FINAL REPORT OF THE

COMMITTEE TO EXAMINE THE CAUSES OF REPEATED EXTREME HEAVY RAINFALL EVENTS, SUBSEQUENT FLOODS AND LANDSLIDES AND TO RECOMMEND APPROPRIATE POLICY RESPONSES

Kerala State Council for Science Technology and Environment

Submitted to

Kerala State Planning Board

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Composition of the Committee

Chairperson	
Prof. K.P. Sudheer	Executive Vice President, KSCSTE & Principal Secretary (Ex-officio), S&T Department, Government of Kerala
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Prof. S.K. Satheesh	Indian Institute of Science, Bengaluru
Dr. D. Sivananda Pai	India Meteorological Department, Pune
Dr. K.J. Ramesh	India Meteorological Department, New Delhi
Dr. Sachin S. Gunthe	Indian Institute of Technology Madras, Chennai
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Chief Engineer	Irrigation, Design and Research Board, Government of Kerala
Chief Engineer (Dam Safety)	Kerala State Electricity Board
Member Secretary	Kerala State Disaster Management Authority, Government of Kerala
Director	Centre for Water Resources Development and Management, Kozhikode
Co-opted Members	
Prof. Ravindra Gettu	Indian Institute of Technology Madras, Chennai
Sri. John Mathai	ESSO-National Centre for Earth Science Studies, Thiruvananthapuram
Prof. R. Ramkumar	Kerala State Planning Board

Foreword

During August 2018 as well as in August 2019, the Kerala State experienced some of the most severe Extreme Rainfall Events (EREs) on record. These EREs caused extensive flooding (in most of the river basins) and landslides of high intensity in most districts of the State (specifically along the Western Ghats) resulting in severe damage to both the built and the natural ecosystem. It is to be noted that both these events indicated a major deviation from the normal climatic pattern over the historical period in Kerala, and have occurred in consecutive years, which is a very rare phenomenon. While there were a lot of speculations, theories and scientific perspectives explaining the occurrence of this phenomenon, a concrete and scientific validation was lacking. This phenomenon was a result of various factors ranging from the global climate change to local anthropogenic activities, and the context warranted a comprehensive investigation by a team of scientists and experts drawn across different disciplines, including earth and atmospheric sciences, civil engineering with special emphasis on hydrology, flood, reservoir operation, and landslides, anthropogenic activities resulting in change in land use and terrain stability, and cloud-aerosol interaction.

In this premise, a committee of experts from the disciplines was constituted by the Kerala State Planning Board, Government of Kerala, in consultation with the State Planning Board, to investigate the cause and responses to the flooding and landslides in the aftermath of heavy rainfall in August 2018 and August 2019. The experts were drawn from the Indian Institute of Science Bengaluru, Indian Institute of Technology Madras, Indian Institute of Technology Bombay, India Meteorological Department, National Centre for Earth Science Studies, and different organizations and government departments. The committee was to prepare a quick assessment report, after scientific evaluation of the extreme hazards, containing recommendations that facilitate the formulation of appropriate policy responses, and also to propose a framework for mitigating the hazards. The primary focus of the committee was to address the following concerns:

1. The reasons for the occurrence of such EREs and their causative factors
2. Effectiveness of the capability and potential for accurate forecasting of such events with sufficient lead time
3. The remedial measures for minimizing the severe landslides during such EREs
4. The remedial measures for minimizing the severe flood hazard during such EREs
5. The impact of anthropogenic factors in increasing the severity of the hazard

This report is the outcome of the detailed investigations, deliberations, and discussions with various stakeholders and experts by the committee. It is anticipated that the report would serve as a document for developing disaster preparedness and emergency action plans for the Kerala State for such events in the future.

-Sd-
Prof. K P Sudheer
Chairman of the Committee

16 December 2019
Thiruvananthapuram

Acknowledgments

The committee would like to acknowledge the Kerala State Planning Board, Government of Kerala for entrusting the responsibility of this investigation and to suggest recommendations for policy development. The committee is grateful to the government for having trusted the expertise and experience of the interdisciplinary team drawn from a scientific pool across the country. It was a wonderful opportunity for the members to interact on an interdisciplinary problem that warranted an immediate solution, and the committee acknowledges that the members also have learned a lot of new things during the course of this work.

Working with various line departments was very interesting. The members express their sincere appreciation to all the officers they have interacted with and acknowledge the wholehearted cooperation they received. The line departments and research institutes have provided the requested information and data, well in time, which helped the committee complete the analysis and report preparation on time. A few government departments specifically to mention are Kerala State Water Resources Department (KWRD), Kerala Spatial Data Infrastructure (KSDI), Kerala State Land Use Board (KSLUB), Kerala State Remote Sensing and Environment Centre (KSREC), Kerala State Electricity Board (KSEB) Ltd., Kerala Dam Safety Authority (KSDA), Kerala State Disaster Management Authority (KSDMA) and ESSO-National Centre for Earth Science Studies (NCESS).

Timely completion of this exciting task would not have been possible without the cooperation and coordination from the officers of the Kerala State Council for Science, Technology, and Environment (KSCSTE), especially Dr. S Pradeep Kumar, Member Secretary, and Dr. Harinarayanan, P, Principal Scientist, who coordinated the various activities of the committee. The input provided by the Collectors of different districts of Kerala were very helpful in moulding the activities of the committee. Specifically, we acknowledge the discussions with Dr. Adeela Abdulla, District Collector, Alappuzha (now District Collector of Wayanad) and Mr. Seeram Sambasiva Rao, District Collector, Kozhikode. The support and the assistance offered by various organizations during the field visits of the committee require special mention; specifically, KSDMA, Kerala Forest Research Institute (KFRI), Centre for Water Resources Development and Management (CWRDM), Irrigation Department, and KSEB. The data, field observations and analytical information provided by Prof. Chandrakaran S, National Institute of Technology (NIT) Calicut is also thankfully acknowledged. The committee thanks Dr. Anindya Pain, Central Building Research Institute (CBRI), Roorkee and Mr. Dilli Rao, IIT Bombay for their contributions through field visits and modelling exercise. The committee acknowledges Prof. BS Murty and Prof. Balaji Narasimhan of IIT Madras, for offering constructive suggestions to improve the quality of presentation of the report after a review of this report.

The task of putting together the thoughts, points of deliberations and analytical results into this report was possible with the untiring efforts of a team of scientists and scholars from CWRDM, KSDI, and IIT Madras. The committee place on record their contribution, and gratefully acknowledge the efforts of Mr. Jainet P J, CWRDM, Ms. Dawn Emil Sebastian, CWRDM, Mr. Rajeev K, KSREC, Dr. Arun P R, CWRDM, and Mr. Pradeep G S, KSDMA, Dr. Sahila Beegum, IIT Madras, Ms. Cicily Kurian, IIT Madras, and Ms. Jesna, IIT Madras. A special mention about and thanks to Dr. Jobin Thomas, IIT Madras for his sincere efforts in coordinating the activities of report preparation and field visits of the committee. The secretarial assistance rendered by Ms. Sarah Mathew, KSCSTE is also duly acknowledged.

The committee pronounces that this challenging task of completion of the report was possible only with the cooperation and assistance from various individuals and groups at different levels in different organizations and villages, and the list could be unending. The committee expresses its sincere appreciation to all those who have assisted the committee directly or indirectly to complete its task on time.

-Sd-
Prof. K P Sudheer
Chairman of the Committee

16 December 2019
Thiruvananthapuram

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Abbreviations/Acronyms

AD	Anderson-Darling
CCN	Cloud Condensation Nuclei
CEC	Cation Exchange Capacity
CPWD	Central Public Works Department
CRPF	Central Reserve Police Force
CWC	Central Water Commission
DEM	Digital Elevation Model
DEOC	District Emergency Operations Centres
DM	Disaster Management
ENVIS	Environmental Information System
EPS	Ensemble Prediction System
ERE	Extreme Rainfall Event
FDC	Flow Duration Curves
FEM	Finite Element Model
FOS	Factor of Safety
FRL	Full Reservoir Level
GEFS	Global Ensemble Forecasting System
GFS	Global Forecast System
GI	Green Infrastructure
GSDP	Gross State Domestic Product
GSI	Geological Survey of India
GWT	Ground Water Table
HL	Heat Low
HP	Horse Power
ID	Intensity–Duration
IITB	Indian Institute of Technology Bombay
IMD	Indian Meteorological Department
IMERG	Integrated Multi-Satellite Retrievals for GPM
IOD	Indian Ocean Dipole
ITCZ	Inter-Tropical Convergence Zone
JJAS	June July August September
KS	Kolmogorov-Smirnov
KSCSTE	Kerala State Council for Science, Technology and Environment

KSDMA	Kerala State Disaster Management Authority
KSEB	Kerala State Electricity Board
KWRD	Kerala Water Resources Department
LID	Low Impact Development
LLJ	Low-Level Jet
LSE	Least Square Error
LSGD	Local Self Government Department
LSI	Landslide Susceptibility Index
LULC	Land Use/ Land Cover
MCM	Million Cubic Meter
MISO	Monsoon Intra-seasonal Oscillation
MJO	Madden Julian Oscillation
MM	Modified Mercalli
MSL	Mean Sea Level
MT	Monsoon Trough
NCESS	National Centre for Earth Science Studies
NCMRWF	National Centre for Medium-Range Weather Forecasting
NDRF	National Disaster Response Force
NITC	National Institute of Technology Calicut
NNW	North-Northwest
PRB	Periyar River Basin
PWD	Public Works Department
SDRF	State Disaster Response Fund
SEOC	State Emergency Operations Centre
SSE	South-South-West
TA	Tibetan Anticyclone
TEJ	Tropical Easterly Jet
UM	Unified Model
USACE	U.S. Army Corps of Engineers
WG	Western Ghats
WRF	Weather Research and Forecast
WRIS	Water Resources Information System

Executive Summary

The Kerala State experienced some of the most severe Extreme Rainfall Events (EREs) on record during August 2018 as well as in August 2019. These EREs caused extensive flooding (in most of the river basins) and landslides of high intensity in most districts of the State (specifically along the Western Ghats) resulting in severe damage to both the built and the natural ecosystem. While there were a lot of speculations, theories and scientific perspectives explaining the reasons for occurrence of these phenomena, a concrete and scientific validation was still lacking. These phenomena are a result of various factors ranging from the global climate change to local anthropogenic activities, and required to be investigated comprehensively by a team consisting of interdisciplinary experts. The Committee was entrusted to prepare a quick assessment report, after examining the causes of repeated extreme heavy rainfall events, and subsequent floods/landslides, and suggest recommendations to frame appropriate policy responses. Consequently, the Kerala State Planning Board, Government of Kerala constitute a technical committee. The Committee comprised of an interdisciplinary team of experts from Climate Science, Hydrology, Geology and Civil Engineering disciplines. The Committee was entrusted to prepare a quick assessment report, after examining the causes of repeated extreme heavy rainfall events, and subsequent floods/landslides, and suggest recommendations to frame appropriate policy responses. This document details the summary of the investigations, conclusions and recommendations by the Committee.

The State of Kerala is a narrow strip of land, in the southwestern margin of the Indian Peninsula. It lies between the Western Ghats (WG) in the east and the Arabian Sea in the west. The geographical area of the State is 38,863 square km. The State has a coastal stretch of about 580 km with a width varying from roughly 30 to 120 km. The physiographic profile of the State is classified into three distinct zones: the highlands (elevation > 75 m above mean sea level, and covering the steep and rugged sections of the WG), the lowlands (elevation < 7.5 m above mean sea level, and comprising of the coastal plains), and the midlands (consisting of the undulating hills and valleys) in between.

Kerala frequently experiences flooding and inundation across the low-lying coastal plains, floodplains and broad flat bottom valleys of the river systems and also landslides along with the steeply sloping segments of the Western Ghats. The NCESS has assessed the natural hazard proneness of the State. The assessment indicates that 14.52 per cent of the total geographic area (i.e., 5,643 square km) is prone to flood hazards, with varying proportions as high as 50 per cent for Alappuzha district. A total area of 1848 square km (4.71 per cent geographic area) in the State, extending along the steep slopes of the Western Ghats (i.e., mostly in Wayanad, Kozhikode, Malappuram Idukki, Kottayam and Pathanamthitta districts), is highly prone to the occurrence of landslides. Similar to floods, the occurrence of landslides in the State is mostly triggered by intense rainfall during the extreme rainfall events (EREs).

According to Census 2011, Kerala has a population of 3.3 crores. Kerala is ranked 8th in the population density (859 persons per square km) among the 28 states in India (Census of India, 2011). The distribution of population among the different physiographic units of the State does not show linearity with respect to the areal extent, as the population along the lowlands is much denser compared to the highlands and the midlands.

In August 2018, Kerala experienced two severe EREs, i.e., during August 8th to 9th and August 15th to 17th. According to the India Meteorological Department (IMD), Kerala received a total of 2346.6 mm rainfall from June 1, 2018to August 19, 2018, which is roughly 42 per cent above the normal rainfall. The widespread flooding in August 2018 affected almost 5.4 million people – one-sixth of the State's population. Several districts were inundated for more than two weeks due to the floods. A total of 1,260 out of the 1,664 villages of Kerala were affected. About 341 major landslides were reported from ten districts, where Idukki district was ravaged by 143 landslides, causing a death toll about 104.

Kerala faced yet another ERE between August 7th and 9th, 2019. The State received 'large excess' rainfall to the extent of 123 per cent in August 2019 as compared to 96 per cent excess rainfall received in August 2018. There was 32 per cent deficit rainfall during the months of May, June, and July in 2019. In 2018, there was excess rainfall (8 per cent) during the same period. The antecedent high wetness condition prior to August in 2018 caused a higher level of flooding impact as compared to that in August 2019, which was at a relatively dry antecedent condition. The widespread flooding and landslides across the districts of northern Kerala in 2019 caused severe damage to both the manmade and natural ecosystems. The low-lying areas of the major river systems were inundated, and more than 2 lakh people were displaced. Kerala witnessed 80 landslides in eight districts over three days (August 8-11, 2019) and the death toll crossed 120.

The repeated EREs, and associated floods and landslides caused damage to infrastructure and resulted in the loss of lives and livelihoods. In the context of recurring EREs and associated damages due to flood and landslides, the Kerala State Planning Board, Government of Kerala constituted a "Committee to examine the causes of repeated extreme heavy rainfall events, subsequent floods, and landslides, and to recommend appropriate policy responses" vide order G.O. (Rt) No. 42/2019/S&TD dated 22-08-2019. The Committee was entrusted to prepare a quick assessment report, after examining the causes of repeated extreme heavy rainfall events, and subsequent floods/landslides, and suggest recommendations to frame appropriate policy responses. The Committee comprised of an interdisciplinary team of experts from Climate Science, Hydrology, Geology and Civil Engineering disciplines.

The Committee addressed the following concerns while preparing the assessment report as per the terms of reference:

1. The reasons for the occurrence of such EREs and their major causative factors;
2. The capability and potential for accurate forecasting of such events with sufficient lead times;
3. Reviewing indicators and methods to locate areas prone to severe landslides during such EREs and remedial measures for minimising such hazards and their consequences;
4. Reviewing current maps of areas prone to flood hazard during such EREs and mitigation measures to minimise such hazards; and
5. To focus on the role of changing land use in these hazards

Methods of Assessment, Review, and Analysis

The Committee conducted field visits in several worst-affected areas (in 2018 and 2019) of floods and landslides in Pathanamthitta, Alappuzha, Kottayam, Malappuram, Kozhikode, Wayanad, Idukki and Kannur districts. The Committee also had several rounds of meetings and discussions with experts, officials, and the local community. The Committee addressed the set objectives on the basis of the survey of previous literature and ancillary information, observations during the field visits, interaction/discussion with scientific experts, administrators at different levels, and community.

The Committee used primary as well as secondary data (either observed or simulated or in combination) for detailed analysis. The daily rainfall data (recorded at meteorological stations and 0.25° x 0.25° gridded data) of the India Meteorological Department (IMD) were used for the analysis of rainfall patterns and spatio-temporal trends across the State. The aerosol particle size distribution data, collected from Munnar Aerosol Observatory (established by IIT Madras) were used for the analysis of the effects of aerosols on EREs. The physical properties of the soil samples from the areas of landslide occurrences (collected by the National Institute of Technology, Kozhikode) were used for the numerical modelling of the landslides. Numerical analysis was performed to evaluate the factor of safety of slopes using Finite Element based Computer Program PLAXIS 2D (PLane strain and AXIal Symmetry). The gauge-discharge data, collected from the Water Resources Department, Government of Kerala, Kerala State

Electricity Board (KSEB) Ltd., and Central Water Commission (CWC) through WRIS-India data repository were used for the hydrological analysis. The HEC-HMS, a watershed hydrological model was used to simulate the peak discharge for the actual condition as well as for different scenarios, and the HEC-RAS (2D), a hydrodynamic model was used for the development of flood inundation maps corresponding to different scenarios.

The Committee after detailed deliberations, analysis, and assessment arrived at the following conclusions and recommendations. It is envisaged that the recommendations of the Committee may help the Government to formulate appropriate policies for mitigating the negative impact of such devastating natural hazards in the future.

Conclusions

- The predominant reason for the occurrence of EREs in Kerala in the last two years (2018 and 2019) was the development of deep depression over the northwest Bay of Bengal and neighbourhood, coupled with the influence of the local orographic gradient on the atmospheric circulation, variability in monsoon circulation caused by the transient synoptic-scale and intra-seasonal propagating oscillations. It is to be noted that no noticeable teleconnections of EREs with El Nino Southern Oscillations (ENSO) and Indian Ocean Dipole (IOD) are observed.
- An analysis of the observed southwest monsoon rainfall during 1901-2018 in Kerala, in general, exhibited a decreasing trend over the northern half and along the coastal areas of the State. This observation was significant (at 95 per cent level) in isolated locations in northern parts of the State. The rainfall over the southern region of the State also showed a decreasing (but non-significant) trend. However, the data pertaining to the recent years (1971-2018), showed an increasing trend over most parts of the southern half and some interior areas of central parts of the State with isolated areas showing significant trends. A significant decreasing trend was observed over the northernmost areas of the State.
- There are a large number of predictive models being employed by various agencies across the globe for prediction of EREs, and many of them are being used by the IMD in the Indian context. However, they fail to capture the real mechanism of cloud formation and its impacts on rainfall distribution and pattern during the onset and occurrence of EREs.
- The triggering factor for the occurrence of landslides across Kerala during the EREs in August 2018 and 2019 was the oversaturation of the overburden. Idukki experienced the maximum number of landslides (977 including minor slides) in 2018, whereas Palakkad had the highest count in 2019 (18), followed by Malappuram (11), Wayanad

(10) and Kozhikode (8). Generally, steep sloppy areas having slope more than 33 per cent are more vulnerable to landslide, and the majority of the landslides in the State during the last two years occurred in these terrains. The Committee noted that anthropogenic activities intended for agricultural expansion and water conservation such as terracing, blocking/diversion of stormwater channels and alteration of natural vegetation pattern have amplified the landslide susceptibility of these regions, especially at Kavalappara, Pathar and Puthumala. In addition, soil piping has acted as the triggering factor at a few locations, especially in Northern Kerala.

- The NCESS has prepared a landslide zonation map for Kerala in 2009 on a 1:50,000 scale. The landslides that occurred in the last two years have largely (~80 per cent) fallen in the high hazard zones delineated by the NCESS. There were a few slides in low hazard zones, while some of the high hazard zones were not at all affected during the EREs. This necessitates the inclusion of additional causative factors and refinement of the hazard zonation mapping. It should be performed on a fine resolution (preferably at the cadastral scale). This activity should be followed by the development of landslide risk maps at the cadastral level, which can be used for long term land use planning. The monitoring of ground movement may also be considered as part of long-term research activity.
- The EREs during the last two years were associated with the genesis of deep depression over the northwest Bay of Bengal and nearby areas. An early onset of monsoon along with a large amount of rainfall in June and July 2018 resulted in saturation of the topsoil in most areas. Most of the reservoirs in Kerala had to be filled near the Full Reservoir Level (FRL). The two EREs, subsequently in August 2018 (during August 8th to 10th, and August 14th to 19th), resulted in severe flooding in Kerala. A similar situation, except on the antecedent wetness condition (including reservoir storage), occurred again in August 2019 (during August 8th to 11th) and caused severe flooding in the northern districts of Kerala (north of Ernakulam).
- The floods experienced in the last two years have a large return period (more than 100 years), and the preparedness for such events was less due to their very low probability of occurrence.
- The Committee analysed flood inundation for various scenarios of different reservoir levels and 24-hour 100-year rainfall for the Periyar river basin and developed possible flood inundation maps. Such studies are essential for demarking the flood-prone areas under different conditions and have to be done over all the river basins in the State.
- The existing reservoirs in the State are conservation-oriented and are being operated as per the conditions specified in IS 7323:1994. Accordingly, the policy adopted being “no spilling of water over the spillways will normally be permitted in conservation point of view until the Full Reservoir Level (FRL) is reached. Flood cushion in the reservoirs

is limited between the flood control zone, i.e., between FRL and Maximum Water Level (MWL). When any flood occurs, the policy to release the flood water is adhering to the principle that the releases shall not exceed the inflow into the reservoir". Moreover, the reservoirs harvest water as much as possible to the full capacity during the rainy season. None of them had an operating policy that considered flood control until 2018. After 2018, some of the dams have considered flood control in their revised operation policy. This should be extended to all the reservoirs in the State. Further, the authorities concerned shall explore the possibility of providing some dynamic flood cushion in the conservation zone below FRL for all the reservoirs.

- The Committee recognised the need to define ERE. It was observed that the rainfall value corresponding to the 99th percentile for Kerala is around 120 mm (12 cm). Hence, 24-hr accumulated gridded rainfall ≥120 mm (rainfall of intensity equal to or more than the very heavy rainfall category) can be considered as an ERE.
- There are several natural and anthropogenic drivers of floods in Kerala, among which the prominent are: (1) high-intensity rainfall for prolonged duration, (2) human interventions in the catchment areas, and particularly in the floodplains and riparian zones, (3) unauthorised encroachments leading reduced extent of natural areas and their impaired functionality (4) reclamation of wetlands and lakes that acted as natural safeguards against floods due to urbanisation and development of infrastructure, (5) unexpected EREs and lack of exposure in handling such EREs through reservoir operation and (6) decreased channel capacity due to sedimentation and aquatic vegetation.

Recommendations to mitigate the negative impacts due to:

a) Extreme Rainfall Events

- The current rain gauge network in the State is not sufficient enough to capture the high spatial variability of rainfall because of the orographic barrier, and also in the context of the limited predictive capability of the rainfall forecast models. Therefore, the network density needs to be enhanced to the theoretical level of 1 rain gauge in every 50 square km (approximately 800 numbers). However, considering the varying spatial variability across the different physiographic regions of the State, it is suggested to install a dense network of Automatic Rain Gauges (ARG/AWS; ~ 500 numbers). Priority may be given to regions receiving high-intensity rainfall in short time periods including slopes that have the potential for flash floods. The distribution of the proposed rain gauges can be 50 per cent in the high lands, 35 per cent in the midlands, and the remaining 15 per cent in the low lands and coastal regions.

- It is suggested that a major share (~50 per cent) of the new installations should be Automatic Weather Stations (which can also monitor meteorological parameters such as temperature, pressure, wind direction, wind speed, and sunshine hours) and all of them be connected to a central location through telemetry. These observations would in the long run help to improve the predictive capabilities of the forecast models on a regional scale.
- The land acquisition for installation of new rain gauges, if required, be done in consultation with IMD and other departments in the State, and be completed at the earliest.
- Identify the rain gauges operated by other agencies in the State and link them to the centralised facility being proposed.
- Facilitate the development of the Regional ERE and Flood forecast system combined with Artificial Intelligence (AI) to predict flash floods and to trigger an advance warning through research studies or start-ups.
- The experts observed that there is a temporal change in the size distribution and circulation pattern of the dust aerosols in the State that have an impact on the changing rainfall patterns. However, this needs further research as it is an emerging area of research worldwide. The significance of forest fires across the WG on the aerosol concentration may also be considered.

b) Landslides

While the devastating landslides in the State during the last two years were primarily initiated by the EREs, the major reason for most of them was the instability of the slopes caused due to various anthropogenic activities. Therefore, preventive measures should certainly include slope stabilisation. The following are some of the possible remedial measures:

- Provide a vegetation cover to the degraded slope by either promoting natural vegetation growth or by planting suitable species that help slope stabilisation (example vetiver). The use of vetiver as a binder in laterite cutting is to be evaluated.
- In areas where clear-felling of trees was done, the deep tap roots should be removed and refilled with the earth. This is to avoid over saturation and decay of the taproot system which will lead to soil piping and landslides.
- In areas where plantation crops are planned, the selection of crops, as well as the soil pits for planting them, needs to be carefully chosen according to the package of practice. Unscientific use of machinery for pit formation may lead to increased disturbance of the overburden and cause additional water-holding, resulting in oversaturation.

- The following activities should be avoided so as to prevent the possibility of landslides:
  - ✓ Cutting and levelling for construction of houses on the toe region of slopes having more than 25 per cent inclination and a slope length exceeding 100 m.
  - ✓ Diversion or blocking of stream channels (up to third order) in the upper slopes especially above the settlement.
  - ✓ Ponding of water in the sloping sections over a 25 per cent slope.
  - ✓ Soil conservation practices through contour bunding, or terracing in slopes of more than 25 per cent.
  - ✓ Seasonal cultivation with tilling or pitting activity in the high sloping areas.
  - ✓ Any activity in those sections where either ground cracks or piping has been initiated.
  - ✓ Encroachment of stream banks in the highland region for cultivation or settlement.
  - ✓ Alignment of open irrigation channels on hill flanks with more than 25 per cent slope.
  - ✓ Construction of roads without adequate engineering design in the unstable slopes especially in those segments having higher soil thickness. The hollow portions are to be treated carefully.
  - ✓ Construction of dwelling units in the hollow portions which have been filled up with debris.
  - ✓ Construction of dwelling units on the immediate lower part of a sloping segment that is critically disposed of.
- The following activities can be promoted so as to prevent landslide occurrence:
  - ✓ Drainage of excess rainwater from steeper sections of slope through lined predefined channels.
  - ✓ Afforestation/ tree crops with no tilling activity in such areas with more than 33 per cent slope.
  - ✓ Maintenance of tree belts at suitable intervals in those slopes subjected to seasonal cultivation.
  - ✓ Delineate stable and unstable areas in the uppermost catchments of drainage basins.
  - ✓ Preservation of existing patches of natural forest cover.
  - ✓ Permanent grass cover in extremely sloping sections (> 50 per cent slope).
  - ✓ Land zonation at the micro watershed level involving the local community
  - ✓ Create awareness among the local population regarding landslides.
- All drainage lines (of all orders) are to be maintained properly, especially during rains. The first and lower order streams get obliterated by agricultural practices

such as contour bunding and terracing. These are the areas liable for failures during high rainfall times. The configuration of the basement rock will allow subsurface water to exhort high pore pressure in these areas, which are known as topographical hollows (places where lower-order streams are located). Therefore, before monsoon, all stream / nallas in the slopes need to be cleaned and opened up for the free flow of stormwater.

- Since the topographic hollows are the areas where the failure takes place, location of the hollows needs to be identified, and new houses/buildings to be allowed at least 50 m from either side of the stream channel / hollow area.
- The Government of Kerala should constitute a Committee to conduct in-depth studies and develop guidelines for best practices for allowing mining activities near topographic hollows. A "codebook" may be developed and strong regulatory system may be enforced. Stone quarries should not be allowed near the topographic hollows with more than 1 m overburden; they should be 200 m away from such localities.
- While constructing village roads in the high sloping areas, care should be taken to ensure the free flow of streams across the roads by providing culverts
- The current practice is that only the critical and high hazard areas are now regulated for activities. Settlements are allowed in the downslope of critical and high hazard areas. These areas are susceptible to high causalities during a landslide event. Therefore, an estimate of the runout distance for landslides needs to be assessed based on slope and overburden volume in the high hazard zones so as to regulate settlements at the downstream of the slopes.
- In many hill-road sections, toppling has occurred during rains where the road cuttings in the laterite are more than 3 m. This will cause disruptions in the traffic movement and destabilisation of the upper slope. Proper protection should be given to these laterite road cuttings with adequate weeping holes. In the unprotected slopes, it is better to give a deep-rooted bio cover like Vetiver (locally known as *Ramacham*) if other methods are not feasible.
- While constructing buildings and houses on the hill slopes, the slope geometry is to be maintained. In other words, the cutting and filling of the slopes for construction in the high slope area should be discouraged.
- The runout zone of the upper unstable area is to be considered while planning any infrastructural development on the lower slopes.
- Artificial impounding of water on slopes should be discouraged. In areas identified as high hazard zones, the construction of swimming pools and theme parks to promote tourism should also be discouraged.

- In long slope areas, the toe part should be protected from development activities. In unavoidable circumstances, any disturbance in the toe area should be accompanied by strengthening/protecting of upper slope areas.
- Provide ditch traps and fencing at a highly hazard zone prone to rock falls. Blasting is not a good option because it may trigger further rock falls. Controlled blasting under the supervision of an expert could be done in case of an emergency.
- Unstable slopes can be modified by re-grading, geotextile mats, vegetation and bio-engineering and geotechnical measures such as soil nailing, and wire machine. Anthropogenic activities that can cause saturation of the soil are to be strictly regulated in critical/prone areas. However, in locations where exceptionally deteriorated conditions of moderate dimensions already exist, the slope geometry needs to be scientifically changed to reduce the stress on the unstable mass. This may be done by providing restraining structures to increase the resistance to slide movements. These include providing a buttress, shear keys, retaining walls, rock bolts, and piles. Grouting and electro-osmosis can also be resorted to in very specific cases.
- The Government should encourage people to secure insurance coverage for their assets in high-risk areas.
- The Government should identify (construct if needed) multipurpose shelters designed by qualified architects for temporarily rehabilitating the affected people before and during an event. These shelters in normal times could be used for other purposes such as marriage or meeting for generating funds for its maintenance. These shelters should be at locations that are safe from both floods and landslides.
- Modify the existing landslide-prone area maps (prepared by NCESS) by considering additional causative factors and past occurrences of landslides. A cadastral level mapping with micro watershed boundaries may be desirable in the high hazard zones. In case of an area which is yet to be covered under cadastral survey, maps in a 1:5,000 scale may be prepared based on topographical maps, high-resolution image, and aerial photographs.
- The risk level of the landslide occurrence should be estimated and depicted on the refined hazard zonation maps at the cadastral level by incorporating vulnerability that considers population data, land use, infrastructure, assets, etc.
- Locations of current landslide incidences should be mapped in the hazard zonation maps prepared by NCESS (1:50,000 scale) for ready reference.
- Initiate studies that can help develop rainfall intensity-based probability for landslide occurrences.

c) Flood

The floods of 2018 and 2019 have a large return period (more than 100 years). To fully alleviate the impacts of such floods is practically difficult because any structural measure would not have considered such a high return period of floods due to their very low probability of occurrence. However, mitigation measures and preparedness can be planned to reduce the negative impacts of such calamities. The following are some of the suggestions to reduce the impact of flood in the future:

- As the catchment area of most of the reservoirs of the State drains forest areas, they do not experience heavy silting unlike the reservoirs in other parts of India, especially the ones in Himalayan Rivers. However, the storage capacity of most of the reservoirs in the State might have been reduced to varying extents as there was no periodic desilting action performed in the past decades. This capacity reduction would certainly have lowered the originally designed efficiency of the system. Therefore, the committee recommends that the storage capacity of all the reservoirs shall be evaluated at periodical intervals, say 10-20 years, to determine the amount of siltation on a priority basis, and desilting be planned accordingly if required.
- Several rivers that have reservoirs did not have larger flows in the past as the reservoir releases were minimal. Therefore, the concept of floodway and flood fringe can be introduced for flood zoning. The floodway is the high-risk area, which should be kept free of any construction to allow free movement of floodwater. The level of risk can be determined based on factors like depth and velocity of floodwater, duration of flooding, available flood storage capacity, or rate of rising of floodwater. In the flood fringe area, constructions may be permitted under certain conditions. In regulated rivers, this can be ensured by the controlled release of water (may be of magnitude corresponding to a 2-5-year return period of the virgin catchment) on specified intervals (example, once in 2-3 years) during active monsoon season. Such actions would ensure no encroachment into the river beds immediate downstream of dams.
- Buffer zones are to be demarcated on both the banks of the rivers (50-100 m from the bank) based on the geomorphological characteristics, where no construction is to be allowed. However, the cultivation of seasonal crops can be permitted in these buffer zones. Riverbank maps prepared under River Bank Protection and Sand Auditing project being executed by the Institute of Land Development and Management (ILDM), Revenue Department, Government of Kerala may be used for this purpose. In fact, agencies involved in riverbank mapping and sand auditing projects may be entrusted with this job of buffer zone demarcation.

- The Committee observed several obstructions in the flow channels (including rivers), which caused reduction/restriction of flow downstream resulting in the accumulation of water upstream. This was noted at different locations (Mukkom, etc.) in the 2019 floods. This was specifically observed in the Kallayi River, where sediment accumulation resulted in an island formation that obstructed the river flow by almost 80 per cent. In addition, dumping of construction debris was observed in the river bed at many locations, that also caused restriction to the free flow of floodwater. Therefore, a smooth passage for the flood flow needs to be maintained in rivers. This can be done by periodical monitoring and clearing of river channels/drainage lines. This will reduce the bed roughness of rivers and ensure sufficient conveyance capacity. River cross-section data generated under river bank mapping and sand auditing projects under ILDM may be used for this purpose. River rejuvenation programme as initiated for a couple of rivers like Killi Ar, Karamana may be encouraged and executed throughout the state involving local people, and local self-government departments (LSGDs).
- The existing reservoirs in the State are conservation-oriented, and the policy is to harvest water as much as possible to the full capacity during the rainy season. None of them had an operating policy that considered flood control until 2018. After 2018, some of the dams have considered flood control in their revised operation policy. In the case of other reservoirs, it is suggested to revisit the rule curves by considering the dams as multi-purpose and multi-reservoir water resources systems, and develop integrated reservoir operation policies so as to maintain the balance between flood control and other objectives, such as hydropower generation, irrigation and drinking water uses. In addition, a relook at increasing the flood cushion in most of the reservoirs can be attempted.
- Wetlands such as rice fields, ponds, and lakes used to play a major role in flood control. While there are a large number of wetlands in the State, most of them have deteriorated or been abandoned or reclaimed and have become ineffective in their primary role. Therefore, it is suggested to restore the wetlands in the State on priority.
- Most of the river beds and flood plains have been deposited with sediments during the last two major floods. This has caused a further reduction in carrying capacity. Therefore, rejuvenation of the rivers to their original capacity is required.
- Wherever feasible, consider constructing levees and floodwalls. This should be done after a proper scientific feasibility study.
- It appears that a zonation of flood hazard has not been done for most of the rivers. What is available is only the flood-prone area map, which would only help in planning developmental activities. Flood impact mitigation requires the flood zones

corresponding to different return period floods or return period rainfall. Since the floods are mostly caused by the EREs, it is recommended to simulate and demarcate the flood inundation zones corresponding to different rainfall return periods (example 10, 25, 50, 100, 150 years). In addition, such maps can be prepared for different ensemble magnitudes of rainfall (without assigning any return period), and a library can be built using the simulations. During the onset of EREs, case-based reasoning can be performed on this library to approximate the possible flooding areas, which can be used for evacuation/mitigation. Such models, when developed, can also be used on a real-time basis to demarcate the approximate flooding zones.

- In addition to the flood hazard zone mapping through simulation, flood risk maps should also be developed. Flood risk maps will show the possible adverse consequences to people, health, livestock, economic activity, the environment, and cultural heritage in the event of floods. The map should show at least the risk to the potentially affected people (during day-time and night-time) including the indicative number of transitory people (example, tourists), aspects of economic activity, protected areas and natural environment, and where present, the facilities causing accidental pollution should they be flooded.
- An effective flood warning system is to be developed and implemented on priority. Since the predictive capability of the rainfall forecast models is limited, the flood warning systems cannot be fully dependent on the rainfall forecasts. Therefore, flood warning systems that depend on flood discharge at upstream locations and the time of travel to a downstream location may be planned and developed. This kind of warning system will mitigate human/livestock casualties. Telemetry systems can be effectively utilised for this purpose.
- Develop operation and maintenance manuals for flood gates and shutters. Perform maintenance, operation, and monitoring during the pre-monsoon period, and rectify the issues at regular intervals. Trials and test operational procedures should be performed at defined intervals. Ensure timely gate operations during flood events.
- It is noted by the Committee that flood accumulation in the lower Kuttanad region was mostly due to insufficient capacity to discharge the flood water to the ocean. Therefore, it is suggested to clear the sandbars near the Thottappalli Spillway on a regular basis and ensure the original width of the channel (downstream of the spillway) for smooth flow of the floodwater. Also, an increase of the width (~to 300 m) of the lead channel to the Thottappalli spillway is recommended.
- It is noted that the dwellings in the lower Kuttanad region are scattered and are aligned along the bunds. This reduces the effectiveness of evacuation in case of a

severe flood event. Therefore, it is suggested to facilitate settlement at identified clusters.

- Since forests cover the majority of the catchment area of the rivers of the State, research studies may be carried out to understand the significance of forested watersheds in flood hydrological response.

d) Recommendation for Sustainable Housing in Hazard Zones

In the flood-prone areas of the State, building controls are not stand-alone solutions to mitigate flood risk. Instead, they need to be implemented in conjunction with other flood mitigation measures. Building controls are important to reduce damage to buildings and their contents. Setting the minimum floor levels for residential buildings and other structures in flood risk areas can reduce the frequency and extent of flood damage. The minimum floor level should be determined from the flood levels derived from significant historical flood events or floods of specific annual exceedance probabilities.

- Erection of fences/compound walls, whether solid or open, can affect the flood flow behaviour and flooding pattern by altering flow paths. The impact of such structures will depend on the type of fence and its location relative to the flow path. Hence, controls should be considered in relation to the type of fencing permitted, or to limit its location or height depending on the geographic area. In general, solid fencing, especially to ground level, should not be erected across flow paths where it might act as a dam. Open fencing is preferable.
- Flow velocities, flow depths and associated debris loads can affect the structural soundness. Hence, the structural soundness of the buildings in the flood-prone areas needs to be considered for the local hydraulic conditions.
- Emergency services (for example, water treatment and distribution, power generation and distribution, and communication services) might be disrupted during floods. Hence, the vulnerability of the emergency services to floods must be minimised. Service providers should also consider the emergency response and recovery planning for floods for key assets.
- Landslides lead to the complete destruction of houses and buildings that fall directly in the path of the flow. Moreover, it was seen that the walls of the buildings that are constructed with load-bearing masonry walls and reinforced concrete slabs were completely destroyed and the slab collapsed as a whole (pancaking type failure). It is difficult to design buildings that are resistant to landslides or floods. Nevertheless, it is recommended that all buildings in areas prone to landslides and floods be designed as per the norms of seismic zone 3, though the region is not in a seismic area. The justification is that the provisions for design in seismic zone 3

regions will lead to better lateral resistance and ensure that the pancaking collapse does not occur. Further, the foundations will also be such that there is better resistance against the force of mud and water.

- Habitations in flood plain, if unavoidable, could be designed as in the case of buildings in the coastal areas that are prone to tsunamis; i.e., the same regulations as in the case of tsunamis could be followed.
- Habitations in steep terrains could be designed such that the slopes are reinforced/strengthened by soil nailing. Further, the design should follow the provisions of design for seismic zone 3. As far as possible, the steep slopes should not be disturbed; if inevitable the building design should be made in such a way that the slopes need not be altered.
- Model structures may be constructed by following the existing provisions for coastal areas taking into account the effects of scouring, lateral impact of boulders and mud, and the maximum expected flood levels.

e) General Suggestion

- The Committee has analysed spatial and non-spatial data collected from different agencies and departments. Therefore, an important suggestion is that a centralised facility/ repository to store and share data may be created. The facility should be a single point contact, where all the data collecting departments should submit the data related to natural/man-made resources and data related to various hazards. This will (a) eliminate the generation of redundant data, (b) bring uniformity to data from different sources, and (c) ensure data quality. A policy should also be developed for sharing the data between different departments or academic and research organisations.
- During interactions with the survivors of landslides, the Committee observed that the traditional/ancestral knowledge of environmental and biological signals has been used to cope with natural hazards, which helped them to forecast the hazards. Hence, the Committee suggests to carry out research investigations to understand the scientific background behind these kinds of linkages. This may be helpful for developing early warning systems.

Recommended Action Plans

Based on the recommendation of the Committee, the following action plans are suggested to the government. The action plans envisage policy developments, detailed scientific assessment/studies, and ground-level plans for different sectors as detailed in the following section.

Type of measure	Immediate (6 Months)	Short Term	Medium Term	Long Term
Policy	Sharing data from different departments to the central facility/ repository which will store and share data related to the natural/man-made resources	Restrict disturbances at the locations of topographical hollows which falls under landslide-prone areas	Restrict settlements in the landslide run-out areas	Minimise/remove relief funds for property loss during hazards in high hazard-prone areas for the individuals who deny the mitigation measures of the government
	Restrict quarrying/ mining activities at high landslide-prone areas. Appropriate regulations also need to be made for quarrying/ mining activities at low landslide-prone areas	Conduct a mandatory environmental impact assessment for new developmental projects in the high flood/ landslide hazard-prone areas.	Develop integrated reservoir operation policies so as to maintain the balance between flood control and other system objectives, such as hydropower generation, irrigation and drinking water uses.	Restrict financial aids from the government for construction/activities in the high hazard-prone areas.
Scientific	Identify and map regions with potential disasters like heavy rainfall areas, flood-prone areas, landslide-prone areas,	Prepare flood inundation maps at 1:4000 scale	Hazard zonation and mapping of entire Kerala at 1:4000 scale • Flood hazard zonation	Prepare action plans for various levels of public administration/LSGDs to manage various

Type of measure	Immediate (6 Months)	Short Term	Medium Term	Long Term
	etc.		• Landslide hazard zonation • Dam release/breach hazard zonation	situations/hazards and preparation of documents to guide the public about action required during emergencies.
	Identify potential locations of topographical hollows	Prepare landslide hazard area and runout area maps at a 1:4000 scale. Initiate in-situ observations of aerosol microphysical properties (such as size distribution) including bio-aerosols, utilising educational/ research institutions at least in three representative locations; in the plains, on the slopes, and at higher altitudes in the Western Ghats.	Study to determine the model parameters specific to Kerala for physics-based models used in prediction of rainfall as well as the river flow	Studies on understanding the long-term trend of atmospheric aerosols over Kerala, specifically the fine mode aerosols relevant for the cloud and precipitation forming processes, using high-resolution satellite data.
	Conduct detailed Studies on the impact of climate change in land use planning, considering the increasing frequency of EREs and	Conduct studies on improving the predictability of EREs	Studies on the threshold intensity of rainfall by incorporating more automatic rain gauges. Initiate studies on debris flow	Modelling studies to primarily understand the role of aerosol on cloud and rain formation.

Type of measure	Immediate (6 Months)	Short Term	Medium Term	Long Term
	associated floods and landslides.		runout.	
	Studies on the amount of sand carried by all the rivers in the State and the allowable extraction from its bed	Develop risk maps of landslide and flood possibility for the entire state.		
Land Use Management	Identify and mark buffer zones near the banks of rivers where only seasonal cultivation can be done with no construction and any obstruction for flow.	Prepare special land use planning for areas with slopes more than 20°.	In the unprotected slopes, plant a deep-rooted bio cover like Vetiver (*Ramacham*)	Introduce the concept of floodway and flood fringe for flood zoning. In the flood fringe area, constructions may be permitted under certain conditions.
	Removal of deep tap roots after clear-felling of trees and refill with earth (with minimal soil disturbances) to avoid over saturation and decay of tap root system which will promote soil piping and landslides.			
Water Resources	Conduct periodical monitoring and clearing of river channels/ drainage lines	Plan controlled the release of high flow (2- or 5-year return period) at least once in 2-3	Implement measures such as re-enforcement of embankments, lowering the	Consider providing a dynamic flood cushion in the reservoirs, when advance

Type of measure	Immediate (6 Months)	Short Term	Medium Term	Long Term
	thus ensuring a smooth flow of water by reducing the bed roughness of the rivers and to ensure sufficient conveyance capacity.	years in all rivers to demarcate their boundaries.	floodplain area, widening the floodplain by re-location and lowering of embankments, and development of flood bypasses.	warning of extreme rainfall events are available
	Install dense network of Automatic Rain Gauges (ARG/AWS; ~500) with special emphasis on regions receiving high-intensity rainfalls in short time periods including slopes that have the potential for flash floods	Install weather stations for monitoring meteorological parameters (temperature, pressure, wind direction, wind speed, etc. ~50) in high time and spatial resolution; more importantly over the slopes of Western Ghats	Rejuvenate stagnant water bodies such as isolated channels, rivulets, and oxbows in the floodplain.	Perform maintenance, operation, and monitoring during the pre-monsoon period, and rectify the issues at regular intervals. Trials and test operational procedures should be performed at defined intervals. Ensure timely gate operations during flood events.
	Give priority to flood control over irrigation requirements and/or power benefits, especially during ERE forecasts	Create a State level ERE forecast system combined with Artificial Intelligence (AI) to predict flash floods and trigger an advance warning alerting the authorities.	Develop operation and maintenance manuals for flood gates and shutters.	
Construction	Set minimum floor levels for new residential buildings and	Introduce construction standards (including	Construct multipurpose shelters at safe locations	Construction of levees/ floodwalls and restoration of

Type of measure	Immediate (6 Months)	Short Term	Medium Term	Long Term
	other structures in flood-prone areas	materials) and building codes for floodplains and landslide-prone areas.		wetlands.
	Introduce designs of flood resilient buildings	Plan for proper traffic access in the flood hazard zones.	Demonstration of model flood-resilient buildings at various locations	Investigate the structural soundness of the buildings in the flood-prone areas for the local hydraulic conditions.
Revenue		Identify the flood plains and flood levels of 10-, 50- and 100-year return period floods. This needs to be done with the help of scientific studies	Propose one-time financial aid for people residing in the floodplains (high flood-prone areas) to relocate.	
Agriculture	Regulate agricultural activities which allow saturation of the soil in critical/prone areas of landslide.	Restrict cultivation on slopes based on hazard risk; promote cultivation along the contours with provisions for drainage of water.		
Dam/ Reservoir Management		Revisit the rule curves of the reservoirs by considering the dams as multi-purpose and multi-reservoir water resources systems and giving the provision of flood cushion	Desilt the reservoirs. Priority should be given to basins having cascading reservoirs and reservoirs whose capacities have reduced due to silting.	Improve flood warning system with integrated real-time reservoir operation

Type of measure	Immediate (6 Months)	Short Term	Medium Term	Long Term
Data Management	Install a proper hazard warning dissemination system both for administration and the public.	Develop a centralised facility/ repository to store and share data related to the various hazards and natural/man-made resources in the potential hazard areas	Update the centralised facility/repository at regular intervals	
Social/Awareness	Create awareness and communicate to the public about the risk of living in certain areas especially in flood and landslide-prone areas.	Encourage interaction between LSGD and local people about the hazard risk in their area and possible prevention measures.	Train and empower the locals in disaster management activities.	Encourage people in flood- and landslide-prone areas to cover people / properties / agriculture / industries under insurance
	Provide emergency contact details to people	Conduct Workshops, and awareness programs (at educational- and community-levels). Scientific and technical meetings are essential to actively involve and engage stakeholders. Dedicated websites or social media may be used to provide information to the general public and publish		

Type of measure	Immediate (6 Months)	Short Term	Medium Term	Long Term
		surveys and summary reports		

1. Chapter
Background

1.1. Overview

The Kerala State is a narrow strip of land (extending between N. Latitude 08° 18’ - 12° 48’ and E. Longitude 74° 52’ - 77° 22’), in the southwestern margin of the Indian Peninsula, encapsulated between the Western Ghats (WG) in the east and the Arabian Sea in the west. The geographical area of the State is 38,863 km^2, which approximates the size of Bhutan. The State stretches for about 560 km along the Malabar Coast, varying in width from roughly 11 to 124 km (Soman, 2002). The WG (also known as the *Sahyadris*) extending for about 1500 km in the NNW-SSE direction, and retaining a mean elevation of about 1000 m above mean sea level (MSL), is a remarkable geomorphic feature of the State. The geodiversity of the State, ranging from the mountains and peaks reaching 2690 m above mean sea level (MSL) as well as the high-altitude plateaus (e.g., the Wayanad plateau, the Munnar plateau, the Greater Periyar plateau) to valleys at mid-altitude and tropical coastal plains. The physiographic profile of the State is classified into three distinct zones: the highlands (elevation > 75 m above mean sea level, and covering the steep and rugged sections of the WG), the lowlands (elevation < 7. 5 m above mean sea level, and comprising of the coastal plains), and the midlands (consisting of the undulating hills and valleys) in between.

Although the monsoon circulation is not a regional phenomenon specific to the Kerala State (as it concerns four continents and both the hemispheres), the relief barrier (i.e., the WG) extending parallel to the west coast of the State provides a unique orographic framework which steers the atmospheric circulation in such a way as to yield a distinctive rainfall pattern across the State, compared to other parts of the Indian subcontinent (Gunnell, 1997). Even though the Kerala State has not historically been frequently exposed to severe weather-related disasters such as floods and landslides, the orographically controlled climate gradients and thresholds, along with the vast geo-bio-diversity facilitate the Kerala State a wide variety of rainfall regimes and microclimates, which is accompanied by a high risk of adverse weather-related disaster events.

The Kerala State experiences flooding and inundation frequently across the low-lying coastal plains, floodplains and broad flat bottom valleys of the river systems, while landslides along the steeply sloping segments of the WG. An assessment of the natural hazard proneness of the State (CESS, 2010) by evaluating the causative factors and processes related to the natural hazards indicated that 14.52% of the total geographic area (i.e., 5,643 km^2) of the State is prone to flood hazards, with varying proportions as high as 50% for Alappuzha district. The primary factor causing flooding in Kerala due to fluvial processes is the periods of prolonged rainfall episodes and the extreme rainfall events (EREs) occurring during the Indian Summer Monsoon Rainfall (ISMR) season. However, the intensity and extent of flooding are also connected with the changes in the river and floodplain morphology as well as with the modifications in the land use/land cover pattern of the upstream catchment area and riparian zone. The western flank of the WG, forming the highland physiographic unit of the State, covers about 48% of the total geographic area of Kerala and is the major landslide-prone area of Kerala (KSCSTE, 2007). Again, 1848 km^2 or 4.71% geographic area of the State, extending along the steep slopes of the WG (i.e., mostly in Wayanad, Kozhikode, Malappuram Idukki, Kottayam and Pathanamthitta districts), is highly prone to the occurrence of mass movements (CESS, 2010). Similar to flood events, the occurrence of the mass movements in the State is mostly triggered by the intense rainfall during the EREs. However, the sheer pressure exerted by population growth and unscientific management practices, leading to land degradation in the highlands also has far-reaching effects on the occurrence of mass movements.

Accompanying the unique physiographic conditions and geodiversity, the Kerala State is occupied by a population of more than 3.3 crores, with varying livelihood strategies and socio-economic conditions. Kerala ranks the 8th position in the population density (859 persons per km^2) among the 28 states in India (Census of India, 2011). The distribution of population among the different physiographic units of the State does not show linearity with respect to the areal extent, as the population along the lowlands is much denser compared to the highlands and the midlands. The lowlands (i.e., the coastal plains, the floodplains, and the major wetland systems), occupying only about 10% of the geographic area of Kerala, accommodate 61% of the total population resulting in high population density (Sujith, 2016). Hence, the phenomenal combination of the physiographic layout and geomorphic diversity, orographically controlled precipitation regimes, along with the demographic pattern make the State highly vulnerable to damages and economic losses during such disasters.

1.2. The Flood of August 2018

In association with the genesis of a well-marked low-pressure area over the southeast Arabian Sea off Kerala-Karnataka coasts and a well-marked depression over the east-central Bay of Bengal, the southwest monsoon current reached over Kerala on 29th May 2018, three days ahead of its normal date of onset (IMD, 2018). Contrary to the long-term rainfall trends, Kerala experienced a remarkably higher amount of rainfall during the first half of the ISMR season, i.e., from 1st June 2018 to 31st July 2018, which made most of the reservoirs of the State to near full reservoir level (FRL) (CWC, 2018). During August 2018, Kerala State (India) experienced two severe EREs on record, i.e., during 8-10 and 14-19 in August 2018.

The first ERE was the resultant of the formation of a low-pressure system over the northwest Bay of Bengal and neighbourhood on 6th August 2018, which later concentrated into a depression and crossed north Odisha-West Bengal coasts. Subsequently, it was weakened into the well-marked low-pressure area over Chhattisgarh and neighbourhood and finally lay as a low-pressure area over north Madhya Pradesh and neighbourhood on 9th August 2018 (IMD, 2018). The genesis of the depression resulted in the strengthening of low-level westerlies causing widespread rainfall activity along the west coast, including Kerala during 8-10 August 2018. The second low-pressure system was formed over northwest Bay of Bengal and adjoining coastal areas of West Bengal and Odisha on 13th August 2018. Later, it was concentrated into a depression and layover coastal Odisha and neighbourhood on 15th August 2018, moving west-northwestwards, it weakened gradually and lay as a low-pressure area over southwest Madhya Pradesh and neighbourhood on 17th August 2018. Strengthening of the monsoon flow due to the formation of the low-pressure system has caused widespread intense rainfall activity over south peninsular India. Under the influence of the active phase, vigorous monsoon conditions occurred for a week over Kerala including the ERE during 14-19 August 218.

Kerala received a total of 2365.6 mm rainfall from 1 June 2018 to 19 August 2018, which is roughly 42% above the normal rainfall. Among the different districts of the state, Idukki received the maximum rainfall, which was almost 100% excess compared to the normal rainfall (3555 mm against the normal 1852 mm). During 15-17 August 2018, Peerumade recorded the highest rainfall of 818 mm, which is closer to the rainfall recorded at Munnar during the 3-day storm in 1924 (i.e., 897 mm). It is worthy to note that the rainfall over Kerala during June, July, and 1st to 19th of August 2018 was 15%, 18% and 164% above normal respectively (CWC, 2018). Consequently, in August 2018 Kerala experienced the incidence of an extreme flood event due to the rare combination of the occurrence of multiple EREs along with near FRL reservoir storages, which coerced the authorities to open the gates of most of the dams in Kerala. The occurrence of EREs over the saturated soil column triggered a large number of mass movements of varying dimensions. Thus, the extensive flooding and landslides across most districts of the state caused severe damage to both the built and natural ecosystems.

The cumulative amount of rainfall experienced during the first ERE across the State indicates that the total rainfall occurred during the three days (i.e., 8-10 August 2018) in a few meteorological stations (of IMD) of Thiruvananthapuram, Palakkad, Malappuram, and Wayanad districts was more than 50% of the normal monthly rainfall (Fig. 1.1). However, during the second ERE, the total rainfall occurred during the three days (i.e., 15-17 August 2018) in most of the stations (except in Kannur and Kasargod) was more than 50% of the normal monthly rainfall (Fig. 1.2). The widespread flooding in August 2018 affected almost 5.4 million people - one-sixth of the State's population. Several districts were inundated for more than two weeks due to the floods. A total of 1,260 out of the 1,664 villages of Kerala were affected. Seven districts were notified as flood-affected: Alappuzha, Ernakulam, Idukki, Kottayam, Pathanamthitta, Thrissur, and Wayanad. About 341 major landslides were reported from ten districts, where Idukki district was ravaged by 143 landslides. The devastating incident delivered a total of 435 casualties, with 6,85,000 families being affected with loss of assets and property forcing them to temporarily move to relief camps during the peak of the disaster.

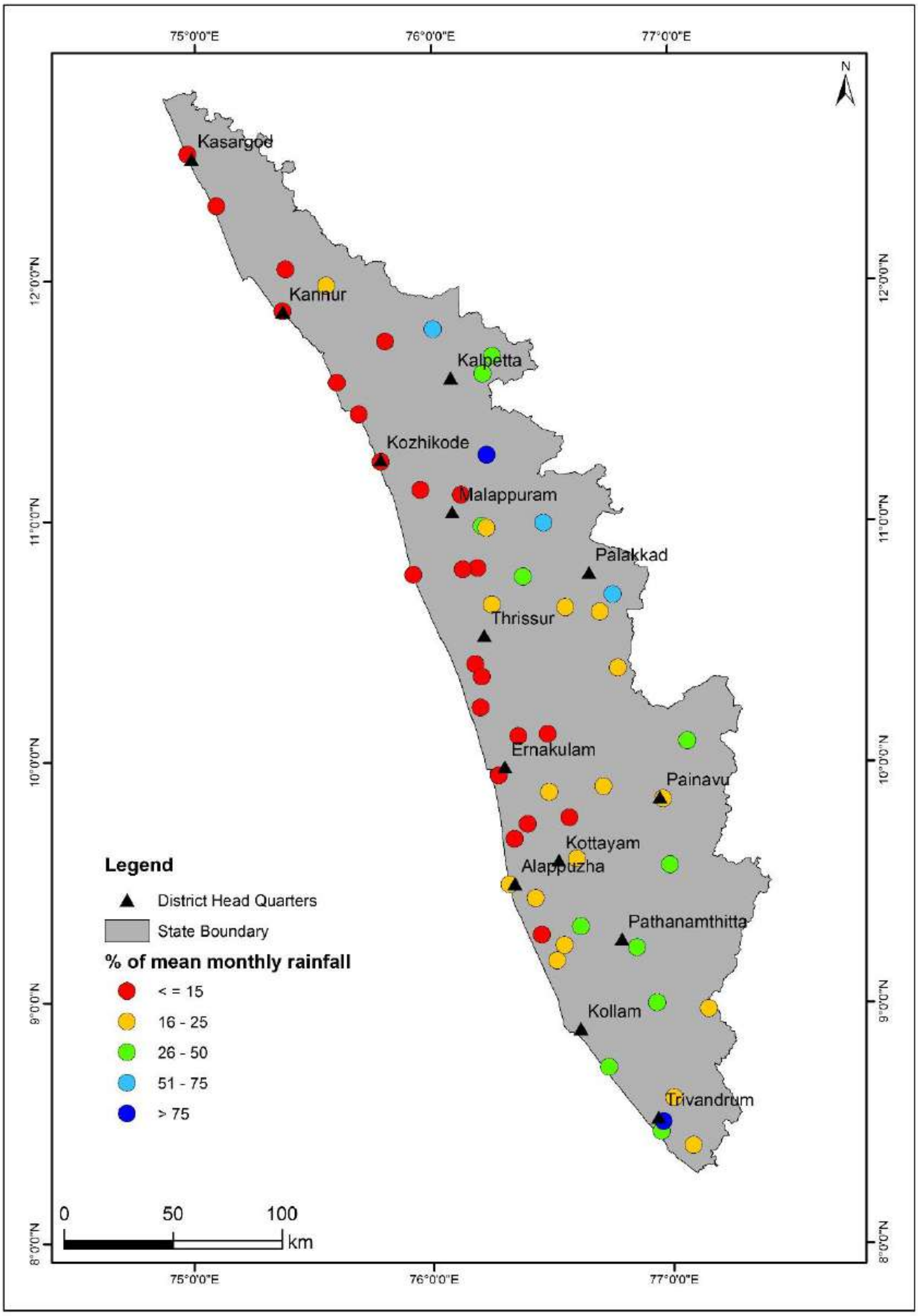


Fig. 1.1: Spatial variability of the total rainfall experienced during the ERE occurred between 8-10 August 2018 towards the contribution of the monthly rainfall

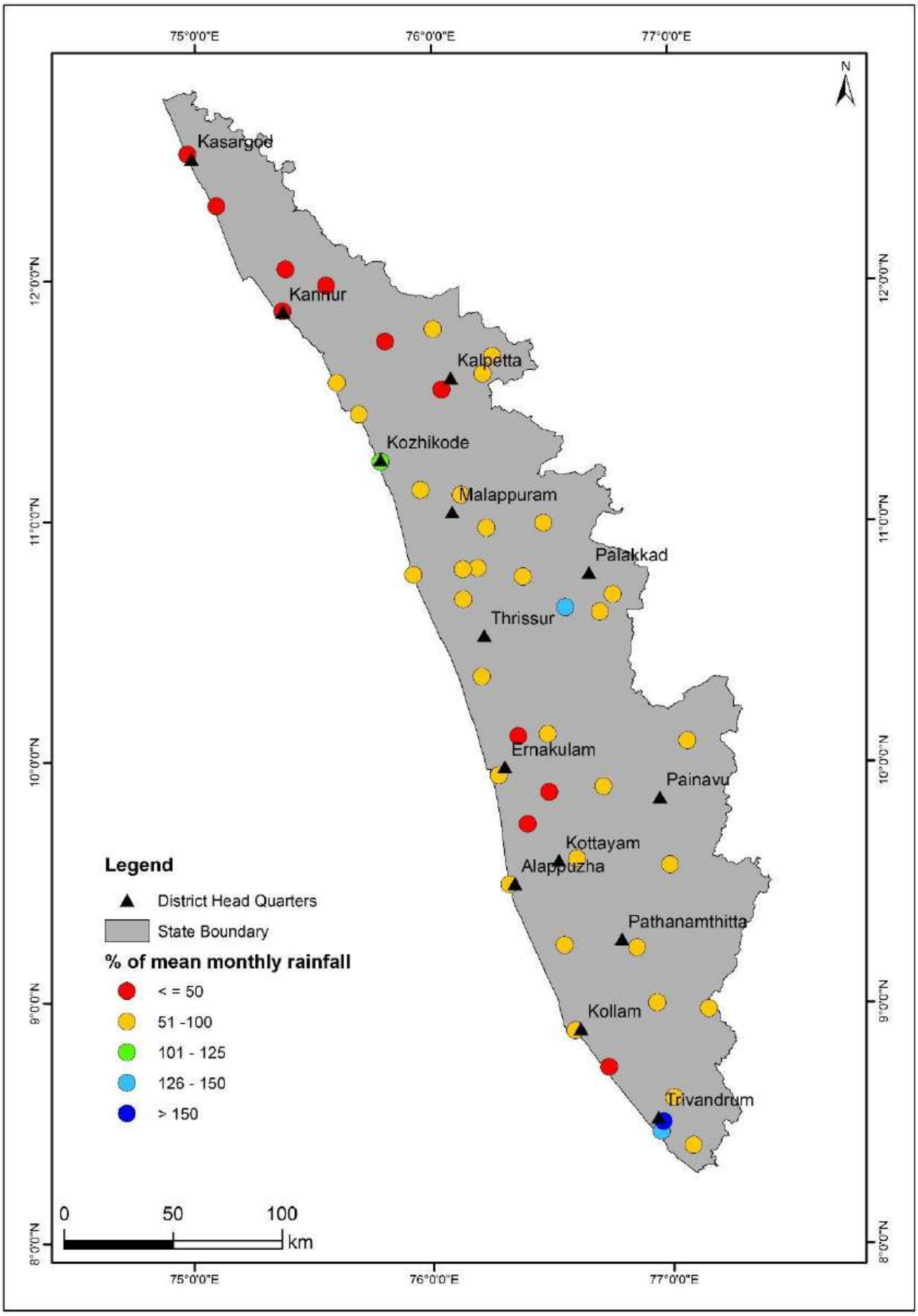


Fig. 1.2: Spatial variability of the total rainfall experienced during the ERE occurred between 15-17 August 2018 towards the contribution of the monthly rainfall

1.3. The Flood of August 2019

As a departure from 2018, the southwest season of 2019 was characterized by a delayed onset and weak seasonal rainfall for June and July months. The onset of monsoon was officially declared by IMD on the 8th of June 2019, and Kerala received 32% deficient rainfall till 31st July 2019. Among the 14 districts, Wayanad district experienced almost 55% deficiency in seasonal rainfall compared to the normal till 31st July 2019. However, during August 2019 Kerala State experienced a severe ERE during 8-10 August 2019. Despite the late monsoon onset and largely deficient rainfall during the months of June and July 2019, the ISMR seasonal rainfall of Kerala ended in the normal category with a percentage departure of +13.

The ERE occurred during 8-11 August 2019 in Kerala was the result of the formation of a low-pressure system and later a depression over the northwest Bay of Bengal off north Odisha-West Bengal coasts on 6th August 2019. It was moved northwestwards and intensified into a deep depression on 7th August 2019, and later it moved west northwestwards and weakened into a depression over northeast Chhattisgarh & neighbourhood on 8th August 2019. On 9th August 2019, the system moved west northwestwards and lay centred over west Madhya Pradesh and adjoining east Rajasthan, and weakened into a well-marked low-pressure area. Under the influence of the system and strengthened monsoon winds, Kerala received large excess (123%) rainfall during August 2019. In August 2018, it was 96% excess rainfall than normal. The most affected districts were Kozhikode (176%), Wayanad (110%), Malappuram (176%), Palakkad (217%), Thrissur (127%) and Ernakulam (140%), which received more than 100% excess rainfall than the normal rain during August 2019. The districts north of Thrissur received more than 1000 mm rainfall between the 1st and 31st of August 2019. The widespread flooding and landslides across the districts of northern Kerala caused severe damage to both the built and natural ecosystems. The low-lying areas of the major river systems were inundated and more than 2 lakh people were displaced. Kerala witnessed 80 landslides in eight districts over the three days (August 8-11, 2019) as the death toll crossed 120. The severe landslides have occurred in Puthumala, Vellarimala, Puthumala, Narikkunnu, Perinjrimala, Koramchalil, Pachakkad, Pazhassimala colony, Mangalassrimala, Meenmutty and Kurumbalakotta area of Wayanad district and Kavalappara, Pathar, Kottakkunnu area of Malappuram district. Landslides in Kannur and Kozhikode districts severely affected many people residing in the hilly region.

The cumulative amount of rainfall experienced during the ERE across the State indicates that the total rainfall occurred during the three days (i.e., 8-10 August 2019) in majority of the meteorological stations (of IMD) of Palakkad, Malappuram and Wayanad districts was more than 50% of the normal monthly rainfall (Fig. 1.3). It may be noted that the total rainfall that occurred during the event in Wayanad district was more than the mean monthly rainfall.

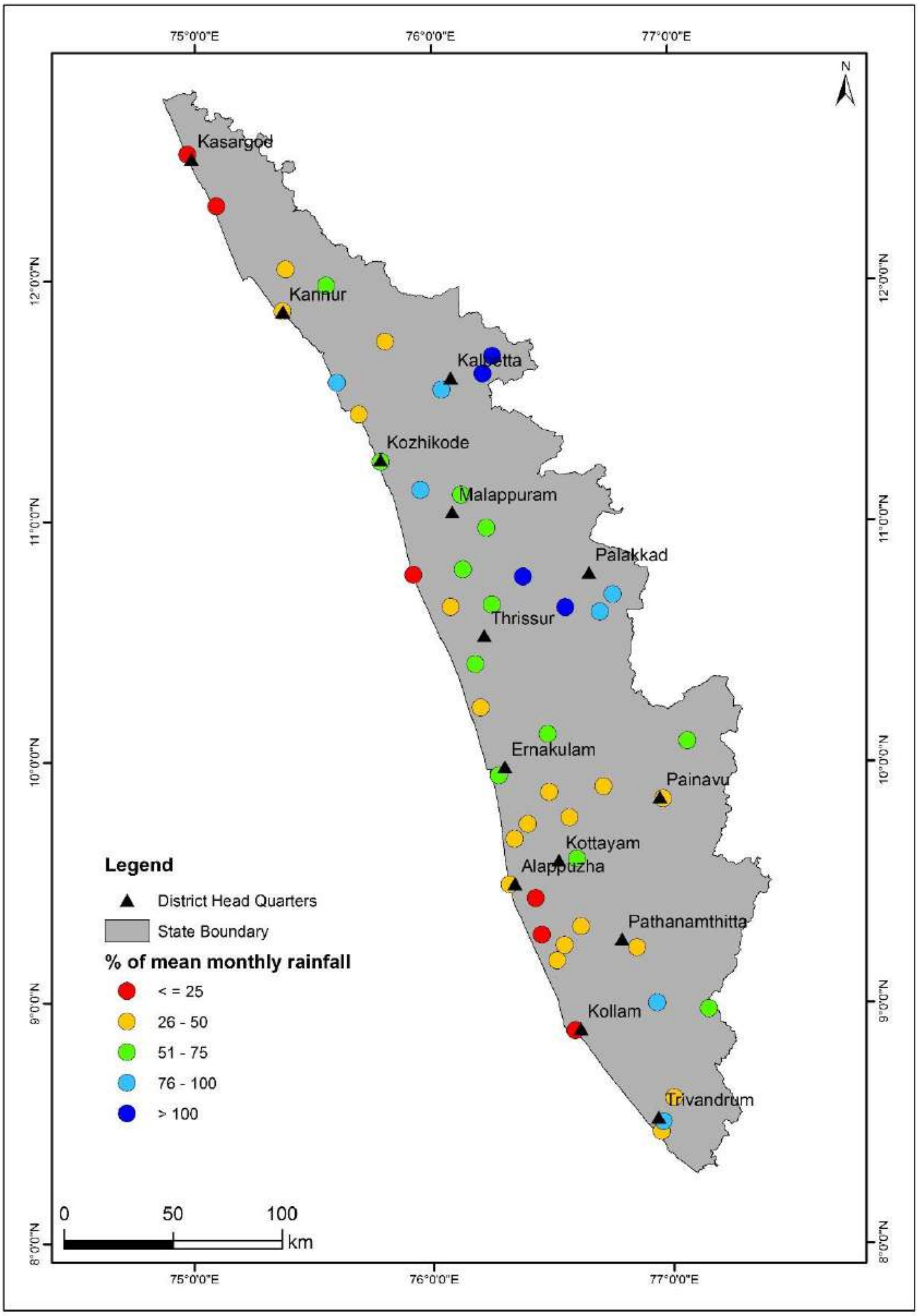


Fig. 1.3: Spatial variability of the total rainfall during the ERE between 8-10 August 2019 towards the contribution of the mean monthly rainfall

1.4. Social and Economic Context

The human population of the State was 3,34,06,061 (Census of India, 2011), which is roughly 3% of the population of India, and among the total population of the State, 52% are women. The decadal growth rate of Kerala's population was 4.9%, the lowest among the Indian States. Kerala has the highest margin of literate persons in the population among the Indian States, where the effective literacy rate is 93.91%. The incidence of poverty in Kerala was significantly lower (11.3% in 2011-12) compared to the national-level statistics (29.5%). The Gross State Domestic Product (GSDP) at constant (2011-12) prices was ₹ 5,13,69,589 lakh in 2017-18, and the per capita GSDP at constant (2011-12) prices in 2017-18 was ₹ 1,48,927. Although Kerala possesses the 20th position in the geographic area among the 28 States of India, the State has been always ahead of other Indian States in achieving demographic and human development indicators. Based on the estimates of NITI Aayog, the State holds the crown position (along with Himachal Pradesh) in achieving the Sustainable Development Goals (SDGs 2018) by the different States in India (Kerala State Planning Board, 2019). Human development in Kerala has been more equitable compared to other states of the country, and Kerala is placed first among states in the human development index (HDI) as well as in the inequality-adjusted HDI (IHDI) (Suryanarayana et. al., 2016).

