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Methodological approaches, gaps, and future directions

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A critical review of flood risk assessment in Kerala Post-2018: Methodological approaches, gaps, and future directions

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ABSTRACT

Study region: The study focuses on Kerala, a state in the southwest of India. Kerala is composed of 14 districts, each characterised by variations in topography, climate, and land use patterns.
Study focus: This review critically analyses the literature on flood risk assessment (FRA) in Kerala, particularly after the devastating 2018 floods. Kerala has experienced sporadic floods in the 21st century, caused by localized heavy rainfall, rapid urbanization and improper management of water resources. The 2018 Kerala Floods was one of the most catastrophic recent floods. Nearly all 14 districts were affected, over 480 people lost their lives, and more than a million were displaced. Anthropogenic factors, such as encroachment on wetlands, sand mining in riverbeds, and inadequate drainage systems in urban areas, have worsened the impact of floods. Despite the long history of flooding, flood management in Kerala has struggled to keep pace with the increasing magnitude and frequency of these events. Factors such as outdated infrastructure, uncoordinated dam management, and poor urban planning have exacerbated the impacts of floods. Against this backdrop, this review on flood risk assessment (FRA) in Kerala evaluates and synthesises existing methodologies to improve understanding of current state-of-the-art FRA in Kerala and provide a foundation for more effective flood management strategies.
New hydrological insights for the region: The review identifies that research conducted after the 2018 floods can be categorised into three broad methodological themes: Remote Sensing and Geographic Information Systems (GIS), Predictive Modeling (including hydrological and hydraulic simulations), and Analytical Approaches (such as machine learning, statistical methods, and multi-criteria decision-making). The spatial focus of the studies reveals significant disparities, with Allapuzha being the most extensively studied district and Thiruvananthapuram receiving minimal attention. The review identifies critical gaps in the literature, including challenges in translating mitigation strategies, urban flooding stemming from poor land use planning, insufficient integration of various flood sources, and limited research on compound extreme events. Highlighting the urgency of translating the quantification of hazard to mitigation and the integration of climate change projections, the article provides avenues for further research for FRA in Kerala.

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1. Introduction

Flooding is one of the most frequent and recurring hazards, characterised by the overflow of water onto dry land resulting from factors such as heavy rainfall, storm surges, poor drainage infrastructure and seal level rise (Chen et al., 2023; Hoq et al., 2021; Kousky et al., 2020; Peng and Zhang, 2022; Stephens et al., 2021). Currently, 23 % of the global population is exposed to flood risk; of this, 89 % reside in low-and middle-income countries (Rentschler et al., 2022). Although flooding occurs globally, most of the flood-exposed population is in South and East Asia, with China and India alone accounting for over one-third of the global exposure (Rentschler et al., 2022; Rubinato et al., 2019). In India, over 65 million people are highly vulnerable to floods and live in poverty. This value represents 16.8 % of 390 million people exposed to flood risk within the country and is projected to increase due to climate change (Dhiman et al., 2019; Mohanty et al., 2020; Nanditha and Mishra, 2024; Rentschler et al., 2022).

India has significant geographic and climatic variability in the north; the Himalayan range influences the climate of the region by contributing to cold temperatures and deflecting the monsoon winds. The Gangetic floodplains experience a more temperate climate (Mohanty et al., 2020; Mohapatra and Singh, 2003). The western ghats produce a wide range of climatic patterns, such as heavy rainfall on the windward side and drier conditions on the leeward side. The Deccan Plateau, in the central and southern parts, is characterized by semi-arid conditions and is a transition zone between the northern plains and the south coastal areas (Mohanty et al., 2020, 2018).

From June to September, the monsoon season in India brings heavy rainfall and significant flooding, affecting 12.16 % of the country according to the Central Water Commission (CWC), heavy rains and floods have resulted in 107,535 casualties and caused over 50 billion USD in damages to public utilities, houses, and crops from 1953 to 2017 (Mangukiya et al., 2022). Flooding in India is caused by high-intensity rainfall, poorly planned reservoir regulation, insufficient drainage capacity, and the failure of flood defence structures (Anandalekshmi et al., 2019; Hussain, 2020a; Lyngwa and Nayak, 2021). Climate change exacerbates these issues, with rising

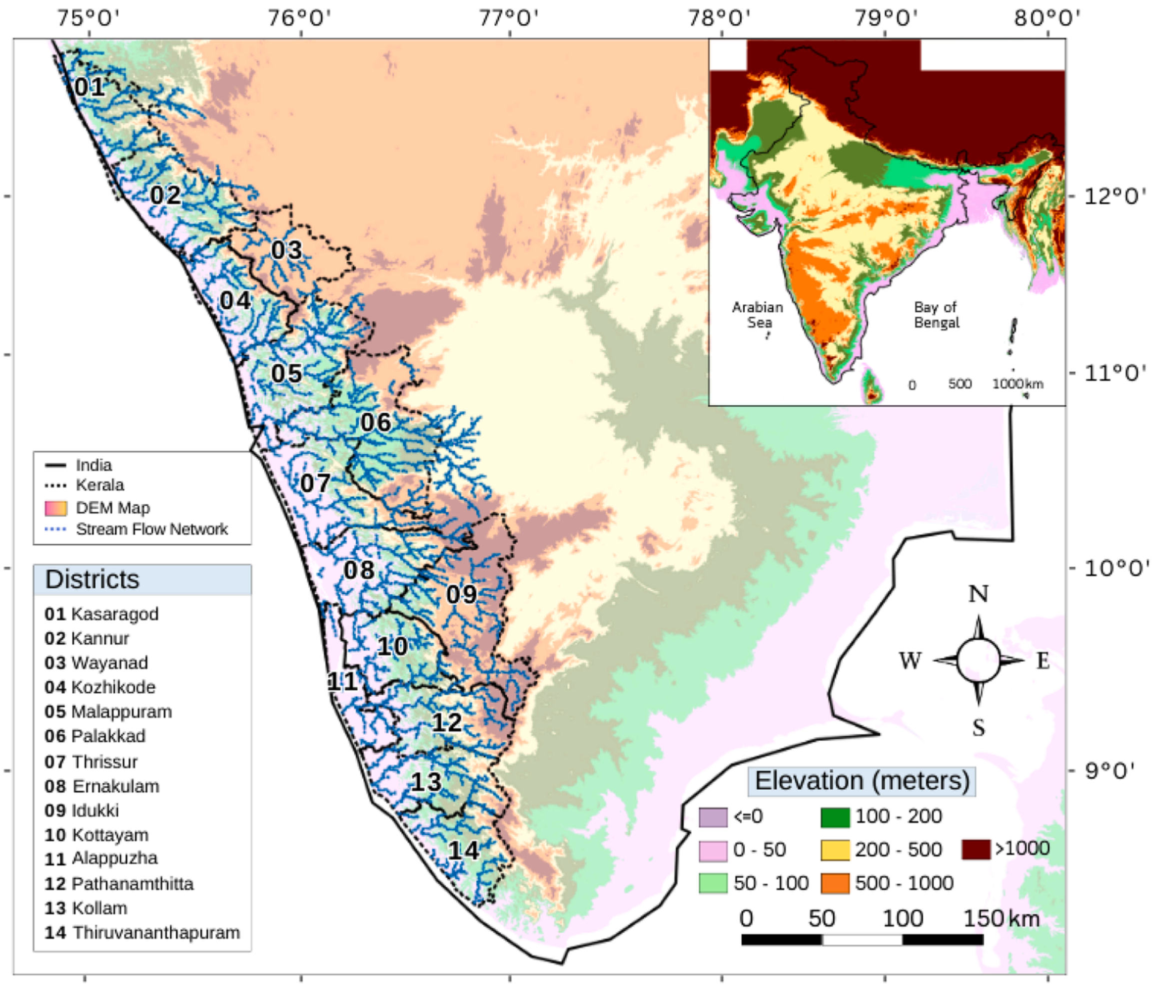


Fig. 1. Location of the 14 districts of Kerala, India. The image highlights the dense river network, and varied elevation of each district within the state.

