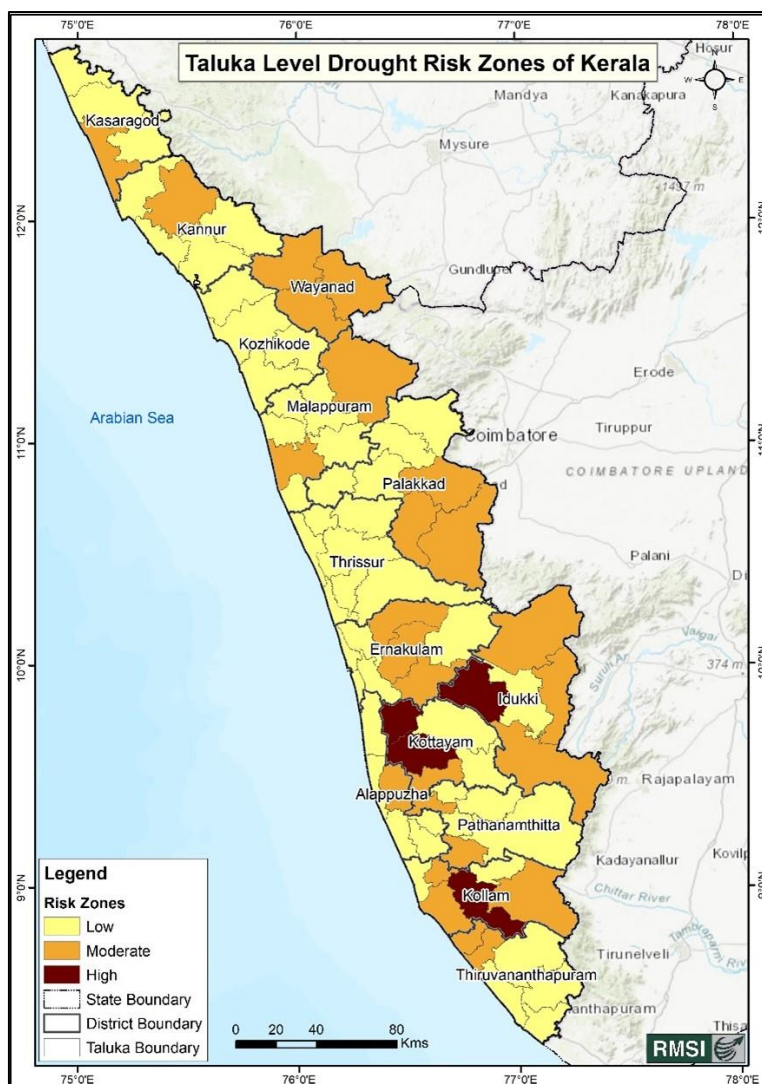


Figure 7-5: Taluka-wise drought risk zone over Kerala

The list of 4 Talukas falling in high-risk zone for drought have been furnished in Table 7-12.

Table 7-12: List of Talukas falling in High-Risk zone for drought

Taluka	District
Thodupuzha	Idukki
Kottarakara	Kollam
Kottayam	Kottayam
Vaikkom	Kottayam

The list of 31 Talukas falling in moderate-risk zone for drought have been furnished in **Error! Reference source not found.**

Table 7-13: List of Talukas falling in Moderate-Risk zone for drought

<b>Taluka</b>	<b>District</b>
Kuttanad	Alappuzha
Aluva	Ernakulam
Kunnathunad	Ernakulam
Muvattupuzha	Ernakulam
Devikulam	Idukki
Udumbanchola	Idukki
Peermade	Idukki
Taliparamba	Kannur
Hosdurg	Kasaragod
Kollam	Kollam
Kunnathur	Kollam
Punalur	Kollam
Changanassery	Kottayam
Nilambur	Malappuram
Tirur	Malappuram
Alathur	Palakkad
Chittur	Palakkad
Palakkad	Palakkad
Adoor	Pathanamthitta
Thiruvalla	Pathanamthitta
Chirayinkeezhu	Thiruvananthapuram
Varkala	Thiruvananthapuram
Mananthavady	Wayanad
Sulthan Bathery	Wayanad
Vythiri	Wayanad

## **8 Conclusion**

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Brochures on catastrophe risk profiles

Brochure is attached as a separate pdf file