Despite the well-performing economic development in the State, the occurrence of EREs and associated floods and landslides on large spatial scales for two consecutive years, viz., 2018 and 2019 imposed a heavy burden on the economy of the State (Government of Kerala, 2018b; Kerala State Planning Board, 2019). The floods have had a severe adverse impact on the livelihood of a large number of people, especially the vulnerable sections. The extensive floods and devastating landslides caused considerable damages to infrastructure, agriculture and livestock, biodiversity, power supplies, and communication networks. The total recovery needs for the flood and landslides of 2018 were estimated to be ₹ 31,000 crores (USD 4.4 billion) (Government of Kerala, 2018b). The impacts of the extensive flooding and landslides (specific to August 2018) to various sectors of Kerala's economy have been discussed in the flowing sections.

1.4.1. Socio-Physical System

Uninterrupted rains from 8th to 18th of August 2018 resulted in widespread destruction in all the major sectors of the state. In a span of 30 days, 445 human lives were lost and over 1.5 million people were moved to relief camps. Kerala has suffered huge economic losses on account of the floods. According to a conservative estimate, close to 2.6% of Kerala's gross state domestic product (GSDP) got washed away by the floods instantly. The devastating floods and landslides caused extensive damage to houses, roads, railways, bridges, power supplies, communications networks, and other infrastructure; washed away crops and livestock, and affected the lives and livelihoods of millions of people in the state. The five worst-affected districts of the state's 14 districts i.e. Idukki, Ernakulam, Kollam, Kottayam, and Pathanamthitta have an estimated population of 11.09, million which accounts for nearly 30% of the state's total population. Cochin International Airport Ltd. (CIAL), one of the busiest international airports of the country got flooded and suspended its operations from 15th to 29th of August 2018 (Government of Kerala, 2018a).

1.4.2. Health Sector

Kerala has the highest life expectancy (almost 75 years), and the highest sex ratio (1,084 women per 1,000 men), across all Indian states. Kerala has made significant advances in all the three components of health transition, namely demographic, epidemiological, and healthcare. Although there was no epidemic outbreak following the floods, health impact was substantial as most health facilities were fully or partially destroyed. Field assessment by Sphere India in 2018 indicated that patients of non-communicable diseases such as diabetes and hypertension missed their medications and medical records. In Wayanad and Palakkad district, some children were found prone to malnutrition. Sleep disturbance and mental health problems in people were noted in multiple districts (Government of Kerala, 2018a).

1.4.3. Educational Sector

Education has played an important part in Kerala's tremendous transition from a rigidly caste-divided society into one of India's most egalitarian states. In January 2016, it became the first Indian state to achieve 100% primary education. However, the disaster brought about the loss of learning materials of students and teachers, disruption of the learning cycle, loss of teaching days and damage to school infrastructure. Schools were used as relief camps and transition/temporary shelters, which disrupted routine academic schedules. There were concerns regarding the loss of mark sheets and trauma to students caused by the event (Government of Kerala, 2018a).

1.4.4. Agricultural and Livelihood Sector

Nearly 52% of Kerala's population lives in rural areas, and 17.15% of the population depends on the agricultural sector (including crops, livestock, and fisheries) for its livelihood. Locations like Kuttanad, have been declared part of the global heritage in agriculture. All three subsectors (crops, livestock, and aquaculture/fisheries) have suffered losses and damages in the flooding and landslides of 2018. Crops were most heavily affected, followed by livestock and fishery/aquaculture. Subsistence agriculture is an important source of income for rural communities (Government of Kerala, 2018a). Among the worst affected were workers in the informal sector, who constitute more than 90% of Kerala's workforce. Thousands of casual workers and daily wage earners, such as agriculture labourers, workers in the coir, handloom, and construction sector and in the plantations, have experienced wage loss for 45 days or more. Hence, there is a critical need for sustained action on livelihood restoration and mainstreaming resilient livelihoods (Government of Kerala, 2018a).

1.4.5. Human Lives and Property

Massive damage to the roads, houses, and other infrastructure occurred in the northern districts of the state because of the landslides due to heavy rainfall. The devastating floods and landslides affected 5.4 million people, displacing 1.5 million to relief camps during the floods, as their homes were inundated with floodwater.

Many buildings have been damaged either fully or partially, potentially affecting .75 million people. Housing damage during the flooding and landslides was caused by the scouring of foundations, settlement of soil, and inundation for several days. Houses in low-lying areas with low plinth heights were damaged much more than houses with high plinths and disaster-resistant features such as plinth and lintel bands. Resultantly, people had to live in temporary shelters or other temporary accommodation until their homes are safe enough for them to return.

1.4.6. Infrastructure

Access to piped water was disrupted for 20% of the state's population. Shallow wells were damaged and water was contaminated in six worst affected districts directly affecting people. The Kerala Water Authority and Irrigation departments run a large network of water supply for drinking as well as for irrigation purposes. Both of these sectors had a broad network of pipelines and canal systems that were passing through the urban and rural areas in Kerala. Irrigation canals, public taps, pipelines, pump houses, check dams, bunds, irrigation pumps, and other irrigation machinery and structures were damaged due to floods, and landslides. Most of the engineering structures washed away by huge landslides and inundated by flooding. Huge losses in machinery, equipment, structural and non-structural assets have been estimated by concerned authorities. Most of the houses had access to sanitation before the disaster; post-disaster, the houses, along with bathrooms, were washed away by the landslides or floods. Additionally, the Public Works Department (PWD) has suffered unprecedented losses, as evidenced by the damage to physical infrastructure, especially roads and bridges. Some roads and bridges have even been completely washed away due to floods, and a total of 9538.45 km of roads have been damaged in Kerala. As many as 510 bridges have been damaged due to the calamity (Government of Kerala, 2018a).

1.5. Response to the Recurring Floods of Kerala

Despite the occurrence of flood and landslides on a massive spatial scale, the less than expected socio-economic impact of the floods and landslides during 2018 and 2019 was chiefly due to the concerned effects and management skills displayed by the government as well as the civil society to control the losses caused by the disaster. The Government of Kerala conducted timely and efficient rescue and relief operations to save many lives, heavily supported by affected communities mobilizing on their own, and effective application of information technology and social media by voluntary youth groups to support rescue operations. The people of Kerala also showed remarkable resilience in the face of adversity to the extent that within one week of floodwaters receding, most people returned to their homes to rebuild their lives.

1.5.1. Government of Kerala

The State administration, in response to the disaster, decentralized the resources and duties down to the district and local body level. All precautionary measures were taken to meet the floods in accordance with the Kerala State Disaster Management Plan, 2016. According to the Disaster Management Plan, the levels of disasters have already been categorized and disseminated as L0, L1, L2, and L3, based on the ability of various authorities to deal with them.

Based on the 1st Long Range forecast, by IMD, the State Relief Commissioner convened a meeting of all the Departmental Heads, District Collectors, Scientific Organizations, IMD, Geological Survey of India, National Centre for Earth Science Studies and representatives of Defence Forces on 16th May 2018, in which all the stakeholders were assigned specific tasks for better preparedness during the monsoon season. (Minutes and circular issued as per Government Letter DM1/217/2018/DMD; dated 28th May 2018).

SEOC functioned under the notified Incident Response System of the State and worked in close liaison with the National Emergency Operations Centre and the National Disaster Management Control Room throughout the monsoon season. Alerts, warnings and public advisories were issued routinely via various channels of communication. Maps of immediate threat zones, due to any opening of the shutters of Cheruthoni dam of Idukki reservoir, overlaid with Satellite Images, were provided to DEOCs of Idukki, Thrissur, and Ernakulam on 28-07-2018 based on the inundation history of 2013 based on a rapid assessment. Print, visual and audio media have carried the warnings on a daily basis for public notice. Daily updates of disaster statistics as mandated by the Ministry of Home Affairs were uploaded to the National Database for Emergency Management.

The Chairman of the KSDMA directly supervised the activities related to the coordination of multiple agencies. KSDMA meetings were repeatedly held during the period of calamity to ensure decision making at the highest level considering the gravity of the disaster, which was notified as L3 calamity requiring assistance from the Government of India. State Executive Committee of KSDMA met 5 times during the calamity and coordinated the response and relief activities. Timely SDRF funds were released to Districts. Detailed orders were issued to alleviate the flood-affected from the flood miseries, which contained 22 specific instructions for each department. Banks were directed not to deduct banking charges from the gratuitous relief funds transferred by the government to the accounts of the beneficiaries.

Crowdsourcing of distress calls was logged to “https://keralarescue.in”, a public portal and SEOC utilized these locations to provide local rescue priority locations to rescue agencies. The crowdsourcing platform also enlisted the details of volunteers willing to work in rescue and relief activities. (For more date wise activities please check the Detail Report submitted to ACS on 8/11/2018). Necessary anticipated actions were taken to ensure that emergency communication is not affected. Alternate arrangements were made through Satellite phones to ensure communication with District Collectors.

The Humanitarian Assistance and Disaster Response request of KSDMA were duly honoured by Central Forces and Armed Forces. This resulted in 58 teams of NDRF, 23 columns of the Army, 104 boats, 94 rescue teams of the Navy, 1 medical team, 9 helicopters, 2 Air crafts, 94 boats, 36 teams of the Coast Guard, 49 boats, 2 helicopters, 2 Aircraft, 27 boats (hired), 22 Helicopters of the Airforce, 23 Aircraft, 2 companies of the Border Security Force, 1 water vehicle team and 10 teams of CRPF being deployed along with 2927 fishermen and 669 boats operating in the State over a period from 14th July to 31st August 2018. As many as 14,50,707 individuals were housed in 3,879 relief camps. 5,31,368 families out of 5,75,449 families were provided gratuitous relief till 15-09-2018. Out of 430 deceased, Rs4 lakhs have been released to 272 families. An amount of Rs 816 crores have been released from State Disaster Response Fund to District Collectors, out of which an amount of Rs 328.07 crores have already been expended on relief and response as on 15-09-2018. An amount of Rs 420.11 crores have been released from Chief Ministers Distress Relief Fund to district collectors out which an amount of Rs 331.13 crores have already been expended on relief.

Systematic steps were taken to plan and implement the reconstruction schemes for which Joint Rapid Damage and Need Assessment. Non-Governmental Agencies were adequately coordinated at the district level in extending relief equitably. Relief assistance was extended as per the norms of the National and State Disaster Response Fund and was decided scientifically as stipulated in the norms. The disaster-affected area was mapped and steps have been taken to permanently map the affected areas using satellite images and crowdsourcing techniques. Steps have also been taken to immediately mark flood-affected areas by keeping permanent markers to ensure that public memory of this catastrophic flood is retained and thereby indirectly steer the public to consider the flood levels when any reconstructions are carried out in these areas. Special orders were issued permitting Local Self Government Institutions (LSGIs) to spend their own funds and in the absence of own funds, they are permitted to utilize funds up to 3 lakhs from plan fund based on the recommendation of District Collector concerned.

Orders citing direction were issued to LSGIs permitting them to engage the services of Electricians, Plumbers, etc also in the ward level committee constituted for cleaning activities, for repairing the electrical, plumbing materials of flood affected houses Control Rooms were opened in all major flood-affected districts and in the office of Director of Urban Affairs, Commissioner of Rural Development and Director of Panchayaths under the control of Central Control Room open in Local Self Government Department. Control Room is coordinating the activities and closely monitoring the post-flood cleaning activities in Urban/Rural areas. Some directions/guidelines in connection with post-flood cleaning activities issued from the control room in LSGD, apart from the messages produced above, are produced herewith.

- 8,31,400 carcasses have been safely buried which includes 5,780 large animals, 8,638 small animals, and 8,16,982 birds.
- About 2,79,168 squads worked for cleaning 6,90,785 houses, 5,835 public buildings, and 2,371 public places.
- The squads gathered approximately 4523 MT biodegradable waste and 4690 MT non-biodegradable waste and disposed of 5,850 large animal carcass, 8807 small animal carcass, and more than 8 lakh birds.
- 6568 Skilled Task Force consisting of electricians, plumbers, carpenters, fitters, etc. were mobilized and oriented who attended to the repair in 5003 houses. 50 HP water pumps, 160 pressure pumps, and 69 ordinary pumps were mobilized for cleaning activities. About 15,000 shovels, 75,000 gumboots, 2 lakh gloves, 2 lakh masks, 1 lakh brooms, brush and mops, and 20,000 buckets and mugs were mobilized for cleaning activities in addition to those mobilized locally.
- 2,94,849 wells were disinfected through chlorination using bleaching powder or chlorine tablets.

1.5.2. Civil Society

The community came together to organize rescue and relief work, led by different types of peoples' organizations, ranging from trade unions and student-youth organizations to self-help groups, charitable organizations, sports clubs, and other collective bodies. This was one of the largest civilian rescue operations the state had ever undertaken, with 4,500 fishermen in 700 boats involved in rescue operations. The fishermen had the benefit of local knowledge of habitats and understanding of the rivers to their advantage. Also, they used twin-engine, locally designed fishing boats that can move in shallow waters (less than 2 feet deep) and restrictive spaces. Working with the local authorities, volunteer groups and the police, they were able to rescue over 65,000 people stranded in their homes (Government of Kerala, 2018a).

1.6. Formulation of the Committee

In the context of recurring EREs and associated damages due to flood and landslides, the Government of Kerala constituted a “committee to examine the causes of repeated extreme heavy rainfall events, subsequent floods, and landslides, and to recommend appropriate policy responses” vide order G.O. (Rt) No. 42/2019/S&TD dated 22-08-2019 (Appendix 1.1) to prepare a quick assessment report, after examining the causes of repeated extreme heavy rainfall events, and subsequent floods/landslides, containing recommendations, facilitating the formulation of appropriate policy responses, which will also serve for developing emergency action plans and disaster preparedness for the Kerala State for similar future events.

The committee was constituted by an interdisciplinary team of experts from climate science, hydrology, geology, and civil engineering disciplines. The committee addressed the following concerns while preparing the assessment report:

1. The reasons for the occurrence of such EREs and their major causative factors;
2. The capability and potential for accurate forecasting of such events with sufficient lead times;
3. Reviewing indicators and methods to locate areas prone to severe landslides during such EREs and remedial measures for minimizing such hazards and their consequences;
4. Reviewing current maps of areas prone to flood hazard during such EREs and mitigation measures to minimize such hazards; and
5. To focus on the role of changing land use in these hazards

1.7. Methodology

The committee addressed the aforementioned aspects on the basis of a survey of previous literature and ancillary information, observations during the field visits, interaction/discussion with scientific experts, different levels of administration, and community, synthesized information after analysis of primary and secondary data and analysis and simulation-based results. The details of the methodology are illustrated in the following paragraphs.

The committee reviewed various types of literature, viz., peer-reviewed scientific articles and assessment reports published by various organizations (both governmental and non-governmental). The committee conducted field visits in some of the worst-affected areas of flood and landslides in Pathanamthitta, Alappuzha, Kottayam, Malappuram, Kozhikode, Wayanad, and Kannur districts in 2018 and 2019 (Table 1.1).

Table 1.1: Details of the field visits conducted by the committee during September-December 2019

Date	Areas Visited
18 September 2019	Kainakary, C-Block and Marthandam Kayal of Kuttanad region
12-13 October 2019	Thaneermukkam, Thottapalli, Krishnapuram, Kayankulam, Thamarakulam, Vallikunnam
20-26 October 2019	Malappuram (Nilambur, Kavalappara, Pathar), Kozhikode (Mukkam, Chathamangalam, Olavanna, Kallayi), Kannur (Sreekandapuram, Chengalayi, Shimoga Colony in Chandanakampara of Payyavoor Gramma Panchayath), Wayanad (Puthumala, Kalladi) and Idukki (Munnar, Devikulam, Gap road)
13-14 November 2019	Pampa river basin (Aranmula, Cherukole, Ranni, Perunad, Pamba, Anathode and Kakki Dams and Kochupamba)
18-20 November 2019	Kavalappara and Puthumala for detailed investigations

Table 1.2: Details of the interaction/discussion conducted by the committee during September-December 2019

Date	Particulars
17 September 2019	The first meeting of the committee members at Kerala State Planning Board, Thiruvananthapuram
18 September 2019	Meeting with district collector of Alappuzha district at Collector's Chamber, Alappuzha
20 October 2019	Meeting with district collector of Kozhikode district at Centre for Water Resources Development and Management (CWRDM), Kozhikode
22 October 2019	Meeting with district deputy collector (Disaster Management), Wayanad district and Divisional Forest Officer, South Wayanad Division
13 November 2019	Meeting with Secretary of Cherukol Grama Panchayath, and with Mr. N.K. Sukumaran Nair, Environmental activist and General Secretary of Pampa Samrakshana Samithi, Kozhenchery.
04 December 2019	The second meeting of the committee members at Kerala State Council for Science, Technology and Environment, Thiruvananthapuram

The committee used primary as well as secondary data (either observed or simulated or in combination) for detailed analysis. The daily rainfall data (recorded at meteorological stations and 0.25° x 0.25° gridded data) of the India Meteorological Department (IMD) The first for the analysis of rainfall patterns and spatio-temporal trends across the State. The aerosol particle size distribution data, collected from Munnar Aerosol Observatory were used for the analysis of the effects of aerosols on EREs. The physical properties of the soil samples from the landslide occurrences (collected by the National Institute of Technology, Kozhikode) were used for the numerical modelling of the landslides. The gauge-discharge data, collected from the Water Resources Department, Government of Kerala, Kerala State Electricity Board (KSEB) Ltd. and Central Water Commission (CWC) through WRIS-India data repository were used for the hydrological analysis. The HEC-HMS, a watershed hydrological model was used to simulate the peak discharge for the actual condition as well as for various scenarios, and the HEC-RAS (2D), a hydrodynamic model was used for the development of flood inundation maps for different scenarios.

1.8. Structure of the report

This report is organized into six chapters. The background problem and premise of the constitution of the committee are discussed in Chapter 1. The information pertaining to the environmental profile of the Kerala State is presented in Chapter 2. The characteristics of the extreme rainfall events experienced in Kerala and the analysis of the data pertaining to the rainfall events are organized in Chapter 3. The causative factors of recurring extreme rainfall events are also discussed in this chapter. The data about the historical occurrence of landslides in Kerala and its causative factors are discussed in detail in Chapter 4. The occurrence of floods associated with the extreme rainfall events in the State is presented in Chapter 5. This chapter also presents the results of the hydrologic analysis of the historical flood in the State. Based on the deliberations and results of the analysis, the conclusions drawn by the committee are discussed in Chapter 6.

2. Chapter 2
Environmental Profile: Kerala

2.1. General

The Kerala State is located on the southern part of the Indian Peninsula, sharing the administrative boundaries with Tamil Nadu and Karnataka (Fig. 2.1). The State, covering an area of 38,863 km^2 is sandwiched between the Arabian Sea in the west and the WG in the east. The shape of Kerala resembles a scalene triangle with its base on the long coast (560 km), and its apex on the WG.

2.2. Physiography and Geomorphology

Kerala has an undulating topography with distinct altitudinal zonation. The elevation of the State varies between below MSL (in Kuttanad region) and 2690 m above MSL (the Anai Mudi peak) (Fig. 2.2). The longitudinal profile of elevation above MSL divides the State into three physiographic zones, viz., the highlands, the midlands and the lowlands including the coastal plain. The highlands include the eastern part of the State characterizing the mountain ranges with the elevation greater than 75 m above MSL and are covered mostly with dense forests along with regions under tea, coffee, cardamom, and other commercial plantations. The midlands (ranging the elevation between 7.5 m and 75 m above MSL) are the region between the highlands and the lowlands characterized by undulating hills and valleys. The physiographic regions of the State are exclusively associated with the geological phenomena, such as the west coast faulting and the upliftment of the WG, and are responsible for the emergence of the unique geo-bio-diversity of the region. Since these geomorphic events occurred more or less in a longitudinal sense, the physiographic regions of the State also follow a similar pattern (KSCSTE, 2007). The lowlands, midlands, and highlands cover about 10%, 42 % and 48 % of the geographic area of Kerala State respectively.

The summit of the WG forms the drainage divide between the west-flowing rivers and the rivers of the plains of Tamil Nadu. The majority of the rivers of Kerala flow in the westerly direction through the highlands and midlands, following the trend of host rocks. The westerly drainage is most prominent and the development of the drainage network has been controlled by the retreat of the WG. The lowlands, and especially the coastal plains are covered by a thick mantle of alluvium. The drainage network of the State exhibits diverse patterns, varying from parallel, rectangular, and trellis to dendritic, indicating the strong controls exerted by the slope of the terrain and structural fabrics. The coastline of the State is fringed by a string of estuaries (*kayals*) into which major west-flowing rivers join its course to the Arabian Sea.

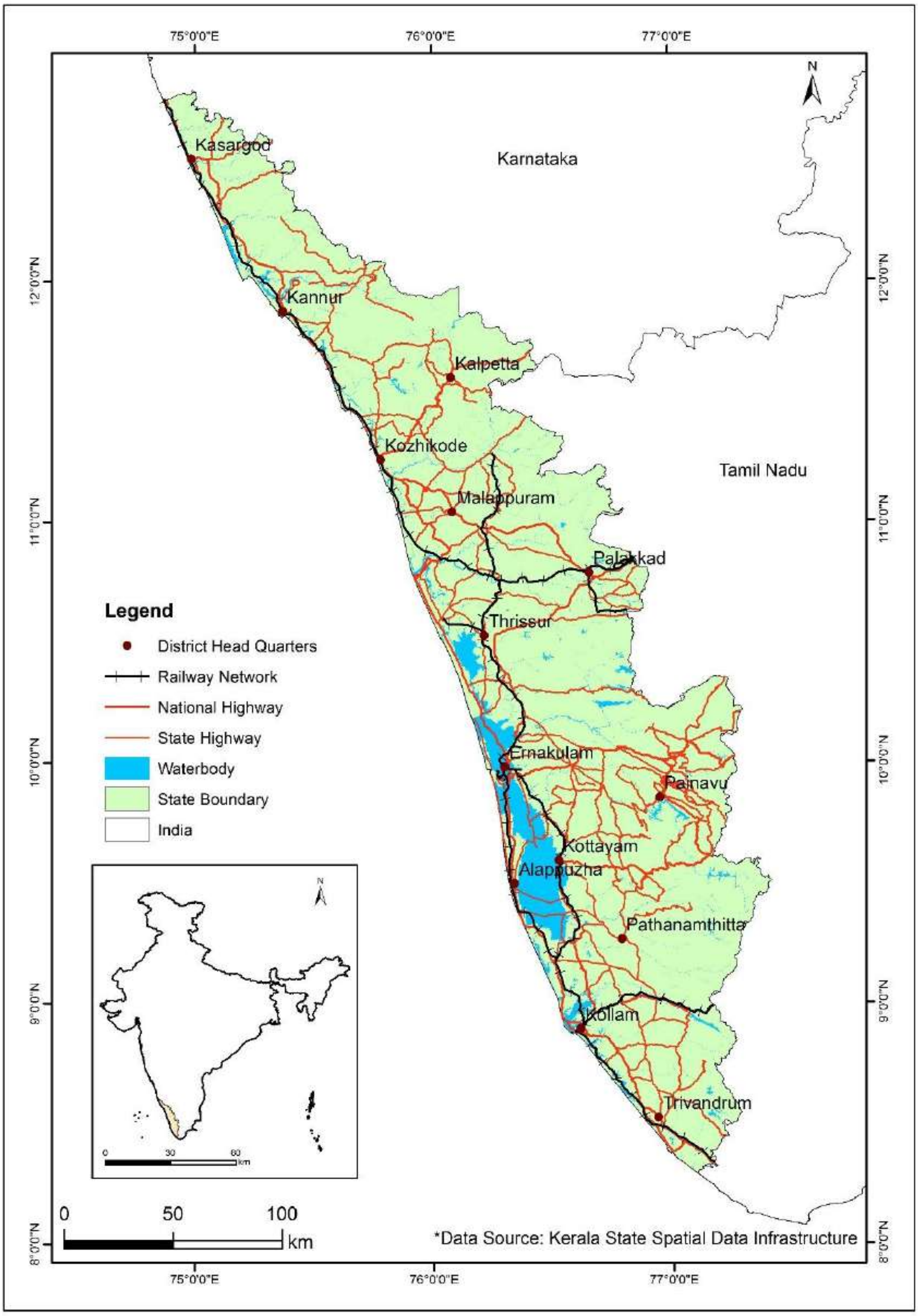


Fig. 2.1: Physical map of Kerala

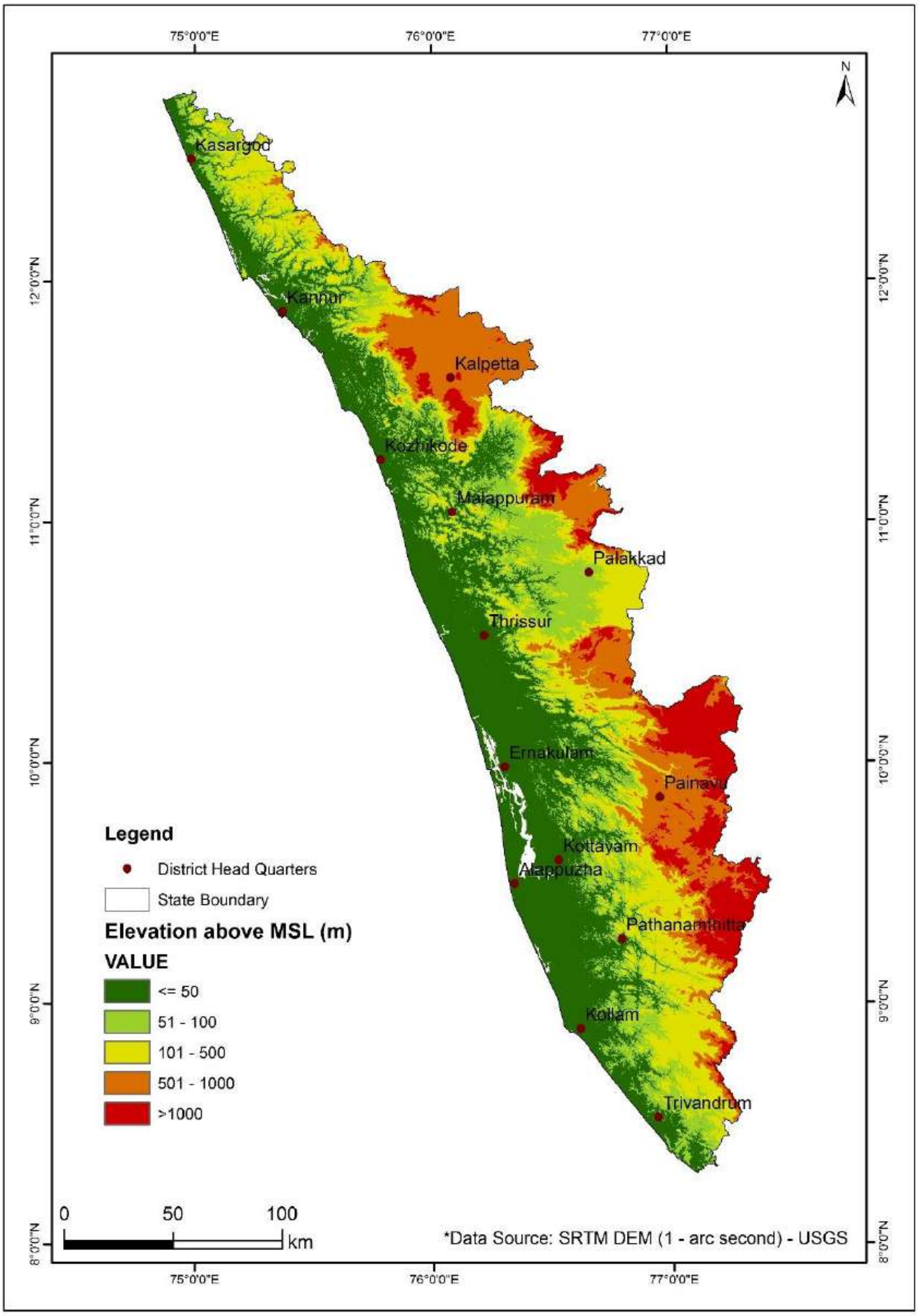


Fig. 2.2: Spatial variation of elevation (above MSL) of the State

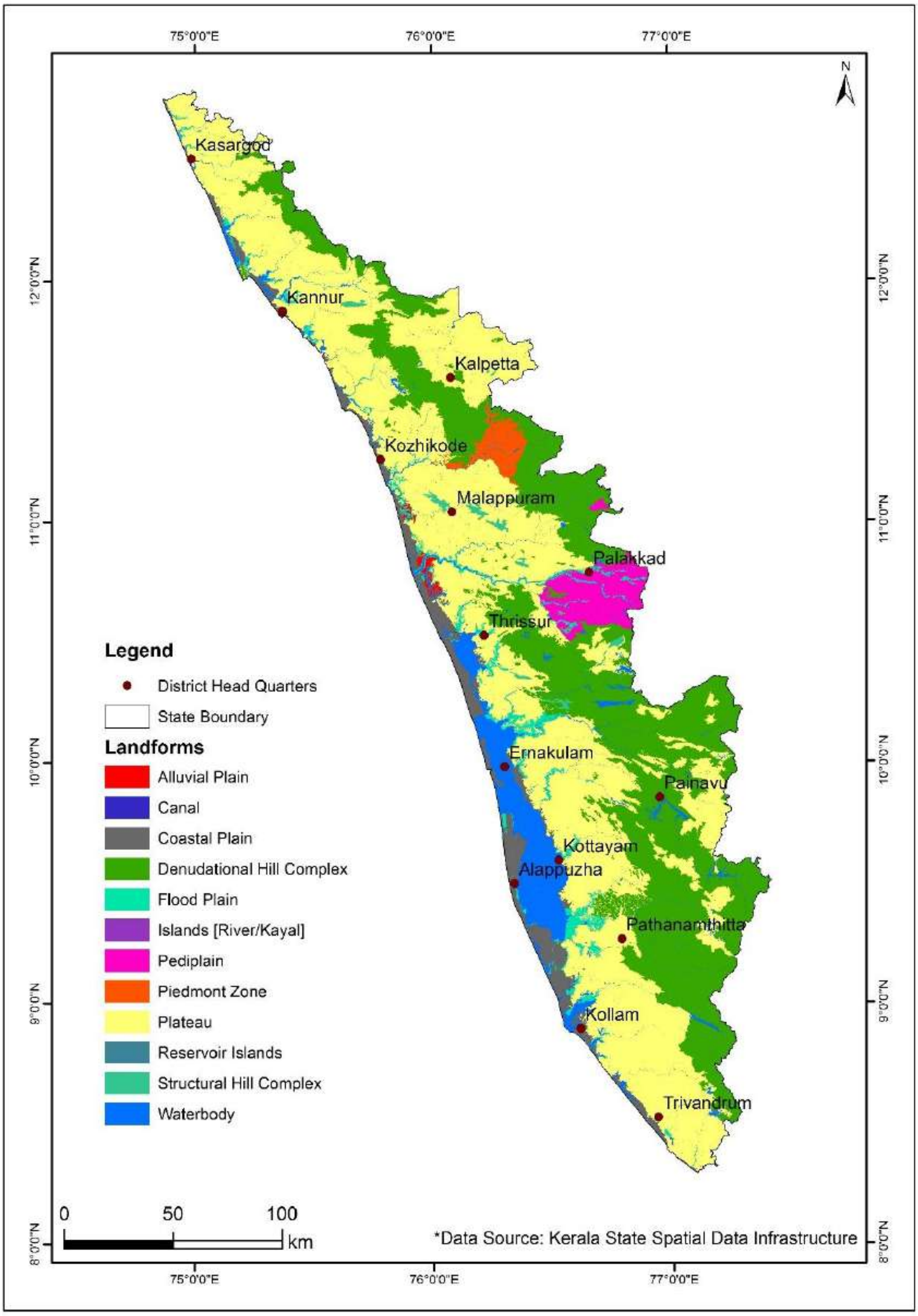


Fig. 2.3: Geomorphological map of Kerala

2.3. Geology

Geologically, Kerala is occupied by Precambrian crystallines, acid to ultra-basic intrusives of Archaean to Proterozoic age, Tertiary (Mio-Pliocene) sedimentary rocks and Quaternary sediments of fluvial and marine origin (Fig. 2.4). The crystallines and the Tertiary sediments have been extensively lateralised. Table 2.1 shows the stratigraphic sequence suggested by the Geological Survey of India (GSI) based on the detailed study during the last three decades (Geological Survey of India, 2005).

Table 2.1: The stratigraphic sequence in Kerala suggested by Geological Survey of India

Quaternary	Pebble bed Kadappuram Formation (marine) Periyar Formation (fluvial) Viyyam Formation (fluvio-marine) Guruvayur Formation (paleo-marine)
Mio-Pliocene	Laterite Warkalli Formation (Sandstone and clay with lignite intercalations) Quilon Formation (Fossiliferous limestone and calcareous marl).
Mesozoic	Gabbro/Dolerite dykes
Younger granites	Alkali granites, granite, granophyres, and other acid intrusives
Charnockites (Younger)	Massive charnockite, incipient charnockite, Cordierite charnockite
Ultrabasic/basics (Younger)	Perinthatta anorthosite, Kartikulam gabbro, Adakkathodu gabbro, Begur diorite
Basic Intrusives	Agali-Anakkatti dykes
Migmatite/gneiss/older granitoid	Garnet- biotite- gneiss with associated migmatites, quartzo-felspathic gneiss, hornblende gneiss, hornblende- biotite gneiss, quartz- mica gneiss
Vengad Group	Quartz-mica schist and quartzite, conglomerate
Charnockite (older)	Mafic granulite, pyroxene granulite, Banded magnetite quartzite and gneissic charnockite
Khondalite Group	Quartzite, mafic granulite, calc-granulite garnetbiotite-sillimanite-cordierite gneiss, garnet-biotitegneiss, leptynite
Peninsular Gneissic Complex	Foliated granite, hornblende gneiss, pink granite gneiss, biotite gneiss
Layered ultrabasic-basic Complex	Peridotite, dunite, pyroxenite, anorthosite
Wynad Schist Complex	Talc- tremolite schist, fuchsite quartzite, amphibolite, calc granulite, quartz sericite schist, kyanite quartzite, garnet - sillimanite gneiss/ schist, magnetite quartzite, kyanite mica schist

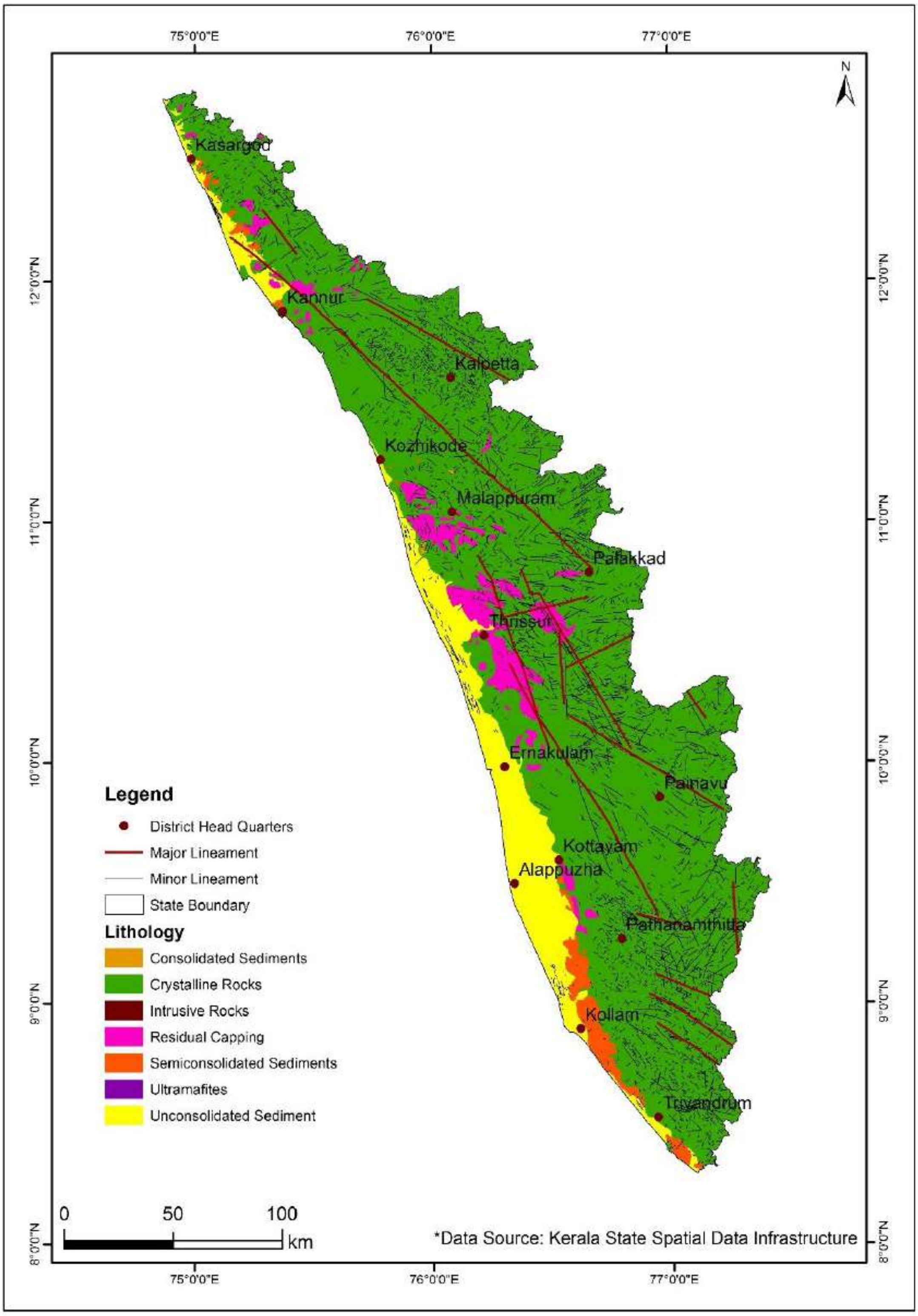


Fig. 2.4: Geological map of Kerala

2.4. River Basins and Drainage Network

Kerala has 44 rivers of which 41 flows westwards to join the Arabian Sea and the rest flows towards the east and joins the Bay of Bengal. All the rivers in the state are monsoon fed. The longest stretch of the river is 244 km (Periyar) and the smallest is 16 km (Manjeswar). The three east flowing rivers in Kerala are Pambar, Kabani, and Bhavani. Kabani contributes to Karnataka whereas Pambar and Bhavani flow towards Tamil Nadu. Figure 2.5 shows the map of the river basins, and drainage networks of Kerala, while Table 2.2 describes the major attributes of the river basins (e.g., river basin area, length of the river, district, main tributaries, average annual rainfall, and average streamflow). Appendix 2.1 shows the map of the individual river basins (Centre for Water Resources Development and Management, 2017).

2.5. Climate

The Kerala State lies in the extreme southwest of the Indian sub-continent bordered by the Arabian Sea on the west and the WG on the east. As per Koppen's classification, the climate of this coastal state is tropical monsoon with most parts of the state experiencing large amounts of rainfall during monsoon season and hot summer except over some southern parts, where the climate is tropical savanna with seasonally dry and hot summer weather. However, for the purpose of meteorological services, the entire state has been classified as one meteorological subdivision. The state experiences four seasons; winter season (January-February) having a pleasant and relatively cold climate in and hot, humid climate during the pre-monsoon season (March-May). The principal rainy seasons of Kerala are the south-west monsoon (June-September) and north-east or the retreating monsoon (October- December) with most parts of the state receiving 75-85% of the annual rainfall during the southwest monsoon season. In the next section, the spatial and temporal variability of various rainfall features over Kerala during the southwest monsoon season is presented.

2.5.1. Spatial and temporal variability of Rainfall

Table 2.3 shows the mean and coefficient of variation (CV) of the monthly and seasonal rainfall over Kerala computed for the period 1971-2018. During the southwest monsoon season, Kerala receives 1839 mm of rainfall with a CV of 20%. Among the four months, July receives the highest rainfall of 606 mm with a CV of 31% followed by June (mean = 567mm and CV=30%). Thus, Kerala receives more rainfall during the first half (1173 mm) compared to the second half (666 mm). Lowest rainfall is received during September with a CV of 50% indicating strong year to year to rainfall variability during the month. Table 2.3 shows the highest and lowest monthly and season rainfalls recorded during the period along with the years also.

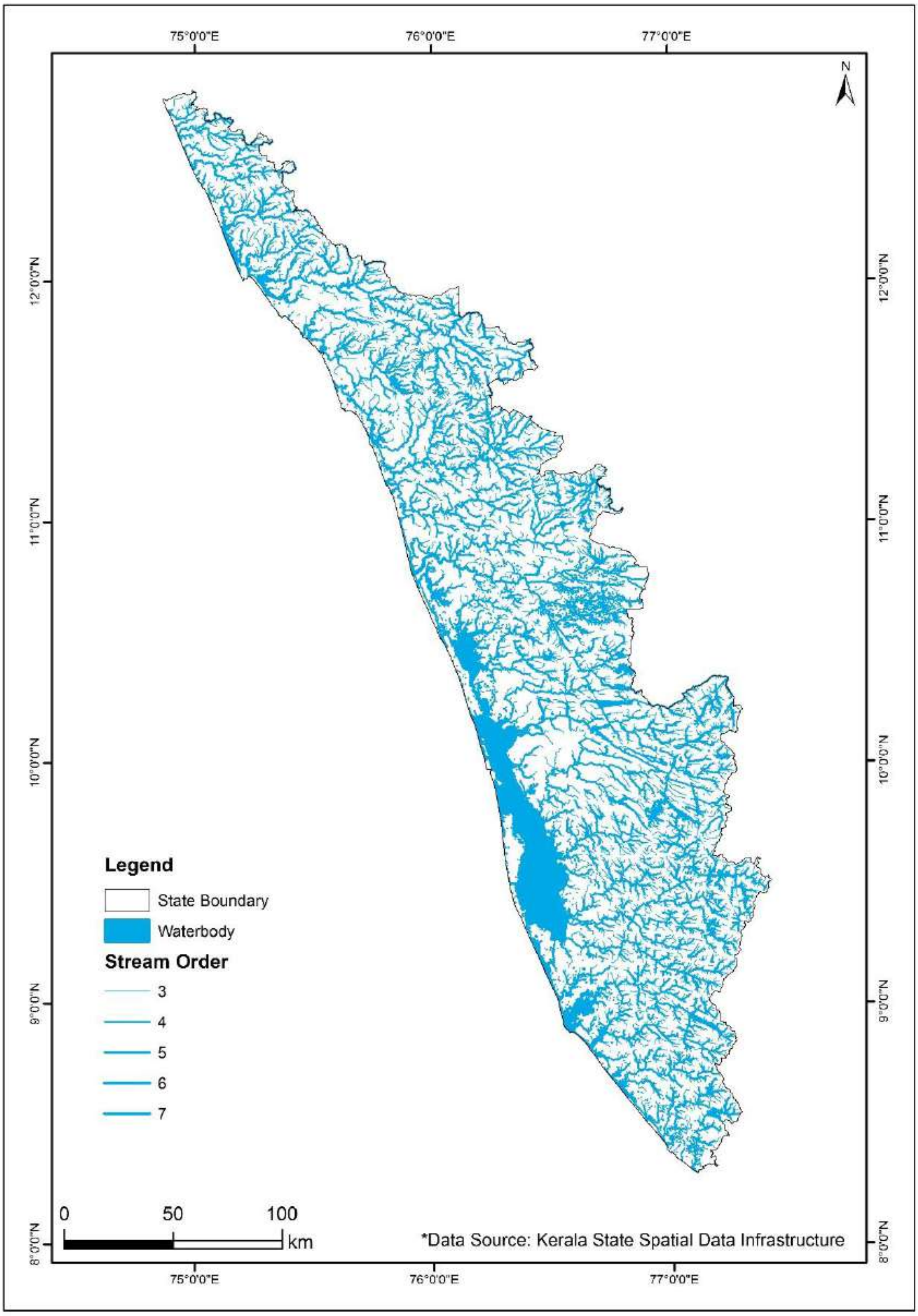


Fig. 2.5: Stream network of Kerala

Table 2.2: Portrait of the rivers of Kerala

Sl. No.	Name of river basin	Basin area (km^2)	Length of the river (km)	District of Kerala through which the river flows	Main tributaries	Average annual rainfall of the river basin (mm)	Average streamflow at downstream gauging station (Mm^3)
1.	Manjeswar	90	16	Kasaragod	Pavuri	3313	79
2.	Uppala	250	50	Kasaragod	Uppala	3141	746
3.	Shiriya	587	67	Kasaragod	Kallajethodu, Kanyanathodu, Eramattihole, Kumbala	3250	1455
4.	Mogral	132	34	Kasaragod	Bettipadi, Muliyar	3349	208
5.	Chandragiri	1406	105	Kasaragod	Payaswani and Chandragiri	3788	3435
6.	Chittari	145	25	Kasaragod	Kalnad, Bekal, Chittari	3386	NA
7.	Neeleswar	190	46	Kasaragod	Aryangal Thodu, Baigote Hole	3313	NA
8.	Kariangode	561	64	Kasaragod and Kannur	Mundore, Padiamala Hole, Ariakadavu Hole	3811	945
9.	Kavvayi	143	31	Kasaragod and Kannur		3439	NA
10.	Peruvamba	300	51	Kasaragod and Kannur	Macharuthode, Mathamangalam, Chalachal, Mukkuttenkarachal, Nitaringapuzha	3524	334
11.	Ramapuram	52	19	Kannur		3392	NA
12.	Kuppam	539	82	Kannur	Pakkattupoya, Alakuttathode, Kuttikolpuzha, Mukkuttathodu, Chiriyathodu	3916	854
13.	Valapattanam	1867	110	Kannur	Srikandapuram, Valiapuzha,	3879	3636

Sl. No.	Name of river basin	Basin area (km^2)	Length of the river (km)	District of Kerala through which the river flows	Main tributaries	Average annual rainfall of the river basin (mm)	Average streamflow at downstream gauging station (Mm^3)
					Venipuzha, Aralampuzha		
14.	Anjarakandy	412	48	Kannur	Kapputhodu, Idumbathodu	3395	426
15.	Tellichery	132	28	Kannur	Dharmadampuzha	3312	73
16.	Mahe	394	54	Kannur and Kozhikode		3680	349
17.	Kuttiyadi	583	74	Kozhikode	Onipuzha, Thotttilpalampuzha, Kadiyangadupuzha, Manathilpuzha, Madappalipuzha	4502	1142
18.	Korapuzha	624	40	Kozhikode	Agalapuzha, Pannurpuzha	3529	343
19.	Kallai	96	22	Kozhikode		3101	NA
20.	Chaliyar	2923	169	Kozhikode, Malappuram and Wayanad	Chalipuzha, Punnapuzha, Karimpuzha, Cherupuzha, Kanjirapuzha, Kurumbanpuzha, Vadapurampuzha, Iruthillypuzha	2889	5697
21.	Kadalundy	1122	130	Malappuram	Olipuzha, Veliar	2862	1290
22.	Tirur	117	48	Malappuram	Vallilapuzha	2787	209
23.	Bharathapuzha	6186	209	Malappuram, Thrissur and Palakkad	Gayathripuzha, Chitturpuzha, Kalpathipuzha, Thuthapuzha	2309	4509
24.	Keecheri	401	51	Thrissur	Chundalthodu	2920	280
25.	Puzhakkal	234	29	Thrissur	Parathodu, Poomalathodu, Naduthodu, Kattachirathodu	2901	99

Sl. No.	Name of river basin	Basin area (km^2)	Length of the river (km)	District of Kerala through which the river flows	Main tributaries	Average annual rainfall of the river basin (mm)	Average streamflow at downstream gauging station (Mm^3)
26.	Karuvannur	1054	48	Thrissur	Manali, Kurumali, Chimoni, Muppili	3024	1232
27.	Chalakudy	1704	130	Thrissur, Palakkad and Ernakulam	Parambikulam, Kuriarkutty, Sholayar, Karappara, Anakayam	2761	1860
28.	Periyar	5398	244	Idukki and Ernakulam	Muthirapuzha, Perinjakutty, Idamalayar, Mangalapuzha	2884	7266
29.	Muvattupuzha	1554	121	Ernakulam and Kottayam	Kaliyar, Thodupuzha, Kothamangalam	3190	4791
30.	Meenachil	1272	78	Kottayam	Kadapuzha, Minadamar, Kalathukadavu	3193	1988
31.	Manimala	847	90	Kottayam and Pathanamthitta	Kokayar, Elakkalthodu	3516	1756
32.	Pamba	2235	176	Pathanamthitta, Idukki and Alappuzha	Kakkiyar, Arudai, Kakkadar, Kallar, Pambi, Pambiar	3771	4061
33.	Achencoil	1484	128	Pathanamthitta, Kollam and Alappuzha		2933	1998
34.	Pallikkal	220	42	Pathanamthitta and Kollam		2369	682
35.	Kallada	1699	121	Pathanamthitta, Kollam and Thiruvananthapuram	Kulathupuzha, Chenduruni, Kalthuruthi	2634	1536

Sl. No.	Name of river basin	Basin area (km^2)	Length of the river (km)	District of Kerala through which the river flows	Main tributaries	Average annual rainfall of the river basin (mm)	Average streamflow at downstream gauging station (Mm^3)
36.	Ithikkara	642	56	Kollam and Thiruvananthapuram	Vattaparambu, Kudumanthodu, Vattamthodu, Kulanjethodu	2199	499
37.	Ayroor	66	17	Thiruvananthapuram and Kollam		1887	22
38.	Vamanapuram	687	88	Thiruvananthapuram and Kollam		2601	647
39.	Mamom	114	27	Thiruvananthapuram and Kollam		1868	112
40.	Karamana	702	68	Thiruvananthapuram	Kaviar, Attaiar, Vaiyapadir, Todiyar	2184	257
41.	Neyyar	497	56	Thiruvananthapuram	Kallar, Karavaliar	1862	210
42.	Kabbini	1920	56.6 (Kerala)	Wayanad	Mananthavadi, Panamaram, Bavelipuzha, Noolpuzha	2812	2478
43.	Bhavani	562	37.5 (Kerala)	Palakkad	Siruvani, Varayar	2175	254
44.	Pambar	384	25 (Kerala)	Idukki	Iravikulam, Myladi, Thirthmala, Chengalar	1614	500

Table 2.3: Mean (mm) and CV (%) of the area-weighted rainfall over Kerala (mm) during the Southwest Monsoon Season for the period 1971-2018

	June	July	August	September	June-September
Mean (mm)	567	606	422	244	1839
CV (%)	30	31	29	50	20
Highest rainfall (Year)	951 (2013)	972 (1974)	727 (2018)	481 (1983)	2501 (2007)
Lowest rainfall (Year)	185 (1976)	208 (2017)	227 (2016)	67 (2016)	1070 (2017)

Figure 2.6 shows the spatial distribution of mean and CV of season (June to September) rainfall over Kerala. Mean rainfall decreases from north to south and from coast to high lands with > 2000 mm received over the northernmost parts of the state and ≤ 1000mm received over southern parts and along the eastern parts of the highlands. The CV is generally low (high) where mean rainfall is high (low) with year to year variability showing increase going from south to north and coastal to the highlands. Figure 2.7 shows the spatial distribution of trends in the SW monsoon season rainfall over Kerala for the period 1971-2018. It is seen that most areas of northern and central parts of the state show significant negative trends. However, some high land areas of south-eastern parts, as well as some isolated high land areas of northern parts of the Sate, show significant positive trends. The remaining areas show hardly any trends. Figure 2.8 shows the interannual variability of the season rainfall area-averaged over Kerala for the period 1901-2018 along with linear trends for the period 1901-2018, 1901-1970 and 1971-2018. For the total period (1901-2018), the time series shows significant decreasing trend. However, no trend was observed for the initial period 1901-1970 and no significant trend was observed for the season rainfall during the recent period (1971-2018.

Figure 2.9 shows the 31-years moving-average of the southwest monsoon season rainfall over Kerala computed for the period 1901-2018. A clear sine-wave type multi-decal epochal variation is observed with above normal rainfall epoch before 1977 and below normal rainfall epoch thereafter. This indicates that the season rainfall over Kerala is currently passing through a below normal rainfall epoch. A fifth-order polynomial fit (red line) over the time series and extrapolation into the future shows that after about 10-15 years, the Kerala rainfall can once again re-enter into an above normal multidecadal epoch. Figure 2.10 shows the spatial distribution of mean and CV of rainy days over Kerala during the southwest monsoon (June to September) season. A rainy day is defined as the day with daily rain >= 2.5 mm. As in the case of season rainfall, the mean rainy days also show the lowest values (≤ 60days) over the southern parts of the State. The highest values (> 80 days) are seen over northern and central parts. In general, the mean values decreased from north to south and from coast to high lands. The CV of the rainy days over the state various from (≤ 20 days) over northern and central parts to > 40 days over southern parts of the state. The CV of the rainy days in general show low (high) values where mean rainfall days is high (low) with year to year variability showing increase going from south to north and coastal to the highlands.

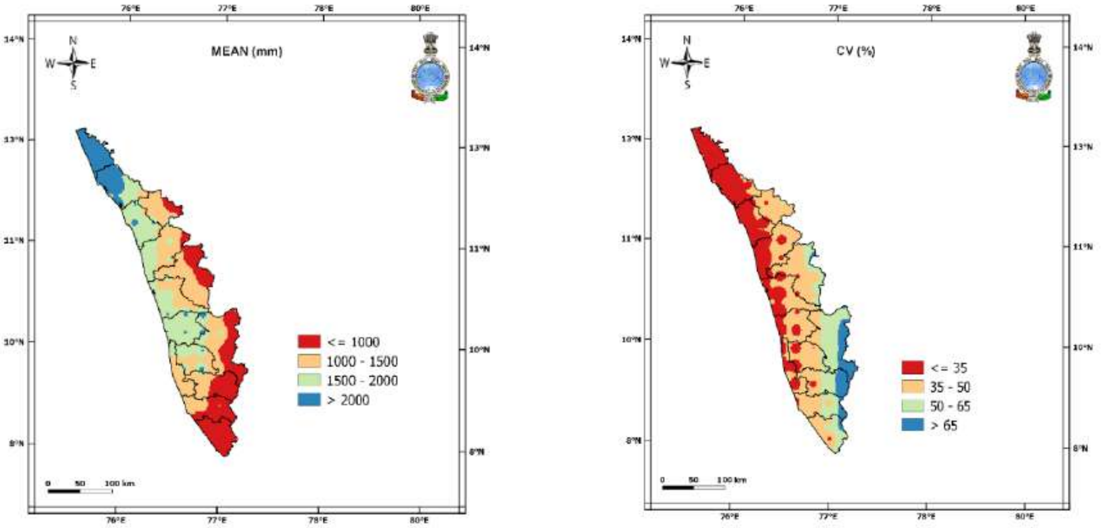


Fig. 2.6: Spatial distributions of the mean (mm) and CV (%) SW monsoon season (JJAS) rainfall (mm) and over Kerala computed based on 1971-2018 data

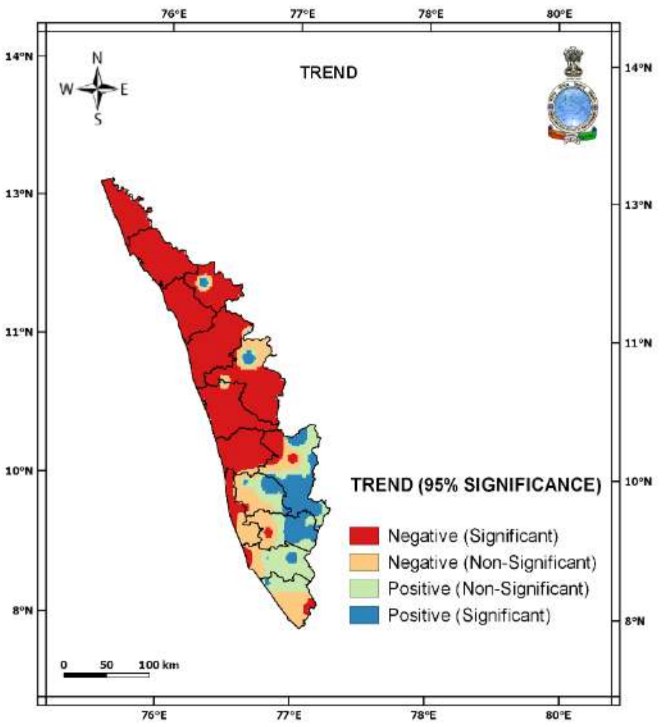


Fig. 2.7: Spatial distributions of linear trends of SW monsoon season (JJAS) rainfall over Kerala

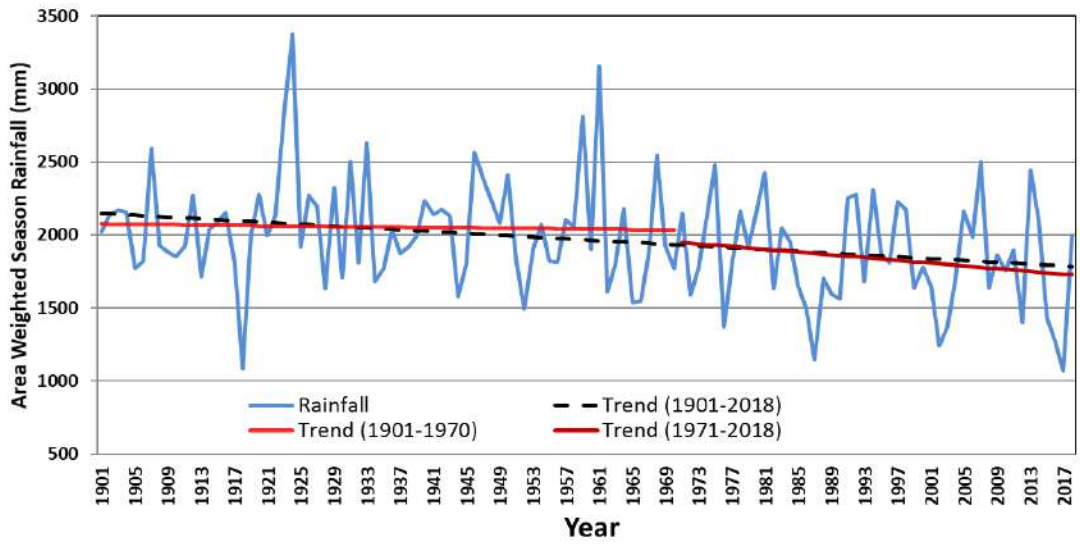


Fig. 2.8: Time-series of area-weighted SW monsoon season rainfall over Kerala state for 1901-2018. The linear trends at three different periods (1901-2018, 1901-1970 & 1971-2018) are also shown.

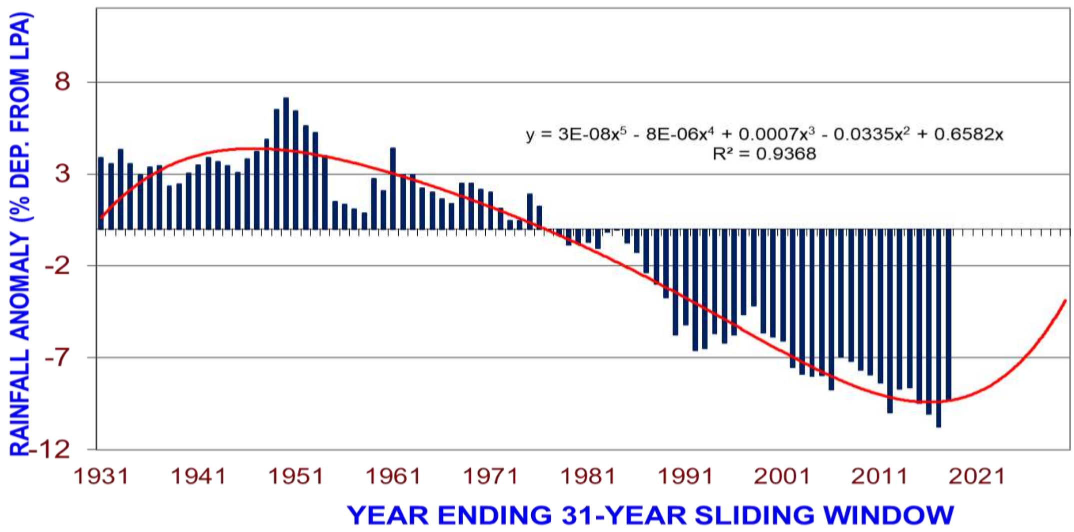


Fig. 2.9: 31-year moving average of seasonal monsoon rainfall (1901-2018)

Figure 2.11 shows the spatial distribution of linear trends in the rainy days over Kerala during the southwest monsoon season for the period 1971-2018. Most areas of the state show hardly any trends with some coastal areas in the southern half and some isolated areas of high lands and interior parts of the state exhibiting significant negative trends. Figure 2.12 shows the interannual variability of the rainy days over Kerala during the southwest monsoon season for the period 1901-2018 along with linear trends for the period 1901-2018, 1901-1970 & 1971-2018. It is seen that during the period, the rainy days over the state various from 83 to 120 days per season with highest during 1947 (120 days) and lowest during 1911 (83 days). For the total period (1901-2018), the time series shows significant decreasing trend. However, no significant trend was observed for the initial period 1901-1970 and the recent period (1971-2018).

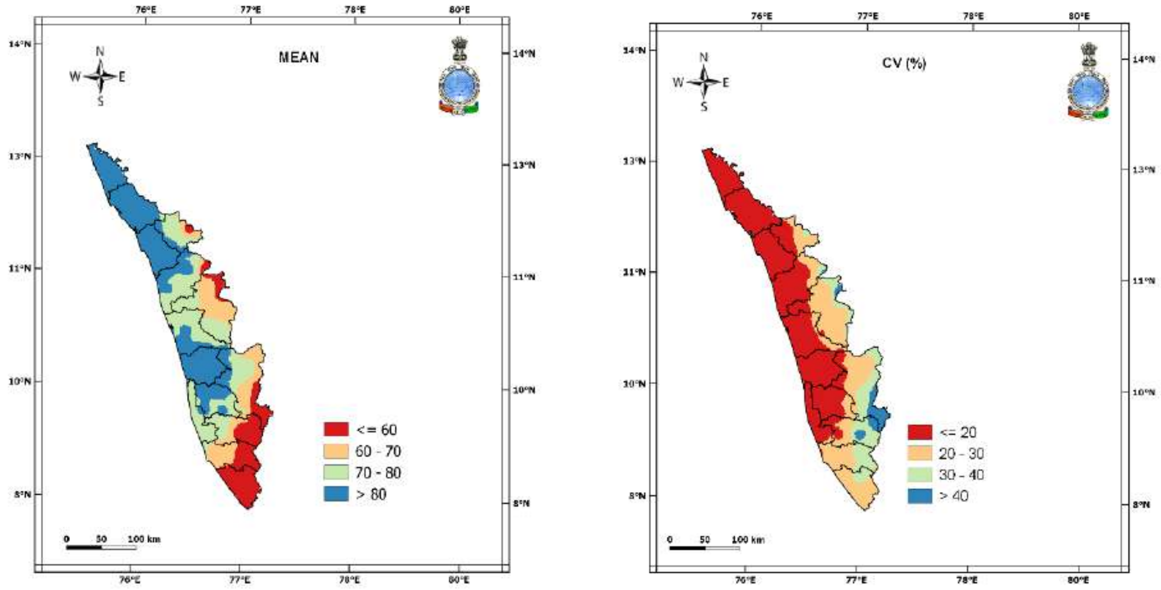


Fig. 2.10: Spatial distributions of the mean (days) and CV (%) of rainy days over Kerala during the SW monsoon season (JJAS) computed based on 1971-2018 data. Daily rain >= 2.5 mm is considered a rainy day

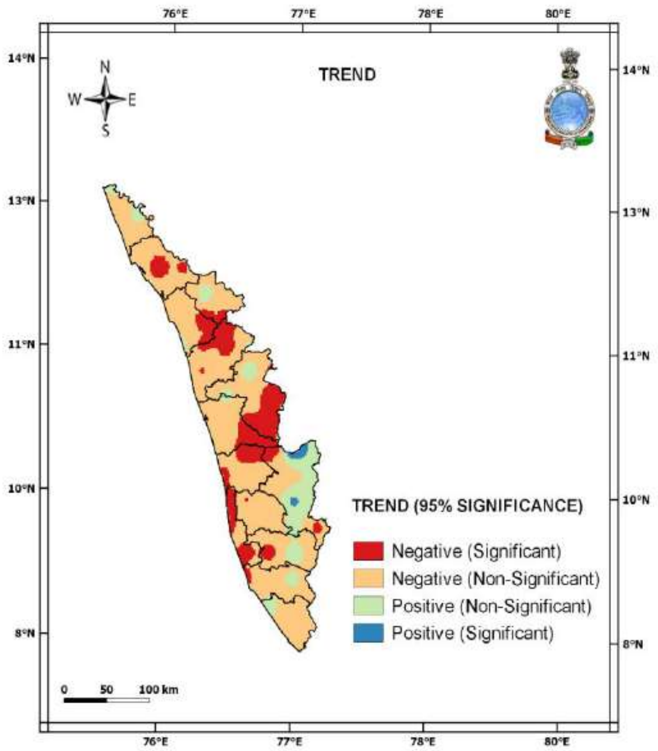


Fig. 2.11: Spatial distributions of linear trends of rainy days over Kerala during the SW monsoon season (JJAS) rainfall. Daily rain >= 2.5 mm is considered a rainy day.

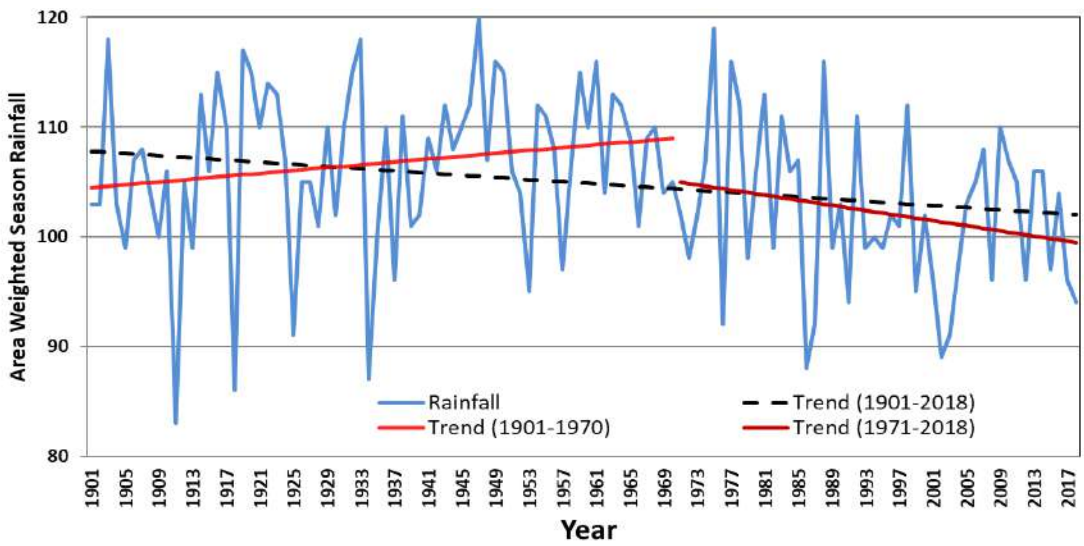


Fig. 2.12: Time-series of rainy days during the monsoon season over Kerala state for 1901-2018. The linear trends at three different periods (1901-2018, 1901-1970 & 1971-2018) are also shown.