South Asian temperatures leading to more frequent floods. The country is highly vulnerable to climate change and experiences prolonged dry periods followed by sudden, excessive rainfall, resulting in extreme weather events such as floods (Turner and Annamalai, 2012). By 2040, the population at risk of severe floods in India is expected to increase six-fold (Jacinth Jennifer et al., 2022; Yaduvanshi et al., 2022)

Case. Study: Kerala

Kerala consists of 14 districts (Fig. 1), which includes a 580 km coastline, agricultural lands, and the Western Ghats, i.e. a UNESCO World Heritage Site (Abe and Erinjery Joseph, 2015). Kerala has a humid tropical wet climate typical of rainforests; it receives its first rains in late May and June, averaging 3107 mm of annual rainfall. Rainfall ranges from 1250 mm in lowlands to 5000 mm in highlands due to orographic precipitation, with approximately 120–140 rainy days per year (Indian Meteorological Department, 2023). The climate within the state is influenced by the Southwest summer monsoon (June to August) and the Northeast winter monsoon (September to December), with 65 % of rainfall occurring during the summer monsoon (Indian Meteorological Department, 2023). The Southwest monsoon, split into the Arabian Sea and Bay of Bengal branches due to the Western Ghats, first reaches Kerala, making it the initial recipient of monsoon rains in India.

With its 44 major monsoon-fed rivers, Kerala is highly vulnerable to flooding due to its unique geography, characterized by fast-flowing rivers and seasonal fluctuations. The state experiences riverine flooding during the monsoon, alongside flash floods in the hilly Western Ghats and urban flooding in cities like Kochi and Thiruvananthapuram, exacerbated by intense rainfall and inadequate drainage systems (Drissia et al., 2019a; Mohan and Adarsh, 2023). Recent consecutive flood events—2018, 2019, 2020, and 2024—emphasise the severity of the issue, with devastating consequences for communities and infrastructure (Hunt and Menon, 2020;

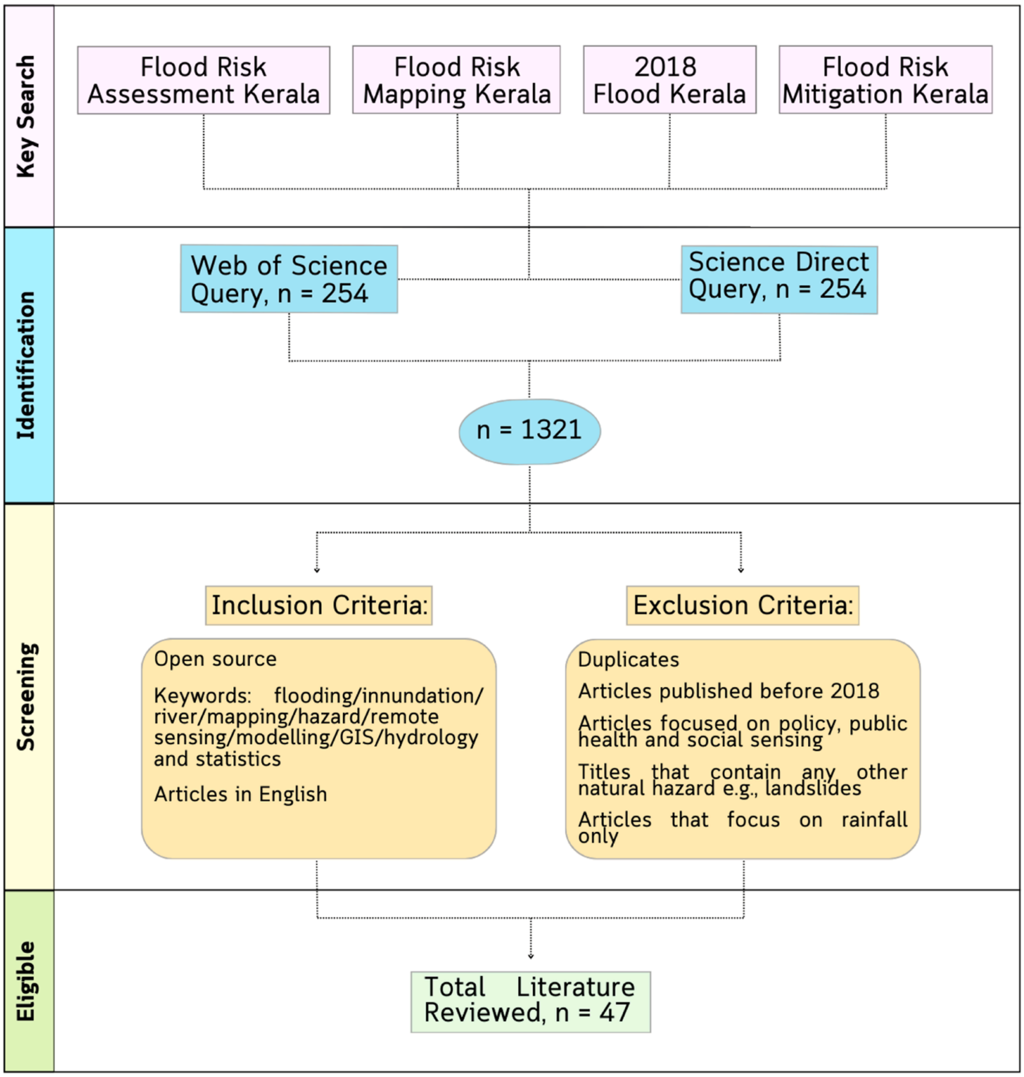


Fig. 2. Methodology highlighting the key search, identification, and screening process to identify relevant literature.

Reddy and Arunkumar, 2023; Sabitha et al., 2023; Vijaykumar et al., 2021). The catastrophic landslides in Meppadi, Wayanad, on July 30, 2024, which claimed 413 lives by August 7, highlight the systemic vulnerabilities that contribute to flood-induced disasters (Nath, 2024).

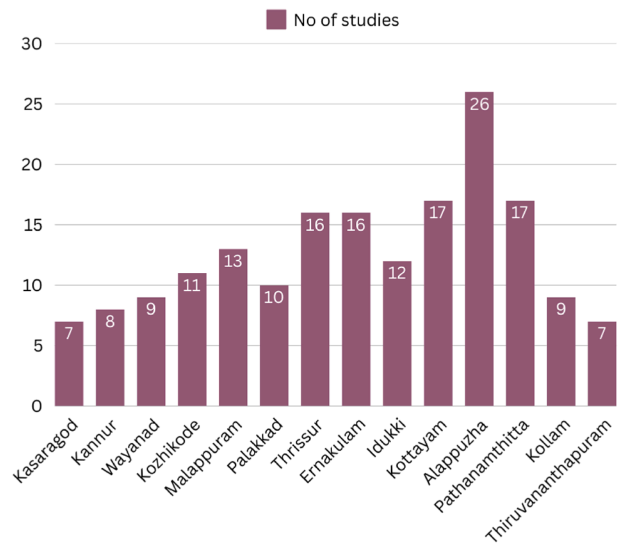
The 2018 floods were among the most severe in the history of Kerala, affecting 13 out of 14 districts, increasing August rainfall by 164 %, and resulting in over 400 fatalities and the displacement of millions (Lyngwa and Nayak, 2021). These events caused extensive economic damage, particularly in agriculture, fisheries, and eco-tourism, sectors integral to the economy of Kerala. Additionally, the degradation of natural flood defences, such as mangroves and backwaters, due to urban expansion and climate change has intensified flood risks (Dykstra and Dzwonkowski, 2020; Sahu et al., 2015; Sivadasan, 2004; Sonu et al., 2022) The sloping topography of Kerala, from the highlands to the low-lying west coast, further exacerbates flood risk during monsoon peaks. The urgency to formulate proactive mitigation measures is heightened by the demographic density of this state economic reliance on vulnerable sectors and increasing exposure to extreme weather events.

Flood risk assessment (FRA) is a critical tool for understanding and managing the impacts of flooding, particularly in vulnerable regions like Kerala. This literature review critically synthesises the latest methodologies in FRA within Kerala, especially in the aftermath of the 2018 floods. FRA, which determines the potential for flooding by analysing topographical, meteorological, and hydrological data, is crucial for safeguarding lives, guiding urban and environmental planning, and improving emergency responses to disasters. The 2018 floods and subsequent severe flood events in 2019 and 2020 exposed weaknesses in existing flood risk management strategies and highlighted the growing challenges posed by climate change, rapid urbanization, and a dense population. By examining remote sensing, GIS, flood modelling, and artificial intelligence applications, this review identifies gaps and limitations in existing research and proposes directions for future studies to defend Kerala against future flooding. While previous research has focused on general FRA in Kerala, this review provides a specific context of the devastating 2018 floods and the subsequent flood events in 2019 and 2020. This timeline-based focus highlights how methodologies have evolved or failed to evolve in response to these events, making the review both timely and critical.

2. Methods

2.1. Literature search

This systematic literature review examined the advancements in flood risk mapping studies in the wake of the 2018 Kerala floods, recognised as one of the most severe flooding events. The method for the literature search focused on studies published after the 2018 Kerala floods to ensure that the most recent and relevant data was included, as outlined in Fig. 2. The search included Web of Science and Science Direct and was complemented by reviews of grey literature, conference proceedings reports and thesis chapters. Keywords and search terms were selected to capture studies pertinent to "flood risk AND mapping", "2018 Kerala floods," and “flood risk AND assessment”. The use of Boolean operators refined the search to studies published from 2018 onwards. The four searches above resulted in 1321 papers for both databases with many duplicates. The database was then cleaned to remove duplicates, journal articles that are not open source, and documents that are not in English. Other exclusion criteria include articles focusing on rainfall only, policy, social sciences and where the case study is not Kerala. The inclusion criteria identified studies that specifically addressed flood risk assessment for any event since the 2018 Kerala floods.



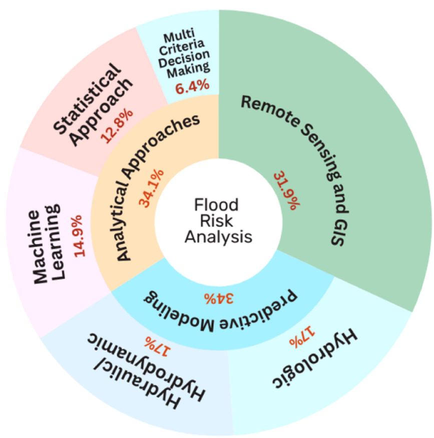


Fig. 3. Results from the analysed study a) showing the percentage of studies by thematic area, b) a percentage of studies by subcategories within the thematic area and c) plots the number of studies per district in Kerala.

2.2. Post-processing

The extracted data were synthesised through a thematic analysis to recognise patterns and methodologies in the post-2018 Kerala floods research, these have been summarised in Fig. 3. Setting the 2018 Kerala floods as a separation point allowed this review to focus on the most current and contextually relevant flood risk mapping studies, thereby providing a clear picture of the gaps that may still exist in the literature. The approaches used for FRA were categorised into three thematic areas:

(i) Remote sensing-based approaches refer to studies that predominantly use remote sensing technology and GIS to process the data to assess flood risk and extent.
(ii) Predictive Modelling approaches: these refer to studies that have used hydrological and hydraulic modelling to assess flood risk and
(iii) Analytical approaches that rely on empirical data can be qualitative or quantitative.

2.2.1. Remote sensing based approaches

The first thematic area identified is remote sensing (RS) based approaches, which play a vital role in collecting data about objects and infrastructure "remotely" using technologies such as synthetic aperture radar (SAR), satellite imagery and space-based observations (Amitrano et al., 2024). Remote-sensing technology is an alternative when ground-based observations are not viable, enabling data collection over expansive areas. The aerial photography and satellite images obtained using remote sensing help understand terrain properties within the catchment to locate the extent of flooding. (Amitrano et al., 2024, 2018; Giustarini et al., 2016). Standard methods of flood detection in SAR images include speckle filtering, thresholding, multi-sensor data fusion and fuzzy classifiers.

2.2.2. Predictive modelling based approaches

Predictive modelling forms the backbone of FRA globally; hence, significant literature exists on the spatial extent, dimensionality, and numerical complexity of the models**.** Predictive modelling approaches have been divided into three main types (Hill et al., 2023; Jodhani et al., 2023; Nkwunonwo et al., 2020; Teng et al., 2017):

1. Hydrological Modelling quantifies water movement and storage within the hydrological cycle**.**
2. Hydraulic Modelling focuses on the behaviour of water in motion, analysing flow patterns and water levels in river channels, pipes, and floodplains.
3. Hydrodynamic Modelling considers the interaction between water bodies and physical forces such as gravity, pressure, and tidal forces accounting for flow patterns, wave motion, and surface water changes.

Hydrological modelling is crucial in understanding and predicting water movement within a catchment. It combines statistical analyses with physical process-based models to simulate the various components of the hydrological cycle (Krebs et al., 2014; Kumar et al., 2023; Peel and Blöschl, 2011; Sood and Smakhtin, 2015). Critical components of hydrological modelling include simulating precipitation, evaporation, transpiration, infiltration, runoff, and storage changes and routing water through hydrologic systems such as rivers and streams. Models can be conceptual, data-driven, or mechanistic, each with varying degrees of complexity and reliance on physical laws, statistical methods, or machine-learning techniques. Inputs for these models typically consist of weather data, land use information, soil properties, and topography, while outputs include hydrographs and water quality parameters.

Hydrological models are often coupled with hydraulic and hydrodynamic models to represent the flow in river channels and overland in one dimension (1D) and two dimensions (2D). The two common spatial extents in hydraulic and hydrodynamic modelling are(Jha and Afreen, 2020; Lin et al., 2005; Teng et al., 2017; Vojinovic and Tutulic, 2009).

- 1D hydraulic models: These models simulate water flow along the main direction of the river or channel
- 2D hydrodynamic models: These models are a more detailed representation of flooding processes by simulating longitudinally and laterally across a grid.

Linked models combine the strengths of both hydrological and hydraulic models. Hydrological models predict runoff and river discharge resulting from precipitation events, while hydraulic models simulate the movement of this water within the modelling domain.

2.2.3. Analytical approaches

The definition of analytical approaches in this paper applies to studies that use a pragmatic framework FRA by emphasising input-output relationships. Analytical approaches range from quantitative to qualitative or a blend of both, using historical data to identify correlations between flood events and their influencing factors. Among the quantitative strategies, statistical, geostatistical, and machine learning (ML) methods stand out for their ability to process large datasets (Binoy et al., 2023; Snehil and Goel, 2020; Yazdandoost and Bozorgy, 2008). This combination of data-driven and expert-informed methodologies presents a holistic toolkit for conducting FRA despite the challenges posed by the stochastic nature of weather. Within the context of Kerala, three main analytical approaches have been identified:

1. Statistical analyses are fundamental to hydrological modelling, particularly in estimating flood frequencies and analysing streamflow trends. Table 1S provides details of the key statistical methods and their applications.
2. Multi-Criteria Decision Making (MCDM) is a methodology designed to assist decision-makers with multiple and conflicting criteria to consider. It provides a systematic approach to analysing, evaluating, and ranking different aspects of a decision problem. Some commonly used MCDM methods are the analytical hierarchy Process (AHP), Technique for Order of Preference by Similarity to Idea Solution (TOPSIS), Elimination and Choice Expressing Reality (Electre) and Preference ranking organisation method for enrichment evaluation (Promethea)(Aruldoss et al., 2013; Ceballos et al., 2016; Mallouk et al., 2016; Yahaya et al., 2010).
3. ML can process large data sets and uncover complex patterns that traditional methods might miss. Some key concepts commonly used in the application of machine learning for FRA include supervised, unsupervised, and ensemble learning. Common algorithms used within the context of flood risk analysis include Adaptive Boosting (AdaBoost), Extreme Gradient Boosting (XGBoost), Artificial Neural Networks (ANNs), Logistic Regression, K-Nearest Neighbors (KNN), and Decision Trees and Random Forests. These algorithms have shown effectiveness in various aspects of FRA, from predicting flood occurrences to mapping flood-prone areas and estimating potential damage (Alexander et al., 2018; Eslaminezhad et al., 2021; Jones et al., 2023; Kulithalai Shiyam Sundar and Kundapura, 2023).