2.6. Soil

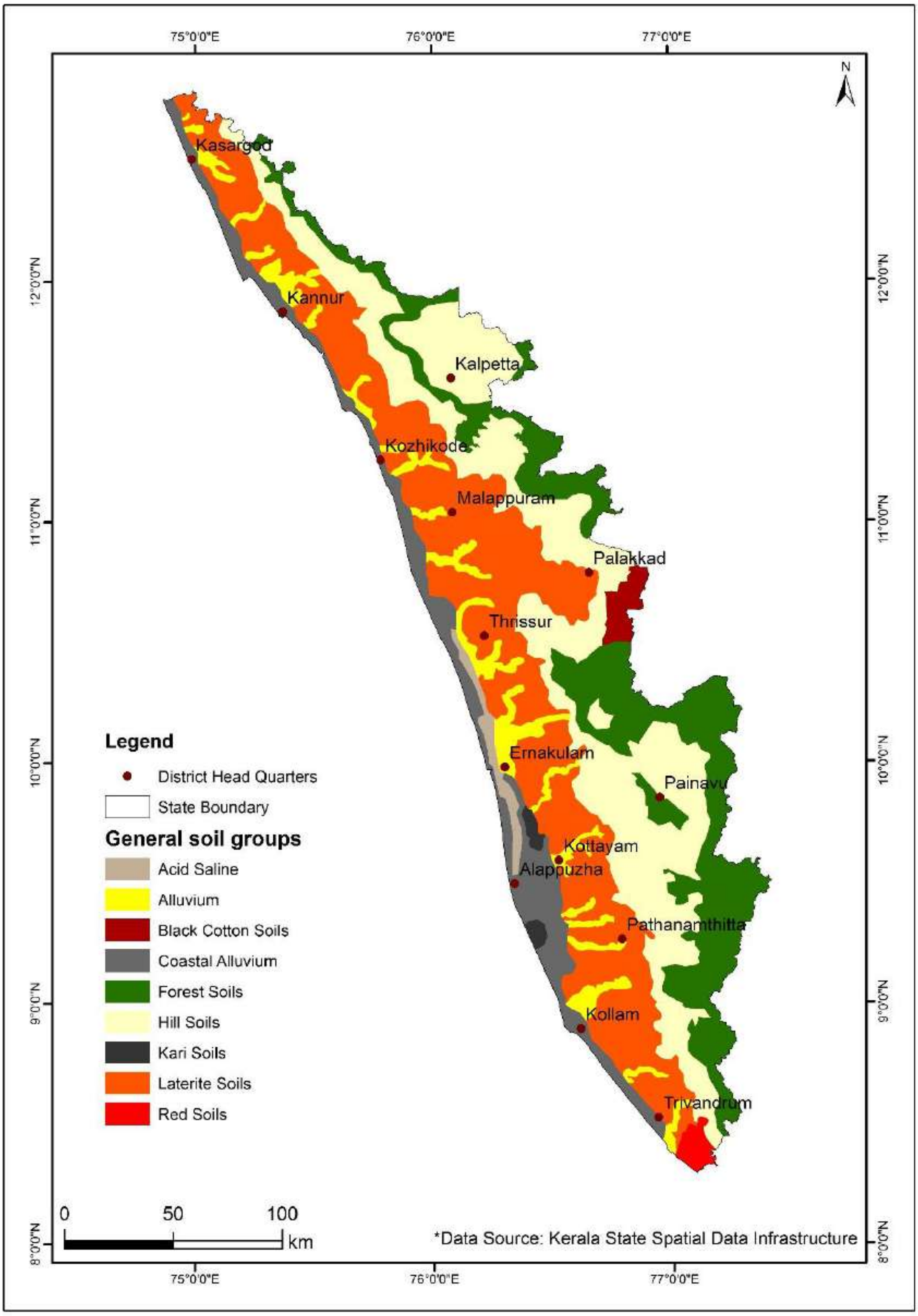
Kerala state has a variety of soil types. The weathering products of crystalline acidic rocks, sedimentary formations and recent and sub recent sediments are the parent materials of most of the soils in the State (Soil Survey Organization, 2007). The dominant soil-forming process in the State is lateritisation which is an intense rock weathering process. Laterite and lateritic soils cover around 60 per cent of the total geographical area of the State. The topo-lithosequence of Kerala, local variations in the rainfall, temperature, vegetation, topography, relief, hydrological conditions, alternate wet and dry conditions particularly from the western coast to high ranges in the east and swift-flowing rivers have led to the development of different types of soil in the State. In general, the soils of Kerala are acidic, kaolinitic and gravelly with low cation exchange capacity (CEC), low water holding capacity and high phosphate fixing capacity (Soil Survey Organization, 2007). The soils of Kerala are broadly grouped into (1) coastal alluvium, (2) mixed alluvium, (3) acid saline, (4) Kari, (5) laterite, (6) red, (7) hill, (8) black cotton and (9) forest soils (Fig. 2.13). The details of the different types of soil of the State are given in the following paragraphs.

The coastal alluvium soils are of marine origin. These soils are identified along the coastal plains and basin lands as a narrow strip. These are recent to sub recent alluvium over crystalline rocks and tertiary sediments. They include beach sand, marshes, paleo sand ridges and very gently to gently sloping sandy plains. These areas generally have a high-water table and, in some areas, it reaches above the surface during the rainy season. The soils of the coastal plains are very deep with a sandy texture. The texture generally ranges from sand to loamy sand with greyish-brown to reddish-brown and yellowish red colour. Sand content ranges from 80% and clay up to 15%. The water holding capacity of this soil is poor due to the predominance of sand. Coconut is the major crop in the area. The other trees grown in this area are cashew and other fruit trees.

The mixed alluvium soils are developed from fluvial sediments of marine, lacustrine and riverine sediments or its combinations. They occur below 20 m MSL in the lowland plains, basins, valleys and along the banks of major rivers. These are mainly noticed close to coastal alluvium, Kuttanad and adjacent area and Kole lands of Thrissur district. The soils are frequently flooded and submerged. Riverine alluvium is seen along the flood plains of rivers and depressions of lowlands. Alluvio-colluvial sediments are seen along the valleys of the midland region. A major area under this alluvium lies below 20m MSL. The soils of depressions and broad valleys are subject to occasional flooding and stagnation. The groundwater table of these soils is high and it reaches above the surface during the rainy season. A wide variation in texture is noticed and sandy clay loam to clay is the predominant texture. Light grey to very dark brown is the common colour of the soil. Paddy and seasonal crops like banana, tapioca, and vegetables are grown in this soil.

The Kari soils are developed on mixed alluvium of marine, riverine and lacustrine. They occur in isolated patches along the coastal plains adjoining the backwaters. The major occurrence is identified at Purakkad, Vaikom, Kaduthuruthy, and Thuravur. It covers an approximate area of 12,000 ha. The area is generally subjected to frequent flooding and water stagnation. These soils have a relatively high proportion of organic residues and severe soil and environmental limitations which pose a threat to crop production. The soil is heavy in texture, poorly aerated and ill drained. The texture of the soil ranges from sandy clay to clay with an intermediate texture of silty clay loam and clay loam. The colour of the soil ranges from dark grey to black. The presence of fossil wood and partially decomposed organic residues below a depth of 50 to 100 cm is a characteristic feature of the soil. Jarosite mottles and nodules of iron sulphide are also noticed. The soil has high acidity, salinity, presence of toxic materials. The only crop grown in this soil is paddy.

The acid saline soils are present throughout the coastal area in patches with a very little extent. The major area of this soil is in the coastal tract of Ernakulam, Thrissur and Kannur districts. The area under these soils comprises low-lying marshes, waterlogged and ill-drained areas near the rivers and streams, which are subject to tidal waves. Sea and backwater tides make these soils saline. During monsoon season, when rainwater and fresh water from rivers enter the fields, salinity is partially washed off. The area under these soils occurs mostly on plains at or below sea level. A wide variation in texture from sandy loam to clay is noticed with dark grey to black colour. Paddy is the only crop that can be cultivated.



Environmental Profile: Kerala

Fig. 2.13: Spatial distribution of the soil types of Kerala

The red soils are red “Teri” soils of sub recent origin resting over tertiary sedimentary formations/ laterites. They are localized in occurrence and are found mostly in the southern parts of Thiruvananthapuram district and in pockets in catenary sequence along the foot slopes of laterite hills and mounds. These soils are identified in undulating plains of lowland with a general slope of 3 to 10%. These aeolian and colluvial deposits are mostly very deep and homogeneous in nature. The texture of the soil generally ranges from sandy clay loam to clay loam with red to dark red colour. Gravels are rarely noticed in these soils. Crops such as coconut, arecanut, banana, yams, pineapple, vegetables, fruit trees, etc., can be grown under proper management.

The laterite soils mainly occur in the Midlands and part of lowlands at an elevation of 10 to 100m above MSL as a strip between the coastal belt and hilly mid upland. The area comprises of mounds and low hills with gentle to steep slopes. There are mainly three types of laterite soils noticed in the state; (1) laterite soil with low gravel content of less than 30% with a reasonable depth between 60 and 150 cm. This category of soil is mainly noticed in the foot slopes of laterite mounds and laterite hills, (2) laterite soils with gravel content of 30% to 80% with depths varying between 60 and 150 cm. These soils are noticed inside slopes and summits of laterite mounds and hills, (3) shallow soils of depth less than 50 cm with indurated laterite and laterite outcrops. These are noticed in the northern districts of Malappuram, Kozhikode, Kannur, and Kasargod. Laterite and laterite soil are the weathering products of rock in which several courses of weathering and mineral transformations take place. This involves the removal of bases and substantial loss of combined silica of primary minerals, in laterite and laterite soils, over acidic rocks, induration and zonation are more pronounced. This induration is greater if the iron content is higher. Laterite soils are generally suitable for the dry land crops because of the high percentage of gravel content and the reduced soil depths. It is mainly cultivated with coconut, arecanut, banana, tapioca, vegetables, yams, pepper, pineapple, fruit trees, etc.

The hill soils are developed from crystalline rocks of archaean age. The crystalline rocks comprise charnockites, khondalite suite granites, gneissic granites, and basic dykes. The hill soils mostly occur above an elevation of 80 m MSL. The area is hilly and has highly dissected denudational hills, elongated ridges, rocky cliffs, and narrow valleys. The general slope range is above 10%. The texture of these soils generally ranges from loam to clay loam with an average gravel content of 10 to 50%. In addition, stones and boulders are noticed in the subsoil. These soils have reddish-brown to yellowish-red/strong brown colour. An increase in clay content is noticed down the profile. The depth of the soil varies considerably from 60 to 200 cm depending on the tie of the land, erodibility of soil and past erosion. These soils are mostly friable and subject to heavy soil erosion. All dryland crops like rubber, coconut, arecanut and fruit trees based on the topography are grown in this soil. Crops such as banana, pepper, pineapple, vegetables can be grown in foot slopes.

The black cotton soils are identified in alluvial plains, terraces and undulating plains of Chittur taluk in Palakkad district in patches. The elevation of the area ranges from 100 to 300 m above

MSL with a gentle to moderate slope. These soils are developed on khondalite suite of rocks traversed by lenticular bands of crystalline limestone and cafe-granulites. These soils are very deep, black and calcareous. The texture of the soil ranges from clay loam to clay. They possess high shrink-swell capacity and hence exhibit the characteristic cracking during dry periods. Coconut, sugarcane, cotton, chilly, pulses and vegetables are grown in this soil.

The forest soils are developed from crystalline rocks of archaean age under forest cover. They generally occur along the eastern part of the State, above an elevation of 300m above MSL. The area is hilly and mountainous with steep slopes, escarpments, elongated rocky summits, and narrow 'V' shaped valleys. The depth of the soil depends on erosion and vegetative cover. The soils are generally immature due to the slow weathering process. Rock outcrops and stones are noticed on the surface and gneissic boulders under different stages of weathering are noticed in the subsoil. The texture of the soil ranges from sandy clay loam to clay with reddish-brown to very dark brown colour. Forest trees, shrubs, and grasses are generally grown in this soil.

2.7. Land use/ land cover

The environmental factors, such as climate, topography, edaphic and biotic factors are responsible for determining the nature and distribution of vegetation patterns of a region. The State, though small in size, has varying topographic and climatic conditions leading to a wide spectrum of Kerala has varying land use/ land cover and cropping pattern. However, the majority of the land area (~60%) of the State is utilized for agricultural purposes (Fig. 2.14) and continues to be the most important sector of the economy of the State. The areal extent of different land use/ land cover types of the State is given in Table 2.4.

Table 2.4: Areal extent of land use/ land cover types of Kerala

Sl. No.	Land use/ land cover	Areal Coverage (km^2)	Per cent Coverage
1.	Agricultural Land	23108	59.5
2.	Beach	9	0.0
3.	Builtup Land	1518	3.9
4.	Forest	10561	27.2
5.	Waste Land	2331	6.0
6.	Waterbody	1257	3.2
7.	Wetland	79	0.2
Total		**38,863**	**100**

*Source: Kerala State Spatial Data Infrastructure

The highlands are dominantly covered by different types of forests, viz., tropical wet evergreen and semi-evergreen forests, tropical moist deciduous forest, tropical dry deciduous forest,

forest plantations, and montane subtropical and temperate grasslands. The built-up lands are mostly clustered in the midlands and the lowlands physiographic regions.

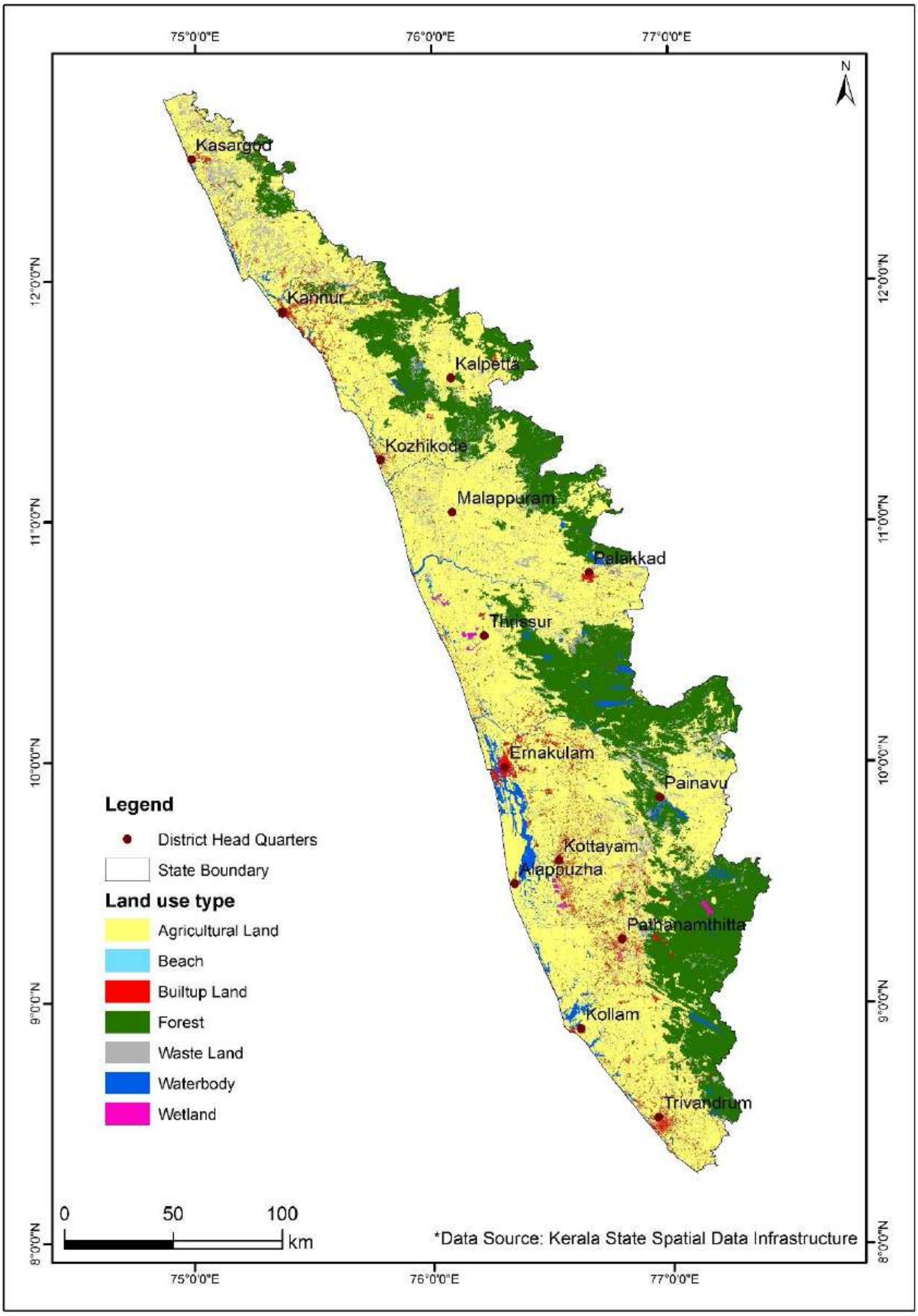


Fig. 2.14: Land use/ land cover types of Kerala (refer Appendix 2.2 for detailed classification)

2.8. Population

Based on the Census 2011 data, the total population of Kerala was 3,34,06,061 people, which forms roughly 3% of the population of India (Census of India, 2011). The decadal growth rate of Kerala's population was 4.9%, the lowest among the Indian States. Among the districts of the State, Malappuram has the highest growth rate (13.4%), and Pathanamthitta has the lowest growth rate (-3.0%) (Kerala State Planning Board, 2019). The most populated district in Kerala is Malappuram (41,10,956), whereas the least populated district in Wayanad (8,16,558). It may be noted that the density of the population increased from 165 per km^2 in 1901 to 859 per km^2 in 2011 (Table 2.5). Although the mid-decades of 20^{th} century relatively higher population growth, the recent decades showed significantly lower growth rate. The spatial variability of the population across the State is shown in Fig. 2.15.

Table 2.5: Decadal variability of the population of Kerala

Year	**Population (in lakh)**			**Decadal percentage of increase in population**			**Population density per km^2**
	Males	*Females*	*Persons*	*Males*	*Females*	*Persons*	
1901	31.91	32.05	63.96	-	-	-	165
1911	35.60	35.88	71.48	11.6	12.0	11.8	184
1921	38.79	39.23	78.02	9.0	9.3	9.2	201
1931	47.03	48.04	95.07	21.3	22.5	21.9	245
1941	54.44	55.88	110.32	15.8	16.3	16.0	284
1951	66.82	68.67	135.49	22.7	22.9	22.8	349
1961	83.62	85.42	169.04	25.2	24.4	24.8	435
1971	105.38	107.59	213.47	26.6	26.0	26.3	549
1981	125.28	129.26	254.54	18.3	20.2	19.2	655
1991	142.89	148.09	290.98	14.0	14.6	14.3	749
2001	154.69	163.73	318.41	8.25	10.5	9.4	819
2011	160.21	173.66	333.87	3.6	6.1	4.8	859

Source: http://keralaeconomy.com/admin/pdfs/Population%20of%20Kerala%20Tables.pdf

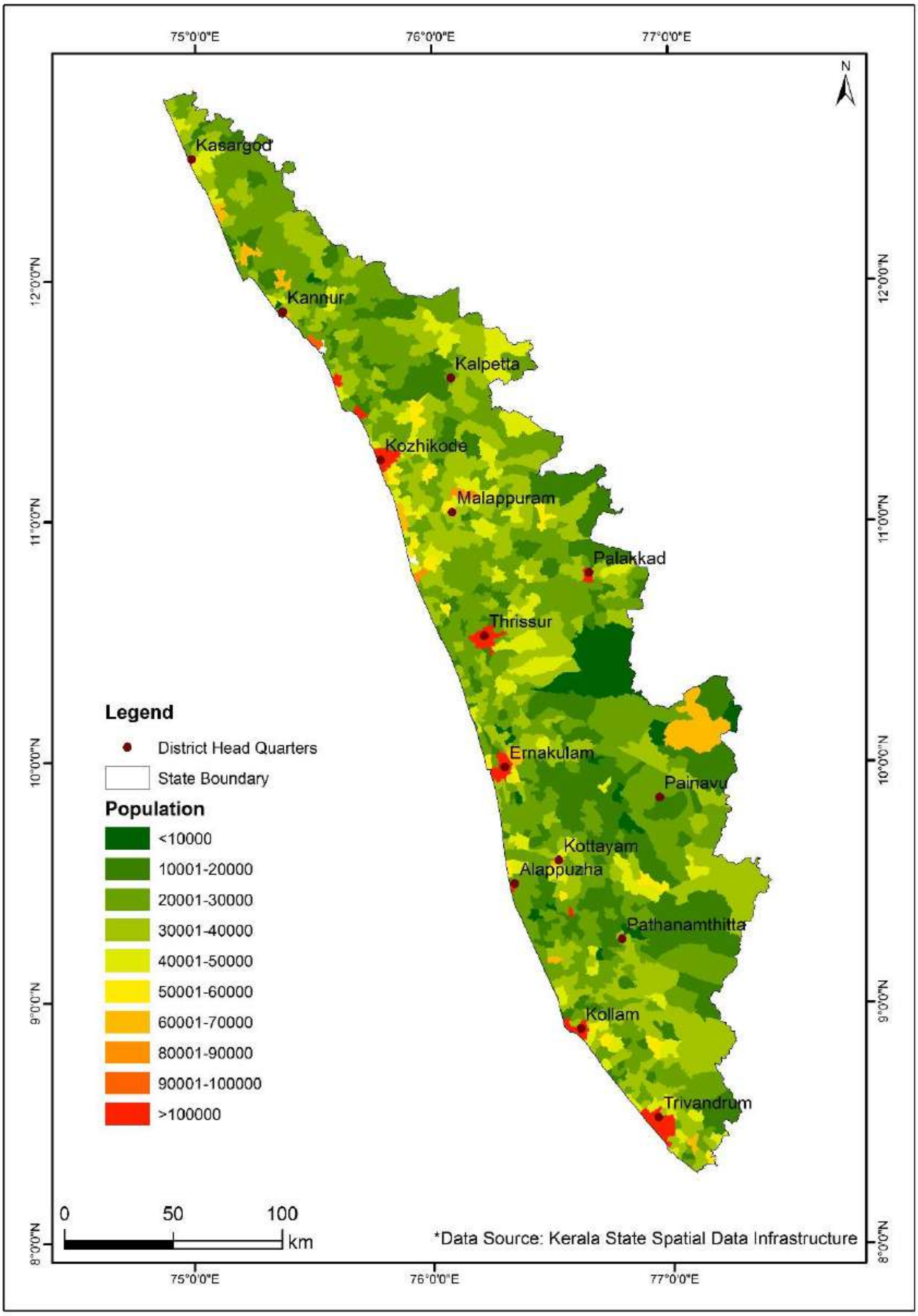


Fig. 2.15: Spatial distribution of population across Kerala

3. Chapter 3
Extreme Rainfall Events (EREs)

3.1. Definition of ERE

As per the present practice by IMD (Forecasting Circular No. 5/2015/3.7), the 24-hour accumulated rainfall has been classified into different categories based on its intensity. The classification is given in Table 3.1. The classification was obtained by using 30 years of daily rainfall from the meteorological stations across India.

Table 3.1: Classification rainfall intensity

Sl. No.	Terminology	Rainfall range in mm (24-h)	Rainfall range in cm (24-h)	Percentile
1.	Very light rainfall	Trace - 2.4		
2.	Light rainfall	2.5 - 15.5	Up to 1	Up to 65
3.	Moderate rainfall	15.6 - 64.4	2 - 6	65 - 95
4.	Heavy rainfall	64.5 - 115.5	7 - 11	95 - 99
5.	Very heavy rainfall	115.6 - 204.4	12 - 20	99.0 - 99.9
6.	Extremely heavy rainfall	≥ 204.5	≥ 21	> 99.9
7.	Exceptionally heavy rainfall	When the amount is a value near about the highest recorded rainfall at or near the station for the month or season. However, this term will be used only when the actual rainfall amount exceeds 12 cm.		

In this section, for examining the EREs in Kerala, IMD daily gridded rainfall data set of high spatial resolution (0.25° × 0.25°) covering a period of 119 years (1901-2019) over India (Pai et al., 2014) have been used. (Pai et al., 2014) used daily rainfall data from all the rain gauge stations over the country available in the archive of National Data Centre, India Meteorological Department (IMD), Pune. The daily rainfall records from 6,955 rain gauge stations in India with varying availability periods were used, which is the highest number of stations used by any studies so far for preparing the grid point rainfall data over the country. Though the spatial density of the station points was not uniform throughout the country, there was a good number of stations representing Kerala.

Figure 3.1 shows the percentile gridded rainfall value against different percentile (from 50th to 100th) obtained using daily gridded rainfall data for the southwest monsoon season (JJAS) for the period 1901-2019. The Figure also depicts a similar plot obtained using daily rainfall data from all the available stations for the same period. It is clearly seen that the rainfall value corresponding to the 99th percentile is around 120 mm (12 cm). In this section, therefore, 24-hr accumulated gridded rainfall ≥ 120 cm (rainfall of intensity equal to or more than the very heavy rainfall category) was taken as an Extreme rainfall Event (ERE).

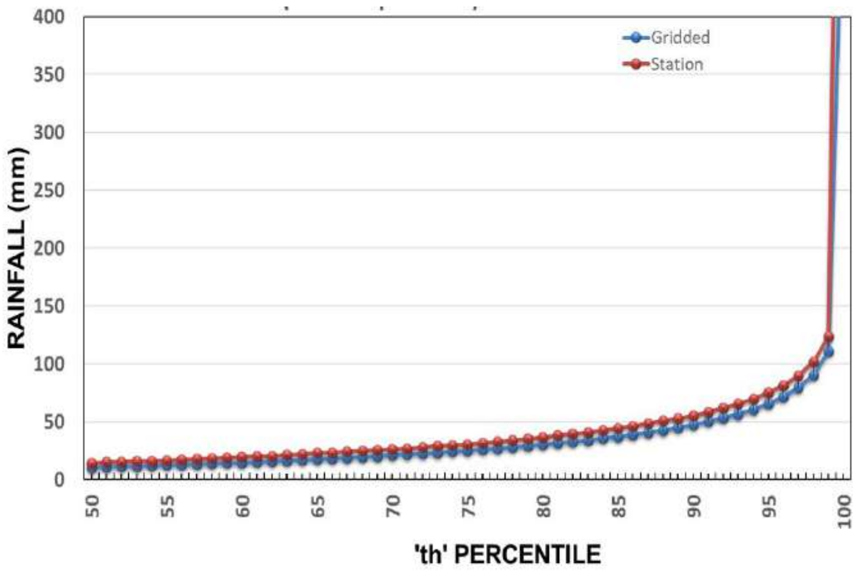


Fig. 3.1: Line diagram showing the daily rainfall (Y-axis) distribution corresponding to the nth percentile (50th to 100th) of the gridded daily rainfall data over Kerala during the southwest monsoon season (June to September) for the period 1901-2019. A similar line plot based on the daily rainfall data of all the available rainfall stations in Kerala.

3.2. Review on historical EREs in Kerala

Figure 3.2 shows the spatial distribution of mean and CV of EREs over Kerala during the southwest monsoon season (June to September). It is seen that the occurrence of the EREs is highest over northern parts and decreases as moving from north to south. The year to year variability of occurrence of EREs is high over most parts of the state. The CV is generally low (high) where mean ERs are high (low) with year to year variability showing increase going from south to north and coastal to high lands.

Figure 3.3 shows the interannual variability of grid point EREs that occurred in Kerala during the monsoon season for the period 1901-2018 along with linear trends for the period 1901-2018, 1901-1970 & 1971-2018. It can be seen that 1924 (number of EREs = 59) experienced the highest number of EREs, followed by 1923 (20 EREs), 1929 & 1911 (17 EREs each), 2018 & 1925 (15 EREs each) and so on. It is interesting to see that 5 of the 10 years that experienced the highest number of EREs are during the 1920s. For the total period (1901-2018), the time series shows significant decreasing trend. However, no trend was observed for the initial period 1901-1970 as well as the recent period (1971-2018).

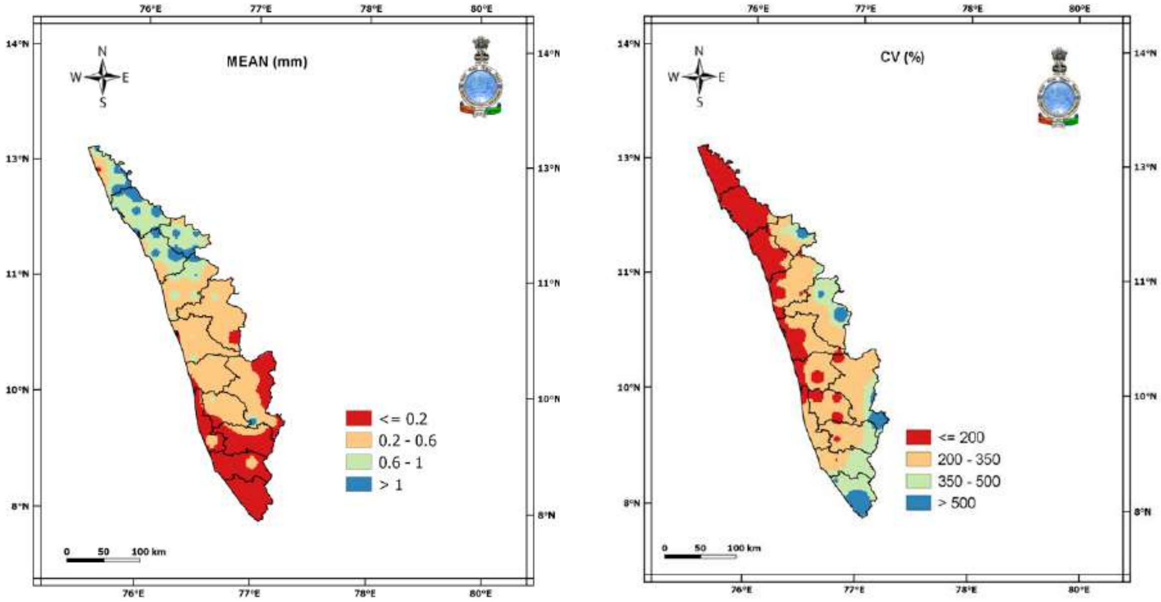


Fig. 3.2: Spatial distributions of the mean (days) and CV (%) of ERE days over Kerala during the SW monsoon season (JJAS) computed based on 1971-2018 data. Daily rainfall >= 2.5 mm is considered as ERE event

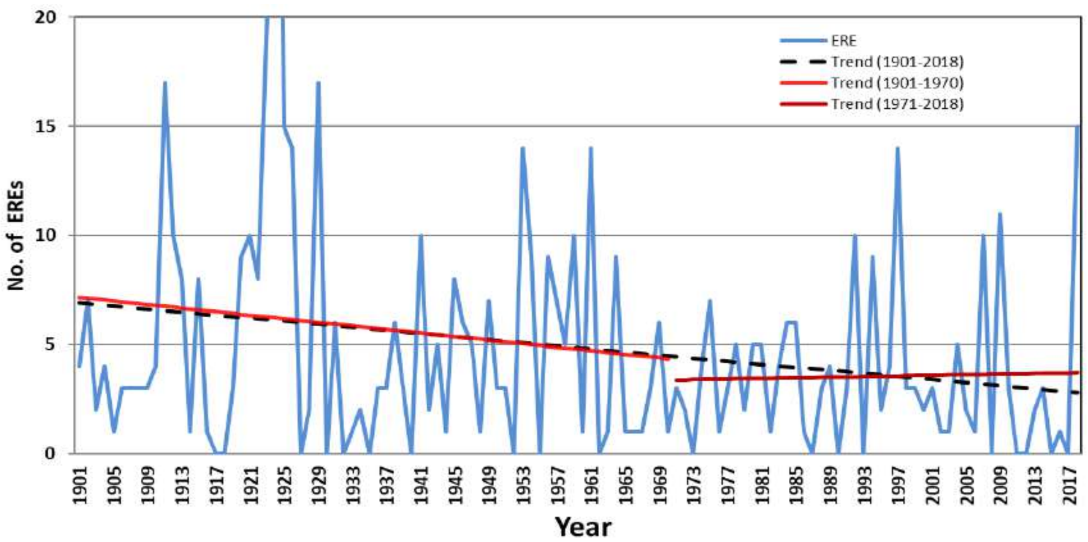


Fig. 3.3: Time-series of ERE events during the monsoon season over Kerala state for the period 1901-2018. Daily rain >= 120 mm is considered as ERE

Daily rainfall variation for the July-August period during the first two years (1924 & 1923) with the highest number of EREs and the recent two years (2018 & 2019) given in Fig. 3.4 (Appendix 3.1), which helps in identifying the exact period of increased rainfall activity over the state during each of these years and also which are the most affected districts.

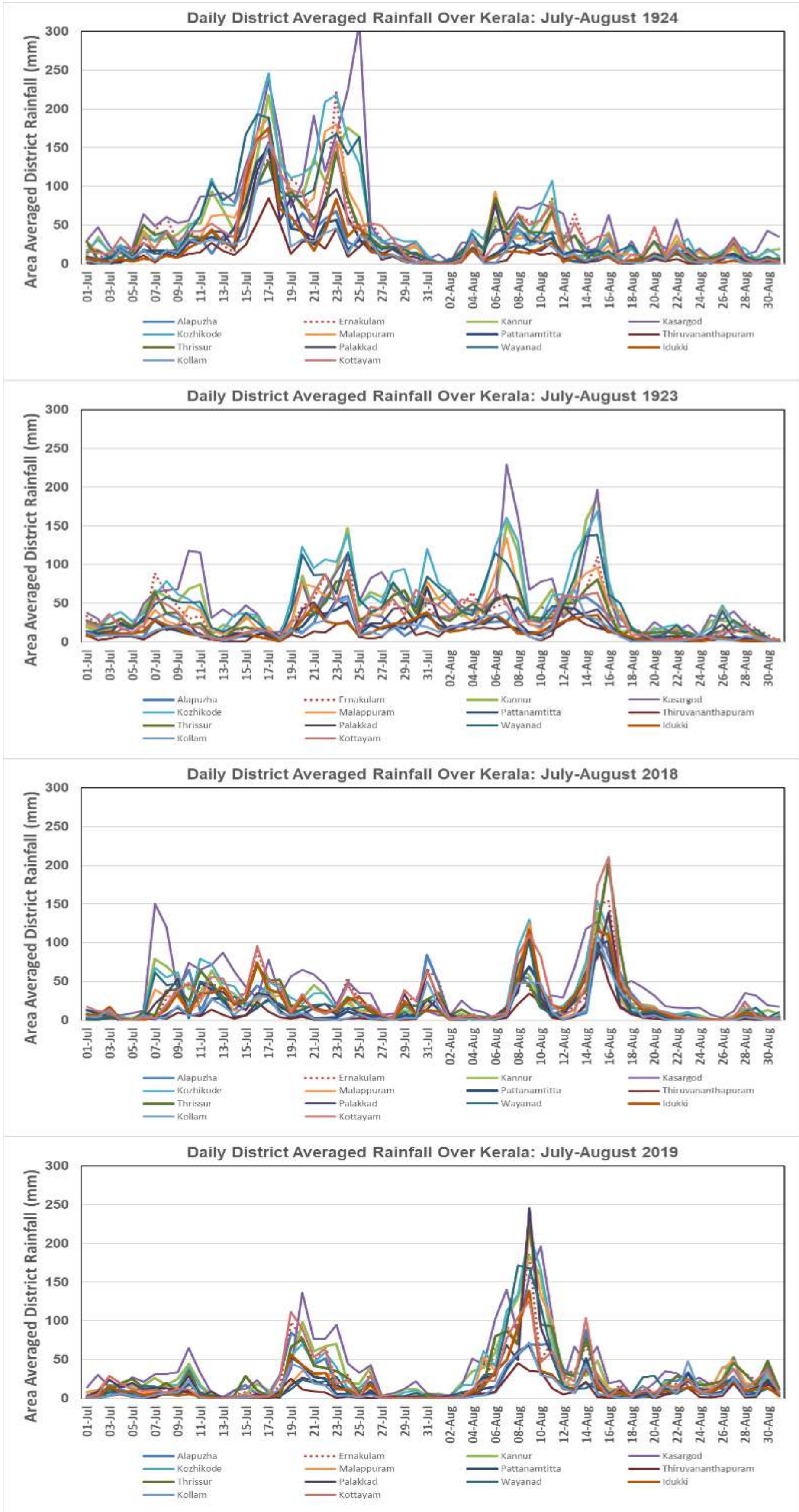


Fig. 3.4: Daily variation of the district averaged rainfall of all the 14 districts of Kerala during the middle of the monsoon season (July and August) for the year 1924, 1923, 2018 & 2019.

3.3. Trends in EREs (historic and climate change scenarios)

Figures 3.5 and 3.6 depict the interannual variation of EREs in Kerala during the period 1901-2018 depicts linear trends at three different periods 1901-2018, 1901-1970 & 1971-2018. For the first two periods, no significant trends are visible. No (or slightly increasing) trend is visible for the recent period (1971-2018). Trends calculated in the number of grid wise EREs (over Kerala during both the southwest monsoon & northeast monsoon seasons for two different periods (1901-2018 and 1971-2018) using gridded rainfall data. The same is shown in Figs. 3.5 and 3.6.

During the southwest monsoon season, in general, negative trends are observed over the northern half and along the coastal areas with only some northern areas showing significant (at 95% level) trends. Hardly any trends are observed over the remaining southern areas of the State. In recent years, positive trends are shows over most parts of the southern half and some interior areas of central parts of the state with isolated areas showing significant trends. Elsewhere, no significant trends are observed except over northernmost areas of the state where significant trends are observed.

In the case of the northeast monsoon season, most parts of the state show no significant trends during both the periods (1901-2018 and 1971-2018).

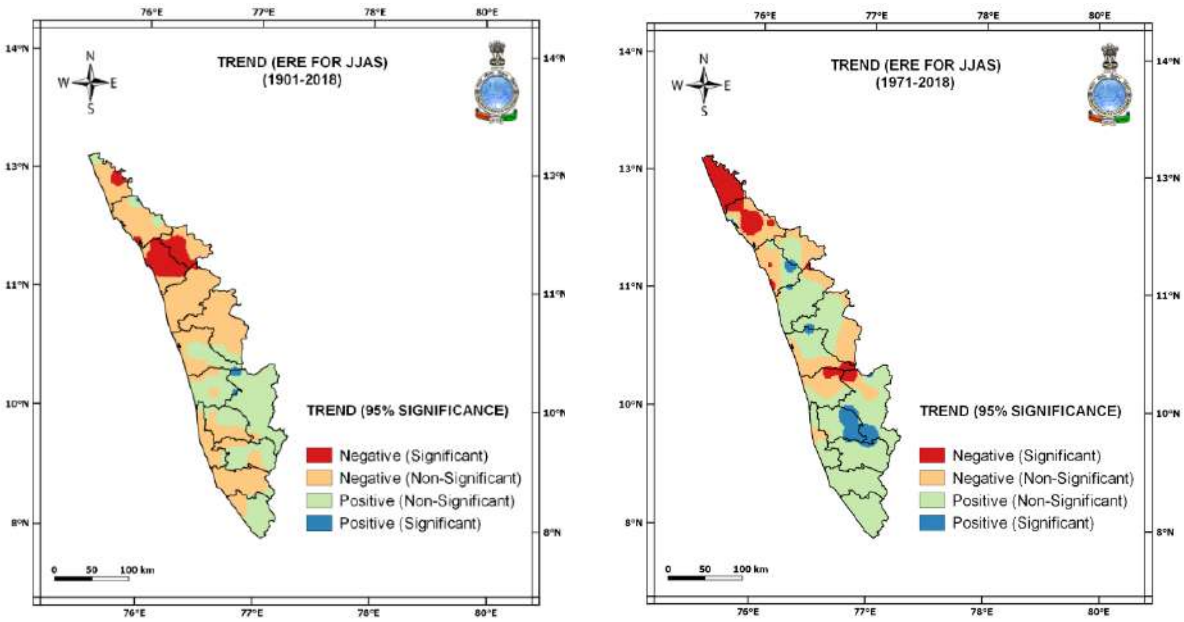


Fig. 3.5: Trend for EREs during the southwest monsoon in Kerala

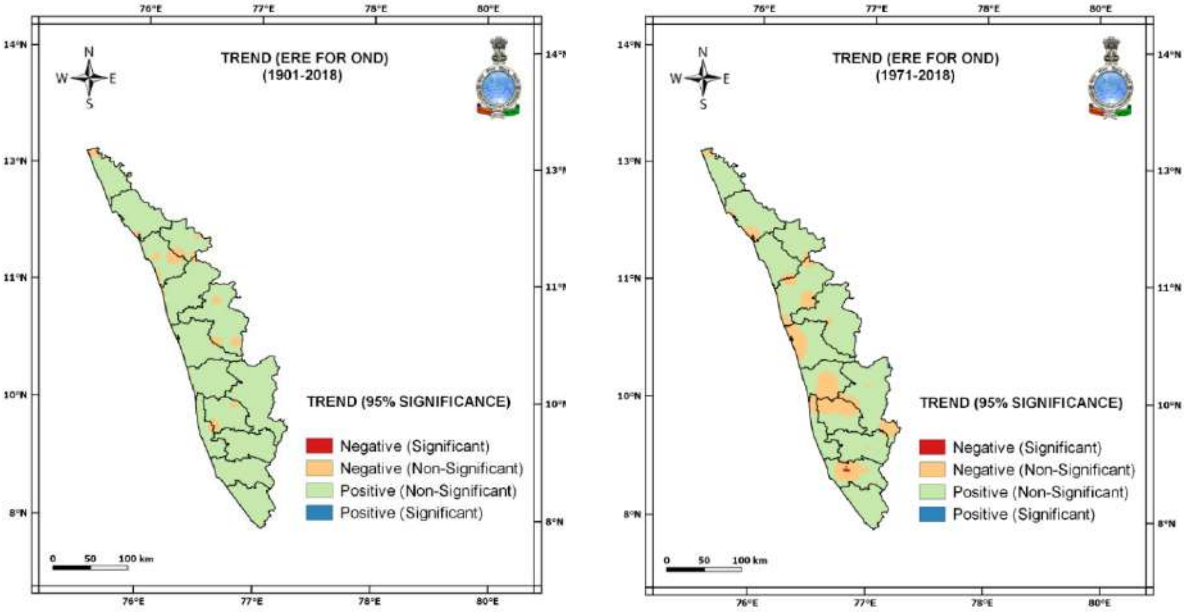


Fig. 3.6: Trend for EREs during northeast monsoon in Kerala

3.4. Driving forces/causative factors of the EREs

Rainfall is caused by the fall of liquid water formed by the condensation of water vapour held by rising warm and moist air. When the amount of moisture held by the air mass is disproportionately large, it results in EREs. The rising of the air can be caused by different lifting mechanisms; (i) surface heating and free convection. For example, during the daytime, the sun heats the earth's surface that in turn heats the air in contact with it. However, Sun does not heat the surface of the Earth evenly. Some surfaces better absorb radiation from the sun and become warmer than surrounding surfaces, e.g., a blacktop surface will typically become warmer than a grass-covered surface or a rocky surface will typically be warmer than wet soil. (ii) dynamic lifting caused by the surface convergence and/or upper-level divergence due to changes in the atmospheric conditions. The changes in the atmospheric conditions have resulted from the movement of weather systems of different spatial and temporal scales like ITCZ, monsoon, low-pressure systems (troughs, low-pressure area, depression, cyclones, etc.) (iii) orographic lifting when the air moves against the mountain slope. The moist air gets cool and saturated as it rises up and over the mountain resulting in cloud formation. Solar heating of the mountain slopes by the Sun also causes air to rise upward through the process of surface heating and free convection described above. Whereas the air rises on the windward side of a mountain resulting in clouds and precipitation, sinking of the air on the leeward side of a mountain causes clear skies and warm, dry conditions

Global warming is another important driving force/causative factor of the EREs. Water vapour in the atmosphere increases with an increase in the atmospheric temperatures. A warmer atmosphere can hold more moisture. According to the Clausius-Clapeyron equation, the capacity of air to hold moisture increases by 7% for each degree of warming. The increase in extreme rainfall is due to a combination of this increase in moisture as well as changes in atmospheric circulation due to global warming. Small localized warmings such as that due to urban centres or changes to land use and land cover can also lead to EREs. Sometimes, these large scale and local scale factors interact and provide feedback to each other, which create favourable conditions for ERE's.

3.5. EREs and monsoon circulation

The EREs along the west coast of India including Kerala during the monsoon season depends on the following components of the monsoon, changes in the location and intensity of which have an important role in varying the lifting of the moist air across the region. When they are stronger than normal and are in a favourable location, it helps in enhanced dynamical lifting of the air and results in EREs.

- Semi-permanent systems such as Seasonal Heat Low (HL), Monsoon Trough (MT), Tibetan Anticyclone (TA), Tropical Easterly Jet (TEJ) and Low-Level Jet (LLJ) or Somali jet, which have a profound impact on the overall strength of the monsoon circulation
- Transient synoptic systems such as troughs, upper air cyclonic circulations, lows, depressions, cyclones, etc. over the Indian monsoon region and west pacific (their intensity and track) that cause an increase in moisture convergence over the Western Ghats.
- Monsoon Intra-Seasonal Oscillation (MISO) that causes northward propagation of monsoon trough. MISO can occur associated with or without the Madden Julian Oscillation (MJO), which is a travelling convective pattern that propagates eastward and is the largest element of the intra-seasonal (30- to 90-day) variability in the tropical atmosphere.

Regional instabilities that lead to EREs can occur and intensify under various combinations of the above factors. When that occurs over a larger region associated with large scale phenomena like synoptic-scale and intra-seasonal propagating oscillations, it can result in large scale EREs for extended periods. Depending on the spatio-temporal scales of the oscillations, EREs can extend over a larger time-period and a larger domain as these oscillations bring in moisture, instability and positive vorticity over a larger region for an extended period (Subudhi and Landu, 2019).

Analysis of EREs during the monsoon season (Pai et al., 2015) revealed increased disaster potential for instant flooding over Central India since 1956 due to significant increasing trends in the frequency (areal coverage) and intensity of the EREs over these regions since the 1950s. On the other hand, the disaster potential over Northeast India and West Coast has increased in terms of the increasing trends in the intensity of the rainfall events. The increasing trends in the EREs particularly over central India were found to be primarily associated with the increasing trend in the monsoon lows during recent decades. The increased instability in the atmosphere due to increased moisture content associated with the global warming trend might have also helped.

3.6. EREs and teleconnections

El Niño occurs when warm water builds up along the equator in the eastern Pacific. The warm ocean surface warms the atmosphere, which allows moisture-rich air to rise and develop into rainstorms. In fact, the disruption in the atmosphere impacts rainfall throughout the world including India. Sea-surface temperatures in the western Indian Ocean becomes alternately warmer and then colder than the eastern part of the ocean. El Nino weakens the flow of moisture-bearing winds from the oceans towards India negatively impacting the summer monsoon, which accounts for over 70-80% of annual rainfall over most parts of the country (Box 3.1).

La Niña is opposite to El Niño and is the build-up of cool waters in the equatorial eastern Pacific, such as occurred in 1988 and, to a slightly lesser degree, in 1998. La Niña’s impacts are opposite those of El Niño. The atmosphere cools in response to the cold ocean surface, and less water evaporates. The cooler, dry air is dense. It doesn’t rise or form storms. In general, the Indian SW monsoon is weaker (stronger) than normal during the El Niño (La Niña) years. Therefore, such large-scale teleconnections could increase ERE’s as well. However, there is no one to one association between EL Nino and all India summer monsoon rainfall.

The Indian Ocean Dipole (IOD) also known as the Indian Niño is a coupled ocean and atmosphere phenomenon characterized by irregular oscillation of sea-surface temperatures in which the western Indian Ocean becomes alternately warmer and then colder than the eastern part of the ocean. During the positive (negative) IOD phase, water over the tropical eastern

Indian Ocean is cooler (warmer) than normal and that over the western Indian Ocean is warmer (cooler) than normal. In general, the positive (negative) IOD is associated with the stronger (weaker) than normal all India summer monsoon rainfall.

However, the association between Indian monsoon and IOD is relatively weaker than that between Indian monsoon and La Niña/ El Niño phases.

Figure 3.7 shows the anomaly in the frequency of EREs over Kerala. In the top diagram, rainfall bars during the La Niña/ El Niño years are indicated with two distinct colours. It is clearly shown that there is no noticeable association of La Niña/ El Niño with EREs in Kerala. For example, 1923 (1924) was an El Niño (La Niña) year, but both the years experienced above normal EREs. As seen in the lower diagram, in the case of IOD also the EREs over Kerala do not show any noticeable teleconnection. This indicates that the EREs over Kerala is more associated with the local orography and variability in the monsoon circulation caused by the transient synoptic-scale and intra-seasonal propagating oscillations. However, it may be mentioned that the activities of these oscillations are also influenced by the remote forcing from both the Pacific and Indian Oceans.

Box 3.1: Distinguishing ENSO from Climate Change

The El Niño-Southern Oscillation (ENSO) is a recurring climate pattern involving changes in the temperature of waters in the central and eastern tropical Pacific Ocean. On periods ranging from about three to seven years, the surface waters across a large swath of the tropical Pacific Ocean warm or cool by anywhere from 1°C to 3°C, compared to normal. This oscillating warming (El Niño) and cooling (La Niña) pattern, referred to as the ENSO cycle has a direct influence on the rainfall distribution in the tropics. According to Climate and Ocean - Variability, Predictability and Change (CLIVAR), a project sponsored by the World Climate Research Programme (WCRP), it is challenging to determine the impact of climate change on ENSO events and its frequencies due to lack of enough observations of ENSO phenomena and because of the complex oceanic and atmospheric mechanisms involved in it.

According to the Intergovernmental Panel for Climate Change (IPCC), climate change is the change in state of the climate that can be identified by changes in the mean and/or the variability of its properties, and that persists over for an extended period, typically decades or longer. However, United Nations Framework Convention on Climate Change (UNFCCC) defines climate change as a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods. While the IPPC refers to any change in climate over time, whether due to natural variability or as a result of human activity as climate change, UNFCCC specifically pinpoints on the changes in climate due to human activities.

The EREs can also occur associated with a combination of factors including local origins such as for e.g. changing land use land cover (LULC) patterns. Over a regional scale, increased dust aerosols could create conducive conditions to enhance the strength of monsoon currents leading to increased moisture convergence over the windward side of the Western Ghats and hence heavy rainfall (Vinoj et al., 2014). These may lead to ERE's under favourable conditions. It is also shown that increased aerosol loading can delay precipitation causing increased accumulated perceptible water in the cloud systems (Bhattacharya et al., 2017), which can eventually result in EREs.

3.7. Orographic effects of the Western Ghats on the occurrence of EREs

The Western Ghats run parallel to the Arabian Sea coast from Maharashtra-Gujarat border to the southern tip of Kerala. The existence of the Western Ghats on the eastern side of the state of Kerala creates a barrier across the path of the southwest monsoon. One of the important factors that enhance rainfall activity over Kerala is the orographic lifting provided by the Western Ghats. Enhanced moisture transport over a small domain concentrated over a particular region causes ERE's. In this sense, increased moisture transport over the Western Ghats could lead to ERE's. Therefore, any increase in moisture from the Arabian Sea due to changes to monsoon flow could lead to an overall increase in rainfall including ERE's.

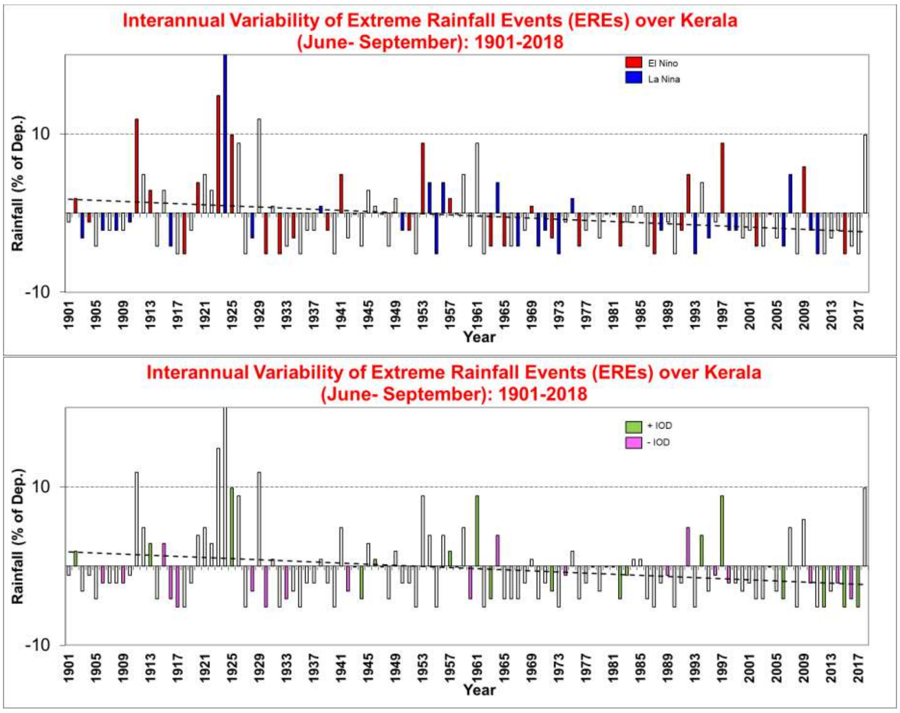


Fig. 3.7: The bar diagrams above show the anomaly in the frequency of EREs over Kerala. In the top diagram, rainfall bars during the La Niña/ El Niño years are indicated with two distinct colours. It is clearly shown that there is no noticeable association of La Niña/ El Niño with EREs in Kerala. For example, 1923 (1924) was an El Niño (La Niña) year, but both the years experienced above normal EREs.

3.8. EREs and cloud properties

Aerosols can increase the frequency of occurrence of ERE's but there is no direct evidence that this occurred in Kerala partly due to the lack of a database. Available observations show that aerosol loading is increasing over India at a rate of 3% per annum. Data also shows an increase in the fine aerosol fraction. An increasing number of fine aerosols would lead to an increase in the number of small cloud droplets (most likely non-precipitating), thus accumulating water droplets. During favourable conditions, when the clouds start raining, such conditions can lead to heavy rainfall.

Some studies have shown short period variability between aerosols over the Arabian Sea and rainfall over the Indian region including the southern parts (Vinoj et al., 2014). Therefore, there is a possibility that increased dust aerosols under the situation of an already excess moisture transport to the Western Ghats could result in higher rainfall than normal leading to the extreme. Manoj et al. (2011) documented the role of absorbing aerosols in modifying the large-scale circulation and moisture transport through direct radiative effect leading to the transition from a break to an active condition. Other studies (Lau and Kim, 2006; Lau et al., 2006) indicated that due to the absorbing nature of some of these aerosols, they may strengthen the monsoon and increase June-July rainfall through the elevated heat pump mechanism. Studies have shown that increased aerosol loading on intra-seasonal time scales increases the break period, by making the atmosphere more stable and delaying raindrop growth. This eventually leads to increased precipitable water accumulated within the clouds, so that when the precipitation occurs, it results in increased intensities (invigoration). This implies that increased aerosol loading may directly result in EREs.

3.9. Effect of aerosols

3.9.1. Role of aerosols in extreme events

Atmospheric aerosols, through its varying size and chemical compositions, are known to play an important role in cloud and precipitation forming processes by acting as cloud condensation nuclei (CCN). As mentioned by Rosenfeld et al. (2008) the increased aerosol concentration can delay but enhance the precipitation through the invigoration of convective activity (Fig. 3.8). This is very important for the pre-monsoon rainfall and also under the constantly polluting environment.

For the given amount of liquid water content under the pristine environments, due to the less but larger cloud droplet number concentration the collision and coalescence efficiency is higher and precipitation can occur even before clouds can cross the sub-zero temperatures. For the same amount of liquid water content, however, under the polluted environment, the number of cloud droplets can be very high causing the reduction in the size of the cloud droplets. This causes a reduction in their collision and coalescence efficiency reducing the chances of rain droplet formation. This results in cloud crossing the sub-zero temperatures causing the formation of ice crystals, which releases the latent heat of freezing and then invigorating the convection making more water available for the cloud, and ultimately resulting in extremely heavy/extreme rainfall.

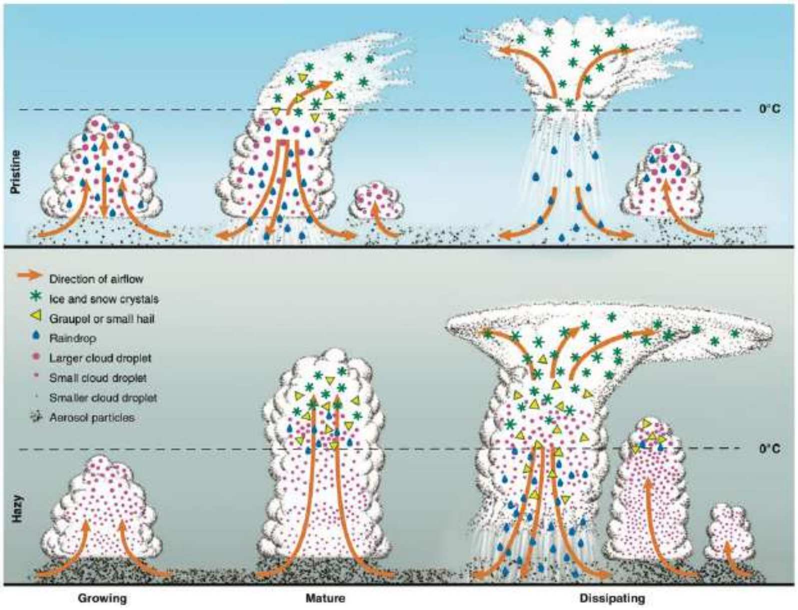


Fig. 3.8: Formation and evolution of deep convective cloud under pristine and polluted environments (as adopted from Rosenfeld et al., 2008)

3.9.2. Effect of aerosols on orographic clouds

The observational-based studies, mainly of the precipitation using the long-term rainfall data are critical in understanding the effect of aerosols on orographic clouds (Choudhury et al., 2019). It has been observed that the orographic precipitation downwind of urban regions is known to be reduced. Thus, it can be concluded that if CCN can be used as a proxy for the pollution then increased CCN concentration on the slopes and in higher altitudes will have more impacts on precipitation than the normal areas, more because the orographic lifting of the clouds can release more moisture (non-monsoon situation in Kerala (Fig. 3.9; clean and polluted).

Under a relatively pristine environment, the orographic precipitation would have a moderate spillover and rimming effect. The implication is if the timescale of microphysical processes is smaller than the orographic advection time-scale ideally precipitation is expected to occur on the lifting side of the mountains. On the other hand, under the opposite condition cloud may cross the barrier causing the precipitation beyond the barrier. The aerosol concentration under the hilly region can basically affect in the following three scenarios:

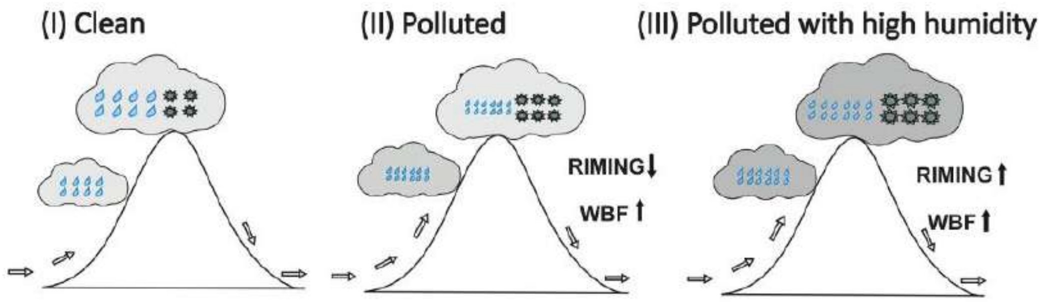


Fig. 3.9: Implication of pollution (CCN) on orographic cloud and precipitation (adopted from Choudhury et al., 2019)

a) A hilly area with a relatively clean region can cause cloud formation during the advection/uplifting of the air mass. Under these conditions the warm clouds, which are generally larger but will have a shorter lifetime.

b) A hilly area with the polluted air mass causing the increased concentration of CCN, which can be a proxy for the pollution can have larger clouds with increased lifetime. These clouds initially will have smaller hydrometeors, which may grow in size as the cloud is lifted due to orographic lifting and as a result of increased condensation may release may make more water available for the cloud. This can cause the suppression of rainfall on the windward region but can substantially increase the precipitation on the leeward side.

c) Under the third scenario, which is similar the scenario 2 but with additional moisture, during the advection, the precipitation may be suppressed resulting from more but smaller cloud droplets. Smaller cloud droplets reduce the collision and coalescence efficiency reducing the cloud droplet to rain droplet conversion rate. This can result in further growth of the cloud and once it reaches the top/leeward side of the mountain, the larger clouds can cause the extremely heavy precipitation/cloud burst.

Thus, for the warm clouds over the small hills where clouds do not exceed the sub-zero temperatures the increased aerosols of hygroscopic nature would directly result in increased CCN and formation of larger clouds. Further, the increase life-time of clouds resulting from additional pollution and aerosols the rain droplets cannot grow big enough to fall down as precipitation on the windward side and could get transported on the hills causing the heavy precipitation. The intensity of rainfall under this scenario would be more governed by the height of the hills, higher the mountains the heavier and extreme would be precipitation for the same amount of CCN and moisture. The constant supply of moisture during the monsoon season would supersede the evaporation effect due to smaller droplets in the clouds.

3.9.3 Regimes of cloud formations: Role of aerosols and updrafts

Using the cloud parcel model, the cloud droplet number concentration as a function of initial aerosol particles and updraft velocity (available of water vapour for condensation) is shown in Fig. 3. It is evident that during the monsoon season the site of Munnar, where the initial aerosol particle number and size distribution was measured represents the aerosol limited regime, implying that increasing aerosol concentration directly forms the cloud droplet and possibly increasing precipitation. This is further substantiated by the excess moisture available during the monsoon seas. Thus we can then define the two regimes of cloud formation a) aerosol limited regime: where more number of aerosol means more cloud droplets and more precipitation and b) updraft limited regime: where already more aerosol are present than required and precipitation would depend on the updraft of the cloud (availability of the water vapour).

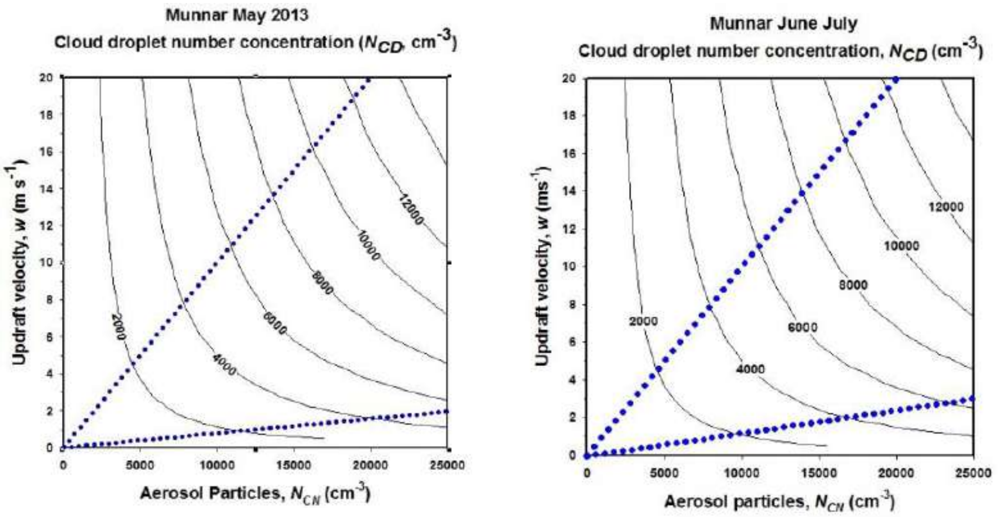


Fig. 3.10: Cloud droplet numbers (shown as counters) as a function of initial aerosol number and size, updraft velocity for contrasting seasons (summer vs. monsoon) at a high altitude site of Munnar in Kerala

The increasing concentration of aerosols over the plains of Kerala may possibly play a major role in the initiation of extreme events. This, in addition to the constant supply of moisture during monsoon season, supports the conversion of updraft regime of cloud formations to the aerosol limited regime. Meaning that the supply of aerosol is directly proportional to the cloud droplets. The further uplifting of clouds due to orographic lifting causes more precipitation. The aerosol size distribution measurements in plains, at ~600 meters and at 1600 meters in highly desirable. In this regard, IIT Madras in association with KSCSTE has constructed a laboratory at Munnar where long-term measurements of aerosol properties pertaining to cloud and precipitation formation are being monitored. As an immediate measure, IIT Madras in association with Centre for Climate Change in Kottayam would explore the possibility of joint funding to support further aerosols measurements in plains and at ~600 meters.

3.10. Impacts of EREs in the regional context

In the regional context, the occurrence of EREs may lead to numerous hazards, for example:

- Flooding leading to risk to human life, damage to buildings and infrastructure, and loss of crops and livestock
- Landslides can threaten human life, disrupt transport and communications and cause damage to buildings and infrastructure.
- Where EREs occur with high winds, the risk to forestry crops is high.

3.11. EREs and climate change

A large amount of the variability of rainfalls related to the occurrence of EREs and their intensities. The frequency of EREs has substantially increased under the warming climate, which is consistent with the observations as well as climate model projections (Ali and Mishra, 2018; Milly et al., 2002). EREs have produced more rain and become more common since the 1950s in many regions of the world, including many parts of India as mentioned earlier. In India, central India has seen the strongest increases in EREs. These trends likely to continue as the planet continues to warm. Warmer air can hold more water vapour. An atmosphere with more moisture can produce more intense precipitation events, which is exactly what has been observed. Increases in heavy precipitation may not always lead to an increase in total precipitation over a season or over the year. Some climate models project a decrease in moderate rainfall, and an increase in the length of dry periods, which offsets the increased precipitation falling during heavy events. In recent years, though some southern parts of Kerala observed increasing trends in the EREs, overall rainfall during the monsoon season and annual rainfall has shown a decreasing trend in recent decades (since 1970).

3.12. Predictive capability of EREs

At present, the following models are used in India for the prediction of EREs at short and medium-range scales by IMD and other MoES institutions

- Global Forecast System (GFS) model with a horizontal resolution of 12.5 km
- Global Ensemble Forecasting System (GEFS) with a horizontal resolution of 12.5 km
- Unified model of NCMRWF with a horizontal resolution of 12Km
- Unified model Ensemble Prediction System with a horizontal resolution of 12 km
- Regional Unified model with a horizontal resolution of 4 km for forecast up to 3 days
- Region Weather Research and Forecast (WRF) model with a horizontal resolution of 9 and 3 km

In recent years, the above models have shown significant skill in predicting the general rainfall patterns during monsoon season with a lead time of up to about 5 days case to case. However, the skill of these models in predicting EREs has been limited with a good model performance on some occasions while failing on some other occasions. Overall, location-specific prediction of EREs is yet to be improved particularly with a lead time longer than 2-3 days.

Figure 3.11 shows the skill score of the GFS 12.5 km model for the operational forecast of rainfall at different intensity and at different lead times along with that of an earlier version of the GFS with a horizontal resolution of 25 km. It is clearly seen that the performance of GFS 12.5 km is better than GFS 25 km. However, the skill score with respect to heavy rainfall forecasting of both the versions is generally very low (Fig. 3.11). Predicting the orographically induced heavy rainfall is one of the most challenging problems for NWP models. This is because of the Over the Indian region the western Ghats are characterized by steep orography and the heavy rainfall in these regions is often due to forced ascent of air parcels over the mountains. The complexity of the meteorological phenomena occurring over the orographic regions and the difficulty of obtaining detailed and precise observational data sets also leads to the poor representation of initial conditions in the NWP model (Panziera et al., 2011).

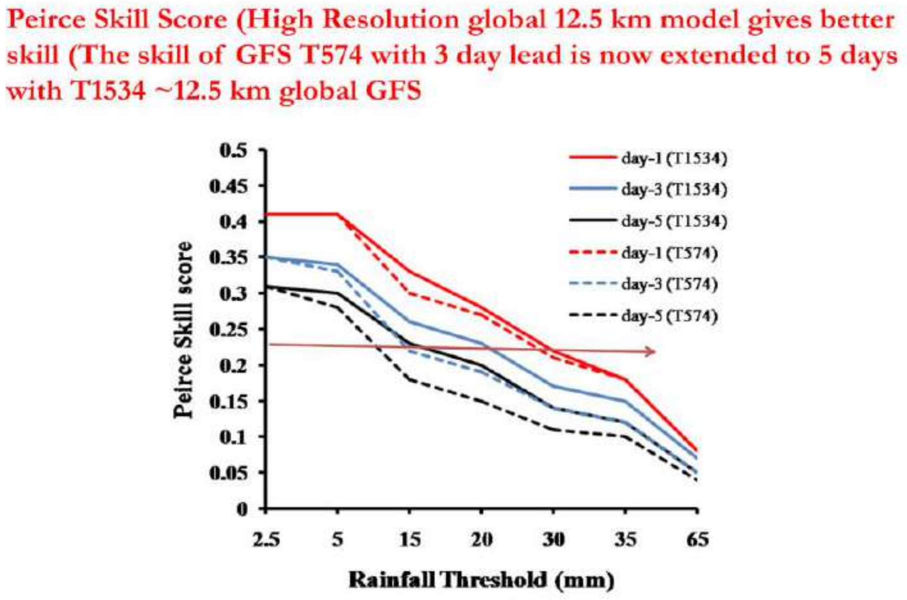


Fig. 3.11: Skill score of GFS 12.5 km model for the operational forecast of rainfall at different intensity and at different lead times along with that of an earlier version of the GFS with a horizontal resolution of 25 km

A recent study (Sharma et al., 2019) reported improved skill of the Met Office Unified Model (UM) in predicting EREs over the hilly regions of India (wester Ghats and NE India) during the monsoon seasons of 2007-2018. The changes in the operational UM during 2007-2018 included improvements in the representation of physical processes, improved dynamics and increased grid resolution from about 50 km in 2007 to 10 km in 2018. With respect to the particular monsoon season of 2013, the highest observed rainfall amounts over Western Ghats (> 10 cm/day) were completely missed in the forecasts. However, the improvement of UM (both resolution and dynamical core) the observed peak rainfall amounts (> 10 cm/day and also > 20 cm/day) were better predicted along the west coast of India during JJAS 2015 and 2018.

Efforts are going on in improving the model performance by

- Generating initial atmospheric conditions as accurately as possible by incorporating all available meteorological observations along with satellite and radar observations.
- Improving the processes that control the dynamic characteristics and predictability of heavy rainfall in the Indian region into the NWP model formulations, including the land surface processes needed.
- Developing ensemble methods/forecasts by running the model several times with slightly different initial conditions to increase our confidence in forecasting heavy rainfall. IMD has recently implemented the world's highest resolution Global Ensemble Forecast System (GEFS) for short-range prediction at 12 km using 21 members of the model. The GEFS prediction system provided probabilistic rainfall for the next 10 days. This ensemble prediction system (EPS) has enhanced the weather information being provided by the current models by quantifying the uncertainties in the weather forecasts and generate probabilistic forecasts and it has also improved the prediction of EREs. The accuracy of ensemble prediction is generally higher than the deterministic model.
- Climate models and observations are improving all the time and the reliability of predictions is likely to improve significantly over the next few years. In particular, new satellites and more detailed models are opening up new possibilities for understanding and predicting how water cycles through the climate system. For example, with a higher model resolution, the ability of models to incorporate the effects of mountains and coastlines has improved which means that small-scale processes, such as convection can be better simulated and this can help model in capturing heavier or more localized events.

3.13. Limitations and uncertainty involved in the prediction of EREs

Being the interrelationships between factors and processes involved in the occurrence of EREs is complex, uncertainties exist in the prediction of EREs. Major limitations in the prediction of EREs are listed below:

- Uncertainties linked to deficiencies of available real-time datasets (temporal and spatial coverage of series, measurement errors, etc.) may affect the estimations of EREs.

- Most of the models are not able to represent the actual orography or topography of a region. So, many times, models fail to capture the real mechanism of cloud formation and its impacts on rainfall patterns and distributions.
- Monsoon rainfall over mountainous regions is strongly controlled by processes and parameterized physics which need to be resolved with adequately high resolution for the accurate prediction of EREs.

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4. Chapter 4
Landslides and Land Use/Land Cover Changes

4.1. General

Kerala experiences landslide every year during monsoon months. In some years, when rainfall is high like that in the years of 2018 and 2019 there are several incidences of landslides causing loss of human lives are reported. Rainfall acts as a triggering mechanism. There is little control on rainfall with present-day technology, however other factors like land use, which is well within societal control. Alteration of land use plays an important role in aggravating landslide hazards. In this chapter, we intend to discuss landslide and land use changes in Kerala. Landslide as defined by Dictionary 'is a collapse of a mass of earth or rock from a mountain or a cliff'. Technically, the term landslide includes "a broad range of different types of motion whereby earth material is dislodged by falling, sliding and flowing under the influence of gravity" (Coates, 1981). Landslide anatomy consists of three parts: the crown, middle region, and toe region. There are various types of landslides (Box 4.1)**.** Landslides in Kerala are mostly in the form of debris flow (Appendix 4.1).

4.2. Landslide hazard zonation

The term landslide hazard zonation applies in a general sense to the division of land surface into discrete areas and arranges them according to degrees of actual or potential hazard from landslides or other mass movements from slopes (David J Varnes, 1984). When the conditions and processes that promote instability can be identified, it is often possible to estimate their relative contribution and give them some qualitative measure from place to place. Hazard zone mapping involves a detailed assessment and analysis of the past occurrence of landslides in terms of their location, magnitude, and frequency with respect to the terrain setup that includes geological, geomorphological and geotechnical factors and extreme events of rainfall. Spatial distribution of old and presently active landslides when compared with different terrain factors and climatic variations reveal the importance of each causative factor. The procedure of landslide hazard zonation involves the identification of elements having a role in causing landslides.

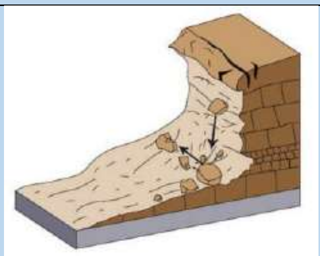
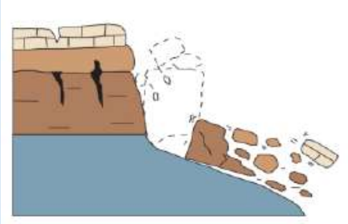
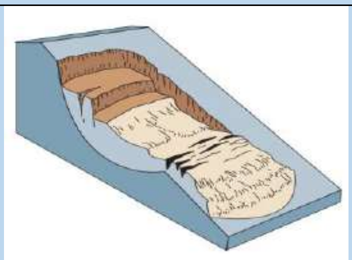
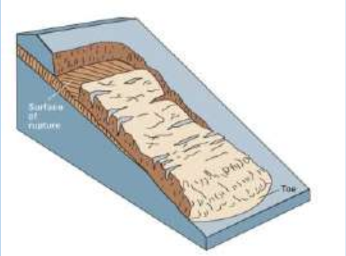
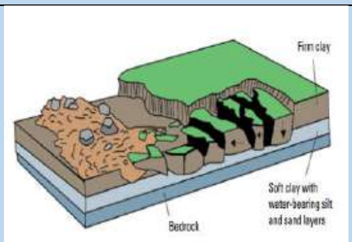
Qualitative landslide zonation is a simple approach wherein the causative factors are integrated in such a way as to arrive at whether a segment of land is unstable or not. The method is based on observations from previous landslide locations. Slope, material that constitutes the slope, land use that includes recent anthropogenic activities, landform, drainage, relative relief, etc. are some of the factors that affect the stability of a segment. Studies from the southern Sahyadris (Thampi, 1997; Thampi et al., 1998) for each of the causative parameters indicate that maximum landslides are located where a) the slope class lies in 25^0-32^0 range followed by

>32^{0} and where slope length lies between 150m -300m, b) the thickness of soil and overburden together exceed 2 m and the material is rich in clay and silt/ poor in sand, c) the landform is denudation hill slopes, plateau edges and residual hills, d) relative relief is in 150-300 m range, e) parallel drainage pattern with drainage density of 3-5, f) land use changes rapidly with manmade interventions, cutting and levelling of land or regions with degraded forests. Another aspect considered is rainfall. In the flanks of the Western Ghats, when the rainfall exceeds 20 cm in a day during a continuous rainy season, landslides are to be expected.

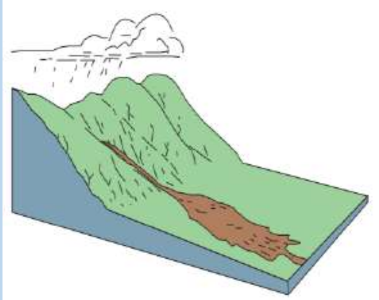
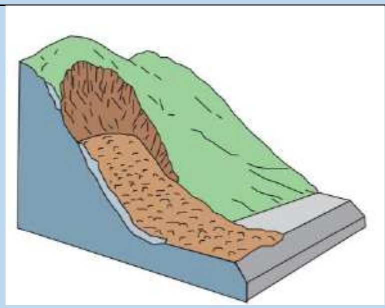
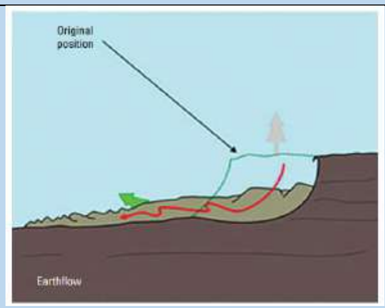
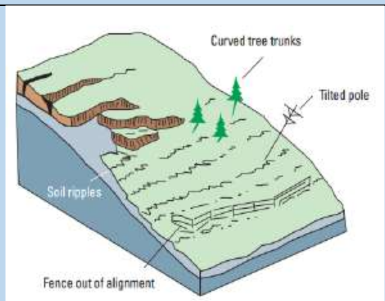
Slope stability analysis requires measurement of soil/rock properties by appropriate field and laboratory methods. The tendency of the soil mass to move down under the influence of gravity is often counterbalanced by the shear strength of the mass. Landslide hazard zonation is also attempted using the index properties of soil and overburden under differing conditions of water saturation. Alternatively, landslide-prone sections in a given terrain can be identified through the numerical rating of factors influencing the slope stability. This is otherwise called quantitative landslide zonation. The procedure of landslide hazard zonation involves the identification of elements having a role in causing landslides. Landslide susceptibility values are assigned to each of them according to their importance. Based on the landslide population per unit area in individual categories, landslide susceptibility index (LSI) numbers are determined. The sum total of these numbers per unit area for each of the causative factors gives an estimate of the landslide susceptibility of any given area. Thus, a unit area can fall in a stable or unstable area depending on the threshold value. The grids falling in unstable conditions are grouped and further the boundary is refined considering the terrain condition.

In India, landslide hazard zonation is attempted on different scales. Regional zonation is normally carried out for the entire country or a region like Himalaya or the Western Ghats. These maps are mostly indicative in nature to highlight the regions that are prone to landslides. It is mostly done on small scales of 1:5 lakh and above. The next level of hazard zonation is called macro-zonation often carried out in a 1:25,000 or 1:50,000 scale. The methodology adopted by the Bureau of Indian Standards involves assigning weights to each landslide hazard evaluation factor. The sum of the weights of all the factors is considered and a threshold for the terrain is arrived at to decide whether a segment of land is unstable or not. These maps are prepared at the district level or for specific regions to assist the planners in preparing the disaster management plans. The inputs to macro-zonation are mostly data available from topographic sheets, air photographs, and satellite images. In a study conducted by CESS (Mathai and Kumar, 2009), macro-zonation was attempted on a 1:50,000 scale for all districts in the State. The methodology adopted by BIS (assigning weights to each landslide hazard evaluation factor) was modified for the Kerala region incorporating the findings of the study done in a segment of Western Ghats (Thampi, 1997; Thampi et al., 1998). Rainfall is taken uniformly as landslides are initiated by peak rainfall in a short period. In most cases, rainfall in excess of 20 cm a day has been the triggering factor. The slope is the main causative factor for landslides in Kerala. They are derived from the topographic sheets.

Box 4.1: Types of mass movements (Source: USGS)

Type of movement	Description	Schematic representation
Falls	Rockfall: Abrupt downward movements of rock or earth or both	
Topple	Topple: Forward rotation out of a slope of a mass of soil or rock around a point or axis below the centre of gravity of the displaced mass	
Slides	Rotational slides: Landslide on which the surface of rupture if curved upward and the slide movement is rotational about an axis that is parallel to the contour of the slope	
	Translational slides: The mass in a translational slide moves out, or down and outward, along a relatively planar surface with little rotational movement or backward tilting	
Spreads	Lateral spreads: A strong upper layer of rock or soil undergoes extension and moves above and underlying the softer, weaker layer	

Box 4.1 (Contd'): Types of mass movements (Source: USGS)

Type of movement	Description	Schematic representation
Flows	Debris flow: A form of a rapid mass movement in which loose soil, rock and sometimes organic matter combined with water to form a slurry that flows downslope.	
	Debris avalanche: Large extremely rapid, often open slope flows formed when as unstable slope collapses and the resulting fragmented debris is rapidly transported away from the slope.	
	Earth flow: The mass in an earthflow moves as plastic or viscous flow with strong internal deformation.	
	Creep (slow earth flow): Creep consists of imperceptibly slow, steady downward movement of slope forming soil or rock.	

Lithology depicted in geological maps provides the main rock types but not the degree of weathering or the weathered product. Most of the landslides in Kerala are debris flows affecting the cover material and not the basement rock. Hence the type of cover material on diverse landform was deciphered from the images. Landform formed the basis of the cover material. Structural aspects are limited to the lineaments derived from satellite images. Data on the structural disposition of individual litho units are not available in this scale. Drainage density and relative relief are derived from topographic sheets. Land use/land cover is taken from the images.

The entire area is divided into 250 x 250 m grids and the assigned weights of individual parameters for each grid are summed up. Based on the total value, each grid area is categorized into different zones of hazard. The weight awarded for each parameter by BIS and by CESS is given in Table 4.1.

Table 4.1: The parameters considered for landslide hazard zonation and the maximum weights to be assigned for each parameter

Parameter	Maximum weight by BIS	Maximum weight by CESS
Slope	2	3
Lithology	2	2
Structure	2	1
Relative relief	1	1
Land use /land cover	2	2
Hydrological condition	1	1
Total	10	10

The maximum weight assigned to each parameter is the maximum value that can be awarded for that particular parameter as given in Table 4.1. However, it needs to be further refined. For this purpose, the subdivision of each such parameter is taken into consideration and weight is awarded accordingly. The first parameter, slope, is further divided into seven categories of increasing inclination (Table 4.2). In the category of less than 15% slope, landslides do not occur and hence the weight is zero. As the inclination increases, weight is also increased. Sub-classes under land use with their respective weights, subclasses understructure, relative relief and drainage with their respective weights are given in Tables 4.3 and 4.4 respectively.

Table 4.2: The subclasses in Slope and Lithology and the respective weights

Slope (3)		Lithology (2)	
0-15%	0	Denudational hills Debris mantled	2
15-25%	0.5	Deeply weathered Middle plateau	1.5
25-35%	1	Residual hills	1.5
35-50%	2	Alluvium (C Plains, Valleys, fl. plain)	1
50-60%	2.5	Lower plateau lateritic	1
60-70%	3	Valleys in denudational hill complex	1.5
>70%	2.5	Pedi-Inselberg complex, structural hills	0.5

Table 4.3: Sub-classes under land use with their respective weights

Land use (2)			
Forest- evergreen, semi evergreen, plantation	0	Agriculture-Plantation-coconut	0
Forest- grassland, scrub	0.5	Agriculture-Plantation-rubber, tea, coffee	0.25
Forest-degraded	1	Agriculture- Mixed crop with tilling	1.5
Wasteland- without scrub	2	Agriculture- single cropland	0
Wasteland- with scrub	1	Agriculture- mixed crop	0
Wasteland- degraded land	1	Builtup land	1
Wasteland- rocky	0.5	Others	0

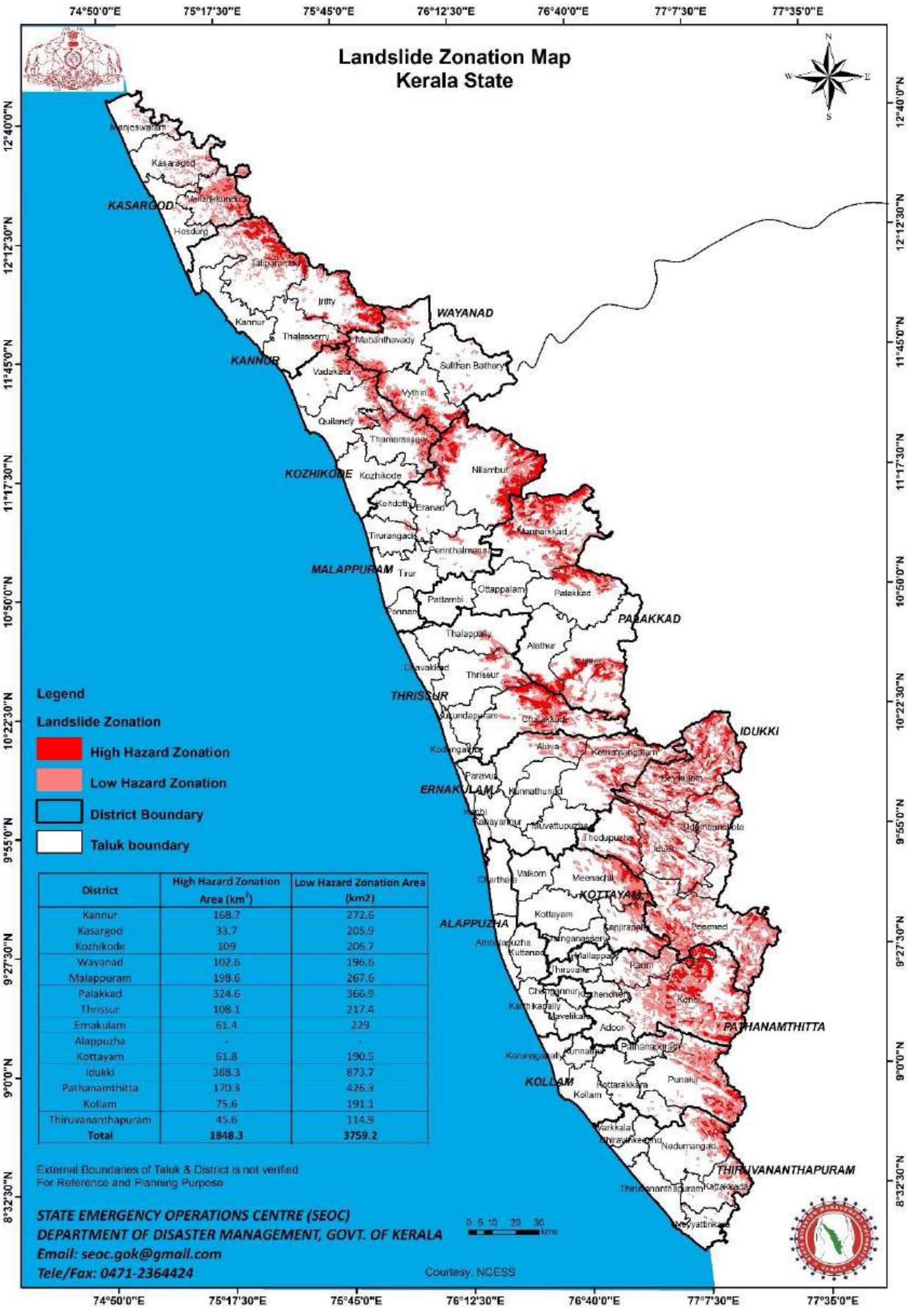
Table 4.4: Sub-classes under structure, relative relief, and drainage with their respective weight

Lineament -Structure (1)		Drainage (1)	
Nil	0	<0.25	0
150 m	0.5	0.25-0.5	0.25
> 150 m	1	0.5-1	0.5
Relative relief (1)		> 1	1
< 40	0		
40-100	0.5		
> 100	1		

The resultant landslide hazard zonation map for Kerala is given as Fig. 4.1, where the hazard zones are demarcated with respect to landslide-proneness.

4.3. Spatial and temporal pattern analysis of landslides

Studies carried out by the Central Road Research Institute indicate a high to very high rate of incidence of landslides in the Himalayas while the Western Ghats indicates a high rate (Rao, 1989) next only to the Himalayas. The Western Ghats is one of the most prominent orographic features of the Indian peninsula fringing the west coast from Tapti estuary in the north to Kanyakumari in the south. The western declivity is steep and usually terraced resembling Ghat or landing stairs from which it derives the name (Pascoe, 1950). These are considered to have been elevated to the present altitude through episodic uplift in stages during the post-Cretaceous period, the uplifted margins being more prone to landslides.



District	High Hazard Zonation Area (km^2)	Low Hazard Zonation Area (km2)
Kannur	168.7	272.6
Kasargod	33.7	205.9
Kozhikode	109	206.7
Wayanad	102.6	196.6
Malappuram	198.6	267.6
Palakkad	324.6	366.9
Thrissur	108.1	217.4
Ernakulam	61.4	229
Alappuzha	-	-
Kottayam	61.8	190.5
Idukki	388.3	873.7
Pathanamthitta	170.3	426.3
Kollam	75.6	191.1
Thiruvananthapuram	45.6	114.9
Total	**1848.3**	**3759.2**

Fig. 4.1: Landslide hazard zonation map of Kerala (https://sdma.kerala.gov.in/maps/)

The entire highland region of Kerala comprising about 40% of its geographical area forms the western slope of the Western Ghats. The elevation of this region varies from 75 m to more than 2500 m incorporating in its varied setting the Wayanad plateau, Kunda hills, Nelliampathy plateau, Anamalai-Cardamom hills, Pirmed plateau, and Agastiamalai hills. The presence of planation surfaces gives a terraced or a step like an aspect to the E-W regional profile of Western Ghats. This result in major slope breaks between the older and younger planation surfaces in which the plateau landform shows old age characteristics while the area surrounding it presents a youthful topography. The plateau margins which surround the remnants of each plateau landforms are usually steep with a considerable linear extent. The slope of this region is steep to very steep with plateau edges and dissected hill margins having 70% to 100% slope.

Almost all the rivers in Kerala originate from this region and flow west actively eroding the slopes resulting in denudational landforms. The soil cover in this region is generally thin without a well-developed soil profile and directly resting over the Precambrian crystalline basement. The rainfall in the highland region is generally above 300 cm with some places receiving more than 500 cm. Added to this is the fact that these slopes, which were once supporting tropical forests, are constantly being deforested due to emergent human activity.

Considering the above factors these plateau margins have all the characteristics that are favourable for mass movements. Human interference in the form of deforestation, active tilling, blocking of drainage, large scale modification of slopes for dwelling units and roads, etc. can upset the equilibrium which when triggered with a high-intensity rainfall promotes catastrophic mass movements. Management of these fragile zones with adequate landslide mitigation strategy must be inbuilt into the watershed management programmes being implemented in the highland region.

All hill slopes including those of Western Ghats are examples of systems in which forces tending to promote movement are opposed by resistance tending to make the slope stable. For any given slope there is an upper zone of denudation where the ground is losing, a middle zone of transportation with neither ground loss nor gain and a lower zone of accumulation with a net gain. The forms of denudation and accumulation slopes are determined by their form at some previous time. The rates of ground loss or gain are not constant in these zones.

Hill slopes are generally classified on the basis of the angle of slope. Simple qualitative terms like gentle, moderate or steep are used while describing a slope. There are various classification schemes in vogue. Most of them use the principle of characteristic angles and limiting angles. Characteristic angles are those, which most frequently occur under particular conditions of rock or climate. The class with maximum frequency is the primary characteristic angle. In many areas, the primary characteristic angle lies in the range of 1˚- 4˚. 20˚- 24˚ range is characteristic of hilly regions. Limiting angles are those, which describe the range of angles within which given forms occur or given process operates under particular conditions of rock or climate. Under humid climate, the upper limit of regolith cover or the lower limit of a rocky face is 40˚. For continuous vegetation and soil cover without rock outcrops, the upper limit is 30˚. It means that if there is a continuous soil cover on a slope of more than 30˚ it has only short-term stability and recurrent landslides can be expected in this region. A stable slope is a slope below the limiting angle for rapid mass movements. The maximum stable angle is given approximately by the equation: $\tan \beta = \frac{1}{2} \tan \phi$, where β is the slope angle and ǿ is the effective angle of shearing resistance. In a study conducted on a segment of Western Ghats, it was found that slopes in excess of 20^0 are unstable when saturated with water (Thampi et al., 1998).

Tectonic uplift and changes are sea level or base level of erosion contributes considerably to the difference in elevation and ultimately the gravitational force. In tectonically deformed areas such as the Western Ghats, diverse landforms are formed due to the multicyclic processes acting on the region. There are numerous streams with rapid erosion resulting in ridge-ravine topography. The entire surface is made up of valley slopes. The ridge crests are gently but continuously convex with steep and long rectilinear sections downslope. The slope abruptly joins the valley floor with little or no concave segment. The frequency of landslide scars particularly from debris flows is noted in the valley slopes.

An overall evaluation of the pattern and nature of landslides occurrences in Kerala reveals the following:

- Debris flow (*Urulpottal* in Malayalam) is the major type of landslide causing considerable damage to life and property. Other forms of landslide like rock falls, earth slumps/slides are of limited occurrence. Debris flow normally results in the development of new first-order streams/widening of existing low order streams.
- Almost all mass movements occur during periods of extreme rainfall often associated with cyclonic events indicating that the main triggering mechanism is over-saturation of the overburden
- Majority of mass movements have occurred in steep slopes with more than 33% slope.
- Mass movements are often limited to the topsoil and overburden without dislodging the basement rock.
- Slope configuration indicating the presence of palaeo-slump material at the toe region and debris-filled hollows in the mid-slope.
- A common factor noticed in these vulnerable slopes that promote the increased incidence of landslides is deforestation in the recent past, cultivation of seasonal crops and increase in settlements. Modification of the toe region where the transported/run out material accumulates especially for dwelling units has taken a heavy toll in the recent past.
- Terracing, contour bunding, blocking or diversion of stormwater channels and other forms of water conservation on slopes of more than 33% adds to the vulnerability of the hill facet.

4.4. Triggering factors (geological, geotechnical, hydrological and environmental) controls

Among all the natural hazards, the locations of places where slope failures/landslides occur are identifiable to a great extent, if the causative factors and immediate triggering factors are understood in a given terrain. In Kerala, intense rainfall and extreme modifications to the slope are the immediate triggering factors. Seismic events of the intensity of more than VII in the Modified Mercalli (MM) scale, whose chances of occurrence in Kerala are extremely remote, could also trigger landslides. The aerial distribution of places susceptible to slope failures could be delineated with a reasonable amount of accuracy, as the causative factors inherent to the terrain are mostly well understood. There is a wide range of factors that individually and collectively influence the stability of slopes. The dominant components include slope, relative relief, geology, drainage, vegetation cover, geotechnical properties, and anthropogenic activities. In addition, the stress condition in a slope is not the same always but changes temporally due to the natural processes active on the slope and due to variant parameters like the degree of water saturation and transient elements like seismic vibrations. This necessitates the evaluation of not only the present stress conditions but also the possibility of their shift due to the processes expected to be active on the slope.

A comprehensive study carried out in a segment of the Western Ghats (Thampi et al., 1998) has brought to light several revealing facts. The importance of each of the dominant causative factors in triggering landslides is given below (also refer the section on zonation)

4.4.1. Slope

Among the slope categories, maximum landslides are observed in the 25^0 - 32^0 class of slope. Landslides have not been recorded from slopes below 16^0. The length of the sloping surface is another factor. It is observed that slides are common to slopes in excess of 150 m length more so if they are facing SW direction.

4.4.2. Relative Relief

It represents the actual variation of altitude in a unit area with respect to its local base level. It is the difference in heights between the highest and lowest points per unit area is directly related to the degree of dissection. The more the intensity of dissection greater is the relative relief. The development of soil on a given land surface and the movement of water on it is strongly influenced by relative relief which in turn controls the stability. Areas having a value in excess of 300 m were found to be invariably unstable.

4.4.3. Geology

Geological information is an important factor that is generally used in identifying landslide-prone areas. The factors that warrant analysis include structure and lithology. Softer rock formations dominant in pelitic fractions are often susceptible to slope failures. Rocks that have undergone multiple brittle deformations or shearing also promote instability. In addition, the surface parallel joints in the basement rock often control the lateral flow of water especially in a high rainfall area like Kerala. A careful analysis of the terrain can help in delineating such zones.

4.4.4. Drainage

In the tropical regions with heavy rainfall, running water is by far the most important agency that transports weathered materials from the highland to the plains. In order to understand something of the complex processes of fluvial transport and erosion, it is necessary to evaluate the drainage characteristics of the terrain. Drainage basins/ Watersheds reveal many details about streams and their geomorphic setup. The drainage pattern and drainage density are two parameters that merit special mention. Areas with parallel drainage patterns are often vulnerable to slope failure. Likewise, areas with higher drainage density in excess of four also indicate instability in the high sloping segments.

4.4.5. Vegetation Cover

The protective role of vegetation ranges from mechanical reinforcement of soil by the root system, raindrop interception by foliage, soil moisture control by evapotranspiration and buttressing and arching by embedded stems. The woody vegetation with deeper roots provides greater mechanical reinforcement and buttressing action. Grasses and herbaceous vegetation, on the other hand, grow close to the surface and provide a tight, dense ground cover preventing surficial erosion. The removal of vegetation should weaken the soil and destabilize slopes. Destruction and gradual decay of interconnected root system were identified as one of the principal causes of increased sliding.

4.4.6. Geotechnical properties

The stability of slopes is greatly affected by the inhomogeneity and anisotropy of the earthen mass as well as the prevailing natural environment. Consequently, the validity of any attempt to ascertain the stability of a given slope largely depends on the ability to deduce the true geological properties in relation to the mechanical properties of the rocks (Záruba and Mencl, 2014). Geotechnical studies bring out the mechanical as well as index properties of rocks and soils in relation to its natural settings. Textural constitution with depth in a soil profile, shear strength parameters under different moisture regime, liquid and plastic limit, bulk density a measure of the compactness of soil and moisture content are measured on undisturbed soil segment and integrated to determine the factor of safety to identify locations that are unstable.

4.4.7. Anthropogenic activities

Manmade changes to the natural landscape of the Western Ghats have resulted in severe degradation leading to instability of segments that are otherwise stable in the natural setup. Human interference in the form of deforestation, modification of natural slopes by cutting and levelling, active tilling, blocking of drainage, construction of roads and dwelling units without consideration of the sensitive nature of the location, etc. can upset the equilibrium which when triggered with a high-intensity rainfall promotes catastrophic mass movements. Management of these fragile zones with adequate landslide mitigation strategy must be inbuilt into the development programmes being implemented in the highland region.

4.5. Rainfall characteristics and landslides

Types and severity of landslide vary markedly from region to region depending on the climate, the pattern of precipitation, types of soil and weathering products. In tropical regions in which deluges due to monsoon or cyclonic storms occur devastating debris flows are initiated within a short time. The impacts of changing patterns in precipitation in recent times often attributed to climate change have also been a major cause of landslides in Kerala state. However, for the purpose of evaluating the thresholds of rainfall as a triggering agent for landslides, real-time records may be incomplete. The distribution of weather stations over the hilly region may also be inadequate. When the rain is very heavy and prolonged, the rate of infiltration into the surface layers of a sloping segment can exceed the transmissivity of the substrate. Consequently, there is an increase in pore water pressure and a reduction in the shear strength leading to failure. From the study of the hilly region in Srilanka, Priyasekappa (1986) has postulated that rainfall in excess of 400 mm in a period of two days can trigger landslides. Studies in the Western Ghats (Thampi et al., 1998) indicated that saturated strata that were critically disposed, failed when the rainfall for the preceding two days was 315 mm. So, for the Kerala region, a two-day rainfall in excess of 300 mm during a continuous rainy period will induce landslides in those sloping segments that are critically disposed of.

4.6. Soil piping and landslides

During the last decade, apart from landslides, land-subsidence has also become common in the Western Ghats during monsoons. Even though the causes for the occurrence of landslides and land subsidence differ, they occur during extreme rainfall events. Whereas the landslides are the different types of movement of earth material down the slope under the influence of gravity and the land subsidence is the result of roof collapse of the subsurface tunnel/cavity formed due to a soil erosion process called “soil piping or tunnel erosion”.

Land subsidence due to soil piping has been noticed in the high land area of Kerala, especially places near to the Western Ghats. Soil piping is caused by internal erosion of soils which leads to the formation of tunnel-like features below ground level. Soil piping or Tunnel erosion is defined as the hydraulic removal of subsurface soil, causing the formation of underground channels and cavities (Boucher, 1995).

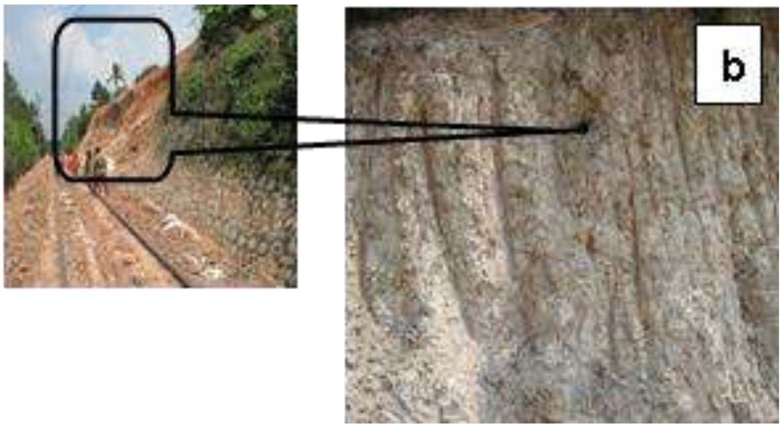


Fig. 4.2: Mulathuruthi railway cutting where a section of the laterite cutting failed

Soil pipes can cause numerous problems. While they start from very small pores, they can cause large failures of soil structure and of engineered structure, such as dams and buildings. Water erodes through the soil out of the pipes, the soil above the pipe is not supported. The pipes can then collapse, leading to gullies, landslides, or stream bank failure. In Kerala, the landslides are generally shallow in nature affecting the critical zone. This is because of the physically strong nature of the Precambrian crystalline basement rocks in the Western Ghats. Similarly, soil piping also is restricted to critical zone.

During the last decade, many piping incidences were reported from different places from the state. According to NCESS studies (Sankar et al., 2016), piping has reported from all districts of Kerala except Alappuzha and Kollam. The juvenile pipes (micro) or small pipes (younger pipes) are identified as conduits for saturating the laterite cuttings making them vulnerable for the toppling type of landslides. Micro pipes are less than 5 cm in diameter whereas the small pipes are less than 30cm. These pipes are clearly visible in road cuttings and railway cuttings. In the year 2012, such an incident has occurred near Mulamthuruthi railway station where a section of the laterite wall has collapsed into a running train during monsoon. Figure 1 shows the Mulanthuruthy railway cutting where a section of laterite cutting failed.

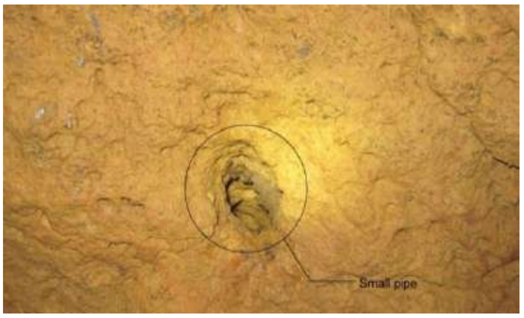


Fig. 4.3: A small pipe formed in the soil column (left); soil-piping affected region (right)

The juvenile pipes and or small pipes when present in large numbers (in Fig. 4.3) in an area indicates the susceptible nature of the soil /terrain soil piping. In the Valamthode area (N11°43'52.9", E75°49'52.7") of Mananthavady taluk of Wayanad district, a debris flow was found to be triggered by pipe flow (Fig. 4.4). After the flow pipe of the size 50cm in diameter was seen in the slide scarp.

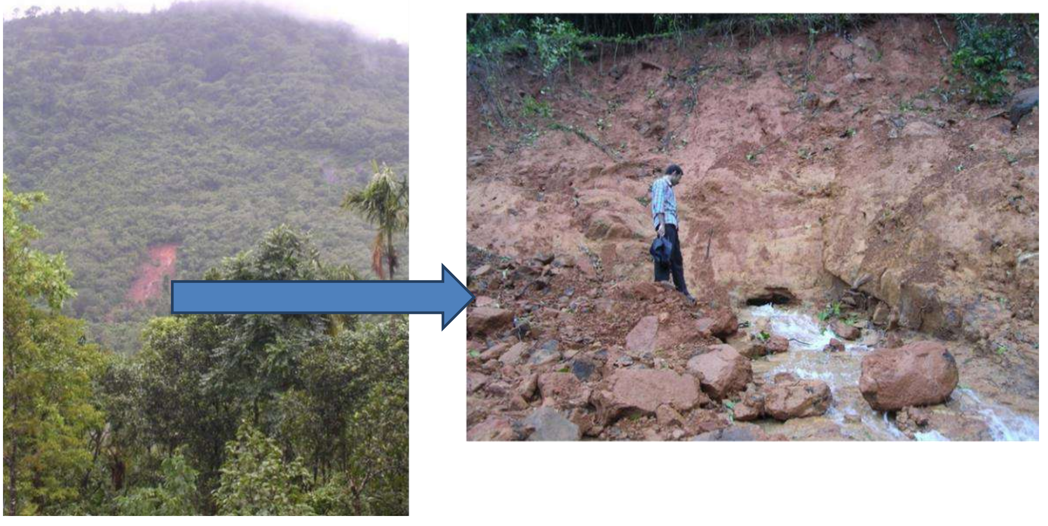


Fig. 4.4: Valamthode debris flow far view (left) and closer view (right)

In the 2018 monsoon also, there were a couple of piping triggered landslides in Thrissur district. Field investigation reveals that in places like Kuranjeri in Thalapalli taluk Pattilamkuzhi in the Thrissur taluk, Pulikkani-Palapilly in the Chalakudy taluk, Ettamkallu in the Thrissur taluk and couple of other slides were initiated by soil pipes. Figure 4.5 shows the Kuranjeri debris flow, pipe outlet, and juvenile pipes.

The 2019 monsoon also reported many incidences of soil piping. Their role in promoting landslides are being investigated. Promoting or mitigating the slope instability of a slope will depend on the type of pipe, location, and intensity of rain. Larger pipes will easily dewater a slope if the rainfall input and pipe flow output balances. Larger input by high-intensity rains will definitely saturate the slope face making it vulnerable to slides. Also, the hydrostatic pressure at the valley end of the pipe which is narrow and like a funnel nose will be beyond the tolerance limits. Whereas in the case of Juvenile or smaller pipes whether they are an independent pipe or part of a dendritic pipe system, they will saturate the laterite column and will make it vulnerable for failures. Vulnerability will increase if there is a road or rail cutting present in the laterite column.

Fig. 4.5: Kuranjeri debris flow (left), pipe outlet (centre), juvenile pipes (right)

4.7. Effect of land-use changes on landslide occurrence

Land use change is one of the main factors among anthropogenic activities that trigger landslides. Physiographically, the landmass in Kerala can be delineated linearly in North-South direction and term East to West in (i) High lands (area at an elevation more than 75 meters above mean sea level) with an area of 18.65 lakh hectares. (ii) Mid land (elevation between 7.5 and 75 meters with an area of 16.23 lakh hectares and (iii) Low lands (elevation lesser than 7.5 meters) with an area of 3.98 lakh hectares. The terrain conditions of High land and Midland, in general, are undulating to very steep with the highest point at Anamudi having 2690 meters above MSL. The low land lying adjacent to shoreline stretches to a length of 590 km of which certain pockets lie below mean sea level (1 to 1.5meters). Geologically and pedologically the entire landmass is both dynamic and fragile which leads to rapid degradation and consequent causes ecological problems. The hilltops of most of the high ranges are covered with shallow soil and rock outcrops. The soil of the high range is dominantly shallow to deep, derived from granite gneiss, weathered into medium to fine texture, acidic in reaction occurring on hill slopes under forest and plantation. They are moderate to well-drained and subjected to varying degrees of erosion from slight to severe. The entire system is fragile and susceptible to varying degrees of degradation. Out of 14 districts in the State, 12 districts experience landslides in the high lands. The process of degradation is accelerated due to biotic influences mainly on account of unscientific land use.

4.7.1. Land use in Kerala

Out of the total geographical area of 38.36 lakh hectares, forest land comprises of 10.82 lakh hectares. The net cropped area is 20.40 lakh hectares (Appendix 4.2). The remaining land of 7.54 lakh hectares consists of land put to non-agricultural uses, barren and uncultivable lands, permanent pastures and grazing lands and under miscellaneous tree crops. Nearly 12.5 lakh hectares are under a system of mono-cropping with plantation crops like Rubber, Tea, Coffee, Cashew and Paddy. The remaining area of 10 lakh hectares is occupied by coconut and miscellaneous crops. A tendency towards a switch over to the cash crops is dominant. Cultivation of plantation crops reduces the opportunity for intercropping with pepper, banana, ginger, turmeric, tapioca, minor tubers, nutmeg, clove, vegetables, etc. Paddy which was one of the dominant crops of the state suffers from the reduction of the cultivable area due to indiscriminate conversion of land to other uses, often for non-agricultural purposes and plantation of unsuitable crops. In contrast to this, the area under rubber cultivation expanded from 1.23 lakh hectares in 1960-61 to 3.46 lakh hectares in 2010-11. This exotic species is being further extended to unsuitable lands also which is detrimental not only to the crops itself but to the land also.

4.7.2. Changes in Land use

Considering land use data for selected categories spanning over two-time points, 2006 and 2016, it emerges that there is a considerable change in land use, particularly under the categories of agricultural fallow lands, seasonal crops, and paddy cultivation. The permanent conversion of paddy land has increased by 135% in 10 years period. Built-up land registered an increase of 40%. Table 4.5 shows the changes in the land use/ land cover pattern over Kerala from 2006 to 2016.

Table 4.5: Land-use/ land cover changes in Kerala (2006-2016)

Sl. No.	Land use type	Area, 2006 (km^2)	Area, 2016 (km^2)	Change (%)
1.	Built-up Land	1521.60	2127.40	39.81
2.	Paddy Cultivating Land	2473.62	2173.70	-12.12
3.	Paddy Converted to Seasonal Crops	169.45	237.91	40.40
4.	Paddy Converted (Permanent)	917.74	2162.25	135.61
5.	Agricultural Seasonal Crops	163.98	80.64	-50.82
6.	Agricultural Mixed crops	13401.27	12021.17	-10.30
7.	Agricultural Perennial Plantation Crops	5899.52	6479.82	9.84
8.	Agricultural Fallow Land	1920.06	518.99	-72.97
9.	Forest	10140.43	10619.42	4.72
10.	Waste Land	1049.04	1263.35	20.43
11.	Waterbody	1206.29	1178.35	-2.32
	Total	38863.00	38863.00	

4.7.3. Major causes of land use/ land cover changes

The land reforms and institutional changes in the State have led to the transformation in the landholding pattern, which has resulted in a shift in the land use/ land cover pattern in the State which is affecting the food security and ecological sustainability in the State (Kerala State Planning Board, 2019). In the regional context, the major drivers of the land use/ land cover changes are discussed in the following sections:

4.7.3.1. Natural

Natural environmental changes interact with the human decision making processes resulting in land-use change. Climatic variations make the ecosystem highly variable and increase the pressure arising from high demands on limited resources. Natural variability leads to socio-economic instability. The adapted management practices increase the vulnerability to climatic fluctuations and thereby trigger land degradation.

4.7.3.2. Economic and Technological factors

These factors influence land use decisions by altering the cost of production, capital flow, investments, trade, and technology. The recent trend is to develop, use and profit from new technologies and intensive commercial agriculture and to stay away from subsistence croplands. For example, better access to credit and markets combined with improved agricultural techniques encourages forest conversion to cropland.

4.7.3.3. Demographic factors

The multifold increase in the population of Kerala during the last century have large impacts on land use (Table 4.6). Population density which was 165 persons per km^2 in 1901 has risen up to 859 persons per km^2 in 2011 and this increase has several detrimental effects like reduced per capita availability of land (less than 0.10 ha) increased demand for housing, urbanization, and migration which is the most important single demographic factor causing rapid land-use changes. Urbanization causes changes in regional consumption patterns and income distribution with impacts on rural land use. Land-use intensification is noted in peri-urban and developing areas.

4.7.3.4. Institutional factors

Local and national policies, environmental policies, decision-making systems for resource management, etc. directly influence land-use changes. Land degradation and other negative environmental consequences of land-use changes are the results of weak institutional policies and strategies. Hence it is of importance that institutions that influence land management decisions should have a concern for the environment. The shift in government policies and social engineering by market forces also has influenced the land-use changes. The incentive to cash crops and marginalization of support and incentives to food crops, over the years, changed the cropping pattern without any consideration of the biophysical production potential of land parcels.

Table 4.6: Population (in lakh) in rural and urban areas of Kerala during the last century

Year	Rural	Urban	Total
1901	59.4	4.5	63.9
1911	66.2	5.3	71.5
1921	71.2	6.8	78
1931	85.9	9.2	95.1
1941	98.3	12	110.3
1951	117.2	18.3	135.5

1961	143.5	25.5	169
1971	178.8	34.7	213.5
1981	206.8	47.7	254.5
1991	214.1	76.8	290.9
2001	235.7	82.7	318.4
2011	174.6	159.3	333.9

4.7.4. The extent of land degradation

Nineteen lakh hectares of the State are under varying degrees of erosional hazard which is insidious, acting like slow poisoning of the land. Accelerated runoff during the monsoons takes away a heavy toll of the fertile soil from the hills to the sea and the degree of erosion is constantly on the increase. It is reported that about 20% of the area is of slightly eroded soils, 69% fall in the moderately eroded category and 4% comes under severely eroded soil category. Six per cent of the area is of rocky land. The problem is getting aggravated year after year due to biotic factors, viz, deforestation, unscientific cultivation, overgrazing coupled with steep slopes, fragile soil system and heavy rainfall. Soil erosion reduces fertility and affects the productivity of the land leading to very poor yield from crops. The general physiographic, climatological and soil characteristics complementarily contribute to serious land degradation hazards. Indiscriminate deforestation, uncontrolled grazing, and unscientific soil and water management practices have aggravated the problem of soil erosion, landslides, etc. at alarming proportions.

4.7.5. Land use change and occurrence of landslides

Alteration of natural vegetation along hill slopes interferes with the hillslope hydrology and often slope stability is lost. A case study in the Gayathri river basin has demonstrated the effect of land use change on the occurrence of landslides.

4.7.6. A case study in Gayathri River Basin

and use Board has conducted a study in the Gayathri river basin. Among the 14 micro catchments of Gayathri sub watershed, micro catchment in the upper reaches lying as part of the Western Ghats and ecologically fragile areas have been identified as landslide-prone areas. This includes 17 micro watersheds spread over the catchment of the Mangalam reservoir, Pothundy reservoir, Vandazhy River, Ayiloor River, Ekshumathipuzha, and Karadiparathodu. Figure 4. 6 shows the details of the Gayathri river basin. The possibility of landslide occurrence had been forecasted for all 17 micro watersheds considering both natural and manmade reasons. Land use Land cover change and anthropogenic intrusions were analyzed for all these watersheds. These manmade factors were found to increase the chance of the occurrence of hazards.

As part of natural calamity that occurred in August 2018, the incidence of the landslide has been reported in 10 micro watersheds out of the above mentioned 17 micro watersheds. This includes one micro watershed in Mangalam reservoir catchment, one micro watershed in upper reaches of Mangalam River, 2 micro watersheds of Vandazhy River, 4 micro watersheds in the critical catchment of Pothundy reservoir and 2 micro watersheds in the catchment of Ayilur River. Human intrusions including land use/land cover change, and quarrying along ridgeline were found to increase the possibility of hazards in addition to the natural factors in 3 micro watersheds falling in the catchment of Mangalam and Vandazhy river (20B39ba, 20B39bb, 20B39as). Human intrusions were found to aggravate the possibility of landslide hazards in more than one location inside the micro watershed (20B39bb) under the Vandazhy River. Destruction of forest in critical catchment and conversion to plantation rubber (58%), along with quarrying has thus been found to increase the intensity of hazard in micro watershed no 20B39bb.

The micro catchments in the upper reaches of the river basin lying as part of Western Ghats are the most critical and ecologically fragile areas prone to calamity hazards especially landslide. The underlying lithology is not congenial for infiltration. High relief and steep slopes in these areas lead to increased runoff. The intensity of rainfall is also high in this region. In many cases more than the relief and slope, the soil becomes the limiting factor. The soil is shallow and lithic with poor water holding capacity inducing erosion and high runoff.

The major land use in these areas is tropical forests. But changes in land cover from deep-rooted indigenous species to plantation crops along with degeneration of existing forest cover has led to the loss of perenniality of streams in the majority of the landslide affected watersheds (20B39ba, 20B39bb, 20B39aj, 20B39ap, 20B39ao, 20B39ar). Micro watersheds in each micro catchment had been prioritized for conservation and rejuvenation taking into consideration the inherent ability to aid infiltration and the extent of damage inflicted by man as part of land use land cover change. Top prioritized micro watersheds in each micro catchment and the strategy for its treatment were also given. Among the landslide reported micro watersheds 20B39bb, 20B39an, 20B39ao have been given top priority for conservation and rejuvenation in the respective micro catchments. The second priority had been given in the case of two micro watersheds 20B39aj and 20B39al.

All the micro watersheds falling in the catchment of the Mangalam and Pothundy reservoirs had been warned as landslide-prone watersheds as part of developing a protocol for IPPE, MGNREGS scheme and it had been mentioned that conservation of forest alone should be the strategy for Natural Resource Management activities and all activities disturbing the soil should be strictly prohibited. The livelihood of ST communities who depend on the forest as their resource base has severely been affected in some of the landslide affected watershed (20B39ar, 20B39bb). Hence, conservation of reserve forest area, rejuvenation of vested forest area, prevention of further conversion to plantation crops and encroachment should be the strategy to prevent further hazards and maintain the river perennial. Thrust for improving the livelihood opportunity of ST communities by improving their natural resource base (medicinal plants and other forest produce) i.e., in the forest should be given in the regeneration activities.

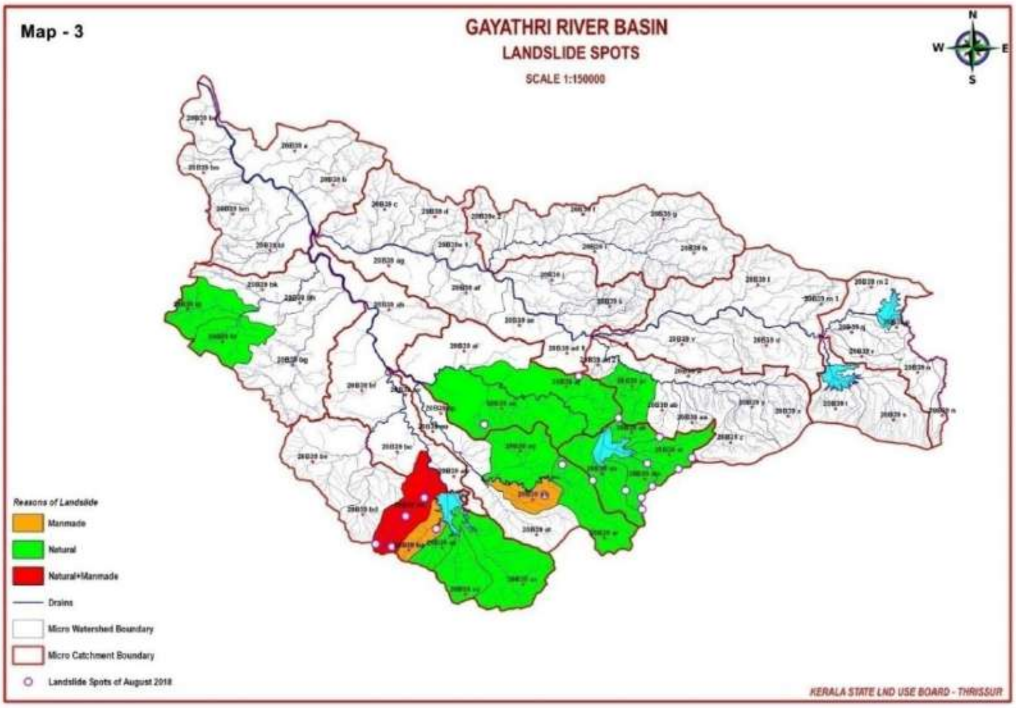


Fig. 4.6: Gayathri River Basin, Kerala

Comprehensive analysis of landslide affected micro watersheds taking into consideration of present status, the result of morphometric analysis indicting its inherent capability for infiltration, land use land cover change, and other human intrusions which have increased the calamity hazards were worked out. Critical analysis of the above-said factors reveals that manmade reasons (land use land cover change and other human intrusions) are the major contributing factors for the occurrence of the landslide and flood hazards.

4.8. Effect of quarrying (and similar activities) on landslides

Studies and experience have shown that there is a close link between hard rock quarrying and slope failures in the form of landslides. Quarrying involves the removal of earth materials from a stable topographical unit such as mountains, hills, etc. Apart from creating environmental problems such as atmospheric pollution, pollution of the surface water resources, depleting the storage of subsurface water resources, quarrying plays an important role in destabilizing the stable slopes.

4.8.1. Causative factors

Causative factors for the occurrence of landslides due to quarrying are discussed in the below sections

4.8.1.1. Type of bedrock

If the bedrock is well foliated, highly fractured, etc then failures might occur during blasting. Chances of fly rock (uncontrolled movement of rocks during blasting) are also more. Massive rocks are relatively safer for quarrying.

4.8.1.2. Location of quarrying

Quarrying should not start from the base of the hill or mountain. In other words, a quarry, however small or big it may be, should have top to bottom approach on a hill slope. Otherwise, quarrying will destabilize the upper slope the same as in the case of toe cutting of slopes.

4.8.1.3. Type of blasting

Type of blasting is very important for generating ground vibrations which are responsible for slope failures. There are different types of blasting methods. Blasting is the process of breaking of bulk rock masses into loose forms using explosive compounds. Here, explosives play a primary role. The explosives are the substances or devices used in blasting. They are used to produce a volume of rapidly expanding gas that exerts sudden pressure on its surroundings and break the mass into pieces. There are three common types of explosives used for blasting as chemical, mechanical, and nuclear explosives. These days the Nonel type blasting is considered to be the safest type of basting in the rock quarries.

Geotechnical studies carried by Thampi et al. (1998) indicate that the Factor of Safety (FOS) of the soil samples from the Western Ghats goes down to 1 in the saturated conditions. The FOS is expressed as the ratio of forces or moments resisting movements to the forces or moments promoting movement. So, during monsoon when the soil is wet and FOS is nearing 1, the rock blasting vibrations could trigger a possible mass movement. A study conducted by Sajinkumar et al. (2014) in the Himagiri Estate landslide area has made the following recommendations:

- ✓ Quarrying: Quarry and crusher unit, located in one of the vulnerable slopes near Himagiri Estate, is one of the main reasons for the land disturbances in the study area. The effect of quarrying in this area can be minimized by the following methods:
  a. Use of controlled blasting for mining

b. No mining/blasting during monsoon season

c. For the operation of the crusher unit during monsoon, stockyards should be constructed and materials should be collected and dumped in the yards for use during monsoon.

4.8.1.4. Overburden and mine waste storage

Quarrying activity generates huge quantities of Over Burden and mine wastes. All quarries should have designated sites for storing overburden and mine waste and should take precautions for its stability. At first, it should be located in topographically lower elevations. These huge dumps are likely to fail like landslides during heavy rains and will cause problems to local staying nearly. So, it should have a proper retaining wall or gabion protection.

4.8.2. Examples of quarry blasting and landslides

Pasukadavu area in the Vadakara taluk of Kozhikode district is an example where a debris flow was initiated due to quarry blasting in 2012. In the Himagiri estate in the Vythiri taluk of Wayanad district slope failure was initiated near a live quarry during monsoon. On the recommendation made by CESS, the Government of Kerala has banned quarrying activities during monsoon.

4.9. Prediction/indicators of landslides

The State of Kerala (India) experienced the worst disaster in its history in the year 2018 and 2019. The majority of landslides in Kerala are triggered by rainfall. Several attempts in the global scenario have been made to establish rainfall thresholds in terms of intensity duration and antecedent rainfall models on global, regional and local scales for the occurrence of landslides. However, in the context of Kerala, the rainfall thresholds for landslide occurrences are not yet understood fully. The concept of rainfall thresholds for the prediction of shallow landslides in the Indian Himalaya was first proposed by Kanungo and Sharma (2014). They were the first to propose such types of thresholds for in India. The empirical threshold was data-driven and is applicable for the Chamoli-Joshimath region of Garhwal Himalayas.

The minimum or maximum level of some quantity needed for a process to take place or a state to change is generally defined as a threshold. In the case of rainfall-induced landslides, however, the minimum intensity or duration of rainfall necessary to cause or reactivate a landslide is known as the rainfall threshold for landslide (Varnes, 1978). Also, a threshold may define the rainfall, soil moisture or hydrological conditions that when reached or exceeded are likely to trigger landslides (e.g., Guzzetti et al., 2007). Wieczorek (1996) defined rainfall threshold as rainfall intensity that facilitates slope instability for a given region. It is understood from the literature that, in general, two types of rainfall thresholds can be defined; physical (process-based, conceptual) thresholds and empirical (historical, statistical) thresholds (Guzzetti et al., 2007). Physical threshold models require detailed spatial information on the hydrological, lithological, morphological and soil characteristics that control the initiation of landslides. These process-based threshold models attempt to extend spatially the slope stability models widely adopted in geotechnical engineering. These models can determine the amount of precipitation required to trigger slope failures and the location and time of the expected landslides.

Empirical rainfall threshold models are evolved by studying the rainfall events that have resulted in landslides. The threshold is usually obtained by drawing lower-bound lines to the rainfall conditions that resulted in landslides plotted in Cartesian, semi-logarithmic, or logarithmic coordinates. Different types of empirical rainfall thresholds for the possible initiation of landslides have been proposed in the literature based on the extent of the geographical area for which they were defined, and the type of rainfall measurement used to establish the thresholds (Guzzetti et al., 2007). Empirical rainfall thresholds may also be grouped in three broad categories based on the type of rainfall measurements: (1) thresholds that combine precipitation measurements obtained for specific rainfall events, (2) thresholds that include the antecedent conditions and (3) other thresholds, including hydrological thresholds. Thresholds established using precipitation measurements obtained from the individual or multiple rainfall events can be further subdivided into intensity–duration (ID) thresholds, thresholds based on the total event rainfall, rainfall event–duration thresholds and (4) rainfall event–intensity thresholds (Guzzetti et al., 2007). Based on the extent of the geographical area, rainfall thresholds for rain-induced landslides with different types of precipitation measurements can be broadly subdivided into global, regional, or local thresholds based on their geographical extent. Regional thresholds are defined for areas extending from a few to several thousand square kilometres of similar meteorological, climatic and physiographic characteristics, and are potentially suited for landslide warning systems based on quantitative spatial rainfall forecasts, estimates, or measurements. Local thresholds consider the local climatic regime and geomorphological setting and are applicable to single landslide or to groups of landslides in areas extending from a few to some hundreds of square kilometres (maybe for the local geographical area or for a highway corridor, etc.). In places, the distinction between regional and local thresholds is uncertain. These available rainfall threshold models may be illustrated as a flow diagram (Fig. 4.7).

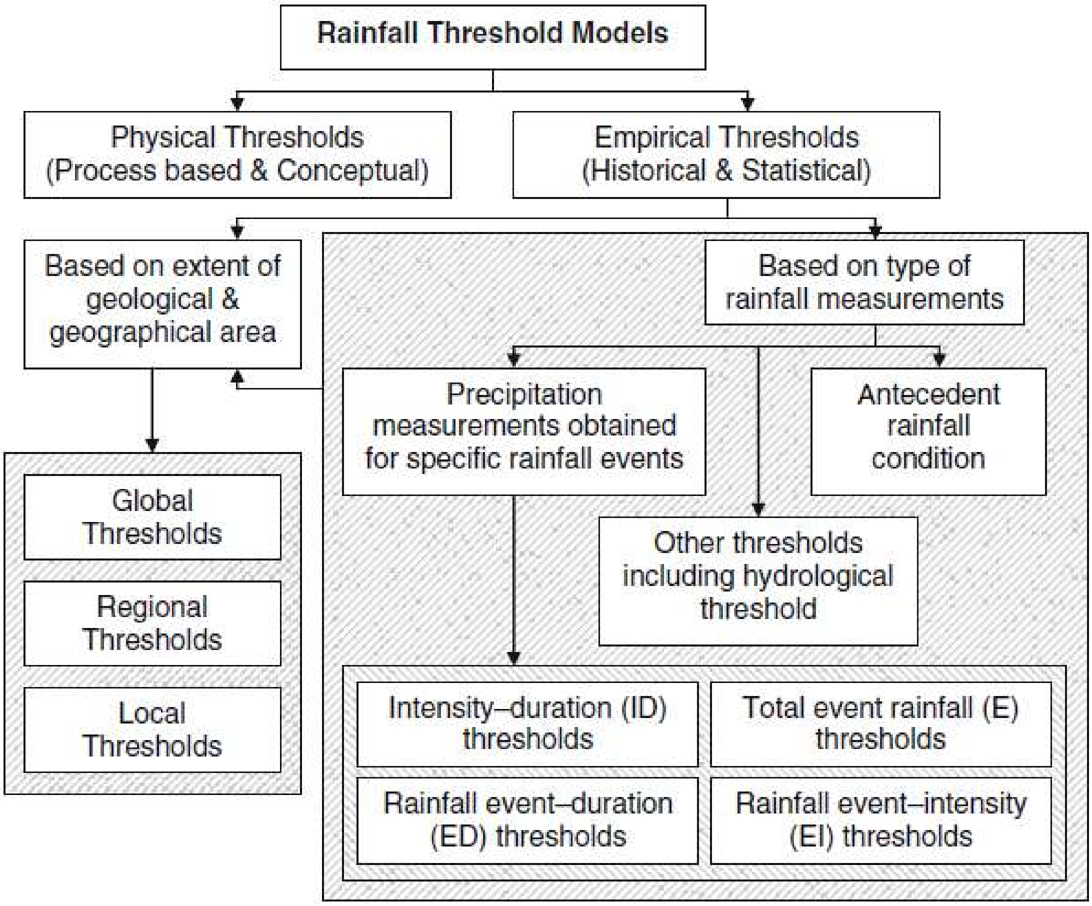


Fig. 4.7: Flow diagram of different rainfall threshold models for landslide occurrences (after Guzzetti et al., 2007; Kanungo and Sharma, 2014)

In order to derive a local rainfall threshold model for the landslide occurrences district wise for northern Kerala, first, the rainfall and landslide information was to be collected extensively at least for the last five years along with their GPS locations. Hourly rainfall intensity in millimetres (millimetres per hour) and duration of rainfall in hours are needed to derive an Intensity-Duration (ID) threshold for the region. The distribution of the rainfall conditions [i.e. log (I) vs. log (D)], that have resulted in landslides, is fitted the power-law distribution with an equation of the type log (I) =log (α)+β log (D) or $I = \alpha D^{\beta}$, where I is the rainfall intensity (in millimetres per hour), D is the duration (in hours), and α and β are empirically derived parameters. In the power-law equation, the coefficient α and the exponent β define the location of the critical intensity value. Secondly, as the duration of rainfall increases, there is a decrease in initiation. In the power-law equation, the exponent β defines the rate at which critical intensity decreases with increasing rainfall duration. The rainfall intensity and duration for all the rainfall events causing landslides in the area may be plotted in a log-log graph and it will appear something like shown in Fig. 4.8.

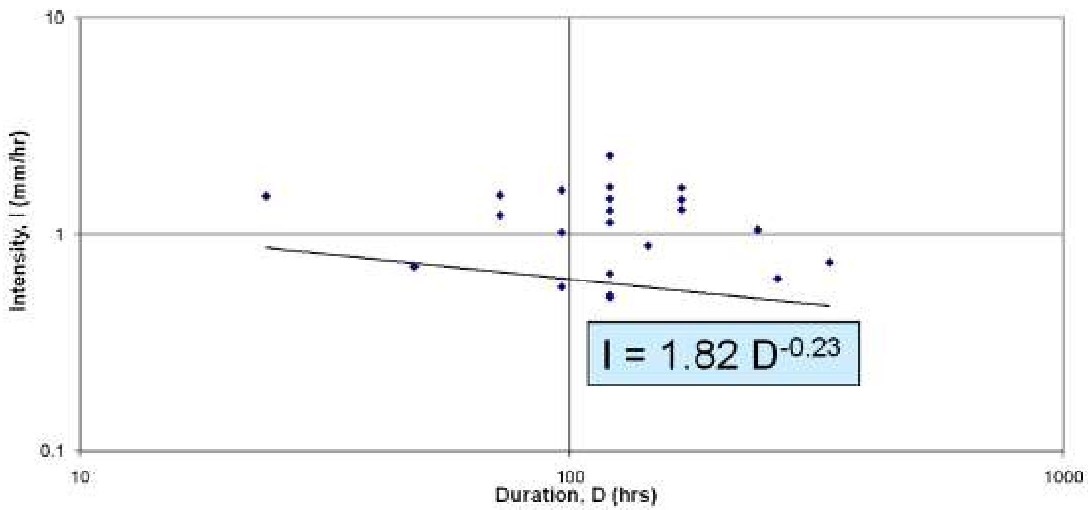


Fig. 4.8: Rainfall intensity–duration (ID) threshold based on estimation from daily rainfall data for the initiation of landslides in Chamoli-Joshimath region of Garhwal Himalaya, India (after Kanungo and Sharma, 2014)

The threshold approach for predicting landslide occurrence using a power-law equation is based upon two assumptions (as mentioned in Figure 4.8). Firstly, there is a nonlinear increase in the probability of landslide initiation with increasing rainfall intensities. This is represented by the actual threshold value for slide or flow initiation. Below the threshold value, there is a lower probability of landslide initiation. At and above the threshold, there is a rapid, nonlinear increase in the likelihood of initiation.

Recently, Abraham et al. (2019) proposed a regional scale rainfall threshold for the Idukki district. This empirical threshold is the only study for the state of Kerala. The maximum duration of a rainfall event observed during the study period was 31 days. The obtained results predict that the intensity of 0.3 mm/h over a period of 31 days can trigger landslides in the region. The maximum number of events occurred at a duration of 7 days for which the minimum intensity to initiate a landslide event was found to be 0.4 mm/h (Fig. 4.9). The lesser value of thresholds for short duration events emphasizes the need for considering antecedent rainfall conditions for defining thresholds. Hence the researchers also proposed thresholds based on antecedent rainfall conditions for Idukki district. A significant share of landslide events is found to be biased towards the antecedent rainfall in all cases. Hence a threshold is defined for 40 days durations of antecedent rainfall considered in the study as shown in Fig. 4.10. From the analysis, it was found that, if three days' antecedent rainfall was considered, 28% of the total events considered are shifted towards daily rainfall, and the remaining 163 landslides are biased towards three days' antecedent rainfall. For other cases, the biasness ratio to daily rainfall and antecedent rainfall was found to be 11:214 for 10 days', 6:219 for 20 days', 3:222 for 30 days', and 1:224 for 40 days' antecedent rainfall prior to the slide event. It is evident from the analysis that the biasness towards antecedent rainfall, which was 72% in the case of 3 days' antecedent rainfall increased to 99.56% when the antecedent rainfall of 40 days was considered as shown in Fig. 4.10.

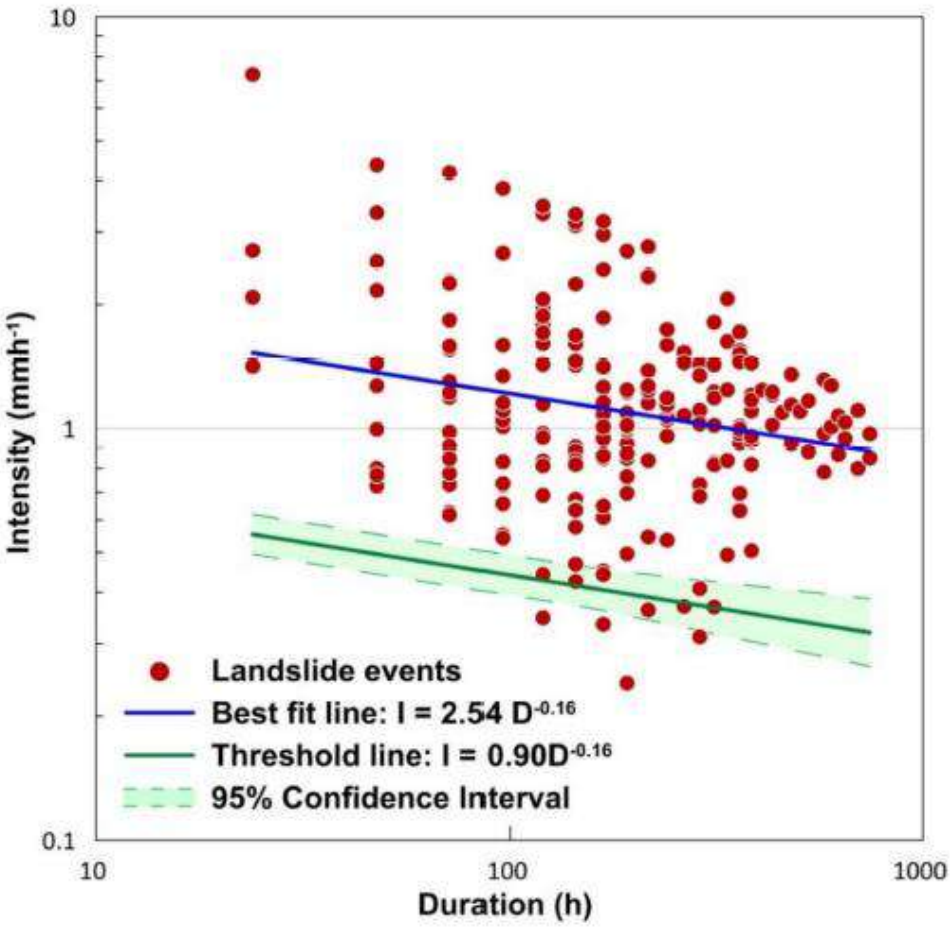


Fig. 4.9: Intensity-duration threshold for the Idukki district on a logarithmic scale (Abraham et al., 2019)

The methodology of establishing rainfall thresholds is the need of the hour. So far, very limited studies had been carried out in Kerala. The empirical nature of the model makes it more vulnerable to false warnings. The model is needed to be supported with extensive data backed up with proper modelling and interpretation. Better resolution rainfall and landslide data are needed to improve upon the threshold models at both local and regional levels and finally to develop a landslide early warning system with an objective to protect human lives from rain-induced landslide disasters.

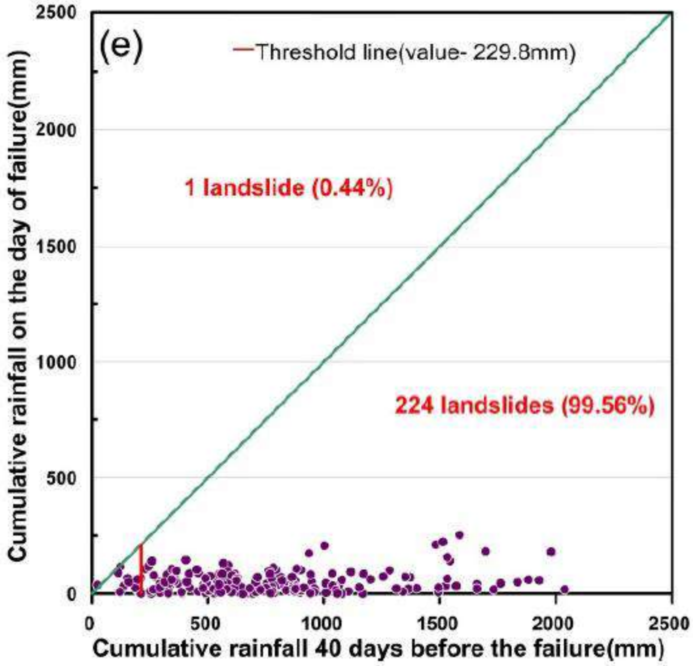


Fig. 4.10: The plot between daily rainfall and antecedent rainfall for 40 days before failure (after Abraham et al., 2019)

4.10. Field observations

Malappuram and Wayanad districts witnessed severe landslides causing loss of many human lives during 7th, 8th and 9th August 2019. Fifty-nine people lost their lives in the Kavalappara area. Some of the dead bodies could not be recovered. There are reports of missing people in the Puthumala area in Wayanad district. A brief account of the field observation in two heavily affected places is provided here.

4.10.1. Kavalappara Landslide, Malappuram district

Field investigation of the landslide that occurred at Kavalappara in August 2019 reveals the following:

The main area affected by landslide in the form of debris flow lies on the north-western flank of a NE-SW trending hill ridge with a peak elevation of 280 m. Several other minor debris flows are also noticed on the hill slopes on either side of Kavalappara todu, a third-order stream that drains the area. The crown region where the debris flow was initiated with a displacement of material has a width less than 100 m only. The width of displaced material increases down the slope and, in the valley, the width of displacement exceeds 500 m. The run-out has further progressed down the valley choking the stream.

The upper slope above 190 m above MSL elevation, where the surface material has been totally removed by the debris flow exposing hard rock, has a slope of 41^0-44^0. A break in slope is observed at this elevation of 190 m above MSL. The grass-covered undisturbed mid-slope region has a natural slope of 28^0-30^0 while the freshly formed debris slope due the landslide is inclined at 18^0-20^0. The lower slopes are less than 18^0. The hill slope is more or less a rectilinear segment with a distinct break in slope between the mid-slope and upper slope at about 190 m. The overall slope length from the crown to the valley where the bulk of the material has been deposited is about 600 m. The morphology of the hill facet has been largely modified by the debris flow. It is also seen that two patches confined to the elevated spurs have been unaffected.

Along the hill flanks, several minor hollows are seen. The junction of the hollow portion with the foot slope shows the presence of springs or the source of first-order streams. In the zone of transportation of this landslide, at least two distinct hollows log-log through which the admixture of stormwater and displaced mud has been conducted mostly as subsurface flow. After the incident, at least two first-order streams have developed in the scoured-out part of the hollow region near the inter junction of mid-slope and foot slope.