3. Results

A total of 47 studies published after the 2018 Kerala flood were chosen to ensure that the most recent and relevant data were perused for this review. These have been summarised in Table 2S, provided in the supplementary material and Fig. 3. Most (34 %) studies used predictive modelling-based and analytical approaches for FRA, and 31.9 % used remote sensing and analytical approaches equally. The percentage of studies using hydrological and hydraulic/hydrodynamic modelling is 17 % for both sub-categories. The percentage of studies utilising statistical, MCDM, and ML methods is 6.4 %, 14.9 %, and 12.8 %, respectively. Over half, i.e., 26 or 56.52 %, of the studies analysed include the district of Alappuzha. Kasaragod was the least-studied district.

3.1. Remote sensing based approaches

In Kerala, Remote Sensing (RS) technology has enabled historical analyses, monitored land use/land cover (LULC) shifts, and investigated the geomorphological causes of flood events. RS has improved the ability to identify areas susceptible to flooding and explore the relationship between historical LULC, geomorphological attributes, and flood vulnerabilities. Vishnu et al., (2020) used RADARSAT-1, Sentinel-1A, and Sentinel-1B datasets for delineating flood-prone zones and lineaments, where lineaments represent distinct linear features across geology, topography, or vegetation variances. While the lineaments inform on the importance of geological features that influence flood risk occurrences, they lack in validating the identified lineaments and clarifying their direct influence on flooding, leaving the mechanisms by which these lineaments modulate flood discharge and accumulation unexplored. Furthermore, the assumption of a direct correlation between alterations in stream channels and active tectonic movements has oversimplified the complex processes governing river pathways. Chithra et al. (2022) highlighted the utility of microwave data, using Sentinel-1 images, over traditional optical data in regions prone to cloud cover, such as Kerala. The findings marked spatial extent in flood-affected zones within Malappuram, which increased from 41.34 km^2 in 2017–68.21 km^2 and subsequently to 87 km^2 during the intervals spanning August 29 to August 21 in 2018. Using methodologies like the Normalised Difference Water Index (NDWI) and Normalised Difference Flood Index (NDFI) was instrumental in differentiating flood zones and mapping flood extents. Furthermore, Dhanabalan et al. (2021) also highlighted the proficiency of SAR for utilising VV polarisation alongside Sentinel-2 imagery and PERSIANN-CCS within the European Space Agency's Sentinel Application Platform (SNAP) framework. Their analysis emphasised the capability of VV polarisation to distinguish flood extents through unique backscatter signatures for aquatic and terrestrial landscapes. This study primarily illustrates the effectiveness of SAR data, mainly through VV polarisation, in mapping flood extents.

Urbanization and anthropogenic activities significantly influence flood risk, as demonstrated by studies such as Ajin et al., (2019) which utilised IRS-P6 LISS-IV satellite imagery and Survey of India topographic maps to map flood hazard zones in the Achankovil River Basin. This study considered hydrological, topographical, and geomorphological factors and urban features like roads to develop and apply a Modified Flood Hazard Index (MFHI) method. The outputs were flood hazard zone maps that classified areas into five hazard categories, ranging from shallow to very high. Key findings indicated that geomorphology, drainage density, and soil type significantly influence flood occurrence. However, the methods used to derive key outputs, such as slope and drainage classes, must ensure that the slope classes accurately represent the diversity of the terrain. If the chosen classes are too broad, they may oversimplify the analysis, neglecting minute variations in the terrain. Similarly, for drainage density classes, the classification must align with the landscape characteristics to maintain the reliability of the assessment. Therefore, a sensitivity analysis should be implemented by varying the class resolution and observing how this variation influences results. The findings show that critical parameters, such as the size of the watershed, affect vulnerability to flood risk by altering natural drainage patterns and increasing flooding, thereby demonstrating the influence of urbanization on heightened flood risk.

Additionally, Kumar and Jayarajan (2021) investigated the effect of urban areas on flood risk using SAR data from C-band Sentinel 1 A and B satellites, Landsat-8 OLI imagery and Open Street map data for flood extent mapping. The Landsat-8OLI data and NSWI were used to delimit the open water features, and the OSM data was used to represent built areas and the transport network. The results showed that settlements with mixed tree crops and farmlands are the most affected areas. Additionally, the study identifies that 28 km^2 of the study area is submerged underwater. Especially unclassified and residential road networks in the regions built were particularly vulnerable to flooding. Focusing on change in LULC using optical, microwave and radar-based rainfall data. Lal et al. (2020) found significant losses in shrubland and cropland between 2001 and 2018. This stresses understanding the links between human-induced changes to the landscape and the increase in flood risk. The study, however, lacks details on specific drivers behind the observed LULC changes and, hence, needs to consider other factors that may contribute to increased flooding. The ability of SAR technology has made it possible to analyse urban areas accurately. However, Vanama et al., (2020) highlighted that using SAR-based flood detection in urban areas can affect the accuracy of flood extent mapping in urban areas due to the SAR signal interaction with flood urban environments, and therefore, relying on a single RS dataset has limitations. The study by Vanama et al. (2020) conducted flood mapping using L-band SAR imagery from ALOS-2 and used a split-window approach paired with Kittler and Illingworth's thresholding algorithm, targeting the 2018 Kerala floods. Despite achieving a 73 % accuracy rate, the study identifies the need to use multi-temporal and multi-frequency SAR data and advanced processing algorithms to overcome urban flood mapping challenges and improve applicability to regions with high geographic variability.

The impact of anthropogenic activities, such as wetland conversion and agricultural practices, on flood risk estimation has also been investigated using RS technology. Rice is the staple food in Kerala; therefore, paddy fields are a significant part of the LULC of Kerala. Although paddy fields are waterlogged, their impact on flood mapping was poorly understood. Hence Kulk et al. (2023) used Multi-Spectral Imaging on board the Sentinel-2 to identify paddy cultivation to improve flood mapping accuracy. The methodology showed that multi-spectral remote sensing is highly accurate, but human intervention is seldom considered. Waterlogged paddy fields are often classed as flooded areas, introducing inaccuracies in estimating flooding. Additionally, dams are crucial in addressing water resource management needs in Kerala; however, they exacerbated the flooding in 2018. The rapid filling of reservoirs required the gates of 35 out of the 54 dams to be open simultaneously. Pramanick et al. (2022), using Sentinel 1 C and TRMM from the Indian Meteorological Department (IMD), found an unusual increase in rainfall during the monsoon of 2018 was the primary cause of flooding. The results showed that Kerala received 53 % more rainfall in August alone than it did from May 2018 to August 2018 when investigating the rainfall patterns and spatial and temporal variation in rainfall extents in Alappuzha Kottayam, Thrissur and Pathanamthitta. The study also demonstrated the benefits of using rainfall data with SAR in identifying flood risk extents. Similarly, Tiwari et al. (2020) used Sentinel-1 SAR VV polarisation to delineate flood extents, validated with Sentinel-2 optical imagery and CHIRPS rainfall data. SAR images were preprocessed to classify water and non-water areas, validated against rainfall patterns, and analysed temporal backscatter changes to identify flood events. Otsu's algorithm was used for flood delineation, which showed an increase in submerged areas, correlating with an observed positive trend in monsoon rainfall from 1981 to 2018 across Kerala. This approach also highlighted the effectiveness of integrating SAR data and rainfall trends in detecting and validating flood events, highlighting the role of temporal analysis in understanding flood processes within the region.