The major land use in the affected site and its vicinity is rubber plantations. The foothill zone on either side of the valley part had a fairly dense linear settlement, a part of which falling in the path of debris flow has been wiped out. The mid-slope region is almost entirely under rubber plantation but signs of isolated dwelling units are also observed. The upper slope is also under rubber but patches of natural vegetation are seen on the western part that is unaffected by the calamity. Multi date satellite images of this location indicate that the upper slope was under natural vegetation in 2007, degraded in 2011, completely cleared in 2012 and fresh terracing for plantation was done after 2018.

The major rock types in the area are hornblende-biotite gneisses with enclaves of amphibolites. They are well foliated and jointed. The rocks are weathered deeply in places, especially in the mafic rich segments. The hill slope, in general, supports reddish clay-rich overburden admixed with large sized boulders of varying size derived from the parent rock. Large-sized boulders of vein quartz indicate the presence of deep-seated fault/fracture planes in the area. Figure 4.11 shows the various images of the landslide with description.

a) General view of the Kavalappara landslide. Looking from the road towards SE. Note the first-order streams developed in the hollow portion. The unaffected patch is visible in the centre of the photograph.

b) The crown region of Kavalappara landslide exposing the hard rock basement overlain by thin overburden consisting of reddish clay material admixed with assorted boulders of varying size. Note the young rubber plants.

c) The upper section of the Kavalappara landslide region exhibits the deeply weathered nature of the material. Reddish material is mainly from the weathering of mafic minerals while the white patches are from felsic minerals.

d) Another view of the upper section of the Kavalappara landslide region indicating the slid surface exposing hard rock. The bulk of the displaced material has accumulated at the zone of the break in slope. Removal of this material partly along the hollows has resulted in depressions that get filled with stormwater.

e) The spur in the centre of the photograph has helped to divert the debris flow at Kavalappara to the hollow region on its either flanks. As a result, the lower slope of the spur remained unaffected by debris movement.

Fig. 4.11: Images of Kavalappara landslide with descriptions

Analysis of the terrain conditions indicates that this location has most of the conditions of a landslide-prone zone. The hill facet is a rectilinear slope having a length of about 600 m. The middle and upper slope is in excess of 20^0, the threshold for the occurrence of landslides in the Western Ghats. The presence of hollows in the hill slopes again channelizes stormwater into it. The area was recently disturbed heavily by the removal of the natural vegetation and construction of terraces for planting rubber. All these factors are in favour of imminent landslide activity. The triggering factor was the rainfall in the region that exceeded 20 cm in a day in a continuous rainy period and the terracing and tilling activity in the upper slope. This area is also identified as a landslide-prone area in the hazard zonation map of Kerala.

4.10.2. Landslides in Puthumala region, Wayanad district

Sudden mass movements involving detachment of debris-laden material from upslope, transportation of the debris and stream deposits down the slope along the valley of the stream by the combined force of stormwater and fluidized mud and its deposition in the lower part of the valley which is relatively flat has led to a disaster in the Puthumala region. Most of the dwelling units located in the lower valley and on either side of the stream banks have been damaged either partly or completely. Although people were shifted to safer places there was a loss of some human lives. Field investigation around this area has revealed the following:

- ✓ Several debris flows are seen on either side of the stream draining to Puthumala. Most of them are confined to the hollows on the hill slope dislodging the cover material in the hollow portion. All these flows are seen in slopes exceeding 25^0. Lunar cracks with about half meter vertical displacement are noted in the eastern slope adjacent to the settlement. Several houses constructed on slopes with a cutting of more than 3 m on loose unconsolidated material have been damaged.
- ✓ The origin of the major debris flow is located on the eastern flank of the stream, in the mid-slope region of the hill slope at an altitude of 1140 m above MSL, and where the rock is in contact with soil and overburden (Lat: 11^0 30’ 02.1” N, Long:76^0 07’ 54.0” E). The crown region is about 50 m wide and slightly widens near the stream.
- ✓ The upper rocky slope is inclined at about 40^0 while the lower debris mantled overburden and soil cover slopes at 31^0. The overall slope length from the crest to the stream is about 350 m in the crow flies distance. The lower slope has a thick overburden rich in reddish clay material admixed with boulders. The upper slope is rocky or with a thin veneer of soil. Major rock type is foliated hornblende biotite gneiss. The main scarp of the landslide is in the natural forest region. The Puthumala thodu near the main scarp is a second-order stream with a small catchment.
- ✓ From the displacement path of the material, it is seen that the debris was not confined to the valley, but crossed over to the valley on the NW side. The vegetation in this NW valley slopes, mostly cardamom and other trees, have been damaged to a great extent.
- ✓ The presence of watermarks at about 1.5 m height on the tree trunks in the undisturbed upper part of the stream indicates the possibility of some kind of temporary ponding of water in this valley prior to the devastating debris flow.
- ✓ The scouring effect of fluidized debris and stormwater on the valley part is evident from the presence of cuttings on either bank. Many dwelling units in this region are removed from its location.
- ✓ The relatively flat land where the main road crosses the valley, at least two metres thick deposit of debris and other material brought down from the upper slope by the stream is seen. The houses in this segment are buried in the muck. Field evidence indicates that the water level at the time of debris flow was at least 3 m above the present floor level.
- ✓ The lower valley and the lands adjoining the stream were well connected with the road network. The density of settlement as observed from the recent satellite images in this area is also high causing a large number of casualties.

Based on general observations and analysis, it emerges that the upper section of the catchment with steep slopes, deep overburden and with relatively dense settlement provide a favourable location for the occurrence of the landslide. The hazard zonation map of Wayanad district shows Puthu mala, Chooral mala, and Vellari mala areas as landslide-prone zones. Multiple debris flows in the hollow along with the main landslide resulted in a large quantity of material being dislodged and moved into the lower valley. The possibility of temporary ponding in the valley head and its subsequent breach leading to heavy discharge of water along the stream causing the damage cannot be ruled out.

Field investigations in two sites, Kavalappara and Puthumalai area bring out that debris flow is the dominating landslide type experienced in these places. There are some bank failures also along the main watercourses. Slides are triggered by heavy rainfall in consecutive days. The rain gauge station in Nilgiris reported 216 cm of rainfall during four days period from 6th to 9th August. Debris flows took place along the hollow portion of the slope drained by a first-order/ second-order stream, gathered momentum and further flowed down into the valley bottom. Slope inclination is found to be > 20^{o} in all cases. Such slopes are reported as unstable slopes in the Western Ghats region. Interventions along the hill/ mountain slopes replacing natural vegetation and shaping of land in the form of terraces contributing to high infiltration have facilitated the failure. It is important to note that landslide affected areas are distributed in the hazard-prone zones of medium and high category in hazard zonation map of the districts. Land use change and doctoring of slopes have upscaled the medium category into the high category manifesting the role of human intervention in aggravating landslides in the State. Construction of settlements not only in the vulnerable slope but also along the path of debris flow appears to be risky. Therefore, it is important to mark the probable track of debris flow and zone of deposition along with landslide hazard zones. The micro watershed-based approach will be helpful in this context. Figure 4.12 shows the image of landslides in the Puthumala region, Wayanad district and its description.

a) The crown region of the major slide is on the left-hand side, the stream draining to Puthumala is in the centre as a linear depression, and the material crossed over to the adjacent valley is on the right-hand side. The tree in the centre of the valley indicated a water mark up to 1.5 m above ground level. Note the rocky upper slope and debris mantled lower slope.

b) The crest part of the ridge on the western side of the stream is now covered with the debris brought down from the crown region. The scoured valley is seen in the far ground.

c) The fractured basement rock is exposed in the stream bed. All the cover material has been removed by the swift flow of water. The rock type is mostly well-foliated hornblende-biotite-gneiss. Closely spaced fractures add to instability in the area.

d) The hollow portion in the eastern slopes is affected contributing to the debris flow in the region. Several such minor flows are seen on the slope with the development of a first-order stream in the hollow portion.

e) Pucca concrete building is damaged by a large-sized boulder fallen from the upper slope. Note the 5m high vertical cutting on loose unconsolidated material on the rear side of the house-made for the construction of the building.

f) The flat part of the valley where the debris was deposited is shown in the photograph. The remains of a house buried above the lintel level are on the right-hand side. The original stream channel is obliterated.

Fig. 4.12: Images of Puthumala landslide with descriptions

4.11. Numerical analysis of Landslides

Numerical analysis has been performed to evaluate the factor of safety of slopes using Finite Element based Computer Program PLAXIS 2D (PLane strain and AXial Symmetry) v2018.01. In this regard, two typical case studies which were critical and occurred at Kavalappara (11.414° N, 76.237° E) of Malappuram district and Munnar town (10.087° N, 77.094° E) of Idukki district in the Kerala state of India are considered for the numerical analysis. These two incidents were triggered in the month of August due to heavy rainfall.

4.11.1. Numerical simulation

Plain strain 15 nodded triangular elements are used to model the slopes which are available in the library of the PLAXIS 2D program. The constitutive models for rock and soil materials are considered as linear elastic and elastic perfectly plastic with Mohr-Coulomb failure criterion respectively. The standard boundary conditions have been chosen for the present analysis which simulates the base of the model is restrained in all the directions and the roller boundaries have been assigned to the sides of the model that means it is free to move in the vertical direction and restrained in the lateral direction. For each problem the size of the mesh is freeze after numerous iterations this process is called mesh optimization and this ensures that further finer mesh will not impact much on the output of analysis rather than timeconsuming. Each analysis has been performed in three steps: Step I is the initial phase analysis in which the model is subjected to gravity load, Step II is the plastic analysis which evaluates the incremental stresses generated in the rock and soil continuum due to rise in the groundwater level and slope instability, and Step III is the safety analysis which evaluates the factor of safety of slopes using incremental multipliers loading type. Each case study has been analyzed for three cases which represent different levels of groundwater table (GWT): Case 1 - water level at the bottom of the slope, Case 2 - water level at rock slope surface (i.e. at the interface between rock and soil), and Case 3 - water level at soil slope surface (i.e. fully saturated condition). Thus, these three cases capture the response of rock and soil materials at various levels of degree of saturation which they underwent during the monsoon season.

During the site visit in the month of October (more than two and half months after the incident happened), it was noticed that most of the failed slope material was removed from the places as part of rescue efforts. Therefore, Prof. Deepankar Choudhury of Indian Institute of Technology Bombay (IIT B) had requested Prof. S. Chandrakaran of National Institute of Technology Calicut (NIT C) to share soil investigation data with IIT B for numerical modelling. Thus, in the present analysis, the index and engineering properties of soil material are taken from the report (Ref: CED/CON/SC/2019175) forwarded by Prof. S. Chandrakaran of NIT C and summary is given in Table 4.7. Since the exact features of the landslides were not available, therefore rough dimensions were considered in the numerical analysis of both the case studies.

4.11.1.1. Case Study 1: Kavalappara site

Based on the field visit and photographs taken during the site visit in the month of October (Fig. 4.11**),** rough dimensions of the slope are considered for numerical modelling and it is shown in Fig. 4.13. The entire slope is divided into three zones, the slope angle (β) of each zone is idealized as 40°, 30°, and 15° for zone 1, 2, and 3 respectively (see Fig. 4.13). The height of the landslide is roughly estimated as 246 m while the width of the slope as 526 m. The Landslide depleted part of 1st zone and entire 2nd zone. The lowest part of the 2nd zone and 3rd zone form the zone of accumulation. Unfortunately, this zone of accumulation is the settlement area of the Pothukal village panchayat near Bhoodanam in Kerala's Malappuram district.

Table 4.7: Variation in the index and engineering properties of soil

Moisture content (%)	**Bulk density (g/cc)**	**Shear strength parameters**		**Grain size distribution (%)**			**Consistency limits (%)**	
		***C* (kPa)**	**φ (°)**	**Silt + Clay**	**Sand**	**Gravel**	**Liquid limit**	**Plastic limit**
4.26 - 18.8	1.34 - 1.76	2 - 74	22.29 - 36.69	20 - 76	21-54	1 - 40	34.5 - 63.1	22.9 - 35.31

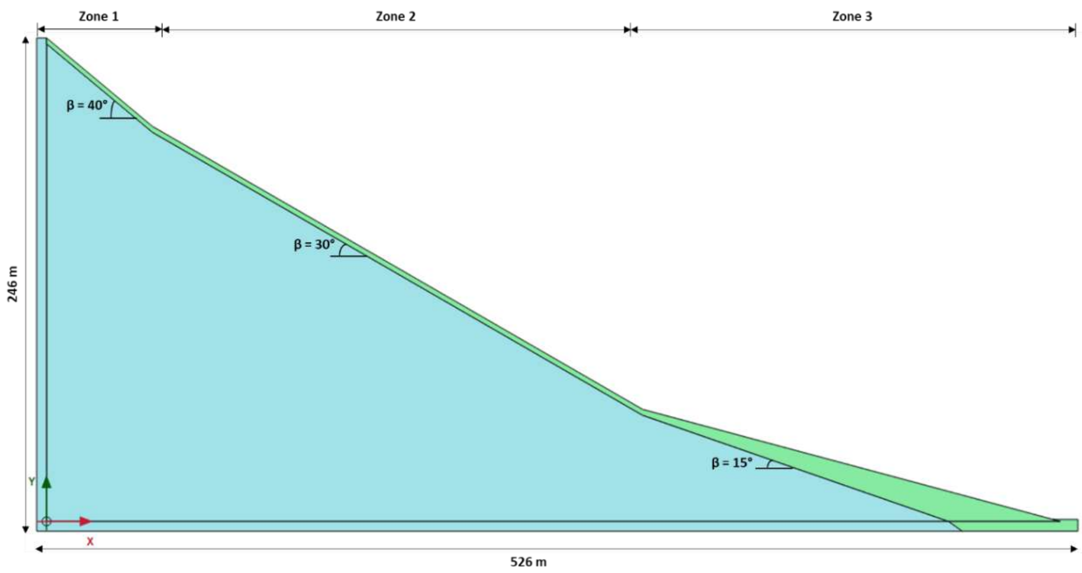


Fig. 4.13: Input geometry of slope in the numerical model at Kavalappara site of Malappuram district

The maximum thickness of the soil material slid during landslide could not be established accurately and approximated nearly 3 m because most of the failed slope material has been removed from the place as part of the rescue effort. Typical finite element mesh discretization of the considered slope model (mesh view) is shown in Figure 4.14. In Case 1 numerical analysis – the water level is considered at the bottom of the model (see Figure 4.15) and the typical estimated geostatic stresses (initial phase) are shown in Figure 4.16. Once the geostatic stresses are stabilized, then plastic and safety analyses were carried out with all these input parameters and slope geometry and obtained the factor of safety as 1.22, which indicates the slope is safe in dry State.

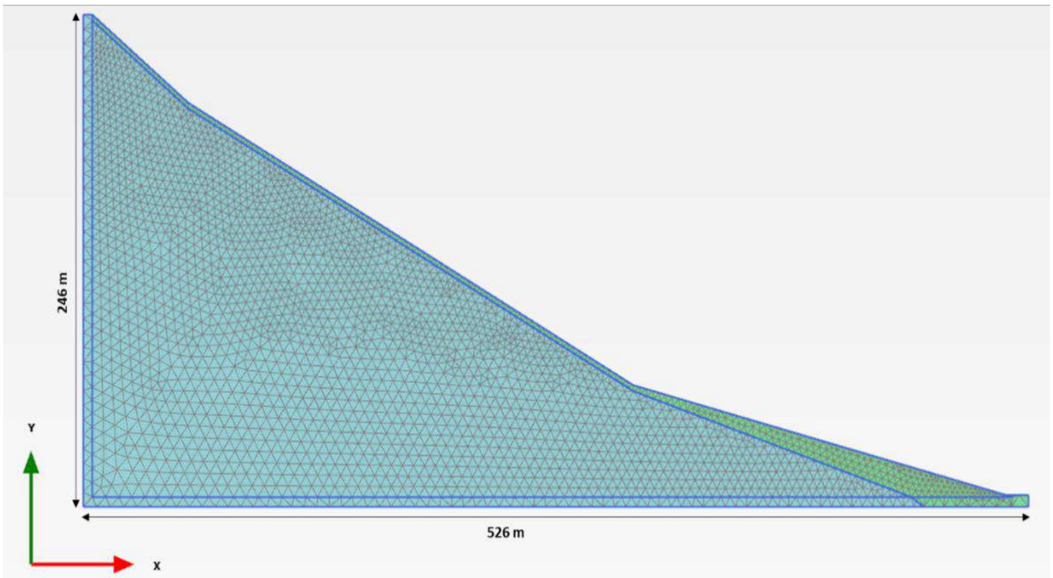


Fig. 4.14: Finite element mesh discretization of slope considered

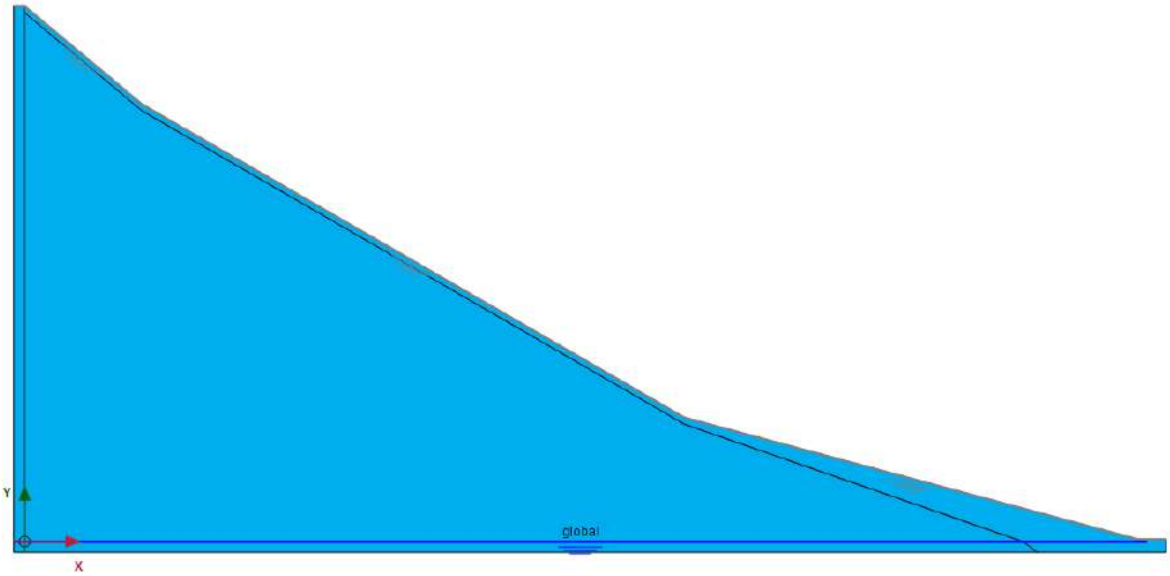


Fig. 4.15: FEM model, the water level at the bottom of the slope (dry condition) - Case 1

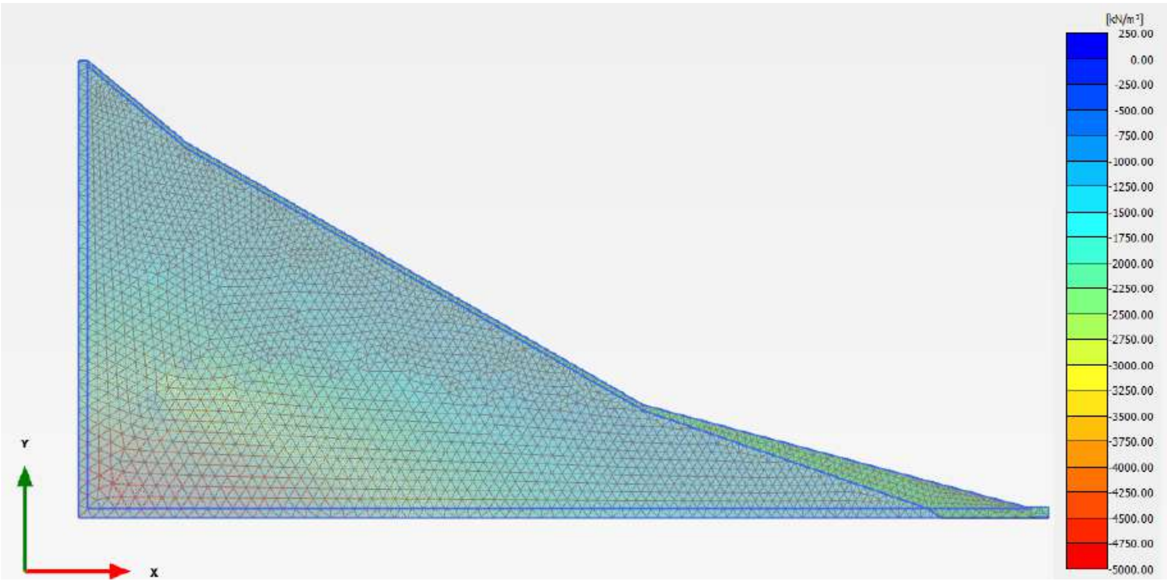


Fig. 4.16: Estimated geostatic stresses (σyy - vertical effective stress) in the FEM model – Initial phase for Kavalappara landslide site

Similarly, the factor of safety for Case 2 (groundwater level at rock slope surface as shown in the Figure 4.17, i.e. partially saturated) and Case 3 (groundwater level at soil slope surface level as shown in the Figure 4.18, i.e. fully saturated) are obtained as 1.15 (safe) and <1 (not safe) respectively.

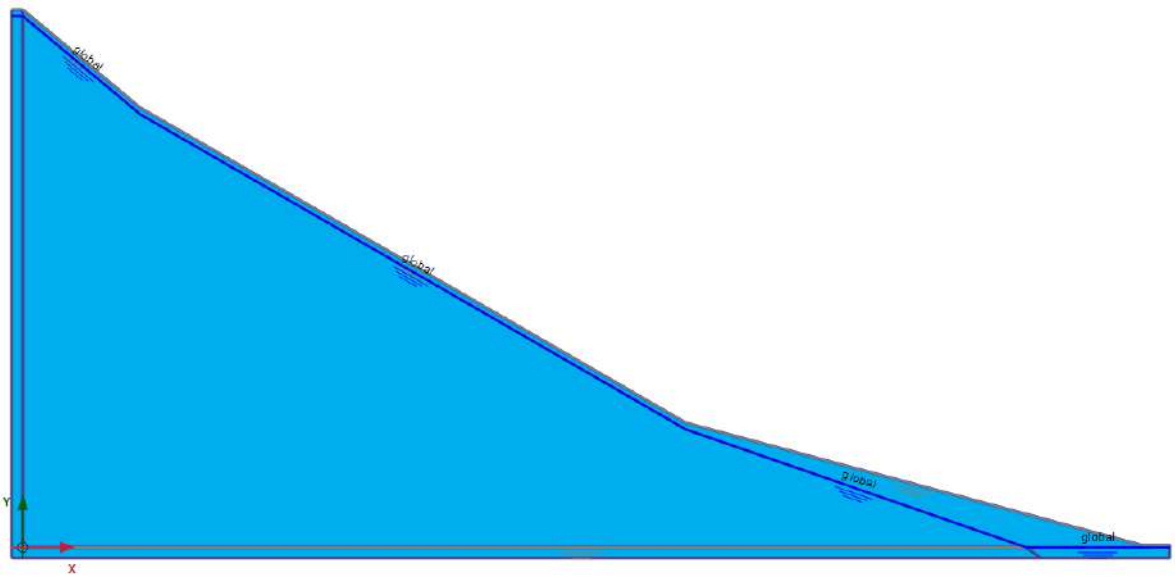


Fig. 4.17: FEM model, the water level at the bottom of the slope (partially saturated) - Case 2

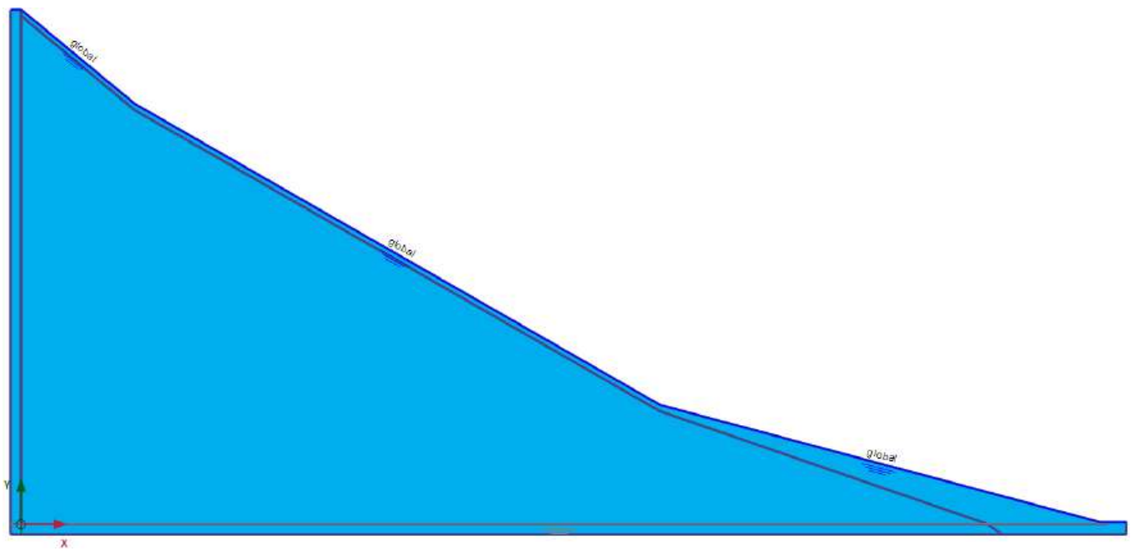


Fig. 4.18: FEM model, the water level at the bottom of the slope (fully saturated) - Case 3

Figures 4.19 and 4.20 show the displacement contours and deformed mesh of the slope at the time of failure (Factor of Safety, FoS < 1) – Case 3. From Figs. 4.19 and 4.20, it is evident that the movement of soil mass was first initiated at the crown of the slope (see Zone 1 of Figure 2) which was also noticed during the site visit in October month.

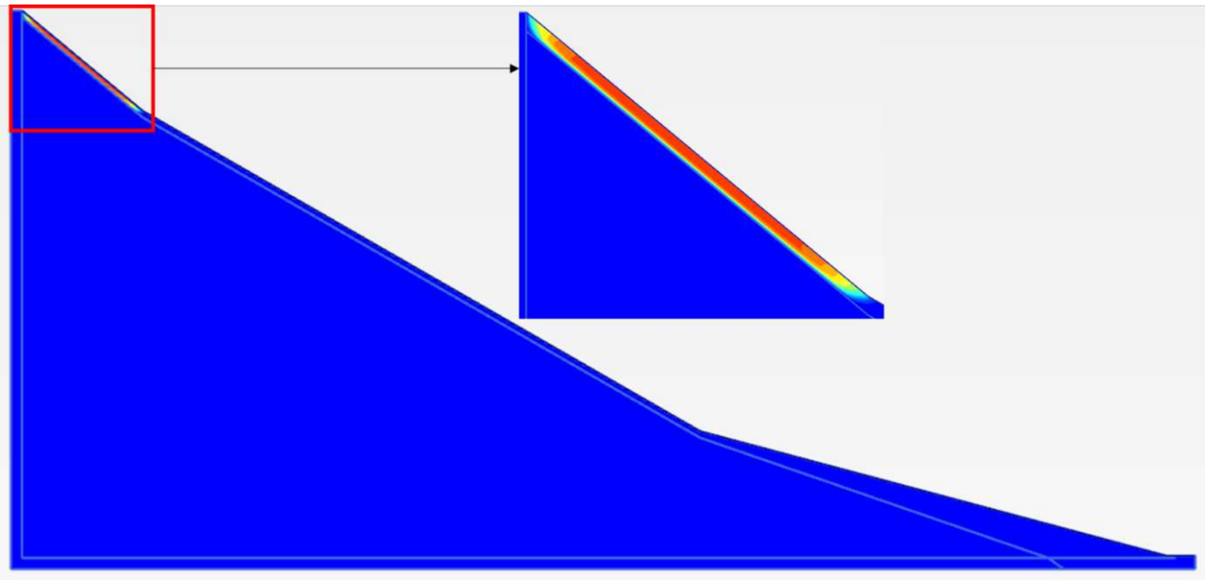


Fig. 4.19: FEM model, incremental displacement contours at the time of failure (fully saturated) - Case 3 (FoS < 1)

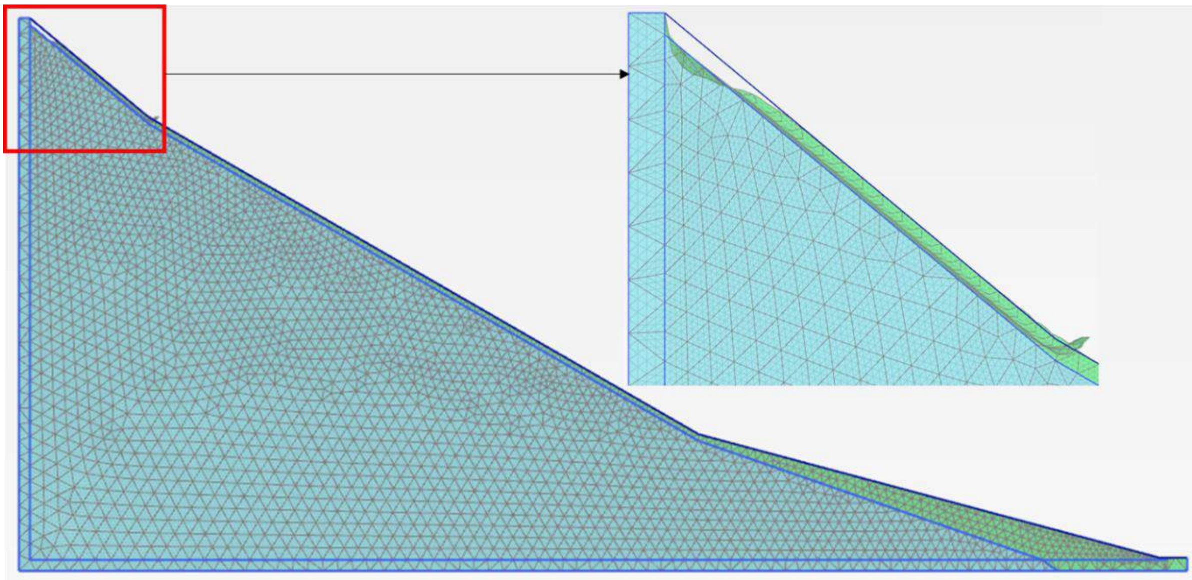


Fig. 4.20: FEM model, deformed mesh shape at the time of failure (fully saturated) - Case 3 (FoS < 1)

4.11.1.2. Case Study 2: Landslides at Munnar town, Idukki district

Five landslides sites in Munnar town of Idukki district were visited during the site visit on 24-25 October 2019, which were occurred during 2018 and 2019. The key observations are summarised in Table 2.

Table 4.8: Summary of landslides occurred at Munnar town, Idukki district (visited during 24-25 October 2019)

No	Lat (°N)	Long (°E)	Place	Remarks	Figure	Occurrence
LS1	10.087	77.094	Munnar Silent Valley Road	• A small stream was there and later it was blocked • Mainly Lateritic soil • Slope inclination - 40° to 50° • Slope height ~ 15m • No casualty	Fig. 4.21 a, b	2019
LS2	10.082	77.073	Govt. College Munnar	• Just beside college building • Elevation 1518m • Drainage block • Cracks observed previously	Fig. 4.21 c	2018
LS3	10.068	77.106	State Bank Office Building	• Due to landslide, the building is tilted and now it is in a non-operational condition	Fig. 4.21 d	2018
LS4	10.036	77.128	Ghat Road 1	• Elevation 1681m • Two casualties • This road made Britishers, then NHAI wants to widen the road and resulted in a big series of landslides • Purely anthropogenic activities caused the landslide	Fig. 4.21 e, f	2019
LS5	10.037	77.130	Ghat Road 2	• Purely anthropogenic activities caused the landslide	Fig. 4.21 g	2019

Fig. 4.21: Landslide occurrences near Munnar, Devikulam and Ghat Road (see Table 4.8 for reference)

Out of five landslides mentioned above in Table 2 which were occurred in Munnar Town in the last two years, the landslide 1 (LS1) is further idealized to analyze using a numerical model. The initial steps of the numerical model such as mesh optimization, boundary conditions, three levels of groundwater table (GWT) remain the same as explained in Case study 1. During the site visit in the month of October, it was identified that most of the soil of LS 1 is Lateritic soil with predominantly clay and slit particles and also most of the failed slope material was removed from the places as part of rescue efforts and the road. Therefore, soil parameters given in Table 1 are considered for Case Study 2 numerical modelling.

Due to the non-availability of exact features of the slope of LS1. Based on the photos taken during the site visit in the month of October, which are shown in Figs. 4.21 a and b, rough dimensions of the slope are considered for numerical modelling and it is shown in Fig. 4.22. The entire slope is divided into four zones, the slope angle (β) of each zone is idealized as 40°, 60°, 15°, and 25° for zone 1, 2, 3, and 4 respectively (see Fig. 4.22). The height of the landslide is roughly estimated at 10 m while the width of the slope as 22 m.

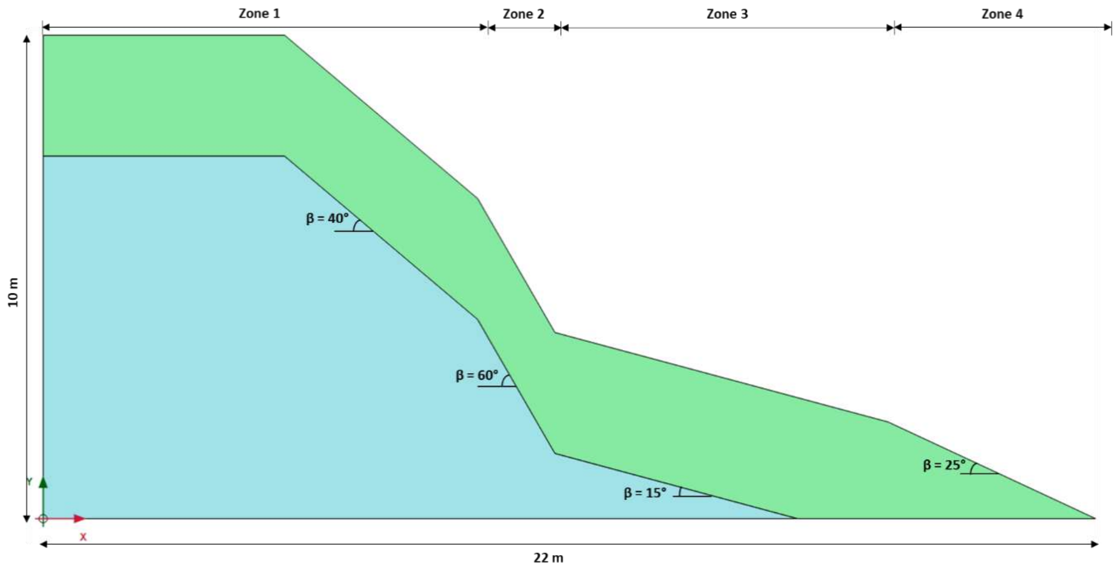


Fig. 4.22: Input geometry of slope in the numerical model at Munnar Silent Valley Road site (LS1)

The maximum thickness of the soil material slid during landslide could not be established accurately and approximated by nearly 2.5 m because most of the failed slope material has been removed from the place as part of the rescue effort. Typical finite element mesh discretization of the considered slope model (mesh view) is shown in Figure 4.23. In Case 1 numerical analysis - the water level is considered at the bottom of the model (as considered in Case Study 1, see Figure 4.15) and the typical estimated geostatic stresses (initial phase) are shown in Figure 4.24. Once the geostatic stresses are stabilized then plastic and safety analysis are carried out with all these input parameters and slope geometry and obtained the factor of safety as 1.3 which indicates the slope is safe in the dry state.

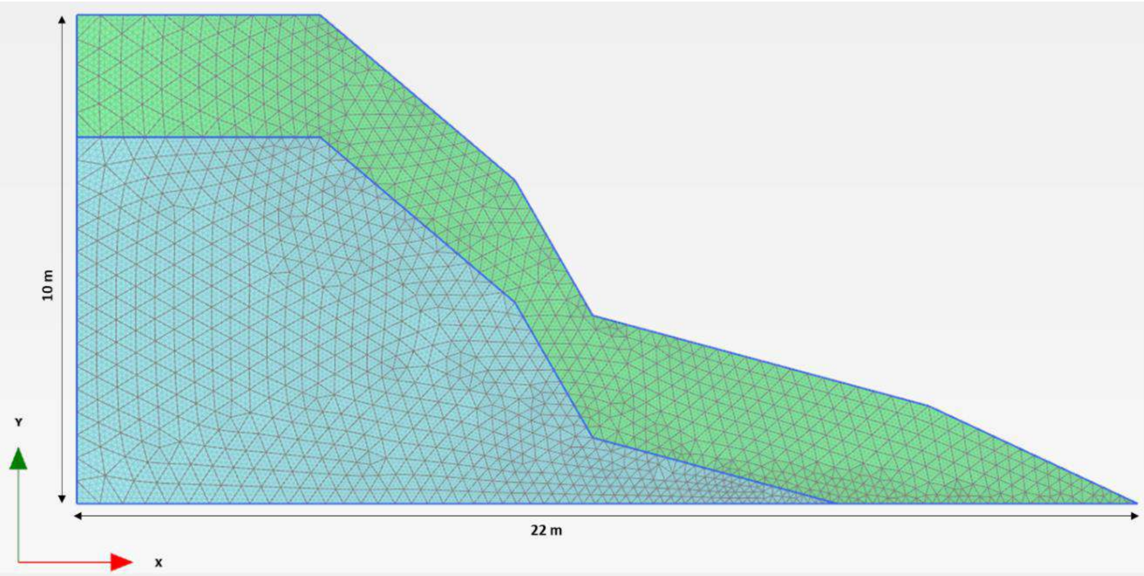


Fig. 4.23: Finite element mesh discretization of slope considered for the numerical model for Munnar Silent Valley Road site (LS1)

Similarly, the factor of safety for Case 2 (groundwater level at rock slope surface as shown in Fig. 4.17 of Case Study 1, i.e. partially saturated) and Case 3 (groundwater level at soil slope surface level as shown in Fig. 4.18 of Case Study 1, i.e. fully saturated) are obtained as 1.2 (safe) and <1 (not safe) respectively.

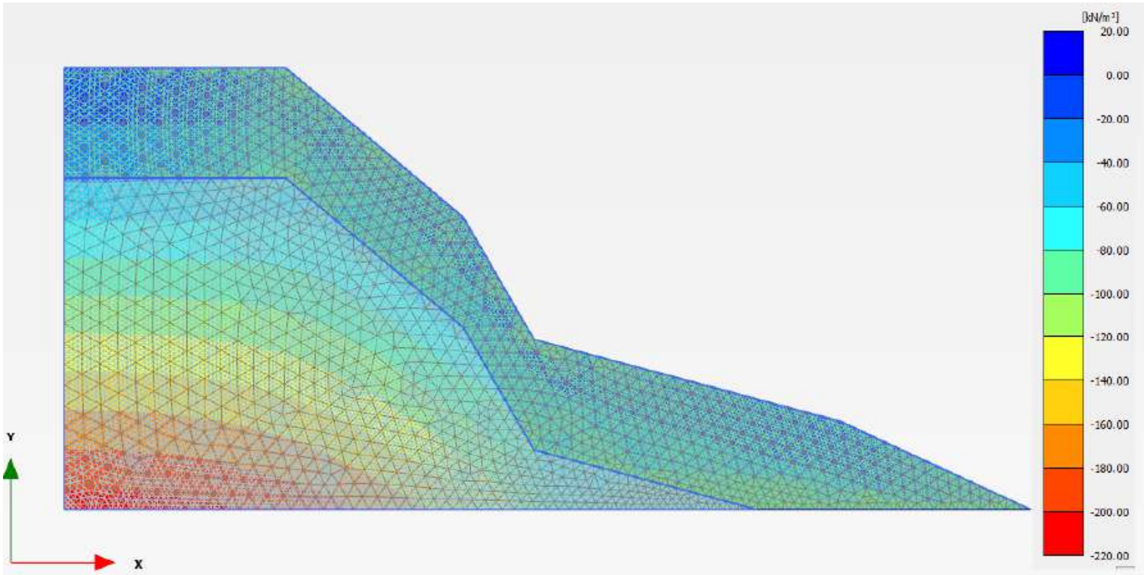


Fig. 4.24: Estimated geostatic stresses (σyy - vertical effective stress) in the FEM model - Initial phase for Munnar Silent Valley Road site (LS1)

Figures 4.25 and 4.26 show the displacement contours and deformed mesh of the slope at the time of failure (FoS < 1) – Case 3. From Figs. 4.25 and 4.26, it is evident that the movement of soil mass was first initiated at the crown of the slope (see Zone 1 of Fig. 4.22) and then flows through the entire Zone 2, and 3. The lowest part of zone 3 and entire zone 4 form the zone of accumulation which was also noticed during the site visit.

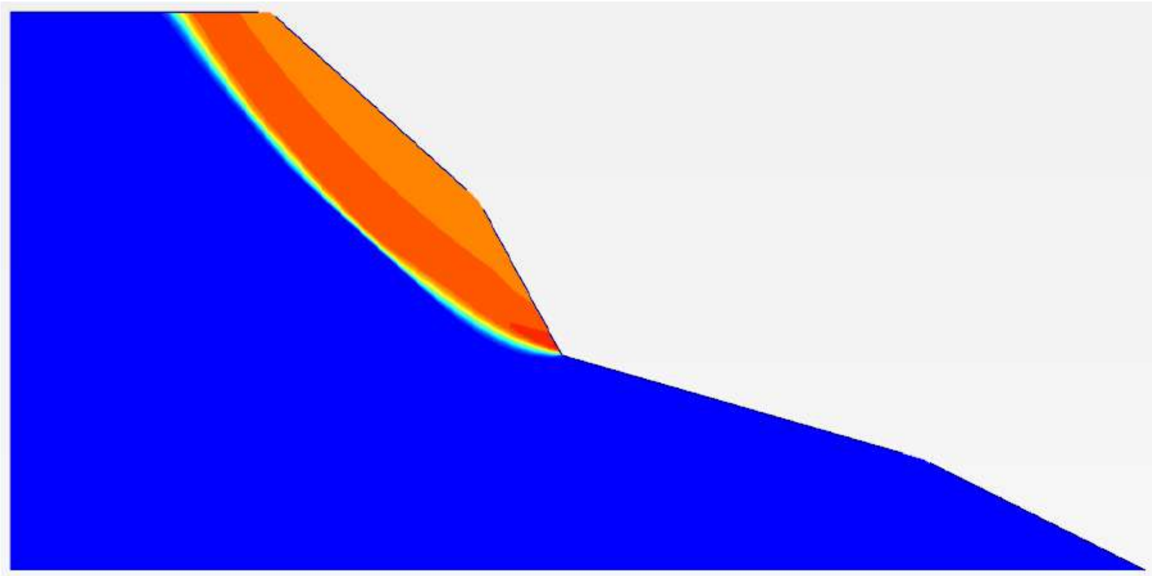


Fig. 4.25: FEM model, incremental displacement contours at the time of failure (fully saturated) – Case 3 (FoS < 1) for Munnar Silent Valley Road site (LS1)

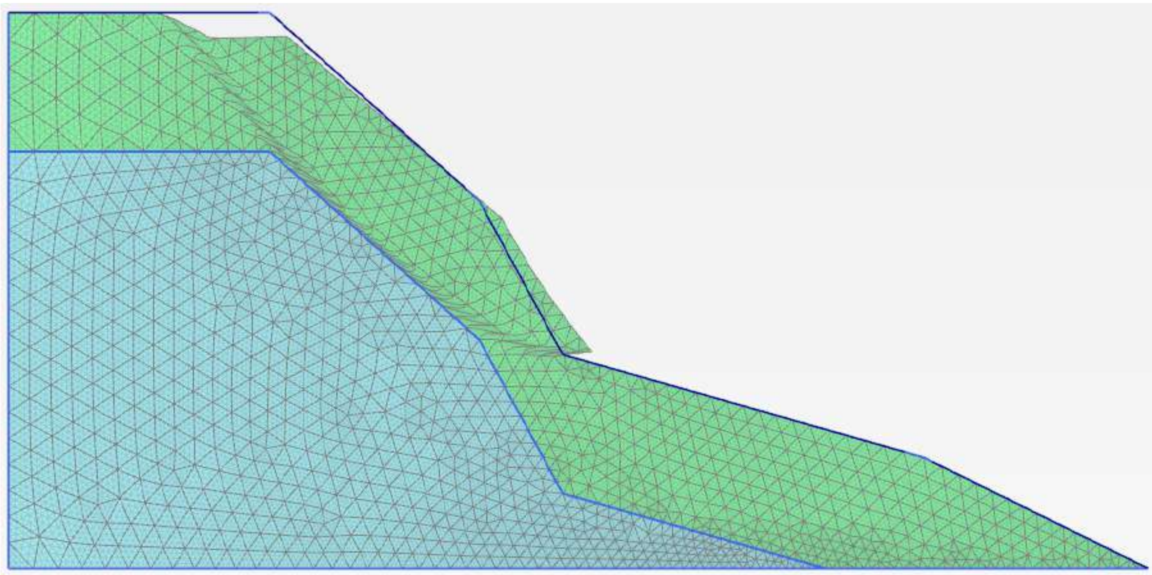


Fig. 4.26: FEM model, deformed mesh shape at the time of failure (fully saturated) – Case 3 (FoS < 1) for Munnar Silent Valley Road site (LS1)

4.11.2. Observations from the modelled output

The catastrophic landslides which occurred along the upslope of Kavalappara (11.414° N, 76.237° E) of Malappuram district and Munnar town (10.087° N, 77.094° E) of Idukki district, Kerala in August 2019 and claimed the lives of more than 55 humans and effected the infrastructure heavily. Heavy rainfall over the previous one week was identified as the triggering mechanism of slope failure. A back analysis is performed on the failed slopes to identify the cause of slope failure/landslide. For this purpose, two typical landslides sites were chosen for numerical analysis using Finite Element based Computer Program PLAXIS 2D v2018.01. PLAXIS 2D program is used to analyze the stability of the pre-slide and pattern of landslide during its failure. Thus, here it has been noticed that a considerable decrease in soil strength (factor of safety as well) due to a sudden rise in the degree of saturation of soil mass which was the result of rainfall infiltration. This is due to the loss of matric suction in the unsaturated zone of soil slope which causes the lowering of strength of the soil. Hence, the stability of soil slopes subjected to rainfall must incorporate the concepts of unsaturated soil mechanics. Moreover, this analysis can be considered as an effort to present the problem in hand from a numerical point of view and laying the emphasis on the physics of the problem.

4.12. Development of landslide risk maps

Debris flows are the rapid mass movement in steep hilly terrains where earthly materials flow down in a valley or channel usually triggered by heavy rainfall. It is usually fast-moving with variable solid concentration and large runout distance. Due to its fast-moving characteristics, debris flow is one of the most hazardous and unpredictable surface processes that result in many losses of lives and property damages. An extremely large channelized debris flow occurred on August 8, 2019, at Puthumala, Kerala. This is shown in Figure 4.27.

In order to assess the extent of damages caused by a debris flow event, numerical modelling and debris flow analysis are very useful tools. There are several approaches to debris-flow modelling. These include the empirical approach, the discrete approach, and the continuum approach. In the empirical approach, calculations of the volume, speed, runout distance, and the extent of debris flow are based on the historical observations of a large number of events. In the second approach using the discrete method, debris flow is modelled using many small elements that interact with each other. The third approach is based on continuum models in which the body of the debris is considered to be a continuum. The formulation of the model is based on physical laws such as Newton's law of motion, the law of the conservation of mass, and the law of the conservation of energy. The equations governing the motion of the debris are derived to calculate the flow characteristics, such as velocity, depth, runout distance, etc. (Wang et al., 2010). Numerical techniques, such as the finite element method, finite different method, or the block continuum method, are often used to provide the numerical solution for the debris flow analysis. Due to the complexity of the rheology of debris material and the size of a typical debris flow, it is still not possible to adopt a discrete approach that requires large computation of resources. The continuum model is a more practical approach to obtain solutions for realistic debris flow problems.

Fig. 4.27: Deposition zone of debris flow material in the Puthumala region

During the moving process of debris flow, material from the channel boundary is often eroded and mixed with the main body of the debris and becomes part of the flowing debris (Iverson, 2000). This process of increasing the mass by eroding the material from the channel is called entrainment. There are various models in calculating the amount and rate of entrainment in debris flow analysis. Figure 4.28 shows that several entrainments had taken place during the event of August 8, 2019, in the Puttumala region. The failure had taken place between the interface of the topsoil and the bedrock due to saturation during the heavy rainfall.

Topographic input in terms of 3-dimensional digital elevation models is an important and basic input for debris-flow modelling. The dimension of the channel or cross-sectional area in the topographic input should match with the real field observation. In low-resolution elevation models, there may be chances of missing important features while high resolution (1 m or less) may take an excess computation time which may lead to overestimation of simulation.

Debris flows runout modelling is carried out to obtain the flow intensity parameters such as debris flow runout distance, flow velocity, debris flow height and pressure along the path. Detailed mapping of the area must be conducted during extensive fieldwork after the event and various parameters such as runout length, deposition height, and deposition pattern must be collected from the field. Generally, back analysis of the debris flow is considered for calibrating the model and to find out the best-calibrated values of model input parameters. All the channels are needed to be identified and such simulation will help us to identify the areas that will be affected in case of such large-scale channelized debris flow incidents. The local people must be made aware of the probable runout distance. And if possible, maybe relocated away from the deposition zone to save life as these incidents are very rapid and extremely hazardous in nature. Landslide risk map can only be prepared after the channelized debris flow hazard is quantified using these advanced numerical techniques.

Fig. 4.28: Entrainment signature of debris flow in Puthumala region

4.12.1. Procedure for development of landslide risk map

Vulnerability is commonly integrated into risk analysis. This concept has been transferred to landslide issues by various researchers (Einstein, 1988; Gill, 1974; Hearn and Griffiths, 2001, etc.). One comprehensive publication summarising various attempts addressing landslide risk is the proceedings of a workshop on landslide risk assessment edited by Cruden and Fell (1997). Since then, various case studies have been published on landslide risk (e.g., Finlay et al., 1999; Hearn and Griffiths, 2001, etc.). Generally, the risk is based on the definition of the United Nations Disaster Relief Organisation (1979), which is expressed in the general function.

$$R = H \times E \times V \quad (1)$$

where,

R = *Risk*, referring to the expected number of lives lost, persons injured, damage to property, or disruption of economic activity due to a particular event;

H = *Natural Hazard* defined as the probability of occurrence of a potentially damaging event within a specified time and a given area;

E = *Elements at Risk*, including population, buildings and engineering structures, infrastructure areas and lines, public service utilities and economic activities;

V = *Vulnerability*, relating to the (potential) results from event occurrence expressed with qualitative, semi-quantitative or quantitative methods in terms of loss, the disadvantage of gain, damage, injury or loss of life. The product of *Elements at Risk* and *Vulnerability* is also often expressed as consequences (Wu et al., 1996).

The first step is the development of a landslide hazard map. Landslide hazard zonation in and around Kerala region can be determined using geospatial techniques. Being a landslide-prone area, a hazard zonation can be attempted using terrain fragility concept. The fragility concept mentioned here is a fast and cost-effective model for identifying landslide-prone areas, especially in the Western Ghats (Abraham and Shaji, 2013).

A base map of the study area needs to be prepared from the survey of India toposheets (scale 1:50,000) with extensive field surveys, to locate the palaeo as well as potential landslide occurrences in the study region. Detailed geological mapping of various profiles is required to carry out along the study region for identifying potentially unstable profiles. The methodology involves the preparation of various thematic/ factor maps using GIS software such as (1) slope; (2) land use; (3) relative relief; (4) drainage pattern; (5) drainage density; (6) landform and (7) surface material for fragility quantification. For more details, please see the work of previous researchers (Abraham and Shaji, 2013; Glade, 2003, etc.).

This technique includes allotting weights or marks to these causative factors and ranks the terrain as per the total weight into different categories of fragility. Thus, appropriate weightage is needed to assign to the above mentioned various parameters considering the terrain conditions, field data, and previous researchers work (viz., Abraham and Shaji, 2013; Mathai and Kumar, 2009; Thampi, 2006, etc.) and also verify these values with weights which are prescribed in the Bureau of Indian Standards (Indian Standard [IS:14496], 1998). Table 4.9 depicts the sample of such weights which are considered by Abraham and Shaji (2013), one may use these values with proper validation and technical expert judgment. A summation of all parameters generated through terrain evaluation is used to estimate the fragility of the terrain. In this regard, the study area needs to be divided into square grids of preferable dimensions.

This grid is superposed on each factor map and the respective weight of each factor is allotted for all grids. After repeating the exercise with all the factor maps the cumulative weight value for each grid of the study area was arrived at. Based on the cumulative weight value of all factors the grids are categorized into highly fragile, fragile, moderately fragile and stable, resulting in the preparation of a fragility(zonation) map. In addition to getting an overall fragility picture of the segment, the output will give the individual hot spots as far as terrain stability is concerned on a 1:50,000 scale. The overall terrain fragility (FI - fragility index) of a segment is calculated as follows:

$$FI = W/G \tag{2}$$

where, *FI* - fragility index; *G* - is the total number of grids falling within the segment; *W* - is the total weight of all grids falling within the segment.

Table 4.9: Sample weights for the different terrain parameters (Abraham and Shaji, 2013)

Sl. No	Terrain Parameter	Weight Allotted
1	Slope	30
2	Land use	20
3	Relative relief	10
4	Drainage pattern	10
5	Drainage density	10
6	Landform	10
7	Surface material	10
Total weight		100

Details of each individual terrain parameters are needed to investigate carefully and then further subdivide them into various categories, like for the slope segment, it is dependent on various factors like slope angle, slope form, slope length, the material of which it is formed, antecedent moisture content, etc. The previous researchers (Abraham and Shaji, 2013; Long and De Smedt, 2018) used slope angles to further subdivide the slope terrain parameter into various classes. In a similar manner, other terrain parameters also can be split into various categories by considering literature or perform extensive field assessment.

The summation of the seven parameters generated through terrain evaluation provides the required clues on the fragility of the terrain. The overall terrain fragility of a segment is calculated using Equation 2. Based on the cumulative weight value of all factors the grids are categorized into highly fragile, fragile, moderately fragile and stable. When the total weight of a grid is greater than 75, the grids are classified as highly fragile zone i.e. these are very unstable zones where slope failures are likely to occur. When the total weight of a grid is between 61 to

75, it is classified as a fragile zone whereas between 40 to 60 and less than 40 are termed as moderately fragile and stable zone respectively. The geospatial analysis and fragility ranking map provide landslide hazard zonation which gives a general picture of the stability scenario.

Once the landslide hazard maps are completed, then the landslide risk analysis can be performed using the Equation 1 and elements at risk units such as residential areas, industrial areas, multiple-use areas, special areas, agricultural areas, pasture, motorway and country road, vineyards and forests. These units can be digitized from official land use plans. For each element at risk, a damage potential can be defined and assigned, which is based on the review of the previous researchers' work (Leone et al., 1996; Michael-Leiba et al., 2000; Ragozin and Tikhvinsky, 2000) and on data from national statistics yearbooks. The above-mentioned researchers proposed the tables which provide vulnerability values for each element at risk based on the back analysis of specific past events; for instance, Ragozin and Tikhvinsky (2000) examined past landslides and earthquake events, but also assumed missing values.

Table 4.10 depicts the example of the vulnerability of various elements at risk with respect to landslides including debris flow given by (Michael-Leiba et al., 2000). Michael-Leiba et al. (2000) proposed Table 4.10 based on the analysis for Cairns City Council in Australia, for people and buildings on hill slopes, data were derived from the Australian Landslide Database and for roads on hill slopes, the assessment is based on information provided by the Cairns City Council. Although numerous assumptions were made in order to provide vulnerability values for landslide risk analysis at a regional scale, moreover their approach has a practical application and is indeed of high interest for planning agencies (Glade, 2003). Repeat this exercise for all the considered grid points and then prepare the risk map by mapping the risk values which is evaluated at each grid point. Finally, considering a suitable scale (proposed by any technical committee or previous researchers or code provisions), classify the risk as low, moderate, high, and very high.

Table 4.10: Vulnerability of various elements at risk with respect to landslides including debris flows (modified after Michael-Leiba et al., 2000)

Process	Vulnerability of		
	Residents	Buildings	Roads
Landslides on hill slopes	0.05	0.25	0.3
Susceptible to proximal debris flow	0.9	1	1
Susceptible to distal debris flows	0.05	0.1	0.3

4.12.2. A case study from literature

An extremely large rock avalanche occurred on April 9, 2000, at Yigong, Tibet, China. It started with an initial volume of material of 90 × 10^6 m3 comprising mainly of loose material lying on the channel bed. The rock avalanche travelled around 10 km in horizontal distance and formed a 2.5-km-long by a 2.5-km-wide depositional fan with a final volume of approximately 300 × 106 m^3. An energy-based debris flow runout model is used to simulate the movement process with a new entrainment model. The entrainment model considers both rolling and sliding motions in calculating the volume of eroded material. Entrainment calculation is governed by a second-order partial differential equation which is solved using the finite difference method. During entrainment, it is considered that the total mass is changed due to basal erosion. For Yigong, the profile used in the simulation was extracted from a digital elevation model (DEM) with a resolution of 30 m× 30 m (Fig. 4.29). Also, the profile of the channel bed is adjusted accordingly due to erosion at the end of each calculation time step (Figure 4.30). Measurements obtained from site investigation, including deposition depth and flow height at a specific location, are used to verify the model. Ground elevation-based DEM before and after the event is also used to verify the simulation results where access was difficult. It is found that the calculated runout distance and the modified deposition height agree with the field observations. Moreover, the back-calculated flow characteristics based on field observations, such as flow velocity, are also used for model verifications. The results indicate that the new entrainment model is able to capture the entrainment volume and depth, runout distance, and deposition height for this case.

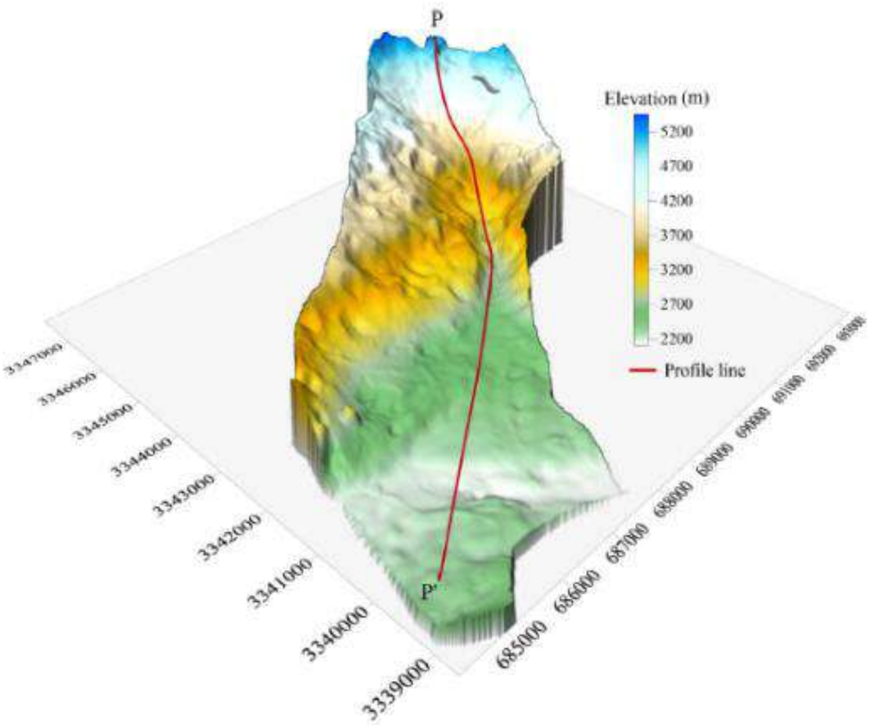


Fig. 4.29: Digital elevation model of Yigong rock avalanche (after Kang et al., 2017)

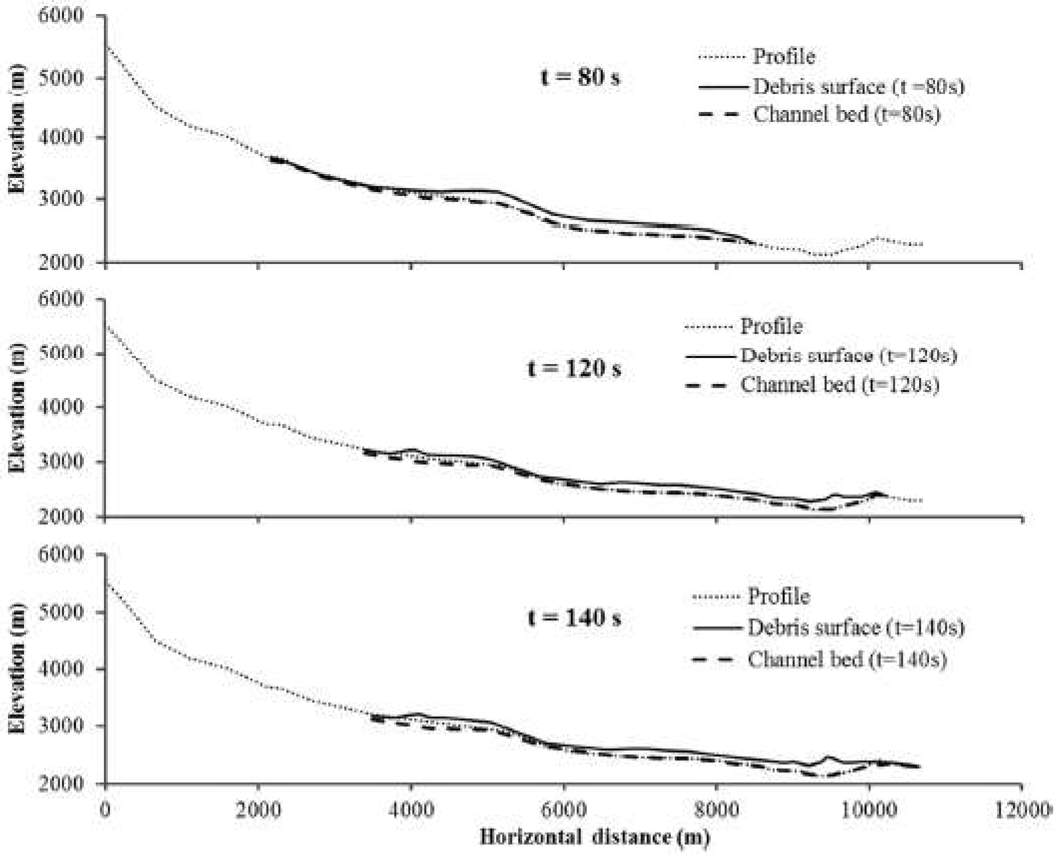


Fig. 4.30: Change of profile in each simulation steps (after Kang et al., 2017)

According to Varnes (1984), evaluation of landslide risk aims to determine 'expected degree of loss due to a landslide (specific risk) and the expected number of lives lost, people injured, damage to property, and disruption of economic activity (total risk)'. Fell et al. (2005) advocated a framework for quantitative risk assessment consisting of two steps. The first step is hazard analysis covering landslide characterization and analysis of frequency. The next step is consequence analysis consisting of characterization of consequence scenarios and analysis of probability and severity of consequence. Risk analysis is based on hazard analysis and consequence. Based on this information it will be possible to estimate risk. Both qualitative and quantitative methods can be applied according to scale, data availability, and scope and purpose of hazard and risk assessment. The second step is a risk assessment. It covers value judgments and risk-tolerance criteria. Regressing risk estimation and risk tolerance it is possible to work out risk.

Mallet and Maquaire (undated) provided an overview of risk assessment methodologies for soil threats as followed in EU countries. Some of the methodologies are significant and lessons can be drawn for developing landslide risk maps of Kerala. An instrument of risk assessment is suggested in Box 4.2.

Box 4.2: Landslide Risk Mapping

Objective	:	*Risk Mapping*
Scale	:	*1: 5,000/ cadastral scale*
Methodology	:	*Semi-quantitative*
Data	:	*Topography, lithology, seismic data, geomorphology map, drainage map, rainfall data, soil map, landslide inventory, land use/ land cover, geotechnical map (correlation between physical features of clay and the hydrological conditions), hazard zonation map (already prepared in 1:50,000 scale), elements at risk, socio-economic data, risk zonation map (combination of hazard zonation and map of element at risk)*
Techniques	:	*Archival work, map analysis, remote sensing, field, monitoring, GIS, laboratory analysis, statistical analysis*

5. Chapter 5
Flood

5.1. Introduction

Floods are the most frequent and damaging of natural hazards globally. The floods in Kerala are mostly associated with the EREs during the monsoon season (Box 5.1). The intensity, as well as the spatial extent of rainfall, contributes to the risk of flash floods more than the total quantum of rainfall. The majority of the flood mitigation measures are long-term solutions related to watershed management. However, this section addresses both the short-term and long-term mitigation measures that can be used in the monsoon season based on the analysis of the watershed hydrology of the river basins of Kerala.

5.2. Historical floods in Kerala

As per available documentation and web information, starting from 1341 to 2019, Kerala State has experienced occasional floods of varying magnitudes. However, hardly any information is available about the rainfall pattern or flood discharge during the floods that occurred prior to the 20th century, but citations in the literature. The major flooding events occurred in Kerala State are detailed in the following sections.

5.2.1. Analysis of the historic floods

5.2.1.1. Flood of 1341

Many a book mentions the great Periyar flood of 1341. Newbold (1846) considers the 1341 catastrophe as a large storm, which brought about remarkable changes in the vicinity of Cochin, including the emergence of the new sand bar known by the name Vypin (Bendick and Bilham, 1999), and consequently a new harbour. The Muziris port reportedly silted up as the result of unusual flooding by the Periyar River in 1341 AD. WW Hunter is the first to detail the connection between the flood and the Puthuvaippu area. He states ‘The date at which this island was formed by the action of the sea and river, A. D. 1341, is sometimes used in deeds as the commencement of an era styled Puttuveppu (new deposit)’. The floods in the river Periyar in 1341 choked the mouth of the Cranganore harbour and rendered it useless for purposes of trade, and it was mentioned as an extraordinary flood which opened up an estuary (Padmanabha Menon, 1937). As you delve into the usual Malabar history sources you see mentions that the 1341 year had record monsoons resulting in the Periyar flood and the silting up of the harbour mouth (Source: http://indpaedia.com/ind/index.php/Floods_in_Kerala:_a_history)

Box 5.1: Types of floods

1. Fluvial or Riverine Floods

Riverine flooding, occurs when excessive rainfall over an extended period of time causes a river to exceed its capacity. It can also be caused by heavy snow melt and ice jams. The damage from a river flood can be widespread as the overflow affects smaller rivers downstream, often causing dams and dikes to break and swamp nearby areas.

2. Flash Floods

Flash flooding is characterized by an intense, high velocity torrent of water that occurs in an existing river channel with little to no notice. Flash floods are very dangerous and destructive not only because of the force of the water, but also the hurtling debris that is often swept up in the flow.

3. Coastal Floods

A coastal flood, as the name suggests, occurs in areas that lie on the coast of a sea, ocean, or other large body of open water. It is typically the result of extreme tidal conditions caused by severe weather. Storm surge- produced when high winds from hurricanes and other storms push water onshore- is the leading cause of coastal flooding and often the greatest threat associated with a tropical storm. In this type of flood, water overwhelms low-lying land and often causes devastating loss of life and property.

4. Pluvial or Surface Floods

A pluvial, or surface water flood, is caused when heavy rainfall creates a flood event independent of an overflowing water body. One of the most common misconceptions about flood risk is that one must be located near a body of water to be at risk. Pluvial flooding debunks that myth, as it can happen in any urban area - even higher elevation areas that lie above coastal and river floodplains.

There are two common types of pluvial flooding:

- Intense rain saturates an urban drainage system. The system becomes overwhelmed and water flows out into streets and nearby structures.
- Run-off or flowing water from rain falling on hillsides that are unable to absorb the water. Hillsides with recent forest fires are notorious sources of pluvial floods, as are suburban communities on hillsides.

5.2.1.2. Flood of 1924

The year 1924 witnessed unprecedented and very heavy floods in almost all rivers of Kerala. Heavy losses to life, property, and crops, etc. had been reported. The rainstorm of 16-18, July

1924 was caused by the South-west monsoon that extended to the south of the peninsula on 15th July and caused rainfall in Malabar. Under its influence, heavy rainfall occurred in almost entire Kerala. The area under the storm recorded 1-day maximum rainfall on 17th of July, 2-day maximum rainfall for 16-17, July 1924 and 3-day maximum rainfall for 16-18, July 1924. The centre of the 1-day and 2-day rainstorm was located at Devikulam in Kerala which recorded 484 mm and 751 mm of rainfall respectively. The centre of the 3-day rainstorm was located at Munnar in Kerala which recorded a rainfall of 897 mm in 3 days. The fury of 1924 flood levels in most of the rivers was still fresh in the memory of the people of Kerala. The rainfall distribution in selected river basins of Kerala is given in Table 5.1.

Table 5.1: Rainfall distribution during 1924 flood in Kerala (CWC, 2018)

Name	Basin area (km2)	16 July 1924	16-17 July 1924	16-18 July 1924
		1-Day (mm)	2-Day (mm)	3-Day (mm)
Rest of Kerala	26968	155	260	362
Kallada	1139	165	268	415
Pamba	1620	202	423	551
Periyar	4035	280	502	604
Bharathapuzha	5784	161	291	378
Chaliyar	1992	267	490	599
Valapattanam	1019	232	420	512

5.2.1.3. Flood of 1958

The floods were in the nature of 'flash Floods", they occurred on 7th August 1958 and the rivers chiefly affected by were Muvattupuzha, Meenachil, Manimala, Achencoil and Pamba, the worst affected among them being Manimala. The maximum discharges occurred in these rivers on 8th August 1958 and their values are given in Table 5.2.