Vishnu et al. (2019) explored the interaction of geomorphological and anthropogenic activities utilising Sentinel-1A data to map the flood inundation on August 21 across the districts of Thrissur, Ernakulam, Alappuzha, Idukki, and Kottayam. The flood extent mapping was then analysed against a pre-flood, water-cover baseline derived from the Modified Normalised Difference Water Index (MNDWI), developed using Sentinel-2A imagery from January and February 2018. The study highlighted that while heavy rainfall was the primary driver of the 2018 floods, the geomorphology, particularly in low-lying areas like Kuttanad and the Kole lands, significantly influenced flood severity, with water levels rising to 5 m and 10 m, respectively. This is because the low-lying terrain In Kuttanad is below the mean sea level, contributing to its slower water level decline than Kole lands. This emphasises the role of geomorphological features, beyond meteorological factors, in shaping flood patterns in Kerala. Moreover, the findings acknowledge that anthropogenic activities such as wetland conversion and river channel mining have exacerbated the impact of extreme rainfall events on flooding. For instance, quantifying the percentage of wetland conversion to dry land would help understand how anthropogenic activities have impacted flood risk within the area. Vanama et al., (2021) used multi-temporal SAR (C-Band Sentinel-1A and 1B) and optical imagery (optical world view three images) to analyse the 2018 flood event, utilising change detection techniques like the Ratio Index (RI) and Normalized Change Index (NCI) to improve accuracy, especially where terrain is complex such as in Kerala. The results showed that NCI is the best methodology for change detection for Kerala floods. However, validation, as usual, faces challenges as manual surveys are used and rely on geotagged photographs; although this provides ground truth, the spatial coverage will not be continuous as, in some areas, photographs might be scarce. Additionally, the study assumes that the land surface conditions in the "pre-flood" images are uniform, which oversimplifies the land cover within the area. The results, however, indicate that the combined use of SAR images contributed to a better understanding of flood conditions, and pre-flood images helped minimise overestimation.

Unnithan et al. (2020) used a combination of GNSS-R signals from the Cyclone Global Navigation Satellite System (CYGNSS), which provides near-global, daily, pseudo-randomly distributed signal-to-noise ratio (SNR) point data and Heigh Above Nearest Drainage (HAND) for flood susceptibility mapping in the Periyar and Pamba river basins. The results indicated that the method accurately captured 45 % of the flooding during peak days. Significant overestimation errors were observed, mainly due to the coarse spatial resolution of GNSS-R data and the limitations of the DEM. Additionally, the model showed flooding accuracy ranging from 60 % to 80 %. This is not surprising, given that HAND models oversimplify the complex hydrodynamics of floodplains, including the influence of using vegetation, soil types, and microtopography. These factors can affect flood water movement, depth, and duration but are not directly considered in the HAND calculation. The model assumes that the closest drainage channel is the primary factor influencing flood risk. A study conducted by Joy et al. (2019) is unique as it combines the use of SAR with community engagement for FRA IN THE Meloor panchayat in Thrissur. FRA was conducted using STRM DEM GIS-based tools such as kriging and cost distance methods and post-flood surveys to identify inundated areas due to the lack of satellite images for peak hours of the flood. A combination of the approaches found that some regions were exposed to a flood height of 7.6 m, and 53 % of the area was inundated.

3.2. Predictive modelling based approaches

Modelling is an essential component in FRA and is significant because models can simulate the interactions between rainfall, land surface, and river systems to map flood risk areas. These models enable analysis of the spatial and temporal distribution of water, anticipate flood extents, and contribute to developing strategies for mitigating the impacts of flooding (Guo et al., 2021; Mignot et al., 2019; Unnithan et al., 2020b)

3.2.1. Hydrological modelling

Hydrological models such as the Soil and Water Assessment Tool (SWAT) have been used to study the Chaliyar Basin and the Thuthapuza River. Rohtash et al., (2018) used SWAT to simulate rainfall runoff in the Chaliyar Basin. The SWAT model discretised the 2013.4 km^2 basin into 15 sub-basins and 103 Hydrologic Response Units (HRUs). Meteorological inputs, including daily rainfall and temperature data, were used to drive the model. The findings showed varying rainfall trends across four stations from 1991 to 2011, with trends not statistically significant but displaying both increasing and decreasing patterns. The model efficiency, represented by an R^2 value of 0.69, indicated a satisfactory ability to estimate basin runoff. Additionally, using SWAT, Varughese (2020) modelled streamflow in the Thuthapuzha river basin. The calibration period for their study spanned from 1989 to 2009, with validation from 2010 to 2017. Sensitivity analysis was performed using the p-factor and r-factor, resulting in values of 0.77 and 0.64 during calibration and 0.85 and 0.56 during validation, respectively. The performance of the model was evaluated using the Nash-Sutcliffe Efficiency (NSE), coefficient of determination (R^2), and per cent bias (PBIAS), which showed values of 0.88, 0.88, and −1.4 for calibration, and 0.8, 0.8, and 5.4 for validation, respectively. These statistics indicate that the SWAT model successfully simulated streamflow in the Thuthapuzha watershed, demonstrating its efficacy for regional hydrological studies. Venkatesh et al. (2018) conducted a study using SWAT to model the hydrology of the Manimala River basin in Kerala with a catchment area of 780 km^2. The study focused on the rainfall-runoff relationship from 2000 to 2007, which was utilised to calibrate the model. The results indicated that surface runoff within the basin is primarily influenced by several key parameters such as the Curve Number (CN), the Soil Evaporation Compensation Factor (ESCO); and the Soil Available Water Capacity (SOL_AWC). In contrast, baseflow, the portion of streamflow sustained between precipitation events, was found to be influenced by the Groundwater Revaporation Coefficient (GW_REVAP), which controls the movement of water from the shallow aquifer back to the unsaturated zone and the Baseflow Alpha Factor (ALPHA_BF), which governs the rate at which groundwater is released to the stream. The calibration and validation of the SWAT model were supported by statistical measures such as the RMSE and the NSE, which suggested that the outputs were reliable and acceptable for the hydrological conditions of the Manimala River basin. This detailed analysis of the parameters influencing surface runoff and baseflow, along with the calibration using long-term data, demonstrates the effectiveness of the SWAT model in simulating the hydrological processes of the Manimala River basin.

The Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) was developed primarily to understand how rainfall transforms into runoff. The program excels at simulating direct runoff and flow routing using methods such as Kinematic Wave, Muskingum-Cunge, and Lag Routing. In Kerala, HEC-HMS has been used to model the impact of LULC on flooding within the Meenachil and Chalakudy River Basin. Athira et al. (2022) applied HEC-HMS for flood modelling in the Meenachil River sub-basin, Kerala, using DEMs, Landsat 8 imagery for LULC mapping, and soil data CN to simulate the rainfall-runoff process. The model performed satisfactorily, with NSE and R^2 values above 0.7, indicating a good fit between the observed and simulated discharge. The study identified CN, Initial Abstraction, and Lag Time as the most sensitive parameters influencing model accuracy. The research confirmed the applicability of HEC-HMS for FRA and management in the Meenachil River sub-basin.

The Chalakudy River Basin (1704 km^2), which includes the districts of Thrissur, Palakkad, and Ernakulum, was investigated by Parvathy and Thomas (2021). The basin experiences an annual rainfall ranging from 1800 mm to 3600 mm, with an average yearly streamflow of approximately 1630 mm. Utilising SRTM DEM, soil maps from the European Data Centre, and LULC maps derived from satellite imagery for 1995 and 2018, the research analysed changes over 23 years. Daily precipitation and discharge data were collected from rain gauge stations, and the Arangali gauging station was also used. The study identified a dramatic tenfold increase in urban areas; this urban expansion primarily replaced forests, plantations, and agricultural lands. Using HEC-HMS, it was found that the 2018 flood with the 1995 LULC scenario highlighted a potential 22.69 % reduction in peak discharge, emphasising the role of urbanization in increasing flood severity. This study goes beyond identifying LULC changes and assesses their tangible impact on flooding. For instance, the simulation of the 2018 flood using the 1995 LULC configuration provides a practical measure of the consequences of urbanization on flood risk. The modelling is, however, simplified, as some parameters are constant when simulating the 2018 flood with 1995 LULC. The annual LULC change rate assumes a uniform rate of change over the years, which does not accurately represent the actual rates. However, LULC change rates are often not uniform across the entire study period as they are influenced by various factors such as economic development, policy interventions, and population growth. These factors can cause fluctuations in the rate of LULC change over time. For instance, urbanization might accelerate in specific years due to increased economic development, while other periods might experience slower rates of change. Representing the temporal variation in LULC change rates would involve considering annual or at least decadal variations.