Table 5.2: Maximum Discharge on 8th August 1958 (Ramaswamy, 1985)

Sl. No.	River	Maximum Discharge in m^3/s
1.	Pamba	1274.26
2.	Manimala	673.94
3.	Meenachil	517.07
4.	Achenkovil	288.83
5.	Muvattupuzha	707.92

5.2.1.4. Flood of 1961

The year 1961 also witnessed heavy floods and a rise in the water levels of reservoirs. In 1961, floods were unusually heavy not only in duration but also in the intensity of the precipitation. During the year 1961, the monsoon started getting violent towards the last week of June and in the early days of August, the precipitation was concentrated on most parts of the southern region of Kerala. By the first week of July, the intensity gradually spread over the other parts of the State and the entire State was reeling under severe flood by the second week of July. The worst affected area was Periyar sub-basin and it also impacted other sub-basins. Many of the important infrastructures like highways etc were submerged. After a brief interval, by the middle of July, the monsoon became more violent, affecting the northern parts of the State. The average rainfall was 56% above normal. The maximum daily intensities recorded at four districts in 1961 are given in Table 5.3.

Table 5.3: Recorded 1-day rainfall in different districts of Kerala in 1961 (CWC, 2018)

Sl. No.	District	Rainfall (mm)
1.	Calicut	234
2.	Trivandrum	136
3.	Cochin	189
4.	Palakkad	109

The damage caused by the floods had been severe and varied. It is understood that 115 people lost their lives due to floods and landslides. Over 50,000 houses were completely and partly damaged and about 1,15,000 acres of paddy were seriously affected (CWC, 2018).

5.2.1.5. Flood of 1992

Torrential rains triggered by a cyclone in the Bay of Bengal hit southern districts of Tamil Nadu and Kerala state for few days, causing flash floods and landslides. At least 179 persons were killed (145 in Tamil Nadu and 34 in southern parts of Kerala), several have been reported missing, and more than a hundred rendered homeless. Idukki dam shutters were open for 12 days (https://reliefweb.int/report/india/india-floods-nov-1992-undro-information-reports-1-2; Bhatt SC, 2004).

5.2.1.6. Flood of 2007

Deep Depression formed as part of South West Monsoon and heavy rainfall of more than 25 cm was experienced in the southern states of Andhra Pradesh, Kerala, Central Maharashtra (Vidarbha), Goa, Karnataka, south Orissa, south Chhattisgarh during the third week of June. The states of Andhra Pradesh, Kerala and Karnataka experienced flash floods due to heavy rains. Idukki, Kozhikode, Pathanamthitta, Malapuram, Palakkad, Kottayam, Thrissur Ernakulam, Alapuzha districts of Kerala were affected. 4776 houses were partially collapsed and 454 houses fully damaged in 14 affected districts. 29 deaths have been reported of which 4 persons died due to landslides. Breaches have occurred along seawalls off the coast of Alappuzha, Kollam, Thiruvananthapuram and Kannur districts. Landslips were reported from Wayanad, Kozhikode and Idukki districts. A threat of the outbreak of Chikungunya was observed in some of the districts. (https://reliefweb.int/report/india/india-situation-report-deep-depressionflood-26-jun-2007)

5.2.1.7. Flood of 2013

Heavy rainfall and release of water from the Idamalayar dam caused flooding in the Periyar basin. The measured flow at Neeleeswaram CWC G&D station in River Periyar was 6323.54 cumecs and the gauge reading was 9.455 m. The Chengal Thodu had overflown, forcing residents to shift to relief camps and forcing the closure of Cochin International Airport Ltd. (CIAL) for two days as the runway was water-logged. Fourteen persons died on Monday and several reported missing in landslips triggered by heavy rain in high range Idukki and adjoining districts of Kerala. Eight contingents of Army and National Disaster Relief Force (NDRF) have been called to speed up relief and rescue operations in Idukki and Aluva areas near Kochi where Periyar River is overflowing. While nine lives were lost in landslips, five persons engaged in relief work were killed as a huge block of rock and rubble came crashing down on them at Chiyyampara near Adimali.

5.2.1.8. Flood of 2018

Kerala experienced an abnormally high rainfall from 1 June 2018 to 19 August 2018. This resulted in severe flooding in 13 out of 14 districts in the State. As per IMD data, Kerala received 2365.6 mm of rainfall from 1 June 2018 to 19 August 2018 in contrast to an expected 1658.5 mm of rainfall. This rainfall was about 42% above the normal. Further, the rainfall over Kerala during June, July, and 1st to 19th of August was 15%, 18%, and 164% respectively, above normal. Month-wise rainfall for the period, as reported by IMD, are given in Table 5.4.

Table 5.4: Monthly rainfall and percentage departure from the normal prior to the flood of August 2018

Period	Normal Rainfall (mm)	Actual Rainfall (mm)	Departure from Normal (%)
June 2018	649.8	749.6	15
July 2018	726.1	857.4	18
1-19 August 2018	287.6	758.6	164
Total	1658.5	2365.6	42

Due to heavy rainfall, the first onset of flooding occurred towards the end of July. A severe spell of rainfall was experienced at several places on the 8th and 9th of August 2018. The 1- day rainfall of 398 mm, 305 mm, 255 mm, 254 mm, 211 mm and 214 mm were recorded at Nilambur in Malappuram district, Mananthavadi in Wayanad district, Peermade, Munnar KSEB and Myladumparain in Idukki district and Pallakad in Pallakad district respectively on 9 August 2018. This led to further flooding at several places in Mananthavadi and Vythiri in Wayanad district during 8-10, August 2018. Water was released from several dams due to heavy rainfall in their catchments. The water levels in several reservoirs were almost near their Full Reservoir Level (FRL) due to continuous rainfall from the 1st of June. Another severe spell of rainfall started from the 14th of August and continued till the 19th of August, resulting in disastrous flooding in 13 out of 14 districts. As per the rainfall records of IMD, it has been found that the rainfall depths recorded during the 15-17, August 2018 were comparable to the severe storm that occurred in the year 1924. For entire Kerala, the depth of rainfall realized during 15-17, August 2018 is 414 mm, while the same during 16-18, July 1924 was 443 mm. The district wise rainfall for the southwest monsoon period during 1 June to 22 August in 2018 is given in Table 5.5.

Table 5.5: Accumulated rainfall during southwest monsoon season for different districts of Kerala (Souce: CWC, 2018)

District	Normal Rainfall (mm)	Actual Rainfall (mm)	Percentage Departure from normal (%)	
Alappuzha	1380.6	1784.0	29	Excess
Kannur	2333.2	2573.3	10	Normal
Ernakulam	1680.4	2477.8	47	Excess
Idukki	1851.7	3555.5	92	Large Excess
Kasaragode	2609.8	2287.1	-12	Normal
Kollam	1038.9	1579.3	52	Excess
Kottayam	1531.1	2307.0	51	Excess
Kozhikode	2250.4	2898.0	29	Excess
Malappuram	1761.9	2637.2	50	Excess
Palakkad	1321.7	2285.6	73	Large Excess
Pathanamthitta	1357.5	1968.0	45	Excess
Thiruvananthapuram	672.1	966.7	44	Excess
Thrissur	1824.2	2077.6	14	Normal
Wayanad	2281.3	2884.5	26	Excess
Kerala State	1701.4	2394.1	41	Excess

Periyar, Pamba and Chalakudy River basins were severely flooded. Kuttanad region was flooded for more than a week. Most of the dams were full and had to release water through spillways. 1,259 out of 1,664 villages spread across 14 districts were affected. The seven worst-hit districts were Alappuzha, Ernakulam, Idukki, Kottayam, Pathanamthitta, Thrissur, and Wayanad, where the whole district was notified as flood-affected. The devastating floods and landslides affected 5.4 million people, displaced 1.4 million people, and took 433 lives (22 May–29 August 2018). Close to 14 lakh people had to be evacuated to relief camps during the floods as their homes were inundated with floodwater. Thousands of people also took shelter with relatives and friends. Access to piped water was disrupted for 20% of the state's population (67 lakh people). An estimated 3,17,000 shallow wells were damaged and contaminated in six worst affected districts directly affecting 14 lakh people. Over 95,000 household latrines were substantially damaged affecting nearly 4 lakh people.

Over 1.75 lakh buildings have been damaged either fully or partially, potentially affecting 7.5 lakh people. More than 1700 schools in the state were used as relief camps during the floods. Most of the camps closed after 10 days. Floods affected teaching and learning in almost all the districts with institutions being closed from 2 to 23 days. A total of 1613 schools have been affected by the floods. Some schools in Alappuzha were closed for more than a month (CWC, 2018).

5.2.1.9. Flood of 2019

Between August 8 and 31, 2019, Kerala experienced flood and landslides yet again. 2019 Monsoon had a weak and delayed start. The onset of monsoon was officially declared by IMD on June 8th, 2019. But Kerala state received 32% deficient rainfall till July 31. Normally June and July are the 'Rainy months 'of Kerala. Till 31st July Wayanad, one of the most affected Districts has marked a 55% deficiency in rainfall compared to the long period average (Normal). But due to the influence of low-pressure area and depression formed over the Bay of Bengal and strengthening of Monsoon winds Kerala state received large excess rainfall during the month of August.

During the month of August Kerala received 123% excess rainfall than the long period average rainfall over the State (Table 5.6). In August 2018 it was 96% excess rainfall than the long period average rainfall. Most affected districts in North and central Kerala Kozhikode (176%), Wayanad (110%), Malappuram (176%), Palakkad (217%), Thrissur (127%) Ernakulam (140%) have received more than 100% excess rainfall than the normal rain during the month of August. 7 out of 14 Districts from Kasaragod to Thrissur received more than 1000 mm rainfall from 1st to 31 August.

Table 5.6: Monthly rainfall in various districts of Kerala during August 2019 (Source: IMD)

District	Normal Rainfall (mm)	Actual Rainfall (mm)	Percentage Departure from Normal (%)	
Kasaragod	658.9	1194.5	81	Large Excess
Kannur	554.0	1107.2	100	Large Excess
Kozhikode	510.8	1407.8	176	Large Excess
Wayanad	568.3	1190.8	110	Large Excess
Malappuram	392.7	1084.2	176	Large Excess
Palakkad	324.8	1030.6	217	Large Excess
Thrissur	467.9	1062.0	127	Large Excess
Ernakulam	398.5	957.7	140	Large Excess
Alappuzha	339.1	676.1	99	Large Excess
Kottayam	375.7	763.0	103	Large Excess
Idukki	590.5	979.4	66	Large Excess
Pathanamthitta	333.6	717.7	115	Large Excess
Kollam	258.2	549.3	113	Large Excess
Thiruvananthapuram	144.0	325.0	126	Large Excess
State	426.7	951.4	123	Large Excess

The peak of the rainfall which eventually leads to devastating flood and landslide happened from August 6 to August 14, 2019. In this period Kerala received 602.2 mm rainfall which is 394% excess than the normal rainfall (122.0 mm) expected. All districts received more than 300% excess rainfall for the peak period. Many of the stations of India Meteorological Department have recorded extremely rainfall events (more than 200 mm rainfall in 24 hrs). During this period Vythiri station (Wayanad), Vadakara (Kozhikode), Ottappalam (Palakkad) stations of IMD have recorded more than 1000 mm rainfall in just 6 days.

In comparison with 2018 August, numbers of extreme rainfall events were lesser in 2019 august. But numbers of rainy days are higher in 2019 August and 10 out of 14 districts have recorded monthly cumulative rainfall higher than 2018 August. The calamities were more focused on Northern Kerala. 1038 villages were notified as affected due to floods & landslides. Two districts viz. Malappuram and Wayanad were fully affected. One hundred and twenty-five (125) lives were lost due to floods and landslides, caused exorbitant losses to the agriculture sector. 1795 houses were fully damaged and 14559 houses were severely damaged (Source: KSDMA, memorandum of 2019 Flood).

Table 5.7 provides a comparative analysis of the major floods that occurred in Kerala State from 1341 to 2019.

5.3. Flood prone areas of Kerala

Heavy or continuous rainfall exceeding the absorptive capacity of soil and flow capacity of streams and rivers is leading to recurring riverine flooding in Kerala. In this context, the flood hazard map is very important for assessing the vulnerability and risk of flooding and for planning programmes to mitigate hazard risks, disaster warning systems, and recovery processes.

Table 5.7: Comparative analysis of the major floods occurred in Kerala

Year	Rainfall/Release	Affected areas	Losses
1341	Heavy Rainfall	Periyar Basin	
1924	64% excess rainfall. 443 mm average across Kerala (July 16-18)	Entire Kerala	The destructive flood claimed thousands of lives, animals, and birds, and caused severe damages to the crops and property in Kerala. Most of the areas in the east while Travancore and Cochin State, parts of the Malabar region were submerged under the floodwater.
1958	Heavy Rainfall during 5-7 August	Muvattupuzha, Meenachil, Manimala, Pamba. Manimala worst affected	
1961	56% excess rainfall	Entire Kerala, particularly in Periyar basin	The damage caused by the floods had been severe and varied. It is understood that 115 people lost their lives due to floods and landslides. Over 50,000 houses were completely and partly damaged and about 1,15,000 acres of paddy were seriously affected
1992	Torrential rains triggered by a cyclone in the Bay of Bengal.	Alappuzha, Kollam, Trivandrum	34 died in southern parts of Kerala, several have been reported missing, and more than hundred rendered homeless
2007	Heavy Rainfall	Idukki, Kozhikode, Pathanamthitta, Malappuram, Palakkad, Kottayam, Thrissur Ernakulam, Alappuzha.	4776 houses were partially collapsed and 454 houses fully damaged in 14 affected districts. 29 deaths have been reported of which 4 persons died due to landslides. Breaches have occurred along seawalls off the coast of Alappuzha, Kollam, Thiruvananthapuram and Kannur districts. Landslips were reported from Wayanad, Kozhikode and Idukki districts. A threat of an outbreak of Chikungunya persists in some of the districts.
2013	Heavy Rainfall and Release from Idamalayar	Periyar Basin	Fourteen persons died and several reported missing in landslips triggered by heavy rain in high range Idukki and adjoining districts of Kerala, forcing

Year	Rainfall/Release	Affected areas	Losses
			the closure of Cochin International Airport as the runway was water-logged.
2018	414 mm average rainfall across Kerala (Aug 15-17)	Entire Kerala excluding Kasaragod district. 1,259 out of 1,664 villages spread across 14 districts were affected. The seven worst-hit districts were Alappuzha, Ernakulam, Idukki, Kottayam, Pathanamthitta, Thrissur, and Wayanad, where the whole district was notified as flood-affected.	The devastating floods and landslides affected 5.4 million people, displaced 1.4 million people, and took 433 lives (22 May–29 August 2018). Close to 14 lakh people had to be evacuated to relief camps during the floods as their homes were inundated with floodwater. Thousands of people also took shelter with relatives and friends. Access to piped water was disrupted for 20% of the state's population (67 lakh people). An estimated 3,17,000 shallow wells were damaged and contaminated in six worst affected districts directly affecting 14 lakh people. Over 95,000 household latrines were substantially damaged affecting nearly 4 lakh people. Over 1.75 lakh buildings have been damaged either fully or partially, potentially affecting 7.5 lakh people. More than 1700 schools in the state were used as relief camps during the floods. Most of the camps closed after 10 days. Floods affected teaching and learning in almost all the districts with institutions being closed from 2 to 23 days. A total of 1613 schools have been affected by the floods. Some schools in Alappuzha were closed for more than a month.
2019	Influence of low-pressure area and depression formed over the Bay of Bengal and strengthening of Monsoon winds Kerala state received large excess	Kasargod, Kannur, Kozhikode, Wayanad, Malappuram, Palakkad, Thrissur, Ernakulam. 1038 villages were notified as affected due to floods & landslides. Two districts viz. Malappuram & Wayanad were fully	One hundred and twenty-five (125) lives were lost due to floods and landslides, caused exorbitant losses to the agriculture sector. 1795 houses were fully damaged and 14559 houses were severely damaged.

Year	Rainfall/Release	Affected areas	Losses
	rainfall during the month of August.	affected	

The generation of flood hazard map for the State requires knowledge about the extent of flood plains, the time and duration up to which the flood plains are covered with water during the flood occurrences. The mapped floodplains and its boundary are commonly used in flood mitigation programmes mainly to identify the areas where the risk of flooding is significant. Hazard assessments are then made based on remote sensing, damage reports and field observations.

For Kerala, the flood plains or the flood-prone area are mapped on a 1:50,000 scale using IRS P6 satellite images (Kerala State Disaster Management Authority, 2016). Smooth textured areas on either side of the major streams with a high reflectance, presence of meandering streams, terraces, minor interspersed water bodies, etc. are some of the indicators of the flood plain that can be obtained from the satellite data. Evaluating the landforms, relief, the slope of the land, type of soils, disposition of streams and changes in groundwater levels are also used in evaluating flood proneness. In addition to this, the changing nature of the flood, land-use practices, loss of vegetation, etc. are also considered while assessing flood proneness (Kerala State Disaster Management Authority, 2016).

The total flood-prone area in the state is 5642.68 km^2, which is 14.52% of the total area of the state. More than 50% of the area is identified as flood-prone in the Alappuzha district. The Kole lands of Thrissur district, the coastal tracts of Ernakulam and Malappuram districts and the western part of Kottayam district, flanking Vembanad Lake are other major areas prone to floods. It can be noted that, though Wayanad district is located in an elevated plateau region of the state, the broad flat bottom valleys and flood plains adjacent to Mananthavadi River is marked as the flood-prone area. Idukki district is the least flood-prone area in Kerala owing to the rugged topography and absence of flat bottom valleys (Kerala State Disaster Management Authority, 2016). Table 5.8 shows the flood-prone area in each district in Kerala (District level Natural Hazard Zonation maps for Kerala State, John Mathai and Sreejesh Kumar, Centre for Earth Science Studies, Thiruvananthapuram). Figure 5.1 shows the flood hazard zone map of Kerala (Mathai and Kumar, 2009).

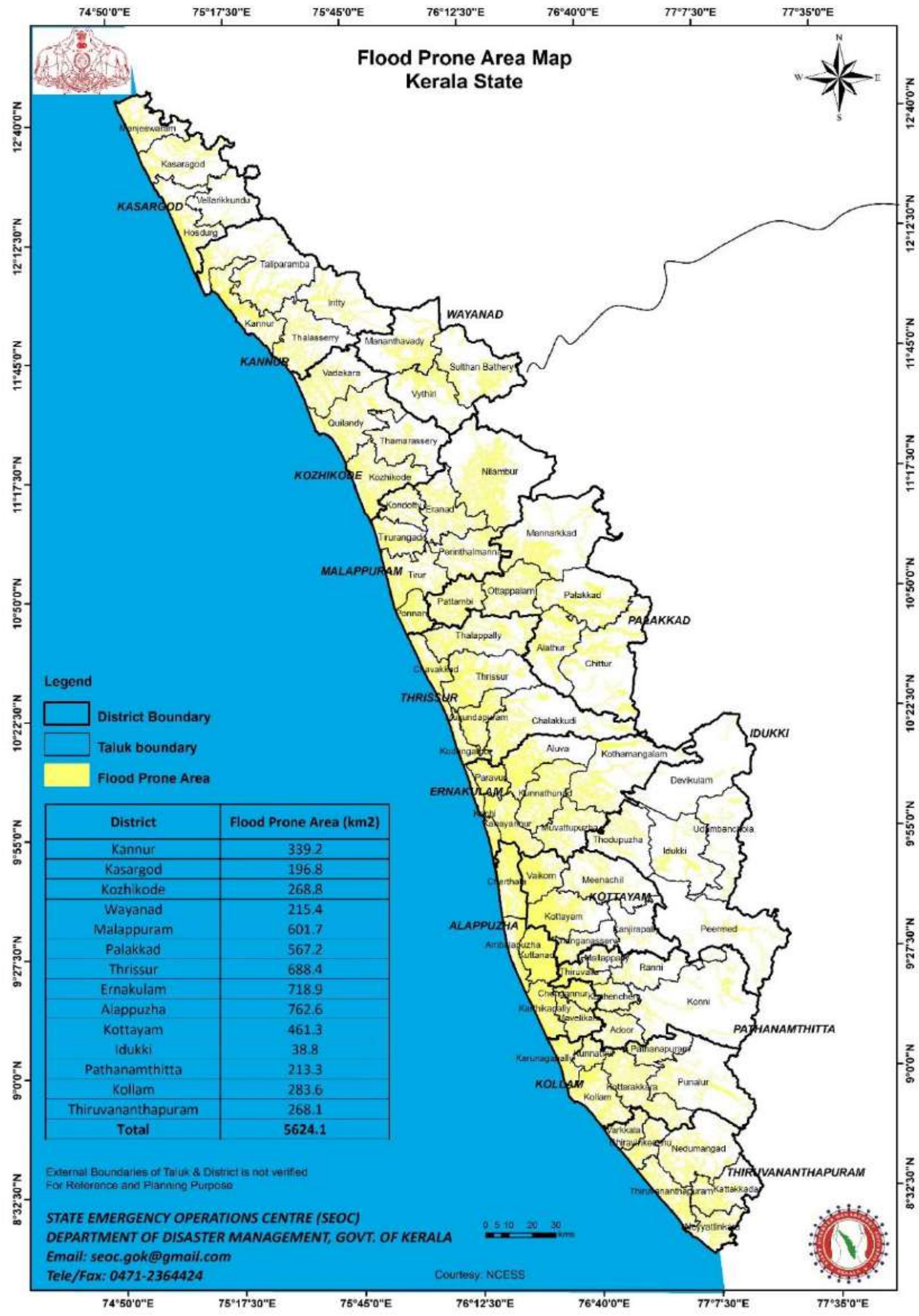
5.4. Floods of August 2018 and August 2019

Kerala received excess rainfall during the monsoon seasons of 2018 and 2019 for which the extreme rainfall events in the latter half of the season played a significant role. The August rainfall in the state was 96% and 123% in excess of the long period average (LPA) in 2018 and 2019 respectively.

Table 5.8: Areal extent of flood-prone areas of Kerala (Source: Mathai and Kumar, 2009)

District	Taluk	Area Km²	Area %	District	Taluk	Area Km²	Area %
Thiruvananthapuram		268.09	12.23	Idukki		38.78	0.89
	Neyyattinkara	72.56	12.68		Devikulam	0.00	0.00
	Nedumangad	68.38	7.39		Thodupuzha	26.87	2.10
	Thiruvananthapuram	65.85	21.32		Udumbanchola	11.35	1.30
	Chirayinkeezhu	61.28	15.92		Peermade	0.00	0.00
Kollam		283.62	11.41	Thrissur		688.44	22.65
	Karunagapally	56.63	31.83		Chavakkad	89.47	36.81
	Kollam	72.28	18.75		Kodungaloor	48.10	33.09
	Kottarakkara	75.31	13.62		Mukundapuram	225.91	17.27
	Kunnathur	38.50	27.61		Thrissur	181.39	27.45
	Pathanapuram	40.51	3.30		Thalapally	143.59	21.05
Pathanamthitta		212.76	8.00	Palakkad		567.16	12.66
	Adoor	48.26	14.70		Ottapalam	194.67	22.97
	Kozhenchery	51.24	5.60		Mannarkad	89.08	7.42
	Mallappalli	16.73	10.98		Palakkad	97.49	13.61
	Ranni	14.61	1.34		Alathur	107.65	18.88
	Thiruvalla	81.92	48.45		Chitoor	78.11	6.83
Alappuzha		762.57	53.77	Malappuram		601.67	16.93
	Ambalapuzha	73.83	40.42		Ponnani	80.07	40.21
	Chengannur	86.77	59.92		Tirur	109.60	24.39
	Cherthala	115.88	35.64		Tirurangadi	78.70	24.14
	Karthikapalli	127.15	55.18		Eranad	100.69	14.40
	Kuttanad	281.60	92.11		Perinthalmanna	81.21	16.07
	Mavelikkara	77.09	33.61		Nilambur	151.35	11.02
Kottayam		461.33	20.95	Kozhikkode		288.83	12.30
	Changanassery	52.55	20.14		Kozhikkode	133.51	12.93
	Kanjirappally	3.84	0.87		Quilandy	86.65	11.71
	Kottayam	195.00	38.50		Vadakara	67.83	11.77
	Meenachil	50.92	7.54	Wayanad		215.39	10.11
	Vaikom	158.95	49.68		Vythri	60.06	9.72
Ernakulam		718.94	23.50		SulthanBathery	84.12	10.92
	Kochi	51.79	35.76		Mananthavady	71.22	9.61
	Paravur	108.03	56.20	Kannur		339.18	11.45
	Kanayannur	117.16	36.76		Taliparamba	116.45	8.77
	Muvattupuzha	79.63	18.17		Kannur	116.20	26.71

District	Taluk	Area Km²	Area %	District	Taluk	Area Km²	Area %
	Kunnathunad	155.31	32.96		Thalassery	106.22	8.85
	Aluva	136.02	25.33	Kasargod		198.79	9.99
	Kothamangalam	67.91	7.09		Hosdurg	87.07	8.79
					Kasargod	111.70	11.16
Total for the State		5642.68	14.52				



District	Flood Prone Area (km2)
Kannur	339.2
Kasargod	196.8
Kozhikode	268.8
Wayanad	215.4
Malappuram	601.7
Palakkad	567.2
Thrissur	688.4
Ernakulam	718.9
Alappuzha	762.6
Kottayam	461.3
Idukki	38.8
Pathanamthitta	213.3
Kollam	283.6
Thiruvananthapuram	268.1
Total	**5624.1**

Fig. 5.1: Flood-prone areas of Kerala

5.4.1. Flood of August 2018

The peak spell of rains which resulted in the Floods of 2018 occurred between 8th and 17th of August 2018 with a large excess rainfall observed in most of the districts as in Table 5.9. As per IMD, Kerala received 758.6 mm rainfall between 1st and 19th August 2018 against the normal of 287.6 mm, which was 164 % above normal. Out of the 758.6 mm, 414 mm rainfall occurred in just three days, 15th to 17th August 2018.

Table 5.9: Monsoon Rainfall Assessment from 1st to 30th August 2018 (Source: IMD)

District	Actual Rainfall (mm)	Normal Rainfall (mm)	Percentage (%)	Departure from normal
Thiruvananthapuram	373.8	142	163	Large Excess
Kollam	644.1	258.7	149	Large Excess
Pathanamthitta	764.9	352.7	117	Large Excess
Alappuzha	608.2	343.1	77	Large Excess
Kottayam	619.2	386	60	Large Excess
Idukki	1478.9	527.3	180	Large Excess
Ernakulam	648.3	401.3	62	Large Excess
Thrissur	734.7	440.1	67	Large Excess
Palakkad	848.8	333.8	154	Large Excess
Malappuram	913.7	395.3	131	Large Excess
Kozhikode	836	500.9	67	Large Excess
Wayanad	1053.5	592.9	78	Large Excess
Kannur	665.3	540.9	23	Excess
Kasargod	636.9	636.3	0	Normal
Kerala	821	419.3	96	Large Excess

While the second forecast by IMD issued on 30th May 2018 predicted 95% rainfall of LPA in August, the State received a 96% excess rainfall. The spread of the unprecedented rainfall varied across the districts and the actual rainfall received was higher than predicted in the most crucial days of 8th, 15th and 16th of August. The intense unprecedented spell of rainfall began on 8th August 2018. The rainfall initially was active in the northern districts of Kerala causing widespread flooding in Wayanad, Kannur, and Malappuram. Rainfall of 398 mm which is equivalent to one day Standard Project Storm was experienced in Nilambur of Malappuram district on 9-08-2018. According to IMD, one-day rainfall of 305 mm, 255 mm, 254 mm, 211mm and 214 mm respectively were recorded at Manathavady, Peerumade, Munnar, Myladumpara and Palakkad.

The severe rainfall in Wayanad district caused heavy flooding at Mananthavady and Vythiri from 8th to 10th August 2018. On contrary to the predictions, after a relatively low spell of rainfall from 10th to 13th August, the precipitation increased substantially over the entire state attaining its peak on 15th, 16th and 17th of August. This rain spell was widespread and affected the entire state. Cumulative rainfall of 800 mm and 700 mm were observed at Peerumade rain gauge station and Idukki respectively between 15th to 17th August. Heavy rainfall in Wayanad and Idukki caused several landslides and floods. The operations of Kochi international airport were suspended from 15th to 26th August due to flooding of its runway. According to the analysis done by the Central Water Commission (CWC, 2018), 2-day and 3-day rainfall of 15th to 17th August 2018 in Pamba, Periyar and Bharathapuzha basins are almost comparable to Devikulam storm of 16th to 18th July 1924.

CWC compared the depth of rainfall during both the events for the entire state of Kerala and a depth of 414 mm was observed from 15th to 17th August 2018 against the 443 mm from 16th to 18th July 1924. As per the analysis by CWC, Peerumade which lies between Periyar and Pamba basins was the eye of this storm and hence those two basins were most severely affected during the floods of 2018. Since the extreme rainfall events occurred in the latter half of the monsoon season after an excess rainfall of about 8% from May to July 2018 the soils were saturated and led to flood intensification. The full reservoir level was almost attained by most of the reservoirs in the State by July end and the intense rainfall events prompted the authorities to open the gates of the dams, resulting in extensive flooding throughout the state. A satellite image analysis done by Vishnu et al. 2019 showed an 89.6 % increase in area covered by water compared to a pre-flood image. They observed a 5-10 m rise in water level in the Vembanad - Kole wetland system, which is indicative of the disastrous and disruptive nature of the flood.

5.4.1.1. Periyar River Basin

Periyar Basin: 244 km length with a total drainage area of 5,389 sq km. According to CWC (2018), the Periyar river basin received a cumulative rainfall of 588 mm between 15th to 17th August 2018 and the total runoff generated during the same period is 1.93 BCM based on the discharge from Neeleswaram CWC gauging site. The maximum discharge of 8800 cumecs was observed at Neeleswaram on 16th August 2018 at 14:00 hrs. The rainfall in the catchment of the Idamalayar dam was 1100 mm from 8th to 17th August 2018 with a maximum 1-day rainfall of 230 mm on 16th August. Total release from the Idukki reservoir for three days 375 MCM against the inflow of 435 MCM. FRL of the Idukki reservoir is 732.43 m and the Idamalayar dam is 169 m.

8th August	The water level in Idamalayar is 168.06 m
10th August 00:00	The water level in the Idukki dam was 731.82 m. Extra flood cushion was only 40 MCM. Inflow into the reservoir was 649 m^3/s and the total release was 165 m^3/s.
10th August 12:00	The water level in Idukki dam was 731.98 m
10th August 17:00	The reservoir release in Idukki was increased to 868 (750 + 118)

	m^3/s. Inflow dropped to 500 - 700 m^3/s.
Till 13th August 18:00	Discharge of 868 m^3/s in Idukki dam with the water level of 730.62 m
14th August 18:00	The water level in the Idukki reservoir was 730.69 m (flood cushion of 85 MCM)
15th August 18:00 - 16th August 03:00	Discharge from the Idukki reservoir increased to 1615 m^3/s.
15th August 22:00	Peak inflow to the Idukki reservoir was 2532 m^3/s and the release was 1614 m^3/s.
16th August	peak inflow of 1164 m^3/s in the Idamalayar dam. Average spill 1271 m^3/s.
Average Idukki release was 1400 m^3/s with peak discharge as 1500 m^3/s against the average inflow of 2000 m^3/s. The average inflow from Mullaperiyar was 650 m^3/s with a peak inflow of 760 m^3/s.	
17th August 01:00	FRL of 732.24 m in Idukki reservoir
Average Idukki release was 1460 m^3/s with peak discharge as 1500 m^3/s against the average inflow of 1440 m^3/s. The average inflow from Mullaperiyar was 390 m^3/s with a peak inflow of 590 m^3/s.	

5.4.1.2. Pamba River Basin

Pamba Basin: 176 km long. According to the CWC report, the cumulative rainfall between 15th and 17th August 2018 is 537 mm. The 3-day cumulated runoff at Kallooppara CWC gauging site on Manimala River was 277 MCM and 533 MCM at the Malakkara site on the Pamba River. The FRL of the Kakki dam on the Pamba basin is 981.46 m with a gross storage of about 450 MCM. As per the dam site rainfall record, the rainfall recorded from 9th to 20th August 2018 was 1724 mm with 590 mm rainfall on 15th and 16th August 2018. The maximum inflow was 835 m^3/s with a corresponding release of 938 m^3/s (CWC, 2018). According to the CWC (CWC, 2018), the total flood peak observed in the Pamba basin was of the order of 2900 m^3/s.

Four rivers Meenachil, Manimala, Pamba, and Achenkovil drain into the Vembanad Lake. The 3-day cumulated rainfall of 329 mm in the Achenkovil basin created a runoff of 336 MCM, whereas a 437 mm 3-day rainfall in the Meenachil basin created a runoff of 268 MCM. Pamba and Manimala basins together generated a runoff of 1030 MCM as a result of a 3-day rainfall of 517 mm. The total runoff generated in all the four basins together amount to 1634 MCM against the 600 MCM carrying capacity of the Vembanad lake to which all these rivers drain out (CWC, 2018).

5.4.1.3. Chalakudy River Basin

Chalakudy Basin: Chalakudy River is 130 km long and has a catchment area of 1704 Km^2. A cumulative rainfall of 421 mm was observed between 15th and 17th August 2018 leading to a 3-day runoff of 525 MCM at Arangaly CWC gauging site. According to CWC, the maximum discharge at Arangaly was about 2900 m^3/s on 16th August 2018 at 08:00. There are 6 reservoirs on Chalakudy River basin, out of which 4 are operated by Tamil Nadu. Kerala Sholayar, Parambikulam, Tunakadavu, Peringalkuthu have FRL of 811.68 m, 555.26 m. 539.5 m and 424 m respectively. The live storage of the Kerala Sholayar reservoir is 150 MCM and Parambikulam is 381 MCM, whereas Tunakadavu has only 9 MCM live storage. Live storage of the Peringalkuthu reservoir is 30 MCM only. The details of the reservoir operation in the Chalakkudy river basin are given in Tables 5.10 and 5.11. The total inflow into the Peringalkuthu reservoir on 16th August was 258 MCM, whereas spillway capacity was only 196 MCM, resulting in overtopping of the dam (CWC, 2018).

Table 5.10: Reservoir operation of Sholayar dam during 13-19 August 2018

Kerala Sholayar			
FRL 811.68 m, Live storage 150 MCM			
Date	**Water level (m)**	**Inflow (MCM)**	**Spill (MCM)**
13-08-2018	811.68	11.93	11.93
14-08-2018	811.68	32.39	32.39
15-08-2018	811.68	41.99	41.99
16-08-2018	811.68	36.25	36.25
17-08-2018	811.38	23.07	23.07
18-08-2018	811.38	33.36	30.53
19-08-2018	811.07	20.41	14.89

Table 5.11: Reservoir operation of Parambikulam-Thunakadavu dams (13-19 August 2018)

Parambikulam reservoir				
FRL - 556.26 m, Live storage - 381 MCM				
Thunakadavu reservoir				
FRL -539.50 m, Live storage - 9 MCM				
Date	**Inflow (MCM)**	**Spill Parambikulam (MCM)**	**Spill Tunacadavu (MCM)**	**Total Spill (MCM)**
13-08-2018	14.86	11.50	0.00	11.50
14-08-2018	27.23	19.57	0.00	19.57
15-08-2018	61.99	63.60	0.00	63.60
16-08-2018	73.09	67.96	13.46	81.41
17-08-2018	36.93	19.06	14.86	33.92
18-08-2018	20.47	9.79	9.70	19.49
19-08-2018	12.95	9.71	1.84	11.56

5.4.2. Flood of August 2019

Monsoon of 2019, unlike 2018 was weak with 32% deficient rainfall till July 31st and Wayanad, one of the most affected districts has marked a 55% deficiency in rainfall compared to the long period average. According to the 2nd stage long-range forecast by IMD for the southwest monsoon season on 31st May 2019, the monsoon rainfall was expected to be 97% of LPA over the South Peninsula with a model error of ±8%. It is also indicated in the 2nd stage LRF that the forecast probability for 'above normal' rainfall was 10% and ‘excess’ was only 2%. IMD also issued the Long-Range forecast for the Rainfall during the second Half (August-September) of the 2019 Southwest Monsoon on 1st August 2019 in which they predicted that the monsoon rainfall will be 100% of LPA over the country with a model error of ±8%. However, the development of depression over the Bay of Bengal strengthened the monsoon winds leading to 123% excess rainfall than the long period average rainfall over the state for the month of August. Most affected districts of North and central Kerala have received more than 100% excess rainfall than the normal rain during the month of August. 7 out of 14 districts from Kasaragod to Thrissur received more than 1000 mm rainfall from 1st to 31st August (Table 5.12).

Table 5.12: District wise Departure of average Rainfall during the month of August 2019 (August 1 to August 31) – Source: IMD

District	Normal Rainfall (mm)	Actual Rainfall (mm)	Percentage Departure	
Kasaragod	658.9	1194.5	81	Large Excess
Kannur	554.0	1107.2	100	Large Excess
Kozhikode	510.8	1407.8	176	Large Excess
Wayanad	568.3	1190.8	110	Large Excess
Malappuram	392.7	1084.2	176	Large Excess
Palakkad	324.8	1030.6	217	Large Excess
Thrissur	467.9	1062.0	127	Large Excess
Ernakulam	398.5	957.7	140	Large Excess
Alappuzha	339.1	676.1	99	Large Excess
Kottayam	375.7	763.0	103	Large Excess
Idukki	590.5	979.4	66	Large Excess
Pathanamthitta	333.6	717.7	115	Large Excess
Kollam	258.2	549.3	113	Large Excess
Thiruvananthapuram	144.0	325.0	126	Large Excess
Kerala	426.7	951.4	123	Large Excess

The peak of the rainfall which eventually led to devastating floods and landslides happened from 6th to 14th August 2019. In this period Kerala received 602.2 mm rainfall which is 394% excess than the normal rainfall (122.0 mm) expected, with most districts receiving more than 300% excess rainfall for the peak period. Many of the stations of India Meteorological Department have recorded extremely rainfall events (more than 200 mm rainfall in 24 hrs). During this period Vythiri station (Wayanad), Vadakara (Kozhikode), Ottappalam (Palakkad) stations of IMD have recorded more than 1000 mm rainfall in just 6 days.

In comparison with 2018 August, numbers of extreme rainfall events were lesser in 2019 August (Fig. 5.2). But numbers of rainy days are higher in 2019 August and 10 out of 14 districts have recorded monthly cumulative rainfall higher than 2018 August. As the dams were not full due to the deficient rainfall till July 2019, the scale of impact was less compared to 2018.

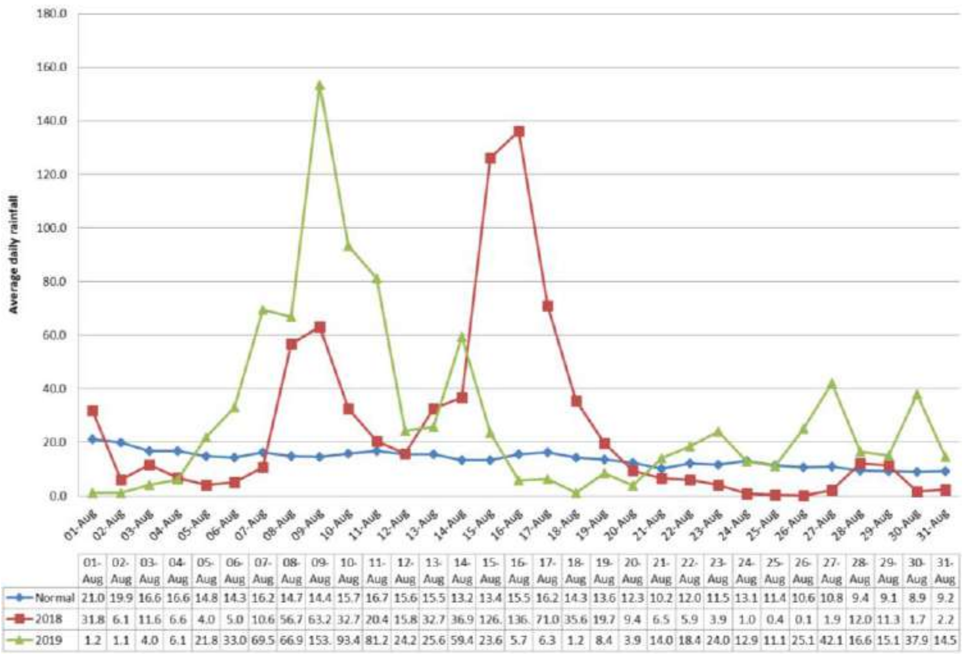


Fig. 5.2: Comparison of average daily rainfall over Kerala State during August month of 2018 and 2019

Table 5.13: Comparison of district wise rainfall for the month of August during 2018 and 2019 (Source: IMD)

District	Normal Rainfall (mm)	Actual Rainfall (mm) August 2018	Actual Rainfall (mm) August 2019
Kasargod	658.9	636.9	1194.5
Kannur	554	665.3	1107.2
Kozhikode	510.8	836	1407.8

District	Normal Rainfall (mm)	Actual Rainfall (mm) August 2018	Actual Rainfall (mm) August 2019
Wayanad	568.3	1053.5	1190.8
Malappuram	392.7	914.5	1084.2
Palakkad	324.8	848.8	1030.6
Thrissur	467.9	734.7	1062.0
Ernakulam	398.5	648.3	957.7
Alappuzha	339.1	608.2	676.1
Kottayam	375.7	617.1	763.0
Idukki	590.5	1478.9	979.4
Pathanamthitta	333.6	764.9	717.7
Kollam	258.2	644.1	549.3
Thiruvananthapuram	144	373.8	325
Kerala State	426.7	820.9	951.4

5.5. Impacts of floods with respect to varying physiography of the State

Geographically, Kerala is divided into three regions, Highlands, Midlands, and Low lands. The Highland consist of mountain ranges in the eastern part of the state which slopes down the Western Ghats. It has a rugged mountainous terrain and this region is predominantly covered with forest. The major plantations in this area are tea, coffee, rubber, and various spices. Most of the rivers in Kerala originate from the Western Ghats. The Midlands is referred to as the region between the mountains and the low lands. This is featured by the undulating hills and valleys. This area is used for intensive cultivation. Cashew, coconut, arecanut, tapioca, banana, etc. are grown in this area. Low lands (coastal areas) are referred to as the strip of area running along the coast with a maximum width of about 25 km from the shore near Alappuzha. This has level topography and is characterized by a marine landform. This constitutes numerous shallow lagoons, river deltas, backwaters and the shore of the Arabian Sea. Coconut and rice are generally grown in this area. The impact of floods with respect to varying physiography of Kerala was reviewed based on topographical classification of the highlands, midlands, and lowlands.

In Kerala, many of the short-run rivers have multi-purpose water storage reservoirs and dams located in the highland and/or midland (Vishnu et al., 2019). The gentle coastal plains of the state are densely populated, and the midland and the highland zones are predominantly utilized for various agricultural activities and commercial plantations. The narrow width of the state between the ridgeline of the Western Ghats and the coastal line along with dense population gives river basins a shorter response time to extreme rainfall events and this results in severe flooding in the State (Sudheer et al., 2019). The impacts of the flood on the natural environment in different parts of the state vary based on the geographical location.

5.5.1. The Highlands

In Highlands, the flood is characterized by the mass flow of soil along with water. The floods in this region are accompanied by landslides of varying scale. Flooding becomes highly severe when the receiving stream has a low capacity to contain the entire soil mass and the water. The sediments and the soil mass that originates from the highlands are carried away by the floodwater and eventually gets deposited at the locations where the velocity of the flood flow is reduced. This results in the huge sediment deposits that may lead to the change in the river profile and the river capacity. Flat bottom valleys in highlands, which are adjacent to rivers are generally prone to floods (e.g., flood plains adjacent to Mananthavady River (Kerala State Disaster Management Authority, 2016). Some of the densely populated towns in the highlands are also prone to flooding (e.g., Munnar town in Idukki District).

5.5.2. The Midlands

Riverine flooding is the most common kind of flooding visible in the midland region. Due to continuous rainfall which exceeds the absorption capacity of the soil and flow capacity of the rivers/streams, water might overflow through its floodplains leading to riverine floods. Reclamation, land modification and settlement in flood plains of rivers are the major causes for the damages in midland regions of the state. One of the best examples of the impact of alteration of flood plains is the case of flooding in the Cochin International Airport. The airport is approximately about 400 metres from the Periyar River, the longest in the State which has the largest discharge potential. A stream channel (Chengal Thodu) and three irrigation canals were realigned to make space for the runway, which is flooded in 2018 (Biggest lesson from Kerala: The developmental agenda should be sustainable, Hindustan Times, Aug 25, 2018). Since the natural streams always tend to recapture the flood plains, a controlled developmental activity is important in the floodplains of all streams in the state (Pala, 2018 and 2019). The meandering of rivers is also cited as another reason for midland flooding (Kerala State Disaster Management Authority, 2016) (Sreekandapuram, 2019). Urban flooding due to the lack of proper drainage pathways for the water to flow into the natural streams is also observed in the midlands.

5.5.3. The Lowlands

The inability of the streams/rivers to accommodate the large quantity of water generated due to continuous rain in the catchment and landslides in the upstream results in flooding in the lowlands. The meandering of rivers also results in flooding in this region. Reduction in the capacity of the flood buffer systems like the Vembanad Kole wetlands due to unscientific management practices is another reason for floods in these areas. In 2018, the high tide activities in the Arabian Sea hindered the flood discharge from the lowlands into the sea and this has led to flooding in some of the coastal regions. The assessment of the 2018 August floods in Kerala using Sentinel-1A satellite imagery indicates that low lying areas in the coastal plains of Kuttanad and the Kole lands of Trissur recorded a rise of water up to 5m and 10m, respectively (Vishnu et al., 2019)

5.6. Sectoral Impacts of 2018 Flood

The EREs in 2018 and 2019, which led to landslides and floods in the state affected different sectors. The number of human fatalities in 2018 and 2019 was 339 and 125 respectively (Table 5.14) according to the memorandum submitted by the Government of Kerala. The impacts of floods exerted on different sectors are given in the following sections.

Table 5.14: Human fatalities occurred during the floods of 2018 and 2019

District	Human Fatalities	
	2018	2019
Thiruvananthapuram	11	0
Kollam	5	0
Pathanamthitta	3	0
Alappuzha	43	6
Kottayam	14	2
Idukki	54	5
Ernakulam	58	0
Thrissur	72	9
Palakkad	20	1
Malappuram	30	60
Kozhikode	16	17
Wayanad	6	14
Kannur	6	9
Kasaragod	1	2
Total	339	125

5.6.1. Agriculture

The unprecedented heavy rains and floods caused widespread damage in agricultural lands in both the years. In Kerala, the majority of the farmers are small or medium-scale farmers. The district-wise agricultural land loss in small and medium scale farms as per the records of

KSDMA is given in Table 5.15. In addition to the deposition of debris and loss of crops in the agricultural lands, many polder walls that protected the farmlands of Alappuzha, Thrissur, Kottayam, and Palakkad were breached. A large number of pump sets were also damaged during the unprecedented rain.

5.6.2. Housing

According to the 2011 housing census, there were 336 houses for every 1000 persons in Kerala. (all-India 273 houses per 1000 persons). The settlement pattern of Kerala is of a rural and urban continuum with different varieties of housing typologies predominantly reinforced cement concrete (RCC). One of the major affected sectors during the floods and landslides of 2018 was housing. According to KSDMA estimates, a total of 1,11,356 houses in urban areas and 6,92,848 houses in rural areas have been affected by 2018 floods in Alappuzha, Ernakulam, Thrissur, Kottayam, Pathanamthitta, and Wayanad. The district-wise details of fully and partially damaged houses in 2018 and 2019 are given in Table 5.16.

5.6.3. Fisheries

Strong winds, rains, and floods caused severe damage to the fisheries sector by damaging assets like boats and nets. Many fish farms were also affected including the government-run farms like the National Fish Seed Farm and Centre for Fresh Water Aquaculture at Neyyar Dam and the National Institute of Fisheries Administration and Management at Aluva during the 2018 flood event. According to KSDMA memorandum, total financial damage of Rs 45,44,800 due to fully damaged nets and of Rs 34,02,000 due to partially damaged nets was caused by the floods of 2018 (Table 5.17). As far as damage to fish farms is considered, 12452.2 hectares were affected in 2018.

Table 5.15: Agricultural loss in various districts of Kerala during the floods of August 2018 and August 2019

District	Agricultural area affected by >33 % crop damage (ha)	
	2018	2019
Thiruvananthapuram	1356.96	629.10
Kollam	869.73	278.76
Pathanamthitta	12085.05	3509.73
Alappuzha	12095.55	470.29
Kottayam	7170.71	2862.04
Idukki	5745.97	999.28
Ernakulam	1296.66	1294.21

District	Agricultural area affected by >33 % crop damage (ha)	
Thrissur	3569.25	2653.42
Palakkad	6250.43	10885.86
Malappuram	5275.4	1611.30
Kozhikode	627.04	274.81
Wayanad	1876.8	3661.18
Kannur	926.53	1496.37
Kasaragod	199.29	388.26
Kerala	59345.37	31014.62

Table 5.16: Damages to houses in various districts of Kerala during the floods of August 2018 and August 2019

District	Fully Damaged Houses (Pucca)		Severely Damaged Houses (Pucca)	
	2018	2019	2018	2019
Thiruvananthapuram	111	9	2940	196
Kollam	95	4	1338	204
Pathanamthitta	741	4	32775	85
Alappuzha	2075	28	18990	423
Kottayam	76	11	656	215
Idukki	615	68	1684	341
Ernakulam	1166	17	1445	195
Thrissur	2889	22	18241	219
Palakkad	1118	58	3604	477
Malappuram	500	795	3731	3409
Kozhikode	107	73	1338	980
Wayanad	702	535	9250	5435
Kannur	121	133	3216	2022
Kasaragod	3	38	74	358
Total	10319	1795	99282	14201

Table 5.17: Economic losses in the fisheries sector in various districts of Kerala during the floods of August 2018 and August 2019

District	Damage to nets and boats (lakhs)	Fish farms affected (ha)
	2018	2018

District	Damage to nets and boats (lakhs)	Fish farms affected (ha)
Thiruvananthapuram	0.565	17.68
Kollam	3.672	98.88
Pathanamthitta	10.596	11.79
Alappuzha	7.008	1319.89
Kottayam	73.497	1030.63
Idukki	4.534	26.07
Ernakulam	24.603	351.04
Thrissur	11.653	4473
Palakkad	2.052	4608.63
Malappuram	1.69	53.82
Kozhikode	1.689	105.35
Wayanad	0	334.51
Kannur	1.551	18.91
Kasaragod	0	2
Kerala	143.11	12452.2

5.6.4. Animal Husbandry

The unprecedented rainfall which triggered flooding and landslide in the state has resulted in the death of a large number of cattle, buffaloes, goat, and poultry. Alappuzha was the worst affected district in 2018.

5.6.5. Power

The heavy loss was incurred by the power sector during the unprecedented rain and subsequent floods in transmission and distribution mains. Many of the substations, power transformers, distribution transformers, etc were submerged in water. According to KSDMA, the total cost incurred during the floods of 2018 for repair work in the power sector was 8503.11 lakhs.

5.6.6. Public Works Department

Due to the extremely devastating monsoon calamity in the form of floods and landslides, Public Works Department (PWD) has suffered unprecedented losses as evidenced by damage to physical infrastructure especially roads and bridges. All types of roads and bridges have been negatively affected. Some roads and bridges have even been completely washed away due to floods. Culverts have also been severely damaged. A total of 9538.45 km of roads have been damaged in Kerala during the 2018 floods (Table 5.18). Idukki was the worst-hit district in this context as 2,130 km of roads have been damaged in the district, followed closely behind by Ernakulam where 2,105 km of roads have been damaged. 510 bridges have been damaged due to the calamity. The highest number of bridges damaged has been in Alappuzha, as 121 bridges have been damaged in the district.

5.6.7. Irrigation and Water

The entire water supply system got totally disrupted due to the flood of 2018. The Kerala Water Authority and Irrigation departments run a large network of water supply for drinking as well as for irrigation purposes. Both of these sectors had a broad network of pipelines and canal systems that were passing through the urban and rural areas in Kerala. Irrigation canals, Public Taps, Pipelines, Pump houses, check dams, Bunds, Irrigation Pumps and other irrigation machinery and structures got damaged due to Floods, landslides, and landslips. Most of the engineering structures washed away by huge landslides and inundated by flooding. Huge losses in machinery, equipment, structural and non-structural assets have been estimated by the concerned authorities. According to KSDMA, the highest loss reported in the water supply sector is in the Thrissur district and Pathanamthitta district is the highest in the irrigation sector.

Table 5.18: Damages to roads and bridges in various districts of Kerala during the floods of August 2018 and August 2019

District	Length of road affected (km)	No. of bridges affected
Thiruvananthapuram	475	5
Kollam	340	48
Pathanamthitta	550	68
Alappuzha	241	56
Kottayam	291	6
Ernakulam	2105	121
Idukki	2130	13
Thrissur	598	41
Palakkad	164	78
Malappuram	1231	18
Kozhikode	332	8
Wayanad	565	9
Kannur	100	20
Kasaragod	416.45	19
Kerala	9538.45	510

Table 5.19: Damages occurred to the irrigation and water supply sectors in various districts of Kerala during the floods of August 2018 and August 2019

District	Irrigation sector - Cost (in lakhs)	Water Supply sector – Cost (in lakhs)	Total
Thiruvananthapuram	745.45	66	811.45
Kollam	1149.50	58.5	1208
Pathanamthitta	11234.15	157.5	11391.65
Alappuzha	3276	136.5	3412.5
Kottayam	1484.50	165	1649.5
Idukki	4182.50	82.5	4265
Ernakulam	5123.50	621	5744.5
Thrissur	8924.51	696	9620.51
Palakkad	5300.90	124.5	5425.4
Malappuram	3370.00	139.5	3509.5
Kozhikode	2342.20	39	2381.2
Wayanad	1674.78	45	1719.78
Kannur	1985.00	12	1997
Kasaragod	466.80	0	466.8
Kerala	51259.79	2343	53602.79

5.6.8. Miscellaneous

The floods caused damage to many public institutions like offices, police stations, etc. Many community-owned assets like public wells, academic institutions, and religious places also were affected during the floods of 2018. One of the major impacts of floods was felt in Chendamangalam where weavers weave a special kind of cotton cloth that has a Geo-indication tag. Around 2000 weavers in Chendamangalam were affected when the floodwaters of the Periyar seeped into their homes, showrooms, dyeing units and factories in August, and those hopes were washed away. The combined losses of the handloom industry in Chendamangalam are estimated at ₹15 crores.

5.7. Flooding in Kuttanad and coastal areas

The Kuttanad wetlands, the Kole wetlands of Thrissur and the Vembanad lake system witnessed a significant increase in water level during the August 2018 floods. The water drained from the 4 contributing rivers of Vembanad lake (Meenachi, Manimala, Pamba, and Achenkovil) generated a runoff greater than 1.6 BCM against the 0.6 BCM carrying capacity of Vembanad lake (CWC, 2018). Vishnu et al. (2019) analyzed the inundated regions using satellite images and observed that the water levels in the Kuttanad and Kole wetlands were slow to decline even after water from most of the other inundated areas began to recede. By overlaying the DEM over the flood inundation map, they estimated that the rise in water level in the Kole wetlands was approximately 10 m, whereas, in the Kuttanad region, the water level rose by approximately 5m. Geomorphology was cited as the reason for the difference in water levels. While Kuttanad spreads over a large extent with a large region below sea level, Kole wetlands are surrounded by physiographic highs. Unscientific method of land utilization, conversion of wetland to dry land, sand mining from the river channel, construction of buildings in the river flood plains etc might have amplified the effects of floods. In Kuttanad, in addition to the extreme rainfall events and the discharge from floods, the tidal action also played a significant role in delaying the discharge of floodwaters. Many bunds and embankments which secured the paddy polders suffered damage during the floods and intensified the impacts in both 2018 and 2019.

5.8. Natural and anthropogenic drivers of floods in Kerala

There are several natural and anthropogenic drivers of floods in Kerala, among which the prominent are: (1) high-intensity rainfall for prolonged duration, (2) human interventions in the catchment areas, and particularly in the floodplains and riparian zones, (3) unauthorised encroachments leading reduced extent of natural areas and their impaired functionality (4) reclamation of wetlands and lakes that acted as natural safeguards against floods due to urbanisation and development of infrastructure, (5) unexpected EREs and lack of exposure in handling such EREs through reservoir operation and (6) decreased channel capacity due to sedimentation and aquatic vegetation.

There are many different studies and views on whether to consider ‘Climate change’ as a reason for the flood occurrences in Kerala. Climate change is one of the most important global environmental challenges that is affecting nature and human existence in the world. Some of the studies on climate change impact on India concluded that the hydrological cycle is likely to be altered and the severity of droughts and intensity of floods in various parts of India may increase (India’s Initial National Communications to the United Nations Framework Convention on Climate Change; India: The Impact of Climate Change to 2030,” prepared by the Joint Global Change Research Institute and Battelle Memorial Institute). A detailed long term (1951-2007) study on climate change impact on India, shows that drying and warming trends during the monsoon season have resulted in a decrease in the total runoff in large parts of the State. Since there is no increase in mean and extreme precipitation and runoff in Kerala over the last six decades, the flood that happened in August 2018 is likely to be driven by anomalous atmospheric conditions due to climate variability rather than anthropogenic climate warming (Mishra et al., 2018). Anomalous atmospheric condition refers to the combination of above-normal seasonal rainfall, state-wide extreme rain, high reservoir storage, and unprecedented extreme rain in the catchments upstream to major reservoirs. Orographic effect and multiscale interaction during extreme rainfall were studied by Baisya and Pattnaik (2019) in the context of the extreme rainfall and flooding during August 2018 in Kerala. The analysis carried out by segregating moisture transport into its mean and perturbation terms shows that an anomalous moisture channel over the Arabian Sea supplied continuous moisture to the Western Ghats, whereas anomalous wind due to a monsoon depression advected moisture towards the southern peninsula resulted in the extreme weather event in Kerala leading to severe flooding.

Geographical location and topographical features of Kerala also play a vital role in bringing heavy rains in Kerala leading to flooding. The Western Ghats is positioned to enhance rainfall along the west coast as it intercepts the moisture-laden air being drawn in from the warm ocean waters as part of the southwest monsoon circulation. Kerala is also facing impacts due to significant changes in its land use. Large scale urbanization has reduced the forest fallow and grassland in the state. The percentage increase in the built-up area from 1985 to 2005 is 79% and there was a reduction of 7.65% in the forest cover in the state. Grasslands and shrublands experienced a significant reduction from 2005 to 2018 (Dixit et al., 2019; Eldho and Sreedevi, 2019). This has resulted in a decrease in infiltration and has led to high runoff. In addition to this, urbanization and developments happening on the river banks or flood plains in Kerala have led to more damages during flooding in the State (Eldho and Sreedevi, 2019).

5.9. Effect of land use/ land cover changes on hydrological response

Land use and the land cover change affect the hydrological response of watersheds. The various features and factors that change in response to change in land use/land cover are leaf area index, evapotranspiration, soil moisture content, interception, infiltration capacity, surface and subsurface flow, base flow contribution to streams, groundwater recharge, surface roughness, runoff and effects the interaction among the vegetation, soil, geology, terrain and climatic processes (Baker and Miller, 2013; Nejadhashemi et al., 2010). The impact of land use/land cover change on hydrological response over a watershed will be more severe in small watershed compared to large watersheds (Apollonio et al., 2016). There are several studies on the impact of land use/ land cover on the hydrological responses.

Dixit et al. (2019) assessed the role of land use/ land cover (LULC) change on the 2018 floods in Kerala. The LULC changes for the period 1985 through 2018 were assessed and a massive loss in forest cover during this period was observed with the highest loss between 1995 to 2005. During this period, many of the evergreen forests changed to either mixed forests or cropland. In the period 2005 to 2018, it was observed that there was a significant reduction in the grasslands and shrublands in the state. The LULC changes between the years 2005 to 2018 have not been as drastic as that of 1995 to 2005.

A study by Kumar (2005) shows that deforestation in Kerala between the years 1940 and 1970 has resulted in a loss of publicly managed forests at the rate of 5000 ha per year. The National

Remote Sensing Agency recorded a deforestation rate of 1.4 % in Kerala for the period from 1972 to 1982 (Nair, 1991). Meunier (1996) documented a decrease in infiltration rate, an increase in runoff and flash floods, and an increase in sediment generation in the mountainous stream as a result of land use change. In Kerala, the sediment production rates in various hydroelectric reservoirs of Kerala have been estimated to be 4.43 to 71.05 $m^3ha^{-1}yr^{-1}$ (Kerala State Planning Board, 2014) and have reduced the reservoir capacities. It is also observed that there is an alarming reduction of forest cover (83%) in the Western Ghats during the last century. There is a significant reduction in the paddy/wetlands (77%) which were mainly converted to homesteads/ perennial tree plantations of coconut and rubber (Eldho and Sreedevi, 2019). Modifications of wetlands are also observed in the state which has high impacts on floodwater retention and post-monsoon water availability in the State.

Study on land use/land cover impact on Pampa River Basin in Kerala (Mayaja and Srinivasa, 2016) over a period from 2001 to 2010 shows that a rapid pace of urbanization (which have resulted in a three-fold increase in the built-up area), massive encroachment of river banks, deforestation, transition in the agricultural pattern, etc. have transformed the land use pattern of this river basin. This has increased the ravage of flood every year on the villages and densely populated regions on the banks of this river.

5.10. Implications of dams and reservoirs in floods

5.10.1. Case Study - I: Role of dams on the floods of August 2018 in Periyar River Basin, Kerala

During August 2018, Kerala witnessed one of its severe flood events owing to the most severe EREs (Extreme Rainfall Events) on record. This caused extensive flooding and landslides across the state. One of the worst affected river basins during this flood was the Periyar River basin (PRB) which is spread among 3 districts of Kerala - Idukki, Ernakulam, and Thrissur. Among them, Idukki received the maximum amount of rainfall, 3555 mm, that was almost 100% in excess as compared to the normal rainfall which is 1852 mm. Periyar River basin is highly regulated by 17 dams and reservoirs (Fig. 5.3) which were almost near FRL (Full Reservoir Level) by the end of July 2018. This rare combination of EREs along with the near FRL reservoir storages made the situation challenging and forced the authorities to open the gates of most of the dams in the river basin, resulting in severe flooding on the banks of Periyar River. The government has faced severe criticism on this issue where the roles of dams and its operations in causing/mitigating the flood have been questioned.

With the help of scientific studies which include watershed modelling and reservoir operations, we can clearly answer such questions, which will further help in planning and management of flood protective measures that can reduce the impact of the flood on the community as well as the environment. A similar kind of hydrological modelling exercise was done by Sudheer et al.

(2019) where they have simulated the real flood scenario of the August 2018 flood along with few other scenarios where a set of reservoir storages (50, 75 and 85% full) were considered as the initial condition for the model simulation.

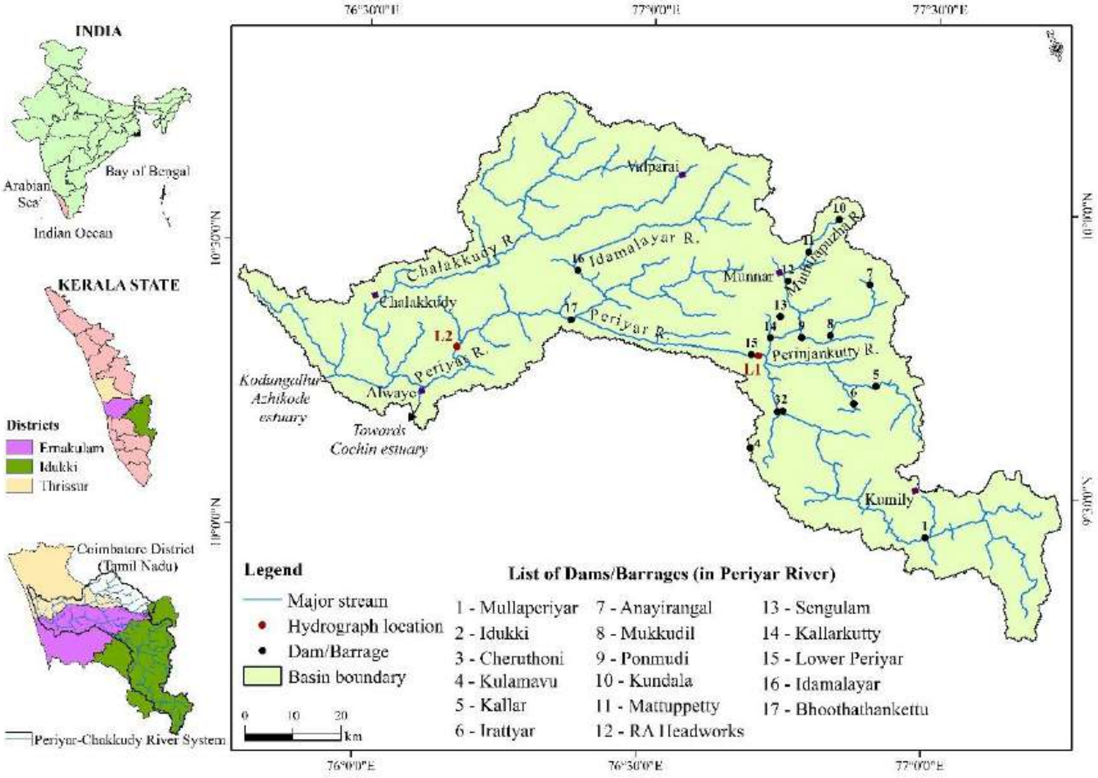


Figure 5.3: Periyar River Basin (including Chalakkudy River System), Kerala, India

5.10.1.1. Materials and Methods

The hydrologic modelling exercise was done using HEC-HMS, a semi-distributed Hydrologic model developed by the US Army Corps of Engineers which predominantly works on dendritic type watersheds. The data used for the modelling were, Digital elevation model (DEM), land use, soil and rainfall data. The SRTM DEM of 30 m resolution was used to generate the stream network of PRB. The elevation of PRB was found to be varying between 0 to 2690 m and the basin contained 144 sub-basins based on its topography. The land use data used was collected from NRSC which was derived from IRS AWiFS data for the year 2010 and has a spatial resolution of 60 m. The major land used class present in the basin is the forest which spreads across the upstream and central parts of the basin. The soil data were collected from the National Bureau of Soil Survey and Land Use Planning. The rainfall data used was Integrated Multi-satellite Retrievals for GPM (IMERG) which is a half-hourly cumulative gridded precipitation. The IMERG data was bias-corrected using a simple ratio method with respect to the IMD rainfall from a few selected locations within the basin. The duration of the rainfall data used was from 1 June to 31 August 2018.

5.10.1.2. Scenarios

The flooding situation of PRB was simulated with varying initial and boundary conditions to assess the basin response. The scenarios considered were i)Virgin simulation run for the 2018 event, ii) Simulation of flood events of August 2018 iii) The reservoirs were considered (25, 50 and 75% full) at the end of July with AMC III conditions and iv) The reservoirs were considered (25, 50 and 75% full) at the end of July with AMC II conditions. The results were analyzed at two locations (L1 and L2 shown in Fig. 5.3). L1 is downstream of the confluence between the Periyar and Muthirapuzha rivers and L2 is a downstream location in PRB where a gauge station is maintained by CWC.

5.10.1.3. Results and discussion

While doing the virgin simulation (scenario-1) where no dams and reservoirs were considered to be present in the basin the simulated event of 2018 showed peak discharges of 8224 m3/s (Fig. 5.4a) and 11990 m3/s (Fig. 5.4b) at L1 and L2 respectively.

In scenario-2, the real flooding condition of the 2018 flood was considered where the reservoirs were 85% full by the end of July 2018 with AMC-III condition in which the soil is assumed to be fully saturated due to the continuous heavy rain in the month of July 2018. In this case, hydrographs at 3 different locations were analyzed as shown in Fig. 5.5. Figure 5.5 a shows the inflow and outflow hydrographs of the Idukki reservoir. A comparison of the measured and modelled peak discharges exhibited less than 10% deviation which indicates a good agreement between the model and the real scenario. Figure 5.5 b shows the simulated flow hydrograph at L1, where the magnitude of the peak flow reached up to 5523 m3/s. Figure 5.5 c shows the flow hydrograph at L2 where the simulated peak flow shows a magnitude of 9965 m3/s. This location corresponds to the CWC gauging site at Neeleeswaram where the observed peak discharge was 8800 m3/s. The comparison between the observed and simulated hydrograph evidently suggests a realistic agreement with a minor difference of 12% in peak discharge prediction. This difference in peak discharge prediction can be attributed to the difference between rainfall occurred and IMERG precipitation data, and uncertainty in the model parameters. When compared with the virgin simulations (scenario-1), it can be observed that the reservoirs were effective in reducing the peak flows by a scale of 2500 m3/s.

In scenarios 3 & 4 the flood that occurred in PRB was simulated by varying the reservoir storage capacities with different soil moisture conditions. Figures 5.6 & 5.7 show the flow hydrographs corresponding to the varying storage capacities (25%,50%,75%) at the end of July 2018 under AMC-II (average) and AMC-III (wet) conditions at L1 and L2 respectively. From the graph, it is observed that antecedent soil moisture condition does not have a significant influence on the peak flow, as the difference in magnitude between both the cases is found to be within 10%. Figures 5.6 a and 5.7 a show that the simulation run corresponding to the storage level at 75% resulted in a peak discharge of 4516 m3/s and 8340 m3/s at L1 and L2 respectively, as compared to the peak discharge of 5523 m3/s and 9965m3/s for 85% storage level (Figure 5.5 b and c). The reduction in storage capacity of reservoirs from 85% to 75% helps reduce the peak flow at L1 by 18% and at L2 by 16%. Similarly, the reduction in reservoir storage from 85% to 50% or 25% reduces peak discharge by 21% at both locations.

From this research, it is apparent that the reservoir operation could not have helped in avoiding the flood situation. On the other hand, the simulations clearly indicate that flood peaks could have been attenuated by the early release of reservoir storage (flood cushion up to 25%) prior to the occurrence of the EREs, though to a maximum level of only 21%. The current reservoir operation policy is based on water conservation, so as to maintain the reservoir level at FRL, throughout the monsoon season, to ensure maximum power generation. Therefore, it is suggested that one should revisit the operation rule curves of the reservoirs and derive fresh rule curves in order to operate the reservoirs, not only as power reservoirs but also as flood control reservoirs. The experience during the August 2018 flood in Kerala underscores the significance of reviewing the flood management strategies and flood mitigation measures.

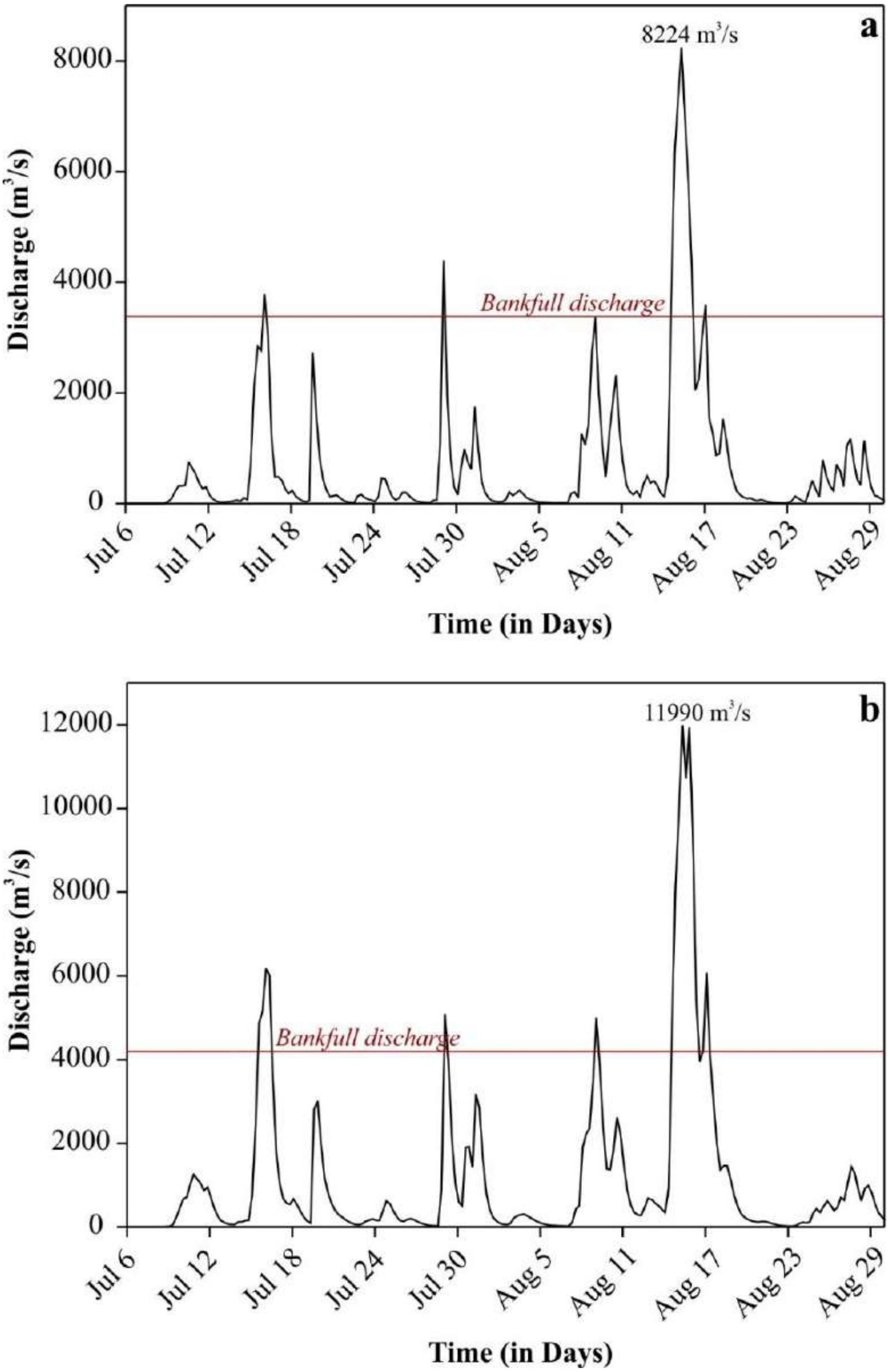


Fig. 5.4: Hydrographs modelled by virgin Simulation of the basin for (a) L1 and (b) L2

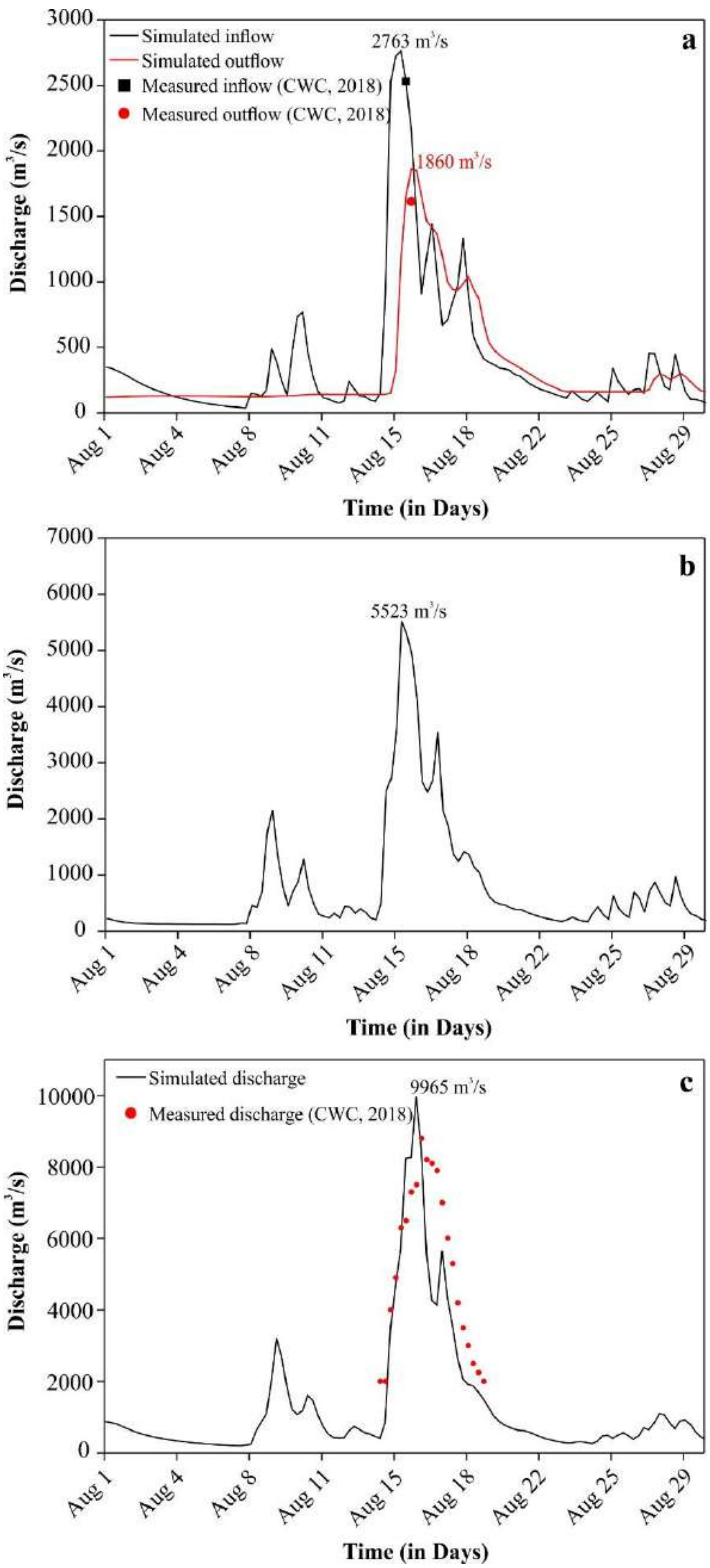


Fig. 5.5: Simulated hydrographs at (a) Idukki reservoir, (b) location 1 (L1), and (c) location 2 (L2). Simulated flows were compared at Idukki reservoir and L2 with measured flows

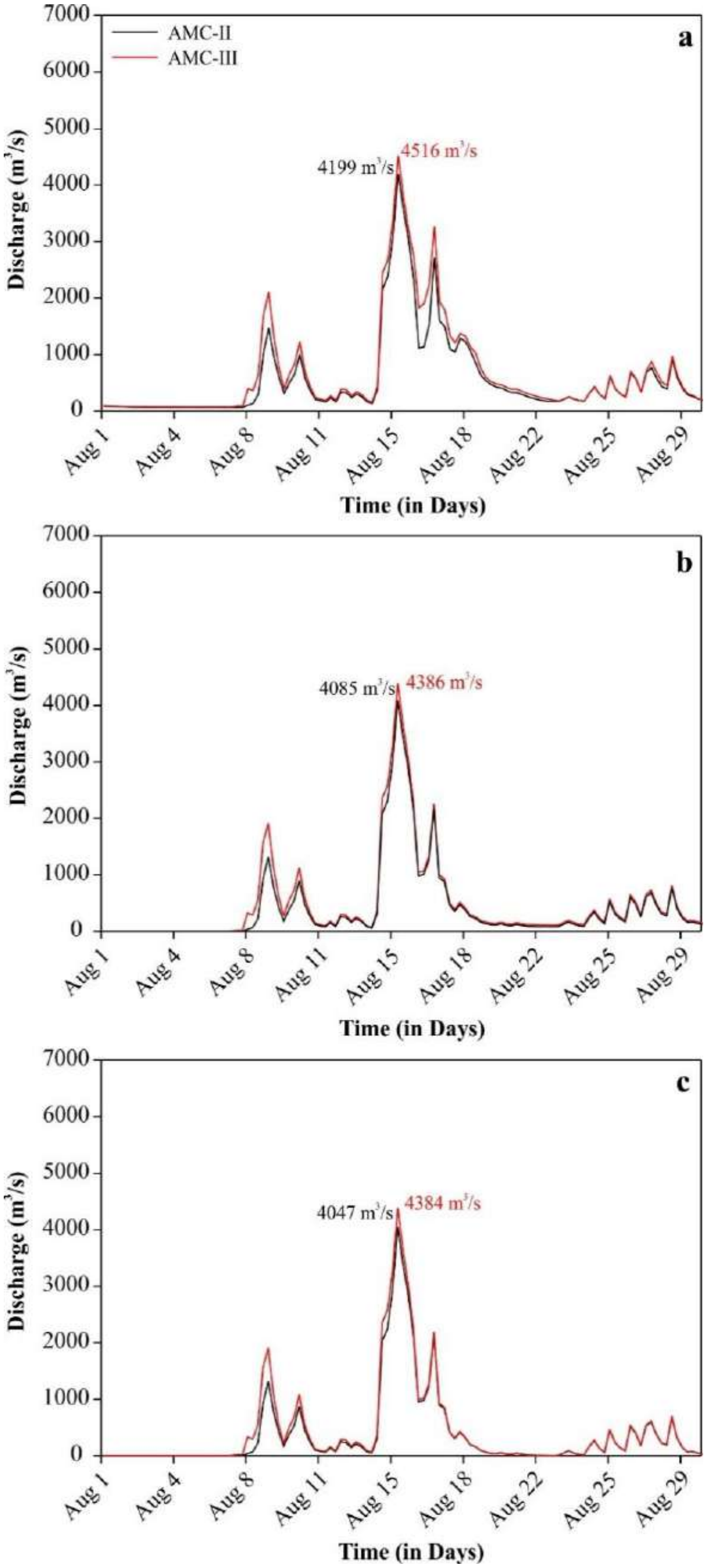


Fig. 5.6: Flood hydrographs at L1 when reservoirs are at storage capacities (a) 75%, (b) 50% and (c) 25% by the end of July 2018 with AMC-II and AMC-III conditions

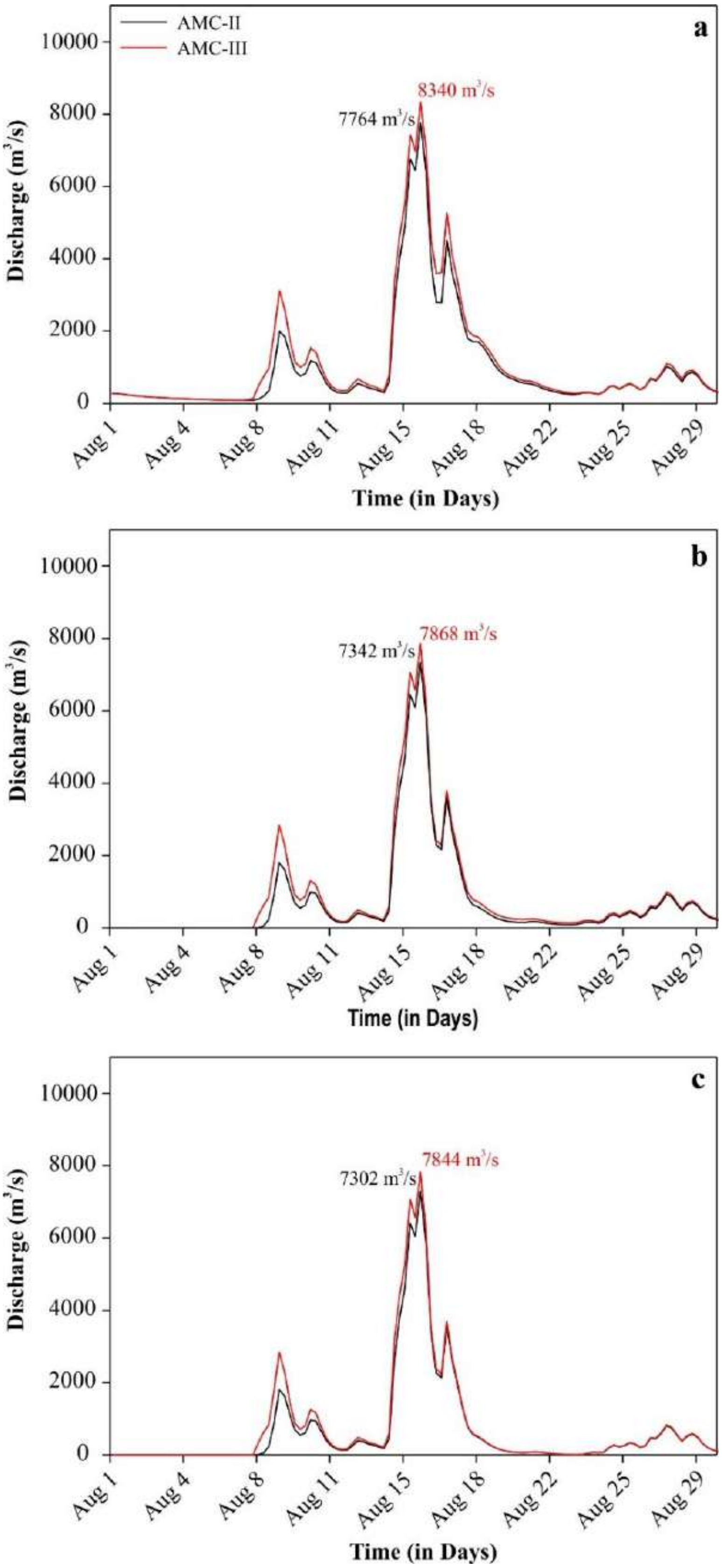


Fig. 5.7: Flood hydrographs at L2 when reservoirs are at storage capacities (a) 75%, (b) 50% and (c) 25% by the end of July 2018 with AMC-II and AMC-III conditions

5.10.2. Case study-II: Flood Inundation mapping for Periyar River

Flood is one of the most devastating and widespread natural phenomena that cause casualties and loss on every inhabited continent. Flood inundation mapping has been accepted as one of the possible solutions which can help the policymakers to prepare appropriate action plans to reduce the impact of flooding on human as well as the environment. In August 2018, the Periyar River basin witnessed one of the largest floods in its history, an event with a 142-year return period, which caused a massive amount of damage to the humans, infrastructures and environment. It is important to study the impact of such major flood events on the basin that would help the authorities to take necessary steps to reduce the impact of such events in the future. This report includes major findings from the study conducted by Sudheer et al. (2018) and results from a flood inundation modelling exercise done for Periyar River based on different initial storages of the reservoirs in the basin. Periyar is the second largest river basin of Kerala with a catchment area of 5398 sq. km and a length of 244 km, makes it the longest river in Kerala.

5.10.2.1. Flood inundation modelling

To develop proper action plans for flood plain protection, it is important to know the areal extent and inundation depth during flooding. Flood inundation modelling is a commonly adopted method that would help the authorities to develop proper action plans to reduce the impact of the flood. A similar exercise was done for the Periyar River using a two-dimensional hydraulic routing model, HEC RAS-2D, developed by the US Army Corps of Engineers. HEC RAS-2D is a widely accepted model for flood inundation modelling which solves the two-dimensional shallow water equations which represent and mass and momentum conservation in a plane. The areal extent considered for the flood inundation modelling in the Periyar River basin comprised an area of 184 sq.km (Fig. 5.8), with an upstream boundary near Onampilly and downstream boundary near Aluva. The data used for setting up the HEC RAS were, terrain data obtained from ALOS - PRISM which is of 30 m resolution and land use data obtained from NRSC which is derived from IRS AWiFS data for the year 2010 with a resolution of 60 m. The elevation of the terrain was varying between 0 to 109.8m with the majority of the area falls within an elevation of 30m. The land use data is used to derive the Manning’s roughness coefficient (n) which is the only parameter in the modelling framework. In this study, the diffusive wave method was used for routing the flood.

5.10.2.2. Scenarios considered

For the analysis, 3 different flooding scenarios were considered resulted from a basin average rainfall of 303.1 mm happened over a duration of 24 h with a 100-year return period. The three different scenarios considered were i) a 24h 100-year rainfall with an initial storage of 50% in the reservoirs ii) a 24h 100-year rainfall with an initial storage of 75% in the reservoirs and iii) a 24 h 100-year rainfall with an initial storage of 85% in the reservoirs.

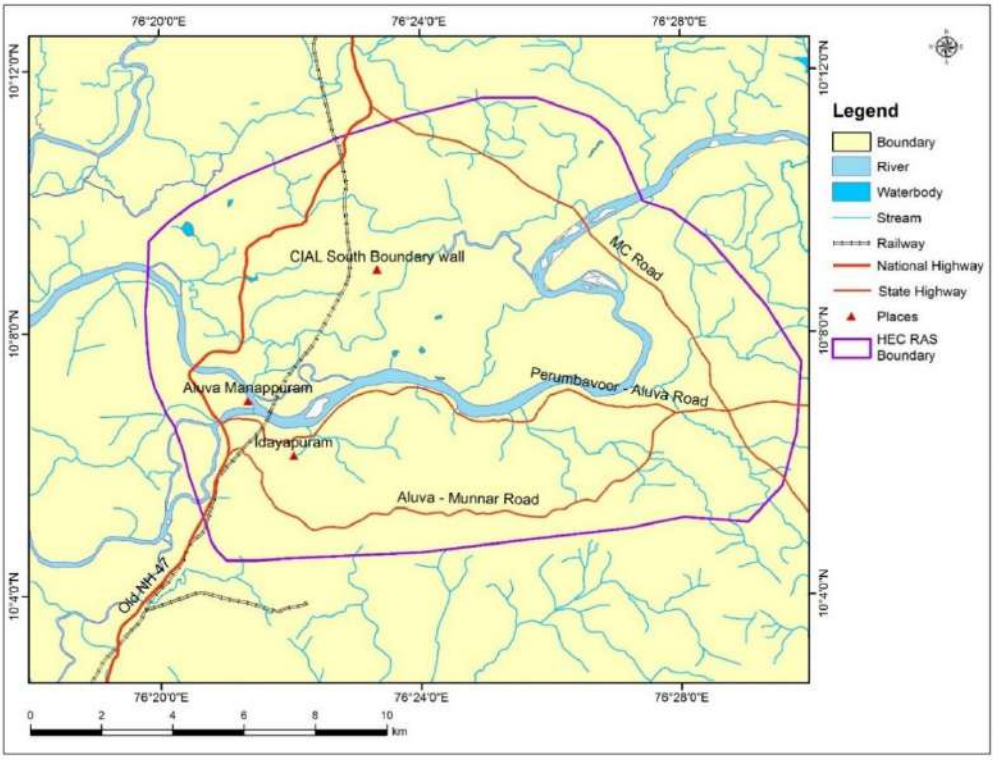


Fig. 5.8: Map showing portion of the Periyar River considered for flood inundation modelling using HEC RAS

5.10.2.3. Results and discussion

The maximum inundation corresponding to the 3 scenarios considered is shown in Figs. 5.9, 5.10 and 5.11. For the first scenario where the reservoirs in the catchment were considered 50% full, the total area inundated was around 63 sq.km which covers more than 34% of the total area considered in the analysis. The peak flow discharge corresponding to the maximum inundation was 6857 m^3/s which is less than the peak flow reported by CWC during August 2018 which is 8800 m^3/s. While examining the maximum inundation extent (Fig. 5.9) the depth of water found to be varying between 0 to 17.42 m with depth above 15 m observed at certain locations within the main channel. The inundation depths at certain locations were noted which are shown in Fig.1. The inundation depth near the boundary walls of the CIAL was found to be ranging between 0.6 to 2.5 m and 6.5 m at Aluva Manappuram. During the August 2018 flood, the maximum depth of inundation near the southern drain of CIAL and at the Aluva Manappuram was 2.1 and 10.5 m respectively. On the southern side of Periyar River, a location at Idayapuram, that marked an inundation depth of 6 m during the 2018 flood found to have an inundation depth of 4.9 m in the first scenario. The above comparison of inundation depths evidently suggests a realistic agreement between the modelled and observed depth of inundation.

The maximum depth of inundation obtained from the second flooding scenario is shown in Fig. 5.10. The depth of inundation was ranging between 0 to 18.7 m with an area coverage of 93.5 sq.km. The peak flow magnitude observed during the simulation was 13815 m^3/s. The depth of inundation obtained at the southern boundary of CIAL, Aluva Manappuram and Idayapuram were 4.67, 7.3 and 5.91 m respectively. In the third scenario, the reservoirs were considered to be 85% full and the corresponding inundation map obtained is shown in Fig. 5.11. The depth of inundation was varying between 0 to 18.9 m with inundation spread over an area of 97 sq.km. The depth of inundation noted at the southern boundary of CIAL, Aluva Manappuram and Idayapuram were 5, 7.5 and 6.12 m respectively.

While doing the flood inundation simulation, it was observed that the entry of water to the CIAL area was mainly due to the reversal of flow in the Chengal stream which is flowing on the North-east side of the airport. During the 2013 flood, one of the major reasons for water entry to the airport area was the flow reversal in the Chengal stream. After the 2013 flood, a pilot study conducted by NIT Calicut recommended about the construction of a flow regulator at the confluence of Chengal stream into the Periyar River. Therefore, in addition to the above-mentioned scenarios, two more scenarios were considered to check the feasibility of providing a flow regulator at the river confluence. The flood hydrographs considered in this analysis were corresponding to scenarios 1 and 3 where the reservoirs were considered to be full up to 50% (scenario-4) and 85% (scenario-5) respectively. The corresponding Inundation maps are shown in Figs. 5.12 and 5.13. When provided a regulator at the above-mentioned river confluence, for the scenario where the reservoirs were 50% full the inundation depth at the southern boundary wall of the CIAL was reduced from 2.12 (scenario-1) to 1.91 m. In scenario-5, where the reservoirs are 85% full, the water depth at the CIAL boundary was observed to be 4.97 m. The results show that even with the provision of a regulator at the river confluence, the inundation can be reduced only to a certain extent. One of the major reasons behind the minimal reduction of water depth in the CIAL area is the presence of other minor order streams that are connected to the Chengal stream from the upstream of the Periyar River during larger floods. To study the feasibility of providing a regulator needs further investigation using fine resolution data.

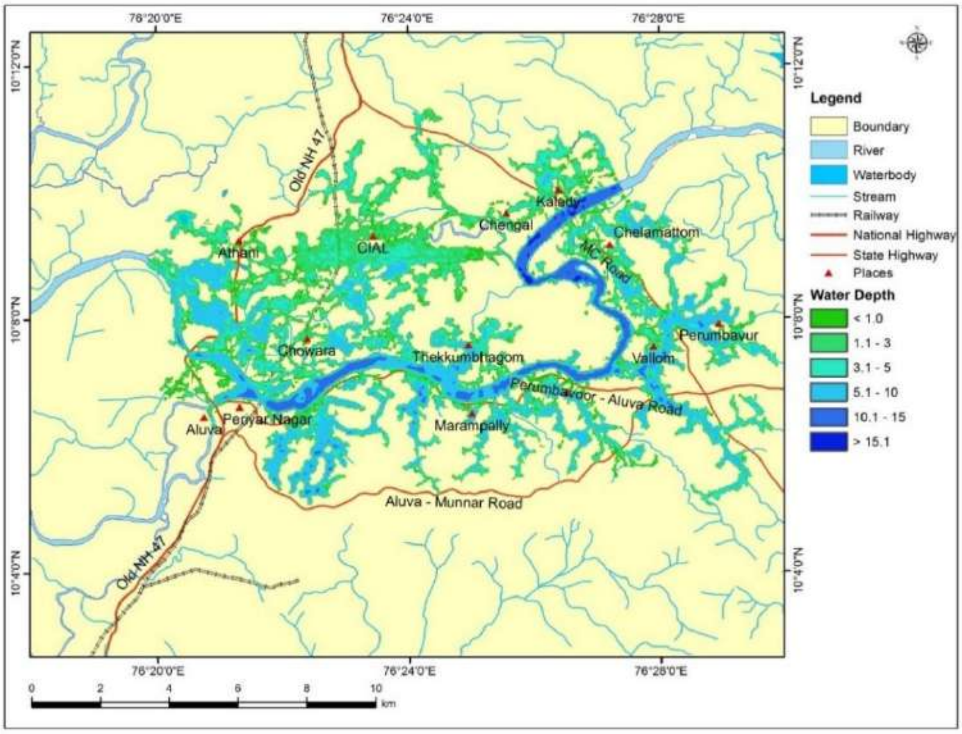


Fig. 5.9: Map showing the maximum depth of inundation corresponding to a 24h 100-year rainfall with an initial storage of 50% in the reservoirs.

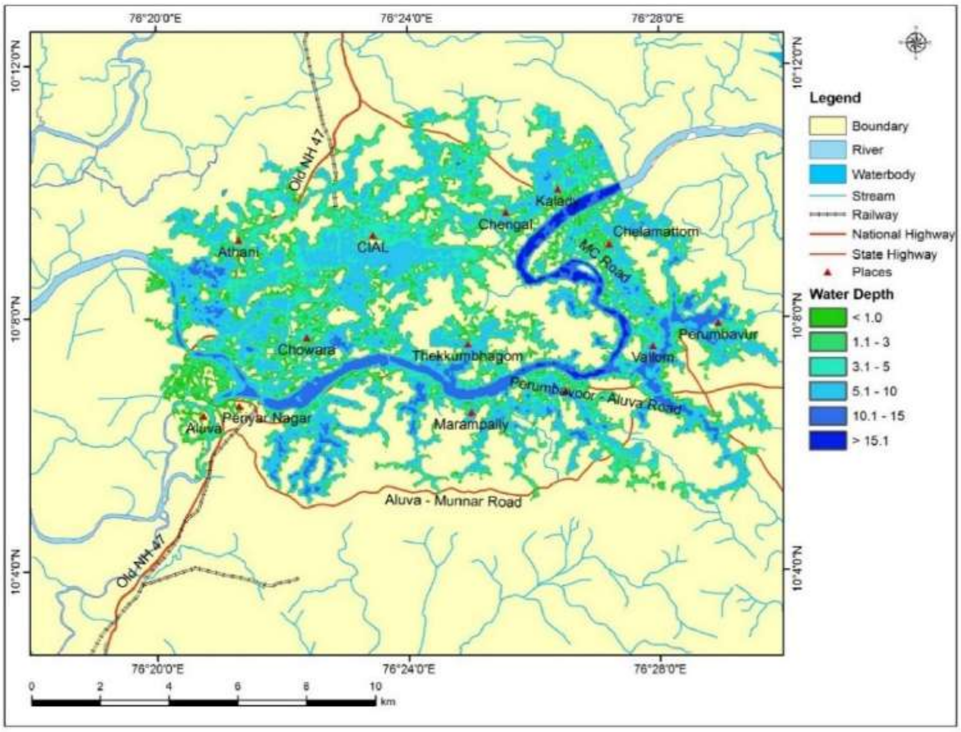


Fig. 5.10: Map showing the maximum depth of inundation corresponding to a 24h 100-year rainfall with an initial storage of 75% in the reservoirs

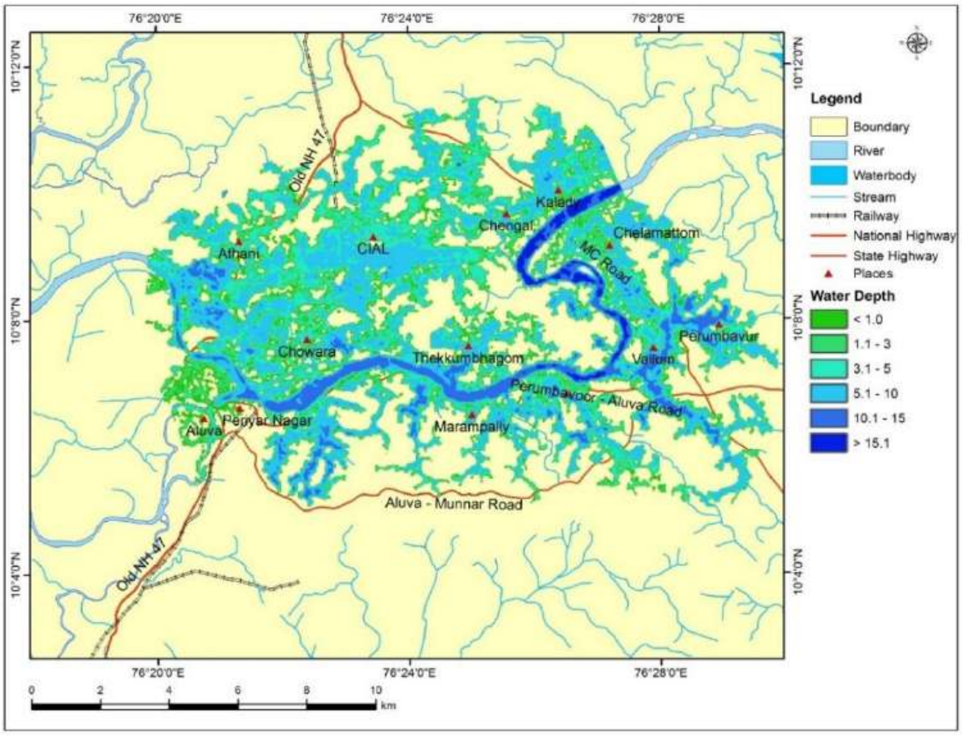


Fig. 5.11: Map showing the maximum depth of inundation corresponding to a 24h 100-year rainfall with an initial storage of 85% in the reservoirs.

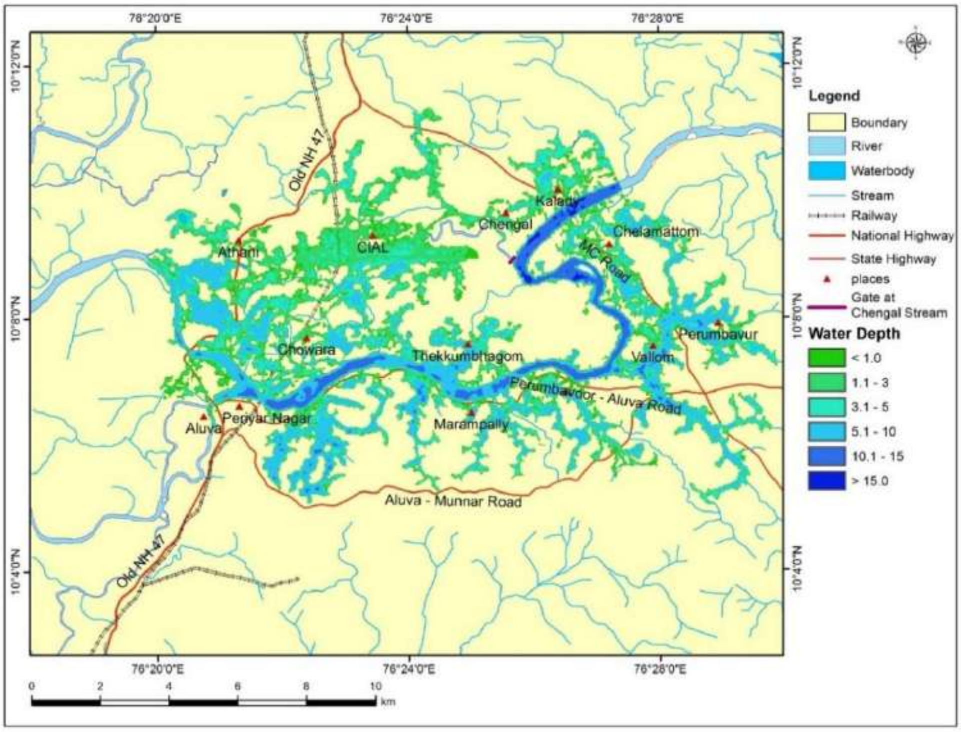


Fig. 5.12: Map showing the maximum depth of inundation corresponding to a 24h 100-year rainfall with an initial storage of 50% in the reservoirs and with the provision of a flow regulator at Chengal Stream and Periyar River confluence.

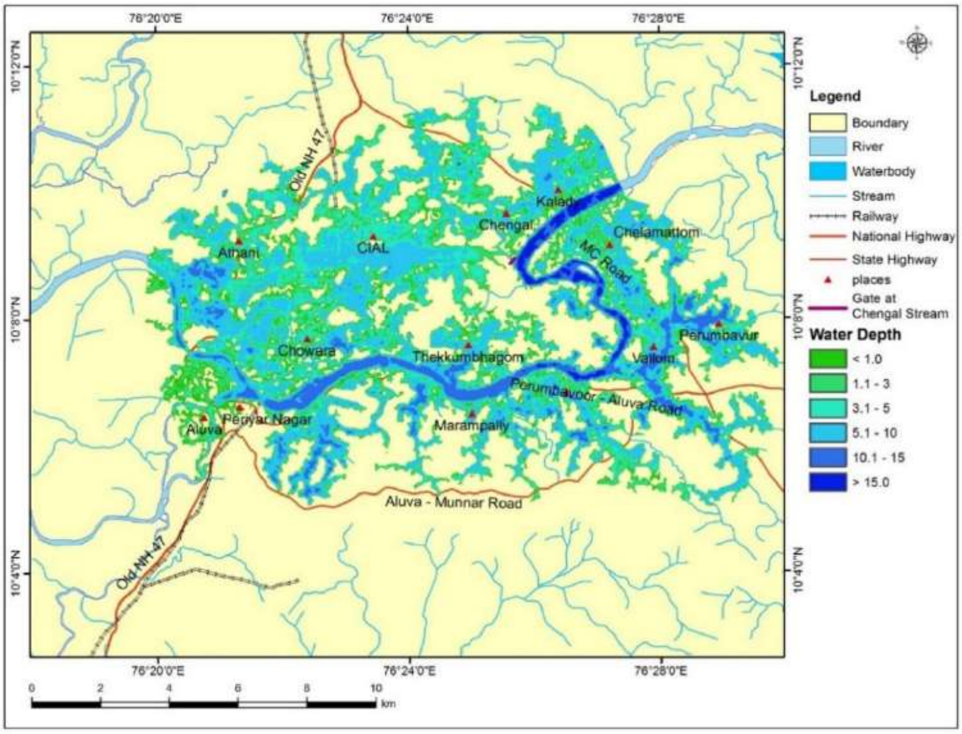


Fig. 5.13: Map showing the maximum depth of inundation corresponding to a 24h 100-year rainfall with an initial storage of 85% in the reservoirs and with the provision of a flow regulator at Chengal Stream and Periyar River confluence.

5.10.3. Role of reservoir operation in flood control

Reservoir operations for flood moderation, as one flood-management option, play an important role in protecting people and their socio-economic activities in floodplains from flooding. Reservoir operations, however, have the potential to alter flow regimes, fix river shape or separate river channels from the floodplains under new flow and sediment regimes. The need for sustainable development has highlighted the importance of addressing the negative consequences of such flood-control and protection measures on natural flow regimes that have the potential to threaten human security, including life, livelihoods and food and health security (WMO, 2006).

Flood moderation reservoirs store all or a portion of the floodwater in the reservoir, particularly during peak floods, and then releases the water slowly. Space within a reservoir is generally reserved to store impending floods. Small-to-medium floods generated from the catchment are fully captured by the reservoirs but extreme flood events are only partially attenuated and their transformation downstream is delayed. The extent of attenuation depends on the available storage capacity vis-à-vis the magnitude of the flood event (WMO, 2006). The purpose of the reservoirs for flood management may be required only for a few days or weeks in any particular year in order to:

- Store floodwater to reduce discharge downstream;
- Keep space empty for the storage of impending floodwater (storage space in the reservoir is required);
- Maintain appropriate operation in accordance with flow discharge into the reservoir.
- In order to provide maximum attenuation of the peak floods, it is imperative that maximum possible storage space is available when the floods approach the reservoir. This can be achieved by drawing the reservoir level down to the minimum possible. The need to store water for other socioeconomic purposes, however, presents contradictory demands. Long-range inflow forecasting forms an important tool to provide decision support in such cases.

5.10.4. Flood mitigation during conservative reservoir operation

The present practice of reservoir operations, based on rule curves that are predominantly guided by direct economic benefits ignoring the ecosystem requirements, needs to be reviewed. It may be noted that sometimes, with some minor structural modifications, the existing reservoirs can adapt to the managed flows.

5.10.4.1. Conservation

Reservoirs meant for augmentation of supplies during the lean period should usually be operated to fill as early as possible during filling period, while meeting the requirements. All water in excess of the requirements of the filling period shall be impounded. No spilling of water over the spillway will normally be permitted until the FRL is reached. Should any flood occur when the reservoir is at or near the FRL, the release of floodwaters should be affected, so as not to exceed the discharge that would have occurred had there been no reservoir. In case the year happens to be dry, the draft for the filling period should be curtailed by applying suitable factors. (I.S. 7323-1994)

Flood control zone - This is the storage space earmarked as temporary storage for absorbing high flows for alleviating downstream flood damages. This should be space emptied as soon as possible to negotiate the next flood event. (I.S. 7323-1994)

Conservation zone - This storage space is used for the conservation of water for meeting various future demands. This zone is generally between FRL and dead storage levels. (I.S. 7323-1994)

5.10.5. Significance of dam operation rule curves

A rule curve is generally based on a detailed sequential analysis of various critical combinations of hydrological conditions and water demands. These should indicate reservoir levels and releases during different times of the year, including operational policies. Rule curves once prepared should be constantly reviewed and, if necessary, modified so as to have the best operation of the reservoirs.

The operational decisions are based on the current state of the system and time of the year, which account for the seasonal variation of the reservoir inflows. A simple rule curve should base the release of the next time period solely on the current storage level and the current time period of the year. A more complex rule curve should consider storages in other reservoirs, specific downstream control points, and the forecasted inflows into the reservoir.

5.10.5.1. Rule curve for Single Purpose Reservoirs

Flood Control: When the protected area lies immediately downstream of the reservoir, the flood control schedules would consist of releasing all inflows up to the safe channel capacity. The principles followed in all cases are detailed below:

Principle 1: When there is appreciable uncontrolled drainage area between the dam and the locations to be protected, operation under principle (1) should consist of keeping the discharge at the damage centre within the highest permissible stage or to ensure only a minimum contribution from the controlled area when above this stage. Operation under this principle aims at reducing the damaging flood stages at the location to be protected to the maximum extent possible with the flood control storage capacity available at the time of each flood event. In order to accomplish this result, it is essential to have an accurate forecast of flood flows into the reservoir and the local inflows into the stream below it for a period of time sufficient to fill an empty reservoir. This is obviously an ideal case. It is difficult to forecast reliably and precisely in quantitative terms the rainfall. Thus, there is always the risk of facing difficulty in the regulation of run-off from subsequent storms, in order to reduce this element of risk, maintenance of an adequate network of flood forecasting stations both in the upstream and downstream area of the project becomes absolutely necessary. To account for the uncertainty in forecasting the flows, the forecasted flows may be multiplied by a contingency factor for arriving at release decisions. The contingency allowance should be greater than one for flood control and less than one in case of conservation.

Principle 2: The operation schedules based on principle (2) should consist of releases assumed for design flood conditions, so that design flood could be controlled without exceeding the flood control capacity. The operation consists of discharging a fixed amount, which may be subject to associated flood, storage and outflow conditions, such that all excessive inflows are stored as long as flooding continues at specified locations.

Combination of Principles: When both local and remote locations are to be protected, schedules based on the combination of principles (1) and (2) are usually more satisfactory. In this method, principle (1) that is, 'ideal operation', maybe followed to control the earlier part of the flood to achieve the maximum damage reduction during the moderate flood. After the lower portion of the flood reservoir is filled, the regulation may be based on the principle (2) that is, *based on control of design flood', so as to ensure greater control of major floods. In most cases such a combination of methods (1) and (2) would result in the best overall regulation as it combines the good points of both the methods.

In all cases, the procedure for releasing the stored water after the flood has passed would also be laid down in the schedule, in order to vacate the reservoir as quickly as possible for routing subsequent floods. In this way, variation in releases may be made depending on the prevailing, as well as the anticipated conditions of storm/rainfall and run-off.

Conservation: The operational schedule of a conservation reservoir would usually consist of two parts, one for filling period and the other for the depletion period. For each project, it will be necessary to prepare rule curves separately for the filling period and for the depletion period. The rule curves for the filling period may be developed from a study of the streamflow records over a long period. These will show the limits up to which reservoir levels are to be maintained during different times of the filling period for meeting the conservational commitments. The most critical release schedule, which provides for only minimum required flow, is specified by the rule curve, in order to provide for acceptable storage or desired contingency allowances during that critical period. When regulation is guided by such curves, it' would be apparent when restrictions are to be imposed on utilization.

5.10.5.2. Rule curves for Multi-purpose Reservoirs

When separate space allocations for different uses, including flood control are made, preparation of schedules will rarely pose any special problems as the operation for specific uses will usually be independent of each other and will follow the schedules of single-purpose operation for respective functions. In multi-purpose reservoirs, which have flood control as the main purpose besides other conservational demands, the operation should be done in two ways as discussed below:

Permanent allocation for flood space: Permanent allocation of space for flood control at the top of the conservation pool may be kept in the regions where a flood can occur at any time of the year. A study based on historical or generated flood would indicate the storage space required during different periods.

Seasonal allocation for flood space: Seasonal allocation of flood control space during flood season depends upon the magnitude of flood likely to occur. Thereafter, this space should be utilized for storing inflows for conservation uses. The operation plan to this effect should be prepared based on a study of historic and/or generated floods.

Joint use of storage space: For projects envisaging joint use of some of the space for flood control as well as conservational needs, flood control operation should usually be carried out by using part of the conservational storage, which shall be progressively reduced as the season advances. The regulation schedule for the conservation phase should then consist of an additional rule curve, indicating levels which may not be exceeded at any particular time of the monsoon season, except for the purpose of storing floodwater temporarily. Normal filling and dry weather release curves for the conservation use should be drawn as in the case of a single-purpose reservoir.

5.10.6. Integrated reservoir operations

Presently the reservoirs in Kerala are operated based on rule curves/available historical hydro-meteorological data/past experience by various dam owning departments as single entities. This system would not allow efficient integrated operation of cascading/multiple reservoirs in the same basin. The decision-makers/dam managers receive data from the field in a lagged manner which might not ensure timely decision-making processes, especially for flood management. The need for an integrated approach based on real-time data and near-future forecasts is the need of the hour.

5.10.6.1. System of Reservoirs

Regulation schedules for reservoirs operated as part of the system should be prepared separately for each reservoir, based on an integrated plan of operation and considerations. When determining rule curves among the various reservoirs in the system, it should, however, be noted that critical conditions may not be attained in all projects in the system at the same time. In addition, when considering two reservoirs in series, the upstream reservoir release schedule will bias the development of a rule curve at the downstream one. For parallel reservoirs, the best rule curve may require apportionment of releases from two or more reservoirs, based on available storage capacity or other relevant criteria.

Because of the complex interdependence of system operating rules, it is usually necessary to simulate the system operation to determine a workable regulating schedule. After initial curves are estimated, these independent estimates should then be simulated with a hypothetical operation of the system, to ensure that system targets are satisfied, project objectives are maximized and equitable distribution of water within the system is maintained. Thus, an iterative procedure would be required for establishing operation rules that attain these goals. The following points are generally kept in view while developing rule curves for a system of reservoirs.

Balancing of the reservoir: As the balancing of reservoirs is an important consideration, the concept of 'index levels' may be employed, as an aid to making release decisions to keep the reservoir system in a balanced state. The reservoir storage allocation may be subdivided into flood control, conservation, and one or more buffer zones. The top of each of these zones has a corresponding reservoir level, which is assigned an integer or index level. When the index levels in all the reservoirs coincide, the system is in balance. In reservoirs operation, if the current index levels are unbalanced, the releases for the subsequent interval are adjusted as far as possible to restore equilibrium. The index levels are also useful in the regulation of parallel reservoirs with the equivalent reservoir concept.

Apportioning of storage and releases: For an explicit reservoir operation rule that specifies releases of each reservoir as a function of storage volumes, time period and inflows, there are three basic characteristic components for an operation policy. These involve apportioning of storage and release of water among purposes, among time periods and among reservoirs. The governing rules for apportionment are generally as follows:

The space rule: The release among parallel reservoirs be planned in such a way that the ratio of space available in each reservoir to that in all reservoirs equals, as far as possible, the ratio of predicted inflow into each reservoir in the remaining period of drawdown refill cycle to that in all reservoirs. Hence, the probability of some reservoirs being spilt while others being empty is minimized.

The pack rule: It is a flexible rule that specifies useful releases in excess of current demand, perhaps to generate clump energy instead of possible future spills.

The hedging rule: It accepts the current shortage to avoid large shortages in the future and is to be adopted when cost functions for shortages are nonlinear.

5.10.6.2. Real-time operation of reservoirs

The operation of reservoirs based on fixed operation rules, which are developed taking into account the demands and historic/synthetic time series data, often poses difficulties in making appropriate reservoir release decisions due to the uncertainty in the probability of occurrence of the flood event exactly similar to the past event, though the demands could be fairly stable. The operation of reservoirs, therefore, becomes an operation in real-time in which water control decisions have to be taken at each instant of time.

In real-time reservoir operation control decisions are made quickly, for a finite future condition of the system at that instant of time and the forecast of the likely inputs over this time horizon depending on the purpose of the reservoir operation that is flood control, conservation, irrigation and/or power releases.

The use of systems engineering techniques using computer technology should be employed and a computer model needs to be developed for real-time operation. Some of the important aspects of real-time reservoir operation are listed below:

- Collection of catchment hydrological data and water demand data and transmission of the data to the operation manager at the control station through suitable logistics such as hydrological sensors, data loggers and telemetry network;
- Availability of a computer system at the control station;
- A real-time database management system; and
- A computer model having the capability of flow forecast, control decisions forecast with flexibility for modified data entry and updating, preferably in an interactive mode, in shortest possible execution time.

5.11. Hydrological data analysis

5.11.1. Hydrological Database

The major quantities to be measured for the hydrological analysis for a basin are the precipitation and discharge. The precipitation measurement in India is mainly monitored by the India Meteorological Department (IMD), which has 70 stations in Kerala as shown in Fig. 5.14. The Central Water Commission (CWC) monitors discharge at all major rivers across the country, of which 21 are located in Kerala. In addition to the CWC gauging stations, the Kerala Water Resources Department (KWRD) has installed 130 gauging stations across the different rivers. Figure 5.15 shows the locations of both CWC and KWRD stations across Kerala.

5.11.2. Flood Frequency Analysis

Flood frequency analysis can be used to develop a relationship between the magnitudes of discharge with its probability of exceedance (Box 5.2). The data to be used for frequency analysis need to satisfy the criteria of data independence, data sufficiency, climate cycles and trends, watershed changes and data reliability. To perform a valid peak discharge frequency analysis, data used in the analysis must be independent and should not belong to the same event which extends over many days. To minimize the bias in data, at least 10 years have to be considered including both wet and dry years. However, to include the impact of climate cycles on the hydrological records, a longer duration of data of around 30 years need to be considered. Hence, only those stations with data more than 30 years are considered in our analysis. As watershed changes can alter the frequency of high flows in streams, the period of record needs to be altered if significant changes have been observed in the watershed. Another factor that has to be determined is the presence of outliers in data, which have to be removed before the frequency analysis steps.

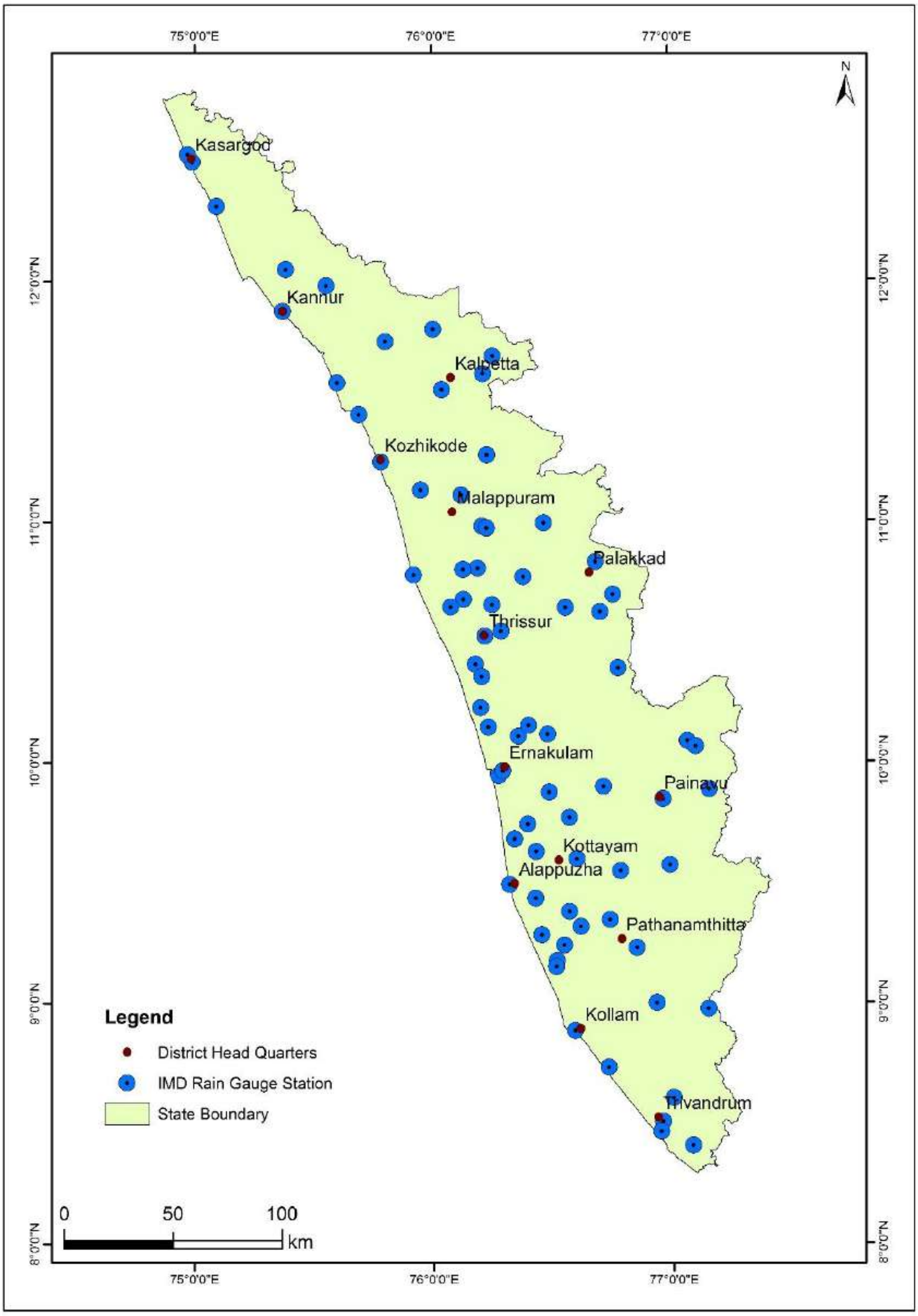


Fig. 5.14: IMD Rain gauge stations in Kerala

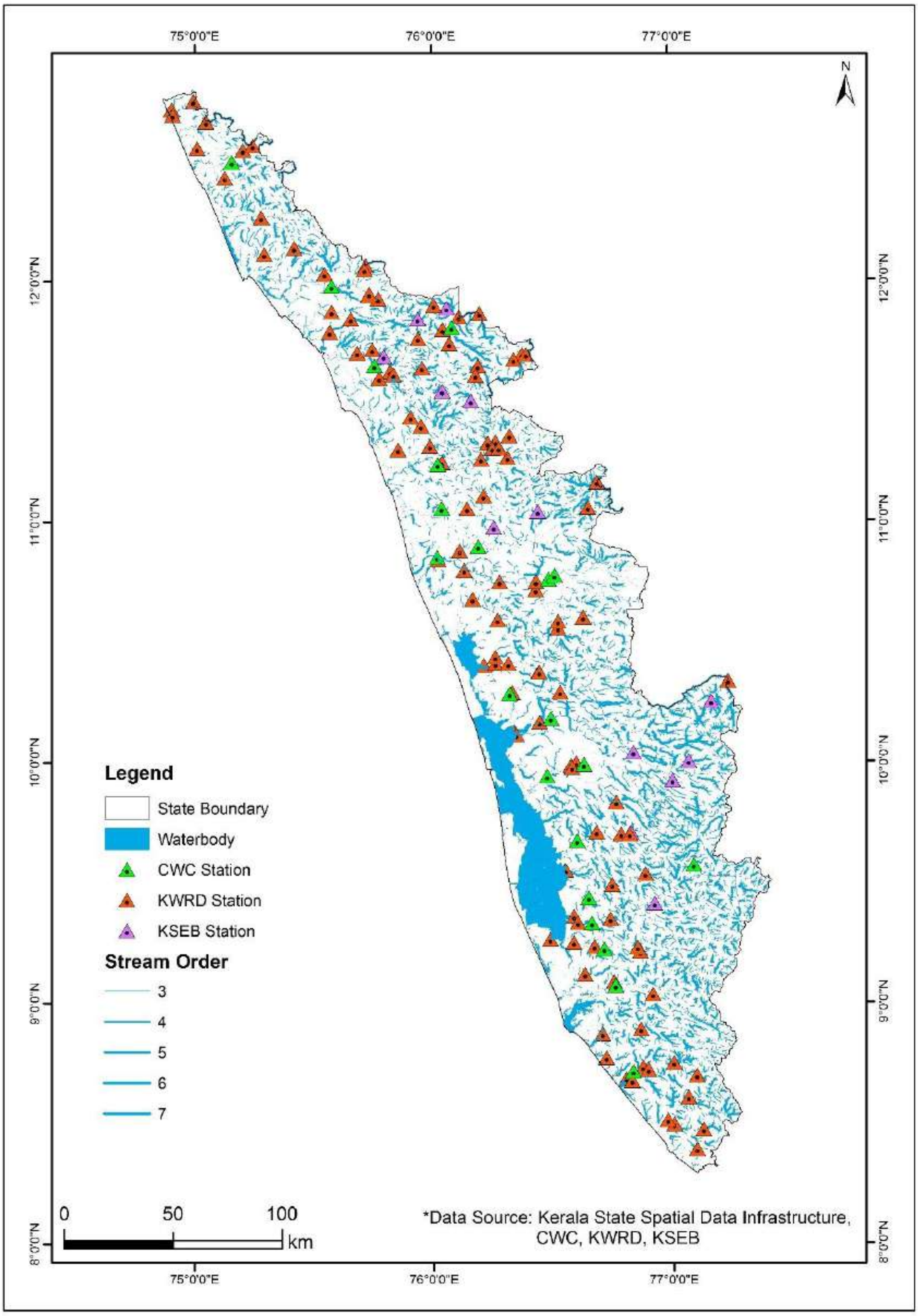


Fig. 5.15: River gauge-discharge locations in Kerala

5.11.2.1. Outliers

Outliers are data that depart significantly from the trend of the remaining data, including which may be inappropriate for frequency analysis. Both hydrologic and statistical conditions have to be considered before including or eliminating the outlier data. The statistical method to identify outlier thresholds is:

$$X_H = \overline{X_l} + K_0 S_l \quad (3)$$

$$X_L = \overline{X_l} - K_0 S_l \quad (4)$$

where XH = higher outlier threshold in logarithm, XL = lower outlier threshold in logarithm, $\overline{X_l}$ = average of annual peak discharge logarithm, K0 = coefficient based on sample size, Sl = standard deviation of the logarithm of annual peak discharge

If the station is greater than +4.0, high outliers are considered first and eliminated. If the station skew is less than -4.0, possible low outliers are identified and eliminated first. If the skew is between -4.0 and +4.0, a test for both high and low outliers are done before eliminating any outliers.

5.11.2.2. Frequency Distributions

Frequency analysis involves statistical analysis of flow for denoting the probability of occurrence of flow at specified points in the stream. Such analysis is required for the planning and design of structures as well for preparedness for future extreme events. Some of the common distributions used for frequency analysis of hydrologic data are log-normal distribution, Gumbel distribution and log Pearson type III distribution. However, the suitability of the distribution varies across the basins and the distribution which best fits the data need to be identified.

Log-Normal Distribution

Since the flow values are always positive the normal distribution which has both negative and positive values need not represent the actual condition. Hence the logarithmic transformation of the data can be used in the normal distribution concepts through the use of log-normal distribution for left bounded data. The log-normal method can be summarised as:

$$X_{LN,T} = \overline{X_{LN}} + K_{LN,T} S_{LN} \quad (5)$$

where XLN, T = logarithm of predicted discharge at return period T, $\overline{X_{LN}}$ = average of annual peak discharge logarithms, KLN, T = normal deviate of logarithms for the standard normal curve, where area = 0.5 - (1/T) and SLN = standard deviation of logarithms of annual peak discharge.

Gumbel Distribution

Peak discharge commonly has a positive skew as a few high values in the record can result in the distribution to not follow a log-normal. To overcome this, the Gumbel distribution can be employed.

$$X_{G,T} = \bar{X} + K_{G,T}S \quad (6)$$

where XG, T = predicted discharge at return period T, $\bar{X}$ = average annual peak discharge, KG, T = a function of return period and sample size and S = standard deviation of annual peak discharge

Box 5.2: Levels of the magnitude of flood

The Flood Magnitude value is a measure of "how severe" a flood is, as a strictly hydrological occurrence (no assessment of damage is implied) which is described by their statistically derived recurrence interval or return period. The return period is based on the probability that the given event will be equalled or exceeded in any given year.

For example, a 1 in 100- year flood is calculated to be the flood flow or level that is expected to be equalled or exceeded every 100 years on average. The 1 in 100-year flood is more accurately referred to as the 1% annual exceedance probability (AEP) flood, since it is a flood that has a 1% chance of being equalled or exceeded in any given year. A 1 in 100-year flood will not simply strike in a particular area once, then leave it be for the next 99 years. It could happen two years in a row, it's just not that likely.

Return period (or recurrence interval), in years	Probability of occurrence in any given year	Percent (%) chance of occurrence in a given year
1000	1 in 1000	0.1
200	1 in 200	0.5
100	1 in 100	1
50	1 in 50	2
25	1 in 25	4
10	1 in 10	10
5	1 in 5	20
2	1 in 2	50

Lo

(Source: http://www.somersetwave.co.uk/downloads/definition-of-flood-magnitude.pdf)

The log Pearson distribution accounts for the skew of the data in addition to its mean and standard deviation. When the skew is small, the log Pearson approximates to a normal distribution. The distribution can be represented as:

$$X_{LP,T} = \overline{X_{LP}} + K_{LP,T}S_{LP} \quad (7)$$

where XLP, T = logarithm of predicted discharge at return period T, $\overline{X_{LP}}$ = average of annual peak discharge logarithm, KLP, T = a function of return period and skew coefficient and SLP = standard deviation of logarithms of annual peak discharge

5.11.2.3. Goodness of Fit

The suitability of a particular distribution can vary across stations and the goodness of fit tests can be employed to find the best distribution to fit the data. These tests cannot be used to puck the best distribution, but to reject possible distributions. These tests calculate test statistics which are used to analyze how well the data fits the given distribution. They describe the differences between the observed data values and expected values from the distribution being tested. The Kolmogorov-Smirnov (KS) test, the Chi-squared (χ2) test and the Anderson-Darling (AD) test are employed in this study to check the goodness of fit and the MATLAB functions for the same have been employed to determine the statistics.

Kolmogorov-Smirnov (KS) Test

KS test statistic is based on the vertical distance between the empirical and theoretical CDFs. A hypothesis is rejected if the test statistic is greater than the critical value at a chosen significance level.

Chi-squared (χ2) Test

The χ2 test is used to check whether the sample comes from a particular distribution by separating the data into a number of bins. This is not considered a high-power statistical test and is not very useful. A test statistic greater than the critical value can result in the hypothesis getting rejected.

Anderson-Darling (AD) Test

The AD test compares an observed CDF to an expected CDF, giving more weight to the tail of the distribution. Thus, the AD test is stronger than the KS test in frequency analysis and a hypothesis is rejected if the test statistic is greater than the critical value.

5.11.2.4. Inferences of Flood Frequency Analysis

The detailed results of the flood frequency analysis are given in Appendix 5.1. The spatial variability of flood discharges of 25-, 50- and 100-year return periods, estimated at different river gauge stations is shown Figs. 5.16 to 5.18.

- To minimize the bias in the data set and to include the effect of climate cycles, stations with more than 30 years of data are only considered in the study. 19 CWC stations and 61 KWRD stations only fit the criteria.
- Data for years up to 2014 were provided by KWRD for the different stations, whereas data till 2018 were available from the Water Resources Information System (WRIS-India) of CWC. However, data for peak flood days of 15th to 17th of August are not available in most of the sites. Peak discharge for Neeleeswaram (Periyar), Arangaly (Chalakudy), Kumbidi (Bharathapuzha), Muthankara (Cauvery), Malakkara (Pamba) and Kallooppara (Manimala) were hence collected from the CWC report on Kerala Floods 2018 and considered as the peak flow of 2018 for those sites.
- Log Pearson type III distribution is found to be the best fit distribution for the majority of the stations and hence, is considered as the standard distribution for all stations in further discussions. The station wise best fit distributions are highlighted in Appendix 5.1.
- For stations with 2018 data, the discharge observed was higher than 100-year return flow.
- Spatial plots with the magnitude of discharge for different return periods based on the Log Pearson type III distribution are depicted in Figs. 5.16 to 5.18.
- Inclusion of 2018 flow values significantly changed the frequency values. For instance, Kalady G&D station operated by KWRD on the Periyar River has a flow of 4869 m^3/s for a 200-year return period, whereas the adjacent CWC G&D station has 7007 m^3/s for the same return period, as the data for 2018 too is included. This shows the influence of the high flows in 2018 on the flood frequency curve.

5.11.3. Rainfall frequency analysis

In addition to the frequency analysis of river discharge data, the rainfall data collected from IMD stations were also subjected frequency analysis to estimate the rainfall of various return periods, such as 25-, 50- and 100-year return periods (Appendix 5.2). The spatial variability of the rainfall frequency analysis for various return periods is shown as Figs. 5.19 to 5.21.