Lastly, Thakur et al. (2020) using HEC-HMS simulated flood flows across 12 major river basins within Kerala, using the Soil Conservation Service (SCS) method for estimating initial loss and runoff transformation, coupled with the Muskingum-Cunge method for channel routing. The findings showed the significant role of intense rainfall events in generating heavy surface runoff across the basins, worsened by clayey soil composition, steep slopes, and urbanised areas. Additionally, the findings showed that while reservoirs initially buffered the excess water, the continuous heavy precipitation eventually opened all significant dams, contributing to widespread flooding. LULC and topography had an impact, particularly in regions like the Vembanad Lake area, prone to severe inundation due to its low-elevation urbanised LULC patterns. Remote sensing was also used to provide accurate data-depth maps, showing the importance of combining the RS approach with predictive modelling tools for practical flood analysis to address challenges associated with data availability. To further enable FRA in data scare regions such as Kerala, Unnithan et al. (2024) developed a novel conceptual flood inundation model that integrates with any hydrological model to generate flood extent maps using the Dynamic Budyko hydrological model to generate runoff rasters in the Periya and Pambariver basins. This advantage of the conceptual model is that it can integrate with any hydrological model, even with regions with differences in data availability. However, it cannot be ignored that the model performance varies significantly with the resolution of the DEM, thus raising concerns regarding the reliability of the model when applied to regions with coarse-resolution data.

Hydrological models such as WRF-Hydro are less popular because they demand extensive data and computation resources. However, Dixit et al. (2022) investigate the relationship between LULC changes and hydrological response in Kerala using WRF-Hydro. The research identified trends in urbanization, deforestation, and afforestation by characterising the changes in LULC conditions from 1985 to 2018. The model was validated through 11 stations. The results showed significant LULC changes with urbanization and deforestation dominating during the late 20th century; this was countered with afforestation efforts by 2018. The discharge simulations exhibited minor changes from 1985 to 1995 but substantially increased from 1995 to 2005, with a slower increase from 2005 to 2018. This longitudinal study provides a holistic view of the LULC changes and their impact on the hydrological response of Kerala. However, the research relies on incomplete reservoir data, which introduces errors in the modelling, especially since reservoirs play an essential role in regulating water flow in Kerala. Inefficient reservoir and dam management are credited as one of the critical drivers of destruction during the 2018 Flood. Hence, physical process-based models have also been used to simulate various management scenarios and their potential impacts.

For instance, Ryan et al. (2020) used HEC-HMS and HEC-ResSim to investigate reservoir management strategies for flood control in the Pamba River basin. The study examined the reduction of peak outflows during flood events through three simulation scenarios.

1. long-run simulations (LRS) over a month of preparation,
2. short run simulations with one week of preparation,
3. immediate run simulations (IRS) representing the worst-case scenario with only one day for intervention.

The results showed that LRS is the optimal reservoir management strategy, which involved substituting the average 2014–2018 guide curve for the baseline 2018 curve, significantly reducing peak outflow to 50 m^3/s. Whereas, IRS, even with adjustments, the peak flow reduction was insignificant, indicating that utilising flood control zone and early release of flood storage significantly mitigates flood severity without compromising primary reservoir functions. The study also covers a wide geographical area; hence, the method can be applied to various reservoir types, sizes and locations. However, there is a need to address the potential risks associated with the outflow limits. For example, structural integrity, downstream impact, and the dam under different operational conditions were not within the scope of this study but still should be quantified. A sensitivity analysis of parameter changes such as rainfall, reservoir characteristics, and operational rules will also help reduce uncertainty.

3.2.2. Hydraulic models

Within the context of Kerala, a mix of modelling approaches (i.e., 1D and 2D) has been used with a noticeable emphasis on 1D hydraulic models. One-dimensional (1D) models, such as the MIKE HYDRO River, are primarily used to understand water flow within river channels. Anju et al. (2021)modelled the Pamba River using 1D modelling via MIKE HYDRO River software, developing essential modules for the river network, cross-sections, hydrodynamic parameters, and boundary conditions. The results achieved high accuracy in simulating water levels along the river. However, the inability of the model to predict downstream flooding raised concerns about its real-world applicability, where downstream reaches are often more susceptible to flooding. Reddy and Arunkumar (2023) coupled HEC-HMS and HEC-RAS for flood risk mapping in the Chaliyar Basin under future climate scenarios (SSP2-4.5 and SSP5-8.5), examining streamflow changes across three future periods. The results anticipated an overall increase in streamflow under both climate scenarios, with significant differences across time frames. The near future (2031–2040) and far future (2071–2080) periods showed higher streamflow under the SSP5-8.5 scenario, while the mid-future period (2051–2060) showed higher streamflow under the SSP2-4.5 scenario.

To understand the impact of urbanization and the role of the drainage system in flooding, Pradeep (2022) used MIKE+ to analyse the drainage network in Kollam. A hydraulic model for the A1 zone of Kollam representing the piped system was used to model flows for October 2021, 2031, and 2041. This study is among the first to address the role of key urban infrastructure, specifically the drainage system, in FRA within Kerala. Using a 1D model for flood simulation has inherent limitations, as they effectively simulate river flows and water levels along a single path. Similarly, Vijayachandran and Singh (2023) conducted an FRA for the Karamana region, for return periods rating 5-year to 500-year using a detailed linked 1D HEC-RAS model with high-resolution data (DEM of 1 m resolutions) to identify the highly vulnerable and the least affected areas.

1D models simplify river systems into one-dimensional flow paths, overlooking lateral movements and interactions between adjacent areas. Hence, these models might fail to accurately represent the inundation patterns in downstream regions, where the flow often becomes wider. Thus, the omission of lateral flows and topographical variations leads to an underestimation of flood extents, as observed in the study. To address the limitations of 1D models in capturing downstream flooding, the study could benefit from using 2D modelling approaches which consider both horizontal and vertical movements of water, allowing for a more complete representation of flood processes (Costabile and Macchione, 2015; Kourtis et al., 2017; Tayefi et al., 2007) Alternatively, a hybrid modelling approach links 1D and 2D elements to represent the modelling domain, combining the efficiency of 1D models in simulating river flows with the spatial accuracy of 2D models in representing flood extents. The methodology could be amended to apply 2D modelling to downstream areas or areas prone to lateral spreading.

Kumar et al. (2023) emphasise the value of 2D modelling in FRA investigated the 2018 floods in Kerala, focusing on the Periyar River Basin. They combined SWAT for hydrological modelling with the International River Interface Cooperative (IRIC) for hydrodynamic simulations. Calibration and validation of the SWAT model gauge discharge stations within the basin showed strong agreement with observed data, demonstrating the realibilty of the model in simulating streamflow. The iRIC model provided detailed flood maps closely matching observed flood extents, verified against field measurements and remote sensing data. The study highlighted the significant role of reservoir operations in influencing flood magnitudes and extents within the Periyar River Basin during the 2018 monsoon season. Additionally, Singh et al. (2022) the importance of reservoirs during the 2018 floods in Kerala by using an integrated hydrologic-hydrodynamic flood modelling framework using HEC-RAS, which includes HEC-HMS for hydrologic modelling, HEC-RESSIM for reservoir simulation and HEC-RAS for hydrodynamic flood routing. The study reconstructed seven historical extreme rainfall-runoff events from 2002 to 2018, focusing on the July-August 2018 flood. The finding indicated reservoir simulations helped attenuate flood peaks before releasing water downstream. The findings of this study showed that reservoir modelling should form a core part of FRA in districts of Kerala, where reservoirs greatly influence the discharge rates and flow during extreme events.