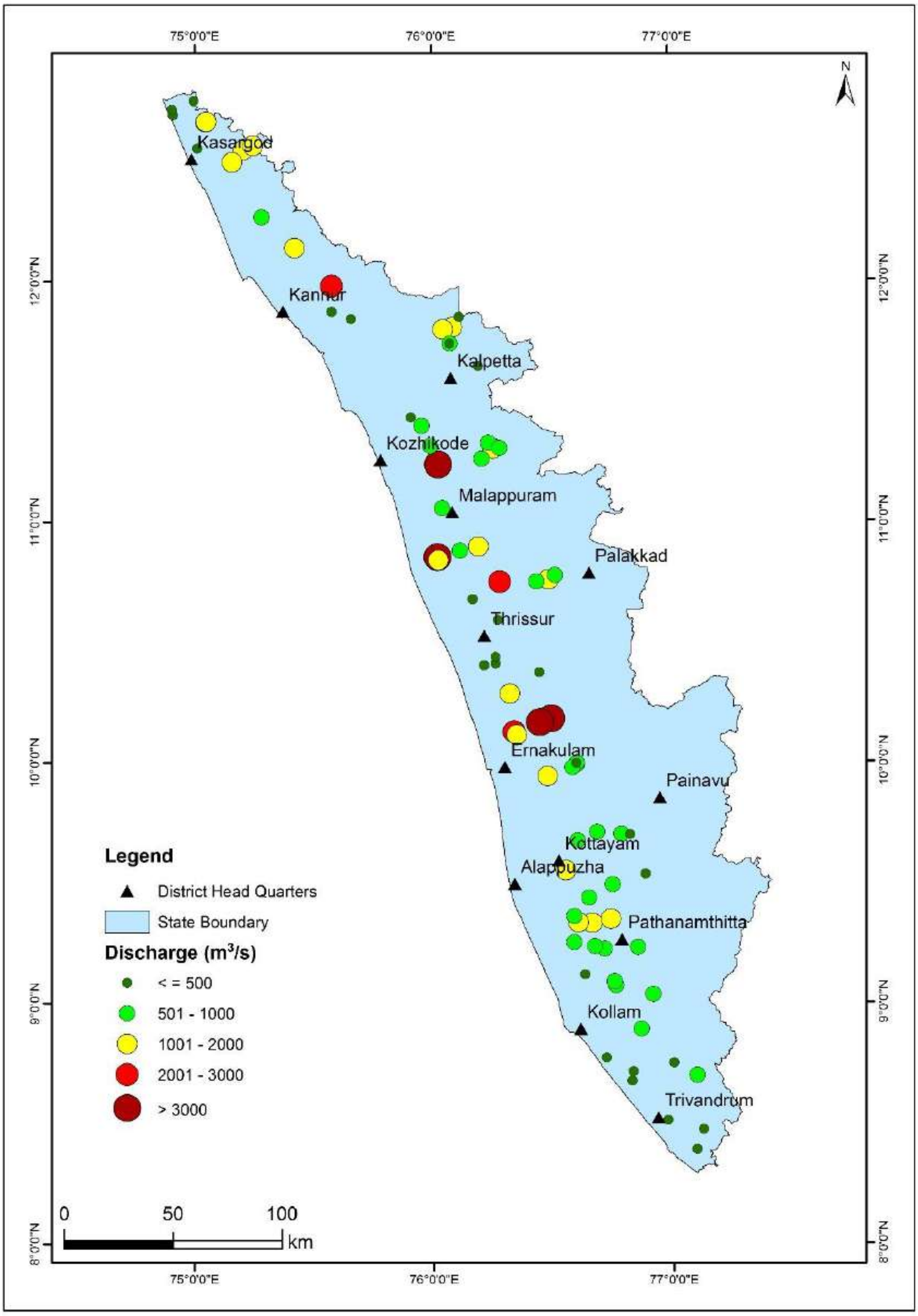


Fig. 5.16: Spatial variation of flood discharge of 25-year return period, Kerala

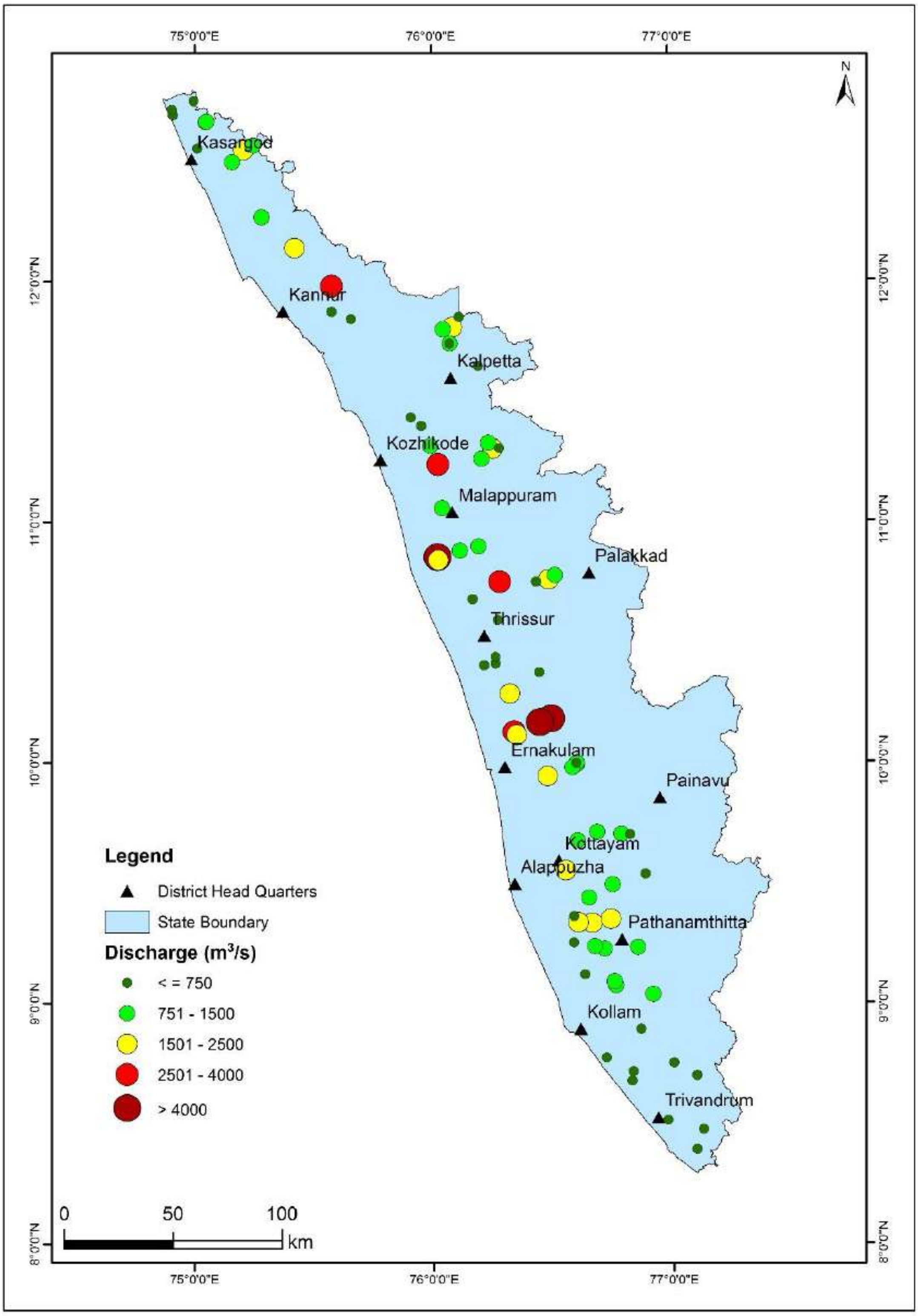


Fig. 5.17: Spatial variation of flood discharge of 50-year return period, Kerala

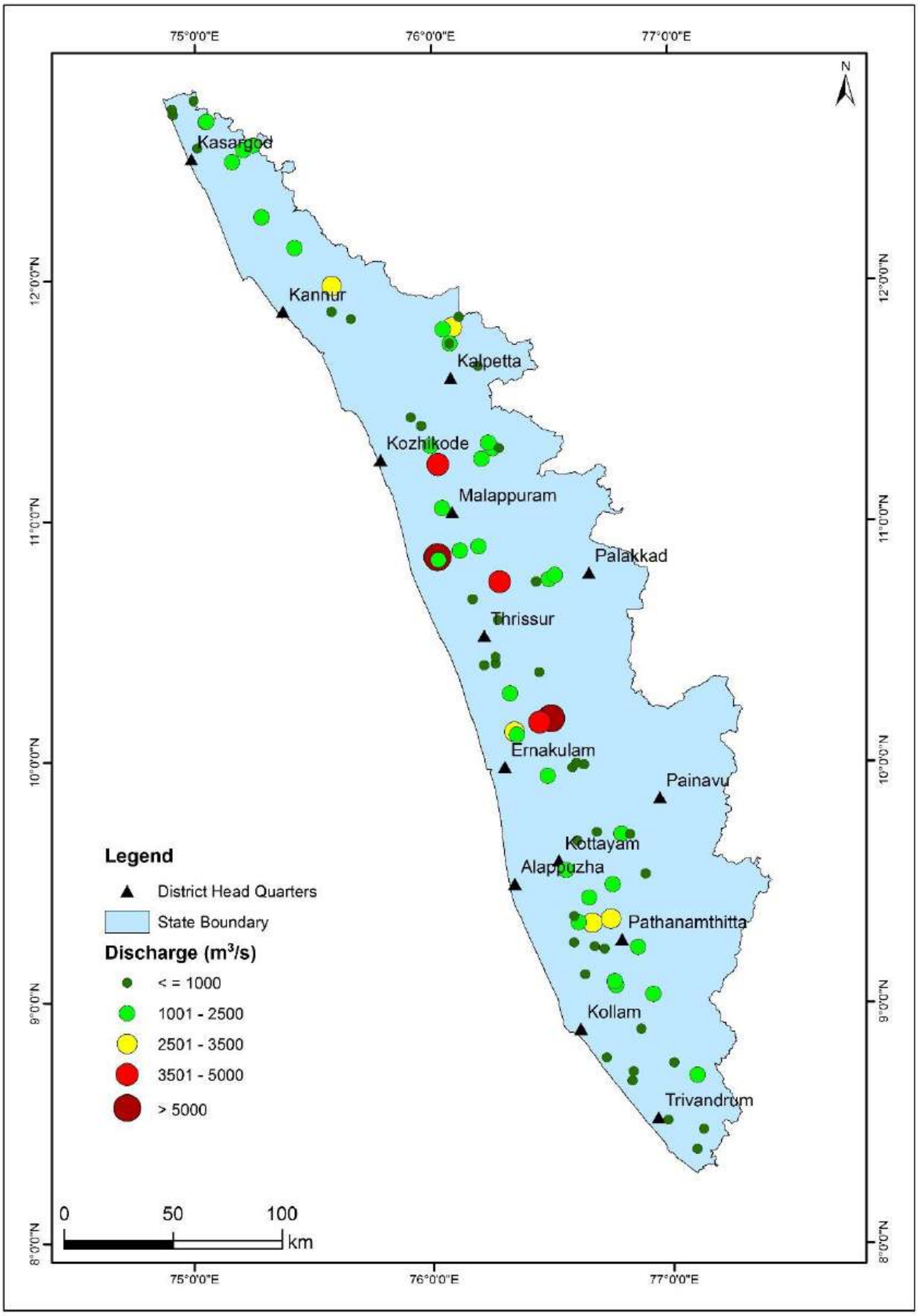


Fig. 5.18: Spatial variation of flood discharge of 100-year return period, Kerala

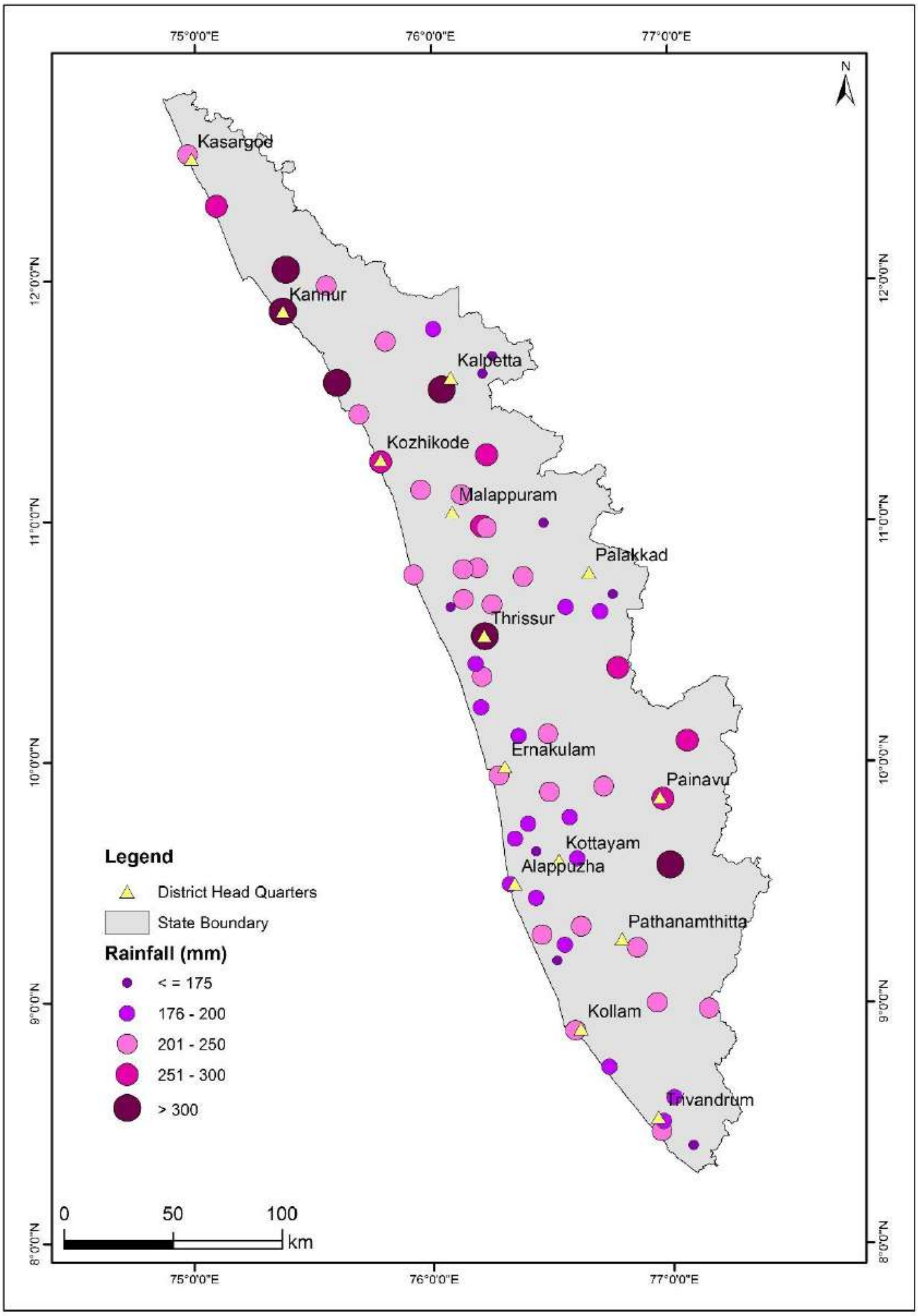


Fig. 5.19: Spatial variation of daily rainfall of 25-year return period, Kerala

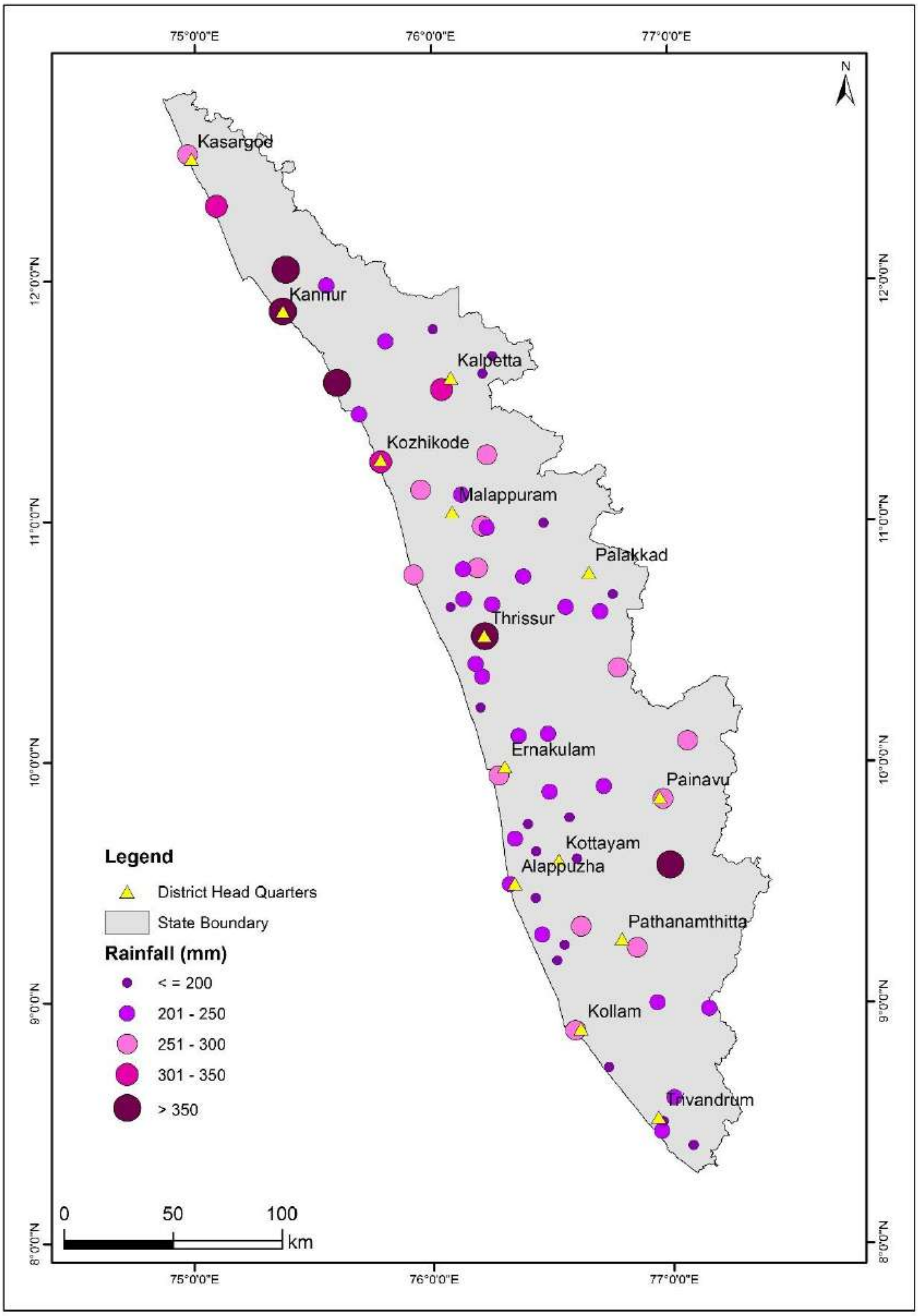


Fig. 5.20: Spatial variation of daily rainfall of 50-year return period, Kerala

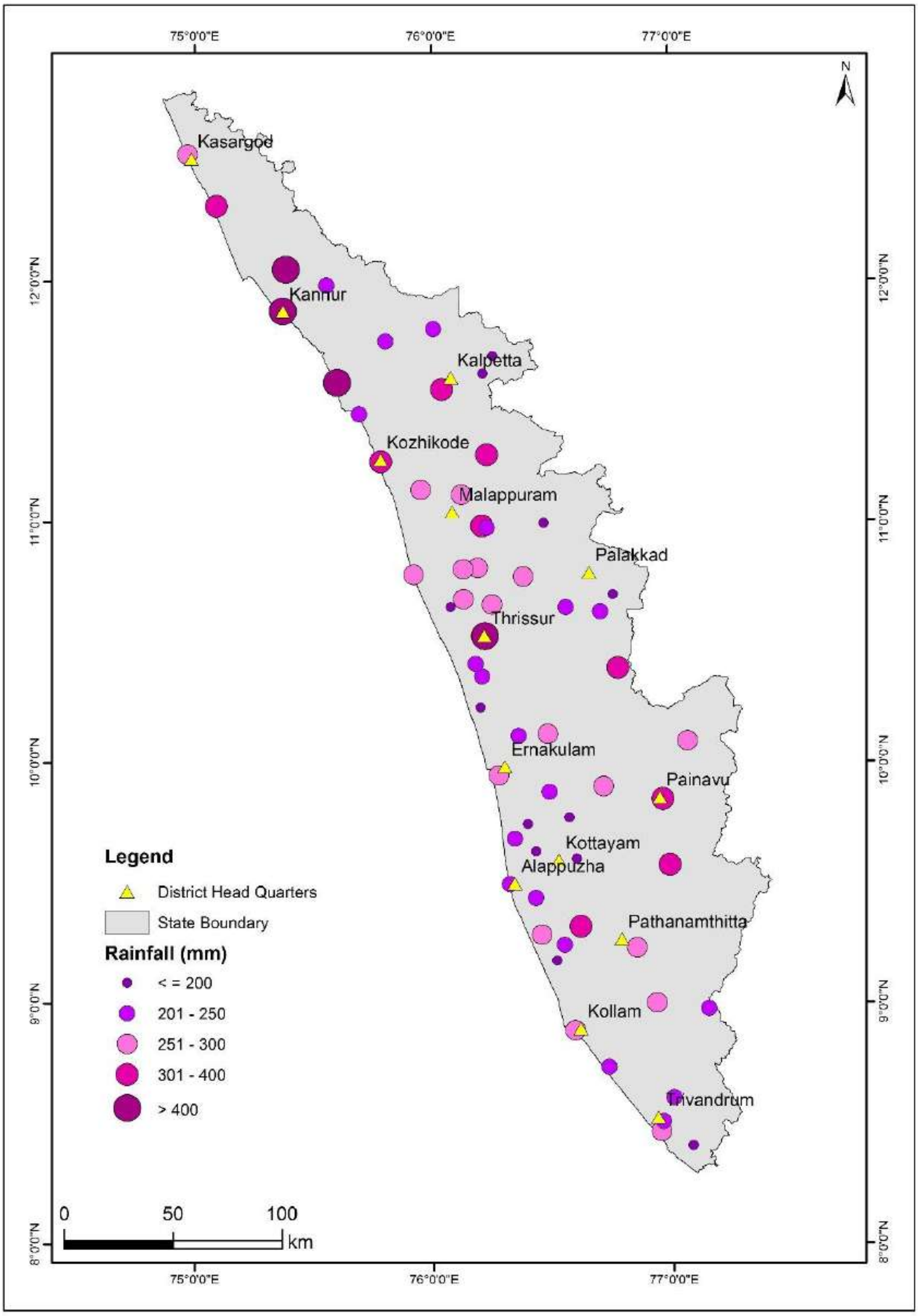


Fig. 5.21: Spatial variation of daily rainfall of 100-year return period, Kerala

5.11.4. Flow Duration Curves (FDC)

The flow duration curve is a plot that shows the percentage of time flow in a stream is likely to exceed some specified value of interest. The flow duration is dependent on the time unit used to prepare it. Generally, mean daily discharges are used. When the mean flow over a longer period is used, the resulting curve will be flatter due to averaging of short-term peaks. Extreme values get averaged more as the time period gets larger. Development of FDC is done by first sorting the data of n time steps in descending order and assigning ranks (m) to them. Exceedance probability is then calculated as:

$$P = 100 * \left(\frac{m}{n+1}\right) \qquad (8)$$

The area under the flow duration gives the average flow, whereas the flow corresponding to 50 % is the median flow. A flow duration curve characterizes the ability of the stream to provide flows of varying magnitude. Information on the amount of time the flows exceed a certain magnitude can be employed for planning purposes. The shape of the curve in the high flow regime indicates the type of flood regime the basin is likely to have, whereas the shape of the low flow regime characterizes the ability of the basin to sustain low flows during dry seasons. Rain caused floods in small watersheds can lead to steeply sloped curves. To understand the flow characteristics of streams in all kinds of conditions, month-wise flow duration curves are prepared in the current study using daily/sub-daily data. The results of the flow duration curve analysis are given in Appendix 5.3.

Variability in the flow curves of the different stations in the same basin indicates the spatial variability of flow regimes across the basin. For example, in the Pamba river basin, the Kurudamannil station at the upstream have relatively flat curves for all months, even though months from January to May have reduced flow. However, at Malakkara and Erapuzha stations located downstream, the dry months (January to May) have steeper curves.

5.12. Flood Management

Flood management refers to all methods and practices that help in reducing or preventing the detrimental effects of floodwaters. This includes (a) measures to control or lower the probability of flood occurrences and (b) measures to reduce the impacts of flooding. In order to manage the flood, flood risk assessments and the development of relevant mitigation measures are imperative. Flood affects living beings and the environment in various different ways.

5.12.1. Flood Risk Assessment

Risk is broadly defined as a situation or event where something of value is at stake and its gain or loss is uncertain. Risk is typically expressed as a combination of the likelihood and consequence of an event. Consequences are measured in terms of harm to people, cost, time, environmental harm, property damage, and other metrics. Choosing the appropriate risk metrics and actively using them in decision making is critical to effective risk management in support of a vibrant economy, thriving ecosystems, and sustainable communities. Flood risk considers explicitly the performance consequences of subjecting people and property to the entire range of likely flood events, given risk management provided by any structural or non-structural measures. One commonly used metric of economic risk is expected annual damage (EAD) or average annual equivalent damage when computed on an annual basis over the period of analysis. Flood risk can be conceptualized as a function of the hazard, performance, exposure, vulnerability, and consequences as depicted in Fig. 5.22.

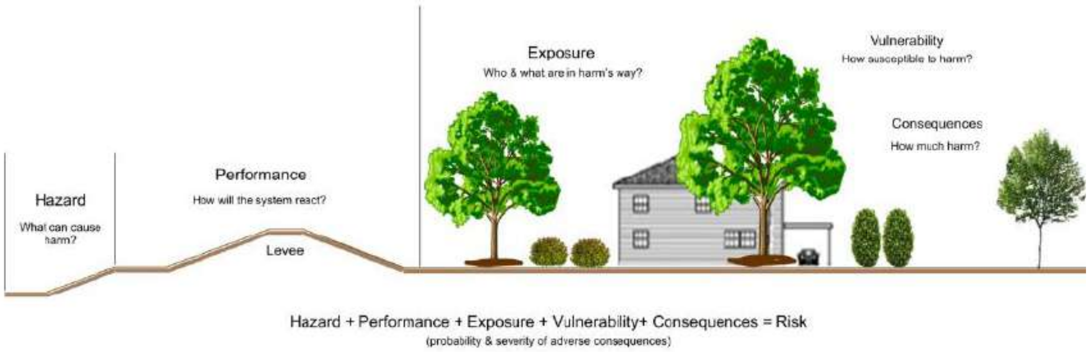


Fig. 5.22: Flood risk conceptualized (Source: USACE, ER 1105-2-101, 2017)

Flood risk assessment refers to the identification of risks associated with floods based on various information. Risks are identified in varying scales/levels (e.g. Nation scale, district or watershed scale, flood plain scale, ecology and environmental scale, infrastructure or property level, community or at the individual level) Flood risk assessments focus on four main components:

- Flood hazard: the probability and magnitude (e.g., depth, velocity, discharge) of flooding
- Exposure: the economic value of assets subjected to flood hazard
- Vulnerability: the relationship of flood hazard properties to economic loss
- Performance: the effectiveness and behaviour of flood protection and damage mitigation measures that modify the flood hazard, the exposure, or the vulnerability

5.12.1.1. Flood hazard

Hazards associated with the flooding can be divided into primary hazards that occur due to contact with water, secondary effects that occur because of the flooding, such as disruption of services, health impacts such as famine and disease, and tertiary effects such as changes in the position of river channels. Throughout the last century, flooding has been one of the costliest disasters in terms of property damage and human casualties. Major floods in China, for example, killed about 2 million people in 1887, nearly 4 million in 1931, and about 1 million in 1938. The 1993 flood on the upper Mississippi River and Midwest killed only 47 people, but the U.S. Army Corps of Engineers estimates the total economic loss at between 15 and 20 billion dollars.

5.12.1.2. Primary Effects

Again, the primary effects of floods are those due to direct contact with the floodwaters. As discharge increases velocity increases.

- With higher velocities, streams are able to transport larger particles as suspended load. Such large particles include not only rocks and sediment, but, during a flood, could include such large objects as automobiles, houses, and bridges.
- Massive amounts of erosion can be accomplished by floodwaters. Such erosion can undermine bridge structures, levees, and buildings causing their collapse.
- Water entering human-built structures cause water damage. Even with minor flooding of homes, furniture is ruined, floors and walls are damaged, and anything that comes in contact with the water is likely to be damaged or lost. Flooding of automobiles usually results in damage that cannot easily be repaired.
- The high velocity of floodwaters allows the water to carry more sediment as the suspended load. When the floodwaters retreat, velocity is generally much lower and sediment is deposited. After the retreat of the floodwaters, everything is usually covered with a thick layer of stream deposited mud, including the interior of buildings.
- Flooding of farmland usually results in crop loss. Livestock, pets, and other animals are often carried away and drown.
- Humans that get caught in the high-velocity floodwaters are often drowned by the water.
- Floodwaters can concentrate on garbage, debris, and toxic pollutants that can cause the secondary effects of health hazards.

5.12.1.3. Secondary Effects

Remember that secondary effects are those that occur because of the primary effects and tertiary effects are the long-term changes that take place. Among the secondary effects of a flood are:

- Disruption of services -
- Drinking water supplies may become polluted, especially if sewerage treatment plants are flooded. This may result in disease and other health effects, especially in underdeveloped countries.
- Gas and electrical service may be disrupted.
- Transportation systems may be disrupted, resulting in shortages of food and clean-up supplies. In underdeveloped countries, food shortages often lead to starvation.

5.12.1.4. Long - term effects (Tertiary effects)

- The location of river channels may change as the result of flooding, new channels develop, leaving the old channels dry.
- Sediment deposited by flooding may destroy farmland (although silt deposited by floodwaters could also help to increase agricultural productivity).
- Jobs may be lost due to the disruption of services, destruction of business, etc. (although jobs may be gained in the construction industry to help rebuild or repair flood damage).
- Insurance rates may increase.
- Corruption may result from the misuse of relief funds.
- Destruction of wildlife habitat.

5.12.1.5. Exposure

Exposure can be defined as people, assets, and values located in floodplains (Field et al., 2012; Kron, 2005). Exposure is a major component of the disaster risk and refers to which is affected by natural disasters, such as people and property (ADRC, 2011). Exposure describes the number of people and the value of structures and activities that will experience hazards and may be adversely impacted by them (Blanchard, 2006; Davidson and Lambert, 2001).

Exposure is the presence of people, goods or other potentially subject to be damaged in areas where floods are occurring (U. UNISDR, 2009) and can be quantified by the number or value of the elements found in flood-affected areas (Merz et al., 2007). Without exposure there is no risk, thus, very fragile elements (e.g. old buildings) that are not exposed to flooding will always have a zero flood risk (De Bruijn and Klijn, 2009). Here, exposure is understood as the number of persons and/or other elements at risk that may be affected by a particular flood event. In an uninhabited area, human exposure is zero. No matter how many floods will affect an uninhabited area the human exposure, and therefore the risk of human loss, remains zero (Thywissen, 2006).

Also, people and buildings are exposed only if they do not have sufficient structural or private measures against the flood (e.g. walls, gravity dampers). In other words, a building is not exposed when it is surrounded by a solid stone wall, because this protective element will keep all the water out. Social conditions also influence the susceptibility to suffer flood damage, by the knowledge about the hazard and age of people affected, for example. The means by which people or organizations use available resources and abilities to face adverse consequences that could lead to a disaster are defined as the coping capacity (UNISDR, 2004). In the social context, exposure is influenced by population dynamics, the ability to manage the environment, inability to get active because of economic and social inequalities (De León and Carlos, 2006). So, in the context of risk-hazard, the exposure term proved to represent the inside of the risk and the external of vulnerability (Costa and Kropp, 2013). When the exposure is a risk component, addresses people and artefacts exposed at high risk (UNDP, 2004).

Regardless of how it is perceived, the exposure is a component without which the risk assessment would not be possible. The ultimate result of the exposure assessment is the map of the exposed elements. According to Schanze (2006), the exposure assessment consists of a cartographic representation of the elements exposed to floods and their classification and may include diverse topics as the environment, heritage, infrastructure, economic or other relevant activities for risk analysis.

5.12.1.6. Vulnerability

There are four major components of flood vulnerability, namely, social, economic, environmental and physical components.

5.12.1.7. Performance

The effectiveness and behaviour of flood protection and damage mitigation measures that modify the flood hazard, exposure, or vulnerability.

5.12.2. Flood risk management and mitigation measures

Flood risk management involves developing and identifying mitigation measures for lowering the vulnerability of people and property, and impacts on nature and the environment. Flood mitigation measures can be grouped into structural and non-structural measures. The following are the list of structural and non-structural mitigation measures towards flood risk management.

In the Kerala context, it would be ideal to introduce an acceptable residual risk concept while implementing strategies for effective flood management

5.12.2.1. Acceptable Residual Risk Concept

In spite of protection measures on planning and operational level, risk cannot be addressed totally. This remaining risk is called residual risk and describes the amount of risk after structural or non-structural flood management measures have been applied. By their very nature, residual risks have a low probability of occurrence. However, the consequences arising from a breach of tidal or fluvial flood defences can be very significant and, in some instances, dangerous to life.

Examples of tools and measures to reduce and transfer flood risk in flood-prone areas (Fig. 5.23). The remaining risk after these techniques are employed is the residual risk. The bar on the far left indicates the initial, unmitigated risk that is faced by a community. Actions taken through the methods indicated in the subsequent bars, which are illustrative, reduce the unmitigated risk. Some of these actions are taken at the federal, state, and local levels, whereas others are taken by the homeowners and businesses at risk. The risk that remains after these actions are taken (bar on the far right) is the residual risk. (Source: modified from USACE, 2006).

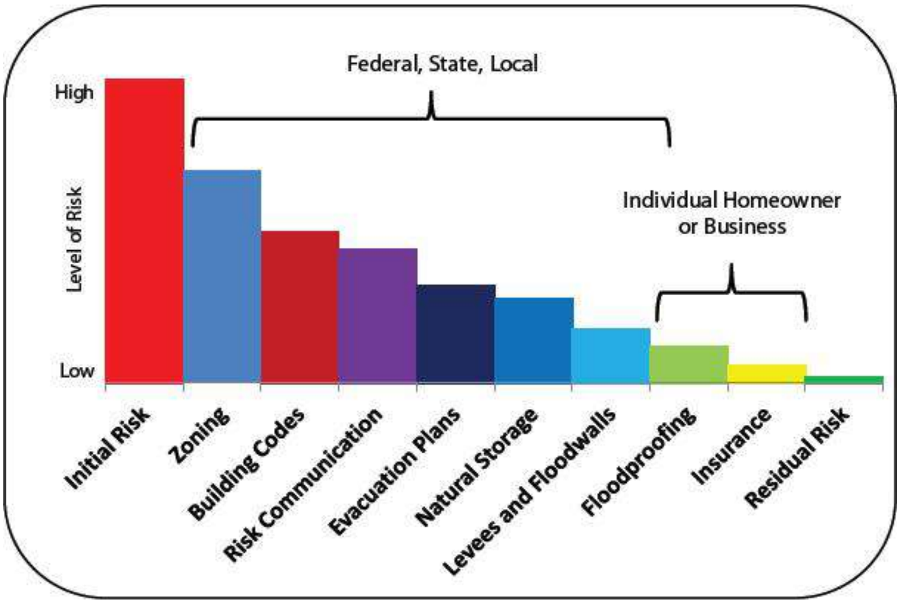


Fig. 5.23: Examples of tools and measures to reduce and transfer flood risk in flood-prone areas

6. Chapter 6
Conclusions and Recommendations

The Committee after detailed deliberations, analysis, and assessment arrived at the following conclusions and recommendations. It is envisaged that the recommendations of the Committee may help the Government to formulate appropriate policies for mitigating the negative impact of such devastating natural hazards in the future.

6.1. Conclusions

- The predominant reason for the occurrence of EREs in Kerala in the last two years (2018 and 2019) was the development of deep depression over the northwest Bay of Bengal and neighbourhood, coupled with the influence of the local orographic gradient on the atmospheric circulation, variability in monsoon circulation caused by the transient synoptic-scale and intra-seasonal propagating oscillations. It is to be noted that no noticeable teleconnections of EREs with El Nino Southern Oscillations (ENSO) and Indian Ocean Dipole (IOD) are observed.
- An analysis of the observed southwest monsoon rainfall during 1901-2018 in Kerala, in general, exhibited a decreasing trend over the northern half and along the coastal areas of the State. This observation was significant (at 95 per cent level) in isolated locations in northern parts of the State. The rainfall over the southern region of the State also showed a decreasing (but non-significant) trend. However, the data pertaining to the recent years (1971-2018), showed an increasing trend over most parts of the southern half and some interior areas of central parts of the State with isolated areas showing significant trends. A significant decreasing trend was observed over the northernmost areas of the State.
- There are a large number of predictive models being employed by various agencies across the globe for prediction of EREs, and many of them are being used by the IMD in the Indian context. However, they fail to capture the real mechanism of cloud formation and its impacts on rainfall distribution and pattern during the onset and occurrence of EREs.
- The triggering factor for the occurrence of landslides across Kerala during the EREs in August 2018 and 2019 was the oversaturation of the overburden. Idukki experienced the maximum number of landslides (977 including minor slides) in 2018, whereas Palakkad had the highest count in 2019 (18), followed by Malappuram (11), Wayanad (10) and Kozhikode (8). Generally, steep sloppy areas having slope more than 33 per cent are more vulnerable to landslide, and the majority of the landslides in the State during the last two years occurred in these terrains. The Committee noted that

anthropogenic activities intended for agricultural expansion and water conservation such as terracing, blocking/diversion of stormwater channels and alteration of natural vegetation pattern have amplified the landslide susceptibility of these regions, especially at Kavalappara, Pathar and Puthumala. In addition, soil piping has acted as the triggering factor at a few locations, especially in Northern Kerala.

- The NCESS has prepared a landslide zonation map for Kerala in 2009 on a 1:50,000 scale. The landslides that occurred in the last two years have largely (~80 per cent) fallen in the high hazard zones delineated by the NCESS. There were a few slides in low hazard zones, while some of the high hazard zones were not at all affected during the EREs. This necessitates the inclusion of additional causative factors and refinement of the hazard zonation mapping. It should be performed on a fine resolution (preferably at the cadastral scale). This activity should be followed by the development of landslide risk maps at the cadastral level, which can be used for long term land use planning. The monitoring of ground movement may also be considered as part of long-term research activity.
- The EREs during the last two years were associated with the genesis of deep depression over the northwest Bay of Bengal and nearby areas. An early onset of monsoon along with a large amount of rainfall in June and July 2018 resulted in saturation of the topsoil in most areas. Most of the reservoirs in Kerala had to be filled near the Full Reservoir Level (FRL). The two EREs, subsequently in August 2018 (during August 8th to 10th, and August 14th to 19th), resulted in severe flooding in Kerala. A similar situation, except on the antecedent wetness condition (including reservoir storage), occurred again in August 2019 (during August 8th to 11th) and caused severe flooding in the northern districts of Kerala (north of Ernakulam).
- The floods experienced in the last two years have a large return period (more than 100 years), and the preparedness for such events was less due to their very low probability of occurrence.
- The Committee analysed flood inundation for various scenarios of different reservoir levels and 24-hour 100-year rainfall for the Periyar river basin and developed possible flood inundation maps. Such studies are essential for demarking the flood-prone areas under different conditions and have to be done over all the river basins in the State.
- The existing reservoirs in the State are conservation-oriented and are being operated as per the conditions specified in IS 7323:1994. Accordingly, the policy adopted being “no spilling of water over the spillways will normally be permitted in conservation point of view until the Full Reservoir Level (FRL) is reached. Flood cushion in the reservoirs is limited between the flood control zone, i.e., between FRL and Maximum Water Level (MWL). When any flood occurs, the policy to release the flood water is adhering to the principle that the releases shall not exceed the inflow into the reservoir”. Moreover, the

reservoirs harvest water as much as possible to the full capacity during the rainy season. None of them had an operating policy that considered flood control until 2018. After 2018, some of the dams have considered flood control in their revised operation policy. This should be extended to all the reservoirs in the State. Further, the authorities concerned shall explore the possibility of providing some dynamic flood cushion in the conservation zone below FRL for all the reservoirs.

- The Committee recognised the need to define ERE. It was observed that the rainfall value corresponding to the 99th percentile for Kerala is around 120 mm (12 cm). Hence, 24-hr accumulated gridded rainfall ≥120 mm (rainfall of intensity equal to or more than the very heavy rainfall category) can be considered as an ERE.
- There are several natural and anthropogenic drivers of floods in Kerala, among which the prominent are: (1) high-intensity rainfall for prolonged duration, (2) human interventions in the catchment areas, and particularly in the floodplains and riparian zones, (3) unauthorised encroachments leading reduced extent of natural areas and their impaired functionality (4) reclamation of wetlands and lakes that acted as natural safeguards against floods due to urbanisation and development of infrastructure, (5) unexpected EREs and lack of exposure in handling such EREs through reservoir operation and (6) decreased channel capacity due to sedimentation and aquatic vegetation.

6.2. Recommendations to mitigate the negative impacts due to:

a) Extreme Rainfall Events

- The current rain gauge network in the State is not sufficient enough to capture the high spatial variability of rainfall because of the orographic barrier, and also in the context of the limited predictive capability of the rainfall forecast models. Therefore, the network density needs to be enhanced to the theoretical level of 1 rain gauge in every 50 square km (approximately 800 numbers). However, considering the varying spatial variability across the different physiographic regions of the State, it is suggested to install a dense network of Automatic Rain Gauges (ARG/AWS; ~ 500 numbers). Priority may be given to regions receiving high-intensity rainfall in short time periods including slopes that have the potential for flash floods. The distribution of the proposed rain gauges can be 50 per cent in the high lands, 35 per cent in the midlands, and the remaining 15 per cent in the low lands and coastal regions.
- It is suggested that a major share (~50 per cent) of the new installations should be Automatic Weather Stations (which can also monitor meteorological parameters such as temperature, pressure, wind direction, wind speed, and sunshine hours)

and all of them be connected to a central location through telemetry. These observations would in the long run help to improve the predictive capabilities of the forecast models on a regional scale.

- The land acquisition for installation of new rain gauges, if required, be done in consultation with IMD and other departments in the State, and be completed at the earliest.
- Identify the rain gauges operated by other agencies in the State and link them to the centralised facility being proposed.
- Facilitate the development of the Regional ERE and Flood forecast system combined with Artificial Intelligence (AI) to predict flash floods and to trigger an advance warning through research studies or start-ups.
- The experts observed that there is a temporal change in the size distribution and circulation pattern of the dust aerosols in the State that have an impact on the changing rainfall patterns. However, this needs further research as it is an emerging area of research worldwide. The significance of forest fires across the WG on the aerosol concentration may also be considered.

b) Landslides

While the devastating landslides in the State during the last two years were primarily initiated by the EREs, the major reason for most of them was the instability of the slopes caused due to various anthropogenic activities. Therefore, preventive measures should certainly include slope stabilisation. The following are some of the possible remedial measures:

- Provide a vegetation cover to the degraded slope by either promoting natural vegetation growth or by planting suitable species that help slope stabilisation (example vetiver). The use of vetiver as a binder in laterite cutting is to be evaluated.
- In areas where clear-felling of trees was done, the deep tap roots should be removed and refilled with the earth. This is to avoid over saturation and decay of the taproot system which will lead to soil piping and landslides.
- In areas where plantation crops are planned, the selection of crops, as well as the soil pits for planting them, needs to be carefully chosen according to the package of practice. Unscientific use of machinery for pit formation may lead to increased disturbance of the overburden and cause additional water-holding, resulting in oversaturation.
- The following activities should be avoided so as to prevent the possibility of landslides:

- ✓ Cutting and levelling for construction of houses on the toe region of slopes having more than 25 per cent inclination and a slope length exceeding 100 m.
- ✓ Diversion or blocking of stream channels (up to third order) in the upper slopes especially above the settlement.
- ✓ Ponding of water in the sloping sections over a 25 per cent slope.
- ✓ Soil conservation practices through contour bunding, or terracing in slopes of more than 25 per cent.
- ✓ Seasonal cultivation with tilling or pitting activity in the high sloping areas.
- ✓ Any activity in those sections where either ground cracks or piping has been initiated.
- ✓ Encroachment of stream banks in the highland region for cultivation or settlement.
- ✓ Alignment of open irrigation channels on hill flanks with more than 25 per cent slope.
- ✓ Construction of roads without adequate engineering design in the unstable slopes especially in those segments having higher soil thickness. The hollow portions are to be treated carefully.
- ✓ Construction of dwelling units in the hollow portions which have been filled up with debris.
- ✓ Construction of dwelling units on the immediate lower part of a sloping segment that is critically disposed of.

- The following activities can be promoted so as to prevent landslide occurrence:
  - ✓ Drainage of excess rainwater from steeper sections of slope through lined predefined channels.
  - ✓ Afforestation/ tree crops with no tilling activity in such areas with more than 33 per cent slope.
  - ✓ Maintenance of tree belts at suitable intervals in those slopes subjected to seasonal cultivation.
  - ✓ Delineate stable and unstable areas in the uppermost catchments of drainage basins.
  - ✓ Preservation of existing patches of natural forest cover.
  - ✓ Permanent grass cover in extremely sloping sections (> 50 per cent slope).
  - ✓ Land zonation at the micro watershed level involving the local community
  - ✓ Create awareness among the local population regarding landslides.
- All drainage lines (of all orders) are to be maintained properly, especially during rains. The first and lower order streams get obliterated by agricultural practices such as contour bunding and terracing. These are the areas liable for failures during high rainfall times. The configuration of the basement rock will allow

subsurface water to exhort high pore pressure in these areas, which are known as topographical hollows (places where lower-order streams are located). Therefore, before monsoon, all stream / nallas in the slopes need to be cleaned and opened up for the free flow of stormwater.

- Since the topographic hollows are the areas where the failure takes place, location of the hollows needs to be identified, and new houses/buildings to be allowed at least 50 m from either side of the stream channel / hollow area.
- The Government of Kerala should constitute a Committee to conduct in-depth studies and develop guidelines for best practices for allowing mining activities near topographic hollows. A “codebook” may be developed and strong regulatory system may be enforced. Stone quarries should not be allowed near the topographic hollows with more than 1 m overburden; they should be 200 m away from such localities.
- While constructing village roads in the high sloping areas, care should be taken to ensure the free flow of streams across the roads by providing culverts
- The current practice is that only the critical and high hazard areas are now regulated for activities. Settlements are allowed in the downslope of critical and high hazard areas. These areas are susceptible to high causalities during a landslide event. Therefore, an estimate of the runout distance for landslides needs to be assessed based on slope and overburden volume in the high hazard zones so as to regulate settlements at the downstream of the slopes.
- In many hill-road sections, toppling has occurred during rains where the road cuttings in the laterite are more than 3 m. This will cause disruptions in the traffic movement and destabilisation of the upper slope. Proper protection should be given to these laterite road cuttings with adequate weeping holes. In the unprotected slopes, it is better to give a deep-rooted bio cover like Vetiver (locally known as *Ramacham*) if other methods are not feasible.
- While constructing buildings and houses on the hill slopes, the slope geometry is to be maintained. In other words, the cutting and filling of the slopes for construction in the high slope area should be discouraged.
- The runout zone of the upper unstable area is to be considered while planning any infrastructural development on the lower slopes.
- Artificial impounding of water on slopes should be discouraged. In areas identified as high hazard zones, the construction of swimming pools and theme parks to promote tourism should also be discouraged.
- In long slope areas, the toe part should be protected from development activities. In unavoidable circumstances, any disturbance in the toe area should be accompanied by strengthening/protecting of upper slope areas.

- Provide ditch traps and fencing at a highly hazard zone prone to rock falls. Blasting is not a good option because it may trigger further rock falls. Controlled blasting under the supervision of an expert could be done in case of an emergency.
- Unstable slopes can be modified by re-grading, geotextile mats, vegetation and bio-engineering and geotechnical measures such as soil nailing, and wire machine. Anthropogenic activities that can cause saturation of the soil are to be strictly regulated in critical/prone areas. However, in locations where exceptionally deteriorated conditions of moderate dimensions already exist, the slope geometry needs to be scientifically changed to reduce the stress on the unstable mass. This may be done by providing restraining structures to increase the resistance to slide movements. These include providing a buttress, shear keys, retaining walls, rock bolts, and piles. Grouting and electro-osmosis can also be resorted to in very specific cases.
- The Government should encourage people to secure insurance coverage for their assets in high-risk areas.
- The Government should identify (construct if needed) multipurpose shelters designed by qualified architects for temporarily rehabilitating the affected people before and during an event. These shelters in normal times could be used for other purposes such as marriage or meeting for generating funds for its maintenance. These shelters should be at locations that are safe from both floods and landslides.
- Modify the existing landslide-prone area maps (prepared by NCESS) by considering additional causative factors and past occurrences of landslides. A cadastral level mapping with micro watershed boundaries may be desirable in the high hazard zones. In case of an area which is yet to be covered under cadastral survey, maps in a 1:5,000 scale may be prepared based on topographical maps, high-resolution image, and aerial photographs.
- The risk level of the landslide occurrence should be estimated and depicted on the refined hazard zonation maps at the cadastral level by incorporating vulnerability that considers population data, land use, infrastructure, assets, etc.
- Locations of current landslide incidences should be mapped in the hazard zonation maps prepared by NCESS (1:50,000 scale) for ready reference.
- Initiate studies that can help develop rainfall intensity-based probability for landslide occurrences.

c) Flood

The floods of 2018 and 2019 have a large return period (more than 100 years). To fully alleviate the impacts of such floods is practically difficult because any structural measure would not have considered such a high return period of floods due to their very low probability of occurrence. However, mitigation measures and preparedness can be planned to reduce the negative impacts of such calamities. The following are some of the suggestions to reduce the impact of flood in the future:

- As the catchment area of most of the reservoirs of the State drains forest areas, they do not experience heavy silting unlike the reservoirs in other parts of India, especially the ones in Himalayan Rivers. However, the storage capacity of most of the reservoirs in the State might have been reduced to varying extents as there was no periodic desilting action performed in the past decades. This capacity reduction would certainly have lowered the originally designed efficiency of the system. Therefore, the committee recommends that the storage capacity of all the reservoirs shall be evaluated at periodical intervals, say 10-20 years, to determine the amount of siltation on a priority basis, and desilting be planned accordingly if required.
- Several rivers that have reservoirs did not have larger flows in the past as the reservoir releases were minimal. Therefore, the concept of floodway and flood fringe can be introduced for flood zoning. The floodway is the high-risk area, which should be kept free of any construction to allow free movement of floodwater. The level of risk can be determined based on factors like depth and velocity of floodwater, duration of flooding, available flood storage capacity, or rate of rising of floodwater. In the flood fringe area, constructions may be permitted under certain conditions. In regulated rivers, this can be ensured by the controlled release of water (may be of magnitude corresponding to a 2-5-year return period of the virgin catchment) on specified intervals (example, once in 2-3 years) during active monsoon season. Such actions would ensure no encroachment into the river beds immediate downstream of dams.
- Buffer zones are to be demarcated on both the banks of the rivers (50-100 m from the bank) based on the geomorphological characteristics, where no construction is to be allowed. However, the cultivation of seasonal crops can be permitted in these buffer zones. Riverbank maps prepared under River Bank Protection and Sand Auditing project being executed by the Institute of Land Development and Management (ILDM), Revenue Department, Government of Kerala may be used for this purpose. In fact, agencies involved in riverbank mapping and sand auditing projects may be entrusted with this job of buffer zone demarcation.
- The Committee observed several obstructions in the flow channels (including rivers), which caused reduction/restriction of flow downstream resulting in the accumulation of water upstream. This was noted at different locations (Mukkom, etc.) in the 2019 floods. This was specifically observed in the Kallayi River, where

sediment accumulation resulted in an island formation that obstructed the river flow by almost 80 per cent. In addition, dumping of construction debris was observed in the river bed at many locations, that also caused restriction to the free flow of floodwater. Therefore, a smooth passage for the flood flow needs to be maintained in rivers. This can be done by periodical monitoring and clearing of river channels/drainage lines. This will reduce the bed roughness of rivers and ensure sufficient conveyance capacity. River cross-section data generated under river bank mapping and sand auditing projects under ILDM may be used for this purpose. River rejuvenation programme as initiated for a couple of rivers like Killi Ar, Karamana may be encouraged and executed throughout the state involving local people, and local self-government departments (LSGDs).

- The existing reservoirs in the State are conservation-oriented, and the policy is to harvest water as much as possible to the full capacity during the rainy season. None of them had an operating policy that considered flood control until 2018. After 2018, some of the dams have considered flood control in their revised operation policy. In the case of other reservoirs, it is suggested to revisit the rule curves by considering the dams as multi-purpose and multi-reservoir water resources systems, and develop integrated reservoir operation policies so as to maintain the balance between flood control and other objectives, such as hydropower generation, irrigation and drinking water uses. In addition, a relook at increasing the flood cushion in most of the reservoirs can be attempted.
- Wetlands such as rice fields, ponds, and lakes used to play a major role in flood control. While there are a large number of wetlands in the State, most of them have deteriorated or been abandoned or reclaimed and have become ineffective in their primary role. Therefore, it is suggested to restore the wetlands in the State on priority.
- Most of the river beds and flood plains have been deposited with sediments during the last two major floods. This has caused a further reduction in carrying capacity. Therefore, rejuvenation of the rivers to their original capacity is required.
- Wherever feasible, consider constructing levees and floodwalls. This should be done after a proper scientific feasibility study.
- It appears that a zonation of flood hazard has not been done for most of the rivers. What is available is only the flood-prone area map, which would only help in planning developmental activities. Flood impact mitigation requires the flood zones corresponding to different return period floods or return period rainfall. Since the floods are mostly caused by the EREs, it is recommended to simulate and demarcate the flood inundation zones corresponding to different rainfall return periods (example 10, 25, 50, 100, 150 years). In addition, such maps can be

prepared for different ensemble magnitudes of rainfall (without assigning any return period), and a library can be built using the simulations. During the onset of EREs, case-based reasoning can be performed on this library to approximate the possible flooding areas, which can be used for evacuation/mitigation. Such models, when developed, can also be used on a real-time basis to demarcate the approximate flooding zones.

- In addition to the flood hazard zone mapping through simulation, flood risk maps should also be developed. Flood risk maps will show the possible adverse consequences to people, health, livestock, economic activity, the environment, and cultural heritage in the event of floods. The map should show at least the risk to the potentially affected people (during day-time and night-time) including the indicative number of transitory people (example, tourists), aspects of economic activity, protected areas and natural environment, and where present, the facilities causing accidental pollution should they be flooded.
- An effective flood warning system is to be developed and implemented on priority. Since the predictive capability of the rainfall forecast models is limited, the flood warning systems cannot be fully dependent on the rainfall forecasts. Therefore, flood warning systems that depend on flood discharge at upstream locations and the time of travel to a downstream location may be planned and developed. This kind of warning system will mitigate human/livestock casualties. Telemetry systems can be effectively utilised for this purpose.
- Develop operation and maintenance manuals for flood gates and shutters. Perform maintenance, operation, and monitoring during the pre-monsoon period, and rectify the issues at regular intervals. Trials and test operational procedures should be performed at defined intervals. Ensure timely gate operations during flood events.
- It is noted by the Committee that flood accumulation in the lower Kuttanad region was mostly due to insufficient capacity to discharge the flood water to the ocean. Therefore, it is suggested to clear the sandbars near the Thottappalli Spillway on a regular basis and ensure the original width of the channel (downstream of the spillway) for smooth flow of the floodwater. Also, an increase of the width (~to 300 m) of the lead channel to the Thottappalli spillway is recommended.
- It is noted that the dwellings in the lower Kuttanad region are scattered and are aligned along the bunds. This reduces the effectiveness of evacuation in case of a severe flood event. Therefore, it is suggested to facilitate settlement at identified clusters.
- Since forests cover the majority of the catchment area of the rivers of the State, research studies may be carried out to understand the significance of forested watersheds in flood hydrological response.

d) Recommendation for Sustainable Housing in Hazard Zones

In the flood-prone areas of the State, building controls are not stand-alone solutions to mitigate flood risk. Instead, they need to be implemented in conjunction with other flood mitigation measures. Building controls are important to reduce damage to buildings and their contents. Setting the minimum floor levels for residential buildings and other structures in flood risk areas can reduce the frequency and extent of flood damage. The minimum floor level should be determined from the flood levels derived from significant historical flood events or floods of specific annual exceedance probabilities.

- Erection of fences/compound walls, whether solid or open, can affect the flood flow behaviour and flooding pattern by altering flow paths. The impact of such structures will depend on the type of fence and its location relative to the flow path. Hence, controls should be considered in relation to the type of fencing permitted, or to limit its location or height depending on the geographic area. In general, solid fencing, especially to ground level, should not be erected across flow paths where it might act as a dam. Open fencing is preferable.
- Flow velocities, flow depths and associated debris loads can affect the structural soundness. Hence, the structural soundness of the buildings in the flood-prone areas needs to be considered for the local hydraulic conditions.
- Emergency services (for example, water treatment and distribution, power generation and distribution, and communication services) might be disrupted during floods. Hence, the vulnerability of the emergency services to floods must be minimised. Service providers should also consider the emergency response and recovery planning for floods for key assets.
- Landslides lead to the complete destruction of houses and buildings that fall directly in the path of the flow. Moreover, it was seen that the walls of the buildings that are constructed with load-bearing masonry walls and reinforced concrete slabs were completely destroyed and the slab collapsed as a whole (pancaking type failure). It is difficult to design buildings that are resistant to landslides or floods. Nevertheless, it is recommended that all buildings in areas prone to landslides and floods be designed as per the norms of seismic zone 3, though the region is not in a seismic area. The justification is that the provisions for design in seismic zone 3 regions will lead to better lateral resistance and ensure that the pancaking collapse does not occur. Further, the foundations will also be such that there is better resistance against the force of mud and water.
- Habitations in flood plain, if unavoidable, could be designed as in the case of buildings in the coastal areas that are prone to tsunamis; i.e., the same regulations as in the case of tsunamis could be followed.

- Habitations in steep terrains could be designed such that the slopes are reinforced/strengthened by soil nailing. Further, the design should follow the provisions of design for seismic zone 3. As far as possible, the steep slopes should not be disturbed; if inevitable the building design should be made in such a way that the slopes need not be altered.
- Model structures may be constructed by following the existing provisions for coastal areas taking into account the effects of scouring, lateral impact of boulders and mud, and the maximum expected flood levels.

e) General Suggestion

- The Committee has analysed spatial and non-spatial data collected from different agencies and departments. Therefore, an important suggestion is that a centralised facility/ repository to store and share data may be created. The facility should be a single point contact, where all the data collecting departments should submit the data related to natural/man-made resources and data related to various hazards. This will (a) eliminate the generation of redundant data, (b) bring uniformity to data from different sources, and (c) ensure data quality. A policy should also be developed for sharing the data between different departments or academic and research organisations.
- During interactions with the survivors of landslides, the Committee observed that the traditional/ancestral knowledge of environmental and biological signals has been used to cope with natural hazards, which helped them to forecast the hazards. Hence, the Committee suggests to carry out research investigations to understand the scientific background behind these kinds of linkages. This may be helpful for developing early warning systems.

6.3. Recommended Action Plans

Based on the recommendation of the Committee, the following action plans are suggested to the government. The action plans envisage policy developments, detailed scientific assessment/studies, and ground-level plans for different sectors as detailed in the following section.

Type of measure	Immediate (6 Months)	Short Term	Medium Term	Long Term
Policy	Sharing data from different departments to the central facility/ repository which will store and share data related to the natural/man-made resources	Restrict disturbances at the locations of topographical hollows which falls under landslide-prone areas	Restrict settlements in the landslide run-out areas	Minimise/remove relief funds for property loss during hazards in high hazard-prone areas for the individuals who deny the mitigation measures of the government
	Restrict quarrying/ mining activities at high landslide-prone areas. Appropriate regulations also need to be made for quarrying/ mining activities at low landslide-prone areas	Conduct a mandatory environmental impact assessment for new developmental projects in the high flood/ landslide hazard-prone areas.	Develop integrated reservoir operation policies so as to maintain the balance between flood control and other system objectives, such as hydropower generation, irrigation and drinking water uses.	Restrict financial aids from the government for construction/activities in the high hazard-prone areas.
Scientific	Identify and map regions with potential disasters like heavy rainfall areas, flood-prone areas, landslide-prone areas,	Prepare flood inundation maps at 1:4000 scale	Hazard zonation and mapping of entire Kerala at 1:4000 scale • Flood hazard zonation	Prepare action plans for various levels of public administration/LSGDs to manage various

Type of measure	Immediate (6 Months)	Short Term	Medium Term	Long Term
	etc.		• Landslide hazard zonation • Dam release/breach hazard zonation	situations/hazards and preparation of documents to guide the public about action required during emergencies.
	Identify potential locations of topographical hollows	Prepare landslide hazard area and runout area maps at a 1:4000 scale. Initiate in-situ observations of aerosol microphysical properties (such as size distribution) including bio-aerosols, utilising educational/ research institutions at least in three representative locations; in the plains, on the slopes, and at higher altitudes in the Western Ghats.	Study to determine the model parameters specific to Kerala for physics-based models used in prediction of rainfall as well as the river flow	Studies on understanding the long-term trend of atmospheric aerosols over Kerala, specifically the fine mode aerosols relevant for the cloud and precipitation forming processes, using high-resolution satellite data.
		Conduct studies on improving the predictability of EREs	Studies on the threshold intensity of rainfall by incorporating more automatic rain gauges. Initiate studies on debris flow	Modelling studies to primarily understand the role of aerosol on cloud and rain formation.

Type of measure	Immediate (6 Months)	Short Term	Medium Term	Long Term
			runout.	
	Studies on the amount of sand carried by all the rivers in the State and the allowable extraction from its bed	Develop risk maps of landslide and flood possibility for the entire state.		
Land Use Management	Identify and mark buffer zones near the banks of rivers where only seasonal cultivation can be done with no construction and any obstruction for flow.	Prepare special land use planning for areas with slopes more than 20°.	In the unprotected slopes, plant a deep-rooted bio cover like Vetiver (*Ramacham*)	Introduce the concept of floodway and flood fringe for flood zoning. In the flood fringe area, constructions may be permitted under certain conditions.
	Removal of deep tap roots after clear-felling of trees and refill with earth (with minimal soil disturbances) to avoid over saturation and decay of tap root system which will promote soil piping and landslides.			
Water Resources	Conduct periodical monitoring and clearing of river channels/ drainage lines thus ensuring a smooth flow	Plan controlled the release of high flow (2- or 5-year return period) at least once in 2-3 years in all rivers to	Implement measures such as re-enforcement of embankments, lowering the floodplain area, widening the	Consider providing a dynamic flood cushion in the reservoirs, when advance warning of extreme rainfall

Type of measure	Immediate (6 Months)	Short Term	Medium Term	Long Term
	of water by reducing the bed roughness of the rivers and to ensure sufficient conveyance capacity.	demarcate their boundaries.	floodplain by re-location and lowering of embankments, and development of flood bypasses.	events are available
	Install dense network of Automatic Rain Gauges (ARG/AWS; ~500) with special emphasis on regions receiving high-intensity rainfalls in short time periods including slopes that have the potential for flash floods	Install weather stations for monitoring meteorological parameters (temperature, pressure, wind direction, wind speed, etc. ~50) in high time and spatial resolution; more importantly over the slopes of Western Ghats	Rejuvenate stagnant water bodies such as isolated channels, rivulets, and oxbows in the floodplain.	Perform maintenance, operation, and monitoring during the pre-monsoon period, and rectify the issues at regular intervals. Trials and test operational procedures should be performed at defined intervals. Ensure timely gate operations during flood events.
	Give priority to flood control over irrigation requirements and/or power benefits, especially during ERE forecasts	Create a State level ERE forecast system combined with Artificial Intelligence (AI) to predict flash floods and trigger an advance warning alerting the authorities.	Develop operation and maintenance manuals for flood gates and shutters.	
Construction	Set minimum floor levels for new residential buildings and other structures in flood-	Introduce construction standards (including materials) and building codes	Construct multipurpose shelters at safe locations	Construction of levees/ floodwalls and restoration of wetlands.

Type of measure	Immediate (6 Months)	Short Term	Medium Term	Long Term
	prone areas	for floodplains and landslide-prone areas.		
	Introduce designs of flood resilient buildings	Plan for proper traffic access in the flood hazard zones.	Demonstration of model flood-resilient buildings at various locations	Investigate the structural soundness of the buildings in the flood-prone areas for the local hydraulic conditions.
Revenue		Identify the flood plains and flood levels of 10-, 50- and 100-year return period floods. This needs to be done with the help of scientific studies	Propose one-time financial aid for people residing in the floodplains (high flood-prone areas) to relocate.	
Agriculture	Regulate agricultural activities which allow saturation of the soil in critical/prone areas of landslide.	Restrict cultivation on slopes based on hazard risk; promote cultivation along the contours with provisions for drainage of water.		
Dam/ Reservoir Management		Revisit the rule curves of the reservoirs by considering the dams as multi-purpose and multi-reservoir water resources systems and giving the provision of flood cushion	Desilt the reservoirs. Priority should be given to basins having cascading reservoirs and reservoirs whose capacities have reduced due to silting.	Improve flood warning system with integrated real-time reservoir operation

Type of measure	Immediate (6 Months)	Short Term	Medium Term	Long Term
Data Management	Install a proper hazard warning dissemination system both for administration and the public.	Develop a centralised facility/ repository to store and share data related to the various hazards and natural/man-made resources in the potential hazard areas	Update the centralised facility/repository at regular intervals	
Social/Awareness	Create awareness and communicate to the public about the risk of living in certain areas especially in flood and landslide-prone areas.	Encourage interaction between LSGD and local people about the hazard risk in their area and possible prevention measures.	Train and empower the locals in disaster management activities.	Encourage people in flood- and landslide-prone areas to cover people / properties / agriculture / industries under insurance
	Provide emergency contact details to people	Conduct Workshops, and awareness programs (at educational- and community-levels). Scientific and technical meetings are essential to actively involve and engage stakeholders. Dedicated websites or social media may be used to provide information to the general public and publish		

Type of measure	Immediate (6 Months)	Short Term	Medium Term	Long Term
		surveys and summary reports		

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Glossary

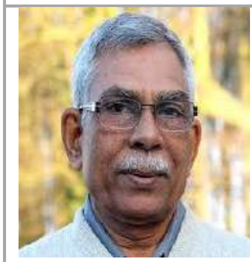
Anthropogenic	The environmental change caused or influenced by people, either directly or indirectly
Climate and weather	Weather refers to a short-term atmospheric condition while climate is the weather of a specific region averaged over a long period of time.
Cloudburst	A cloudburst features very heavy rainfall over a localized area at a very high rate of the order of 100mm per hour featuring strong winds and lightning.
Dead storage level (DSL)	Below the level, there are no outlets to drain the water in the reservoir by gravity.
Dead storage	It is the total storage below Dead Storage Level of the reservoir
Debris flow	A debris flow is a form of a rapid mass movement in which a combination of loose soil, rock, organic matter, air, and water mobilize as a slurry that flows downslope
DEM	Digital elevation models (DEMs) are arrays of regularly spaced elevation values referenced horizontally either to a geographic or projected coordinate system
Depression	The intense low-pressure system represented on a synoptic chart by two or three closed isobars at 2 hPa interval and wind speed from 17 to 27 knots at sea and two closed isobars in the radius of 3° from the centre overland
Drainage basin	The area from which a lake, stream or waterway and reservoir receives surface flow which originates as precipitation
Exceedance probability	Exceedance probability is the per cent chance or likelihood that a given flow will be exceeded in any given one-year period
Exposure	The situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas
Flood plains	The nearly flat portion of a river (stream) valley adjacent to the river (stream) channel; it is built by sediment deposited during floods and is covered by water during a flood
Flood storage	This is a reserve between Full Reservoir Level and the Maximum Water level to contain the peaks of floods
Full reservoir level (FRL)	It is the level corresponding to the storage which includes both inactive and active storages and also the flood storage, if provided for. It is the highest reservoir level that can be maintained without

	spillway discharge or without passing water downstream through sluiceways.
Hazard	A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation
Landslide susceptibility map	A map that ranks slope stability of an area. It shows locations where landslides may occur in the future (without a definite time frame)
Land use and land cover (LULC)	Land cover is the observed (bio)physical cover on the earth's surface. Land use is characterized by the arrangements, activities, and inputs people undertake in a certain land cover type to produce, change or maintain it
Live storage	This is the storage available for the intended purpose between Full Supply Level and Dead Storage Level
Long-period average (normal)	Long-period average of a monsoon season is calculated on the basis of mean rainfall during the June to September over 50-year period
Low-pressure systems	The low-pressure systems over the Indian region are classified based on the maximum sustained winds speed associated with the system and the pressure deficit/ number of closed isobars associated with the system. The system is called as low if there is one closed isobar in the interval of 2 hPa. It is called depression, if there are two closed isobars, a deep depression, if there are three closed isobars and cyclone if there are four or more closed isobars
Maximum water level (MWL)	This is the water level that is ever likely to be attained during the passage of the design flood. It depends upon the specified initial reservoir level and the spillway gate operation rule. This level is also called as the Highest Reservoir Level or the Highest Flood Level
Minimum drawdown level (MDDL)	It is the level below which the reservoir will not be drawn down so as to maintain a minimum head required in power projects
Monsoon	Monsoon has originated from the Arabic word “Mausim” which means season. It is most often applied to the seasonal reversals of the wind direction along the shores of the Indian Ocean, especially in the Arabian Sea, that blow from the southwest during one half of the year and from the northeast during the other.
Percentile	The *n*th percentile of a set of data is the value at which *n* per cent of the data is below it.
Return	Recurrence interval is the average time interval during which a

period/Recurrence interval	given flow is expected to be exceeded one time
Risk	The potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, vulnerability, and capacity
Run-out area	It includes all of the areas that can be reached by a landslide event
Soil piping	Erosion by percolating water in a layer of subsoil resulting in caving and in the formation of narrow conduits, tunnels or pipes through which soluble or granular soil material is removed
Vulnerability	The conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards
Watershed	The terms drainage basin and watershed are often considered synonymous but strictly speaking, a watershed is the divide separating one drainage basin from another
Wetlands	Wetlands are areas where water is the primary factor controlling the environment and the associated plant and animal life. They occur where the water table is at or near the surface of the land, or where the land is covered by water.

Expertise of the committee

 **Prof. K P Sudheer**	Prof. Sudheer is the Executive Vice President, Kerala State Council for Science, Technology and Environment & Principal Secretary (*Ex-officio*), Science & Technology Department, Government of Kerala. He is also a Professor in the Department of Civil Engineering, Indian Institute of Technology Madras, Chennai and Adjunct Professor of Department of Agricultural and Biological Engineering, Purdue University, USA. He specializes in hydrological modelling, flood forecasting, predictions in ungauged basins and applications of soft computing skills in hydrology.
 **Prof. S K Satheesh**	Prof. Satheesh is a Professor at Centre for Atmospheric & Oceanic Sciences, Indian Institute of Science, Bengaluru. He is one of the lead authors of the 5th Assessment Report of IPCC. His expertise extends from oceanography, aerosols, radiation, clouds to climate and field experiments.
 **Dr. D Sivananda Pai**	Dr. Pai is the Head of the Office of Climate Research and Services, India Meteorological Department (IMD), Pune. He has made an outstanding contribution towards climate variability and prediction and has been part of the team that developed operational seasonal forecasting currently used by IMD. Dr. Pai has served as a member of the WMO-CBS Expert Team on Extended and Long-Range Forecasting, co-leader of the WMO Task Team on Regional Climate Outlook Forums (TT-RCOFs) during 2014-16 and was the leader of TT-RCOFs from 2017-2018.
 **Dr. K J Ramesh**	Dr. Ramesh is the retired Director General of the India Meteorological Department (IMD), New Delhi. He has also served as Senior Advisor to the Ministry of Earth Sciences. He specializes in climate and numerical modelling.
 **Dr. Sachin S Gunthe**	Dr. Gunthe is an Associate Professor in the Department of Civil Engineering, Indian Institute of Technology Madras, Chennai. His research focuses on atmospheric chemistry and biophysics, aerosol-cloud-precipitation interactions and the effect of increasing anthropogenic aerosols on Indian monsoon and characterizing properties of atmospheric aerosols to study climate and health impacts.

 **Prof. Deepankar Choudhury**	Prof. Choudhury (FNASc, F. ASCE, FIE, Humboldt Fellow, JSPS Fellow, TWAS-VS Fellow) is an Institute Chair Professor at the Department of Civil Engineering, Indian Institute of Technology Bombay, Powai and Adjunct Professor of Academy of CSIR laboratories (AcSIR), India. He specializes in the domain of geotechnical engineering, earthquake engineering, foundation engineering, soil dynamics, liquefaction, landslides, and computational geomechanics.
 **Dr. Srikumar Chattopadhyay**	Dr. Chattopadhyay, a geographer by profession, is the ICSSR National Fellow, National Centre for Earth Science Studies (NCESS), Thiruvananthapuram. He was a former Scientist-G and Head, Resources Analysis Division, Centre for Earth Science Studies (CESS). He is an expert in geomorphology, environmental impact assessment, natural resource mapping and management, and climate change mitigation and adaptation.
 **Prof. E J James**	Prof. James is Professor Emeritus and Pro Vice-Chancellor of Karunya Institute of Technology and Sciences (Deemed University), Coimbatore. He retired from the Centre for Water Resources Development and Management (CWRDM), Kozhikode as the Executive Director. He was also a member of the National Wetland Committee, Central Wetland Regulatory Authority and ICID Working Group on Sustainable Development of Tidal Areas and presently a member of the governing body of the Wetland International - South Asia.
 **Mr. G Sankar**	Mr. Sankar a Senior Consultant, at the Crustal Processes Group, National Centre for Earth Science Studies (NCESS), Thiruvananthapuram. He was a Scientist-G at the Centre for Earth Science Studies (CESS). He is an expert in the research on land disturbances, landslide hazard zonation, and hazard and vulnerability assessment.
 **Prof. T Jayaraman**	Prof. Jayaraman is a member of the Kerala State Planning Board. He is a Professor at the School of Habitat Studies, Tata Institute of Social Sciences (TISS), Mumbai. Climate change-related issues including climate policies and energy issues, global mitigation and carbon budgets, vulnerability and adaptation are some of his areas of expertise.

 **Padmashri M Chandradathan**	Mr. Chandradathan is the Scientific Advisor to the Chief Minister, Kerala. He was the Director of Vikram Sarabhai Space Centre (VSSC), Thiruvananthapuram. He is a renowned chemical engineer with accomplishments in space technology, mainly in the field of propulsion and solid motors.
 **Mr. Joshy K A**	Mr. Joshy is the Chief Engineer of Irrigation Design and Research Board (IDRB), Irrigation Department, Government of Kerala. He has expertise in water resources engineering.
 **Ms. Supriya S**	Ms. Supriya is the Chief Engineer (Dam Safety) of the Kerala State Electricity Board (KSEB) Ltd. She is specialized in geotechnical engineering, specifically the design of various civil structures of hydroelectric power projects.
 **Dr. Sekhar Lukose Kuriakose**	Dr. Kuriakose is the Member Secretary, Kerala State Disaster Management Authority (*Ex-officio*) and also Head (Scientist), Kerala State Emergency Operations Centre (KSEOC). He specializes in landslides and is an expert in hazard, vulnerability and risk assessments.
 **Dr. Anitha A B**	Dr. Anitha is the Executive Director of the Centre for Water Resources Development and Management (CWRDM), Kozhikode. She specializes in the field of hydrology and water resources engineering.

 **Prof. Ravindra Gettu**	Prof. Gettu is the Prof. V.S. Raju Chair Professor in the Department of Civil Engineering at the Indian Institute of Technology Madras, Chennai. He is the President of RILEM, the International Union of Laboratories and Experts in Construction Materials, Structures and Systems, France, and Fellow of the Indian National Academy of Engineering (INAE). He works closely with industry to promote technology implementation and specializes in the areas of concrete technology and characterization, and sustainability.
 **Prof. R Ramkumar**	Prof. Ramkumar is a non-ministerial member of the Kerala State Planning Board. He is a professor at the School of Development Studies, Tata Institute of Social Sciences (TISS), Mumbai. He is an expert in agrarian studies, agricultural economics, development economics, fiscal policies in India and national identity schemes.
 **Mr. John Mathai**	Mr. Mathai is a Senior Consultant in the Crustal Processes Group of National Centre for Earth Science Studies (NCESS), Thiruvananthapuram. He retired from the Centre of Earth Science Studies (CESS) as Scientist-G. Environmental Impact Assessment of water-related projects, terrain evaluation of landslides and slope stability problems, micro-level surveys for natural resource evaluation and regional planning, water prospecting and conservation techniques are some of his areas of expertise.
 **Mr. Nizamudeen A**	Mr. Nizamudeen is the Land Use Commissioner and Director, Kerala State Remote Sensing and Environment Centre (KSREC). He is an expert in land use planning, watershed management, remote sensing, and GIS. He involved in the panchayat resource mapping, preparation of watershed-based master plans for Local Self Government Departments (LSGDs) and development of natural resources management plan for different river basins in Kerala.