Anupriya et al. (2021) noted limitations associated with 2D modelling due to data insufficiency when modelling floods for the Karuvannur River. Using HEC-HMS and HEC-RAS for hydrological and hydrodynamic modelling, the results showed that peak flows reached 750–755 m^3/s during the 2018 flood events and suggested that constructing a levees would prevent future overtopping of the bands. This study conducted flood modelling and breach analysis of the Karuvannur River in Kerala, India following severe flooding in 2018. The researchers used HEC-HMS for hydrologic modelling and HEC-RAS for hydraulic modelling to analyse a 5.46 km stretch of the river where a breach occurred. They calibrated and validated the models using available discharge data, achieving coefficients of determination of 0.75–0.87 for HEC-HMS and 0.55–0.64 for HEC-RAS. The analysis found that peak flows reached 750–755 m^3/s during the flood event, with bed shear stresses of 38–100 N/m2. The river overtopped its banks at a curved section, where tangential forces from the curvilinear flow likely contributed to the scouring and breaching of the bank. Maximum water depths reached 13.5 m in the channel, with 1.5 m overtopping at the breach location. Based on the modelling results, the study proposes constructing a levee on the right bank, with a top elevation 16.5 m above the channel bottom, including 1.5 m of freeboard, to prevent future overtopping and flooding of adjacent low-lying areas. The authors specify limitations due to data insufficiency of discharge rates and model assumptions of uniform mannings, which affect the quality of the outputs; however, they still provide details into the flood mechanisms for the specified stretch of the river. Jacob et al. (2020) conducted a flood hazard assessment for the Bharathapuzha basin, combining Flood Frequency Analysis (FFA) and hydraulic modelling to estimate flood risks across varying return periods. They used hydrological data from nine gauging sites and a weir, covering annual peak flow data from 1978 to 2004. MIKE FLOOD, which integrates MIKE 11 (1D modelling) and MIKE 21 (2D modelling) to simulate flooding, was applied for 1–100-year return periods. This approach showed a maximum flood inundation area of 8740 ha, with some regions experiencing depths exceeding 2.5 m, indicating that agricultural lands and plantations were most susceptible to flooding. Modi et al. (2021) conducted a hydrodynamic analysis of the 2018 Kerala floods, focusing on the Kuttanad region, to assess the influence of oceanic conditions in exacerbating flood severity. By integrating data from buoy networks, tide gauges, and advanced wind-wave modelling, the study found a significant wave height anomaly off the Kerala coast in July 2018, attributed to powerful swell waves rather than local wind patterns. These swells cause wave setup and elevated nearshore water levels, intensifying the flooding impact. The analysis also pointed to the failure of the Thottappally spillway to effectively discharge floodwaters, further worsened by rising non-tidal sea levels. The findings highlight the importance of considering meteorological, oceanographic, and hydrological factors for a holistic approach to flood assessment that incorporates both inland and coastal processes to strengthen coastal resilience against flood events.

The downside of 2D modelling is its long run times; however, the Fast Flood Simulation (FFS) method developed by the University of Twente effectively addresses this issue. Applied to the Pamba River basin, FFS uses quick flow routing and flood estimations based on steady-state principles to predict peak flood heights. This approach departs from conventional dynamic flood modelling techniques, focusing on rapid computations over large areas. FFS explicitly addresses flooding from coastal sources, accounting for the interaction between inland water flow and coastal water levels, which is crucial for areas prone to both pluvial and coastal flooding. Unlike traditional 1D or 2D models, FFS offers rapid estimation across extensive regions. Glas (2023) investigated the practicality of FFS for flood risk assessment, demonstrating a significant improvement in simulation speed up to 1500 times faster than traditional models. Despite challenges like model sensitivity to grid cell size and data simplification uncertainties, the study confirms the effectiveness of FFS in predicting flood extents and assessing mitigation strategies. However, FFS is a-temporal and does not simulate the temporal progression of flood events, such as rising and receding water levels over time. It provides a quick, broad overview useful for planning and decision-making, where understanding the maximum possible impact is more critical than the exact timing or progression of a flood.

3.3. Analytical approaches

3.3.1. Statistical methods

Flood Frequency Analysis (FFA) helps comprehend the likelihood and magnitude of flooding in specific locations. It focuses on predicting the frequency and magnitude of floods over a certain period. Drissia et al. (2019) investigated flood frequency across Kerala using data from 43 gauging using a dual approach: site-specific analysis and regional flood frequency analysis (RFFA) to understand flood behaviours across the state. Using the Weibull method and L-moments, the study identified the Gumbel (GLO), Generalized Pareto (GPA), and Generalized Extreme Value (GEV) distributions as optimal for predicting flood frequencies, with GPA being particularly prevalent. A strong correlation was observed between predicted flood quantiles and actual gauge readings, especially for shorter return periods. For site-specific findings, the RFFA highlighted Log-Normal 3 (LN3) and Pearson Type III (PE3) as the best-fit distributions for broader regional assessment, indicating that flooding varies on different scales. The study developed index flood equations using 20 topographic features for ungauged areas, providing a new tool for estimating flood quantiles in regions without direct observational data. This framework combined detailed site and regional analysis, offering a comprehensive approach to FRA in Kerala.

However, while necessary for west-flowing rivers in this region, the findings may not apply in areas where hydrological behaviour differs. Mohan and Adarsh (2023) analysed streamflow trends across seventeen river gauge stations in Kerala using 25 years of daily discharge data from the Water Resource Information System (WRIS). The Mann-Kendall test was used for trend detection and L-moments for statistical analysis to assess spatial variations and identify trends in streamflow. Flood frequency was assessed using candidate probability distribution functions, including GEV. Additionally, validation was conducted using tests like Kolmogorov-Smirnov and Anderson-Darling. Both stationary (where the statistical properties of the method generating the time series do not change over time) and non-stationary models (where the statistical properties of the method generating the time series change over time) were developed, with the non-stationary models, including climate indices as covariates. The Akaike Information Criterion (AIC) found that non-stationary models, particularly the Malleswaram station (NSGEV14), which included climate indices, outperformed stationary models for hydrological modelling. This finding acknowledges the importance of climate variability and non-stationarity in improving the accuracy and resilience of hydrological modelling and flood risk management. Chithra et al. (2024) used two models, the bivariate relative frequency ratio (RFR) and multivariate logistic regression (L.R.), to examine the relationship between floods and their causative factors, ultimately identifying areas susceptible to flooding. The study found that 24.4 % and 23 % of the study area i.e., Kozhikode, Wayanad, and Malappuram are at very high to medium flood risk, particularly along the coast around Malappuram.

In two studies, copula models, a statistical approach that captures dependencies between variables, were used. Binoy et al. (2023) focused on FRA in Alappuzah, using Archimedean copulas to analyse the risks of water levels and rainfall, while Anandalekshmi et al. (2019) assessed the compounded impact of extreme rainfall and reservoir storage during the devastating Kerala flood of 2018. The findings from the study conducted by Binoy et al. (2023) showed that compound flood risks were quantified through joint return periods under two scenarios: considering high rainfall or water levels (TRS) and simultaneously (T′RS). The Clayton copula was identified as most suitable for Punnamada, while Gumbel–Hougaard was optimal for Cherthala and Arookutty. Significant areas within Alappuzha were highly susceptible to compound flooding, with notable areas like Punnamada, Cherthala, and Arookutty identified as particularly vulnerable based on specific water levels and rainfall thresholds. Anandalekshmi et al. (2019) investigated the concurrent impact of extreme rainfall and reservoir storage during the 2018 floods; the study found that reservoir levels were consistently above the mean, leading to spillage and significant flood damage. Using copula joint distribution functions, the study highlighted the efficacy of copulas in understanding the dependencies between rainfall and reservoir storage. However, the study highlights that the dams in Kerala are built primarily for hydroelectric power generation and irrigation, suggesting a reevaluation of dam management practices.

Both studies demonstrate copula models as a strong tool for studying the dependencies between various hydrological variables. Binoy et al. (2023) made significant contributions FRA in Alappuzha by using a copula approach to understand the relationship of multiple flood drivers. Their study highlighted the importance of considering flooding due to various factors, including high offshore water levels, streamflow, and energetic waves, which collectively influence the flood risk in the district.Anandalekshmi et al. (2019) provided a broader perspective on the systemic issues surrounding reservoir management during extreme weather events, urging a reconsideration of dam operation policies to mitigate future flood risks. These studies also advocate for assessments of the impacts of compound flooding events in Kerala.

Aju et al. (2024) studied the Kallada River Basin (KRB) in Kerala for flood vulnerability assessment and shelter suitability analysis. The method uses hierarchical cluster analysis, grouping sub-basins regarding flood vulnerability and GIS to identify shelter locations within Pathanamthitta and Kollam. The study found that over half of the sub-basins (51 %) were identified as vulnerable to flooding, 26 % were moderately susceptible, and the remaining (22 %) were not vulnerable to flooding. Within the former, two optimal locations for flood shelters were identified, clustering them based on similarity. This ensures effective emergency responses and community safety during flood events.

3.3.2. *Machine learning (ML)*

Within Kerala, studies have focused on using ML algorithms and hybrid approaches that combine these methods and modelling. Recent studies in Kerala have showcased significant advancements in flood forecasting and susceptibility mapping through ML algorithms. The development of Water Level Artificial Neural Networks (WANN) by Alexander et al. (2018) attempts to improve precision in forecasting flood events. These models, distinguished by their use of wavelet analysis to refine input signals, have demonstrated superior accuracy in predicting peak flood stages and timings, especially for short-term forecasts up to 3 hours ahead. Trained on data from 15 flood events spanning 2011–2015, WANN models outperform traditional ANN models, showing enhanced prediction accuracy for peak stages and timing. Furthermore, a study by Sundar and Kundapura (2023) on the Vembanad Lake System utilised five ML algorithms, including Recursive Feature Elimination, AdaBoost, Random Forest, Gradient Boosting Machines (GBM), and Extreme Gradient Boosting (XGBoost), to assess flood risk. Among these, XGBoost emerged as the most effective, highlighting the importance of feature selection in optimising ML model performance for flood risk prediction. In addition to risk assessment, ML algorithms have also been applied to flood susceptibility mapping. Saravanan et al. (2023) used five boosting algorithms for mapping in the Idukki district, finding that Stochastic Gradient Boosting (SGB) and Gradient Boosting Classifier (GBC) performed notably well, with an Area Under the Curve (AUC) of 92 %. This analysis identified areas near the Idukki Reservoir and Periyar Lake as high-risk zones.

However, the effectiveness of ML algorithms in flood mapping relies upon the optimal tuning of hyperparameters, a process that often involves extensive trial and error. This requirement challenges computational resources and expertise, highlighting a key obstacle in applying these advanced techniques in practical scenarios. Despite these challenges, using ML in flood management in Kerala represents a promising avenue for enhancing the accuracy and efficiency of flood risk assessments. Furthermore, Rajindas and Shashikala (2021) introduced a hybrid methodology that combines numerical modelling with Artificial Neural Networks (ANNs) to predict nearshore wave parameters along the coast of Kerala. This approach aimed to tackle the computational intensity of long-term wave climate analysis, using the capabilities of DELFT3D-WAVE for simulations and integrating high-resolution bathymetry and wind data validated against Wave Rider Buoy measurements. The model dramatically reduces the computational time for simulating wave activity for a year from hours to seconds, maintaining high accuracy levels. Additionally, it identified maximum significant wave heights (3.39 m) and predominant wave directions (southwest, west-southwest), providing details. This methodology streamlines the wave climate analysis process while reducing computation run times; however, it does not fully address how the ANN models might cope when considering the impact of changing coastal processes, such as changes in bathymetry and anthropogenic activities over a long period.

Studies have also investigated LULC analysis using ML and ANN techniques for instance by Vincent et al. (2023) found that AutoKeras is superior over TPOT (both are Python Automated Machine Learning tools), indicating a shift towards more effective automated machine learning (AutoML) tools for predictive modelling where the hyper-parameterisation and model configurations are tuned automatically. This study also highlights the enhanced accuracy of ML models, including Random Forest, XGBoost, and Gradient Boost, over convolutional neural networks (CNNs) in flood mapping, with Bayesian optimisation notably improving 3D-CNN performance. Jeslin and Sumam (2021) demonstrated the efficacy of genetic algorithms in reverse flood routing on the Chalakudy River, using Evolver 8.0 software to optimise model parameters and reduce mean absolute error (MAE). Based on the Pearson Type III distribution and continuity equation, this methodology generates upstream hydrographs, especially in regions without upstream gauging stations. However, the assumption of homogeneity in river conditions could oversimplify the real-world spatial and temporal

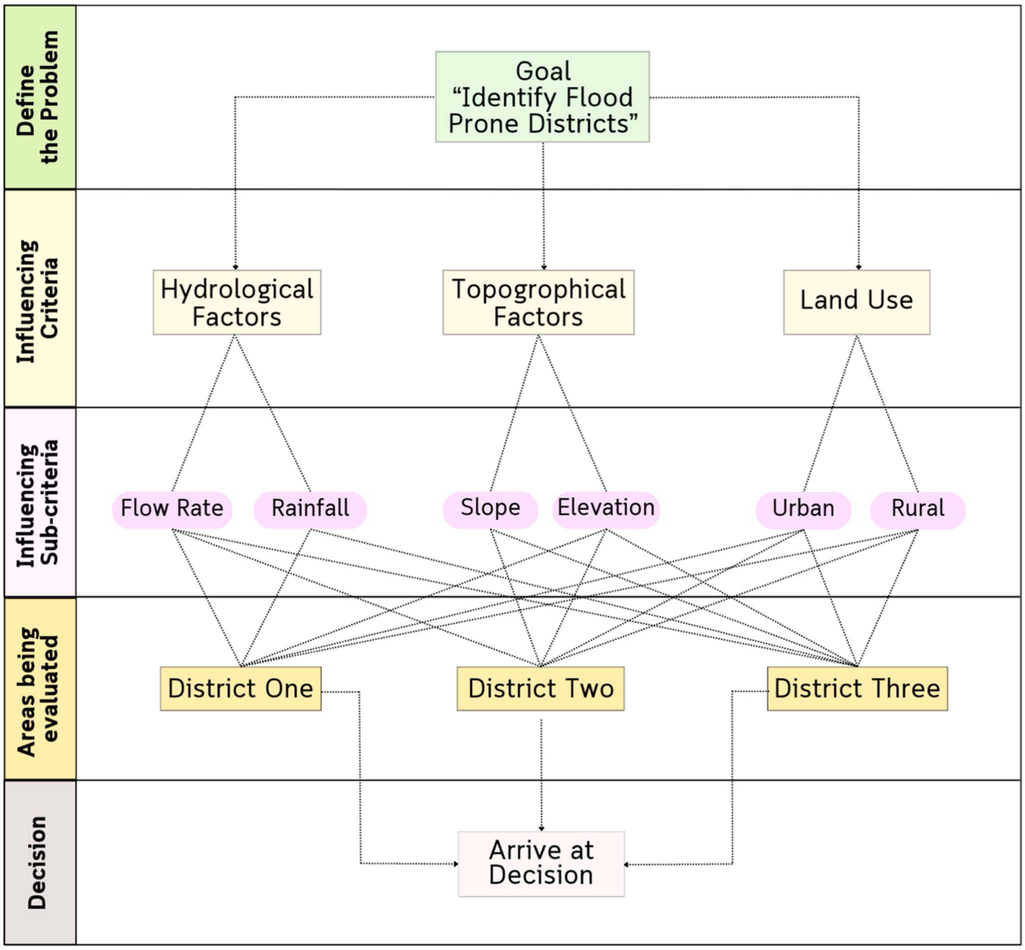


Fig. 4. Key steps of the Analysis Hierarchy Process (AHP) for flood risk assessment.

variability inherited from the real world. Lastly, Devi et al. (2022) explored LULC changes within the Kochi region over three decades, achieving an 80 % accuracy in LULC classification using the multilayer Perceptron (MLP) algorithm and the CA-Markov model. The study highlighted the need to incorporate LULC changes into flood risk models to predict future vulnerabilities amidst rapid urbanization better. The results projected significant shifts towards built-up land by 2100, indicating a critical examination of LULC transitions for improved flood risk assessment.

3.3.3. MCDM

MCDM, particularly the Analytical hierarchy process (AHP), is a standard methodology for assessing and managing Kerala flood risk. Dwivedi et al. (2023) assessed coastal and social vulnerability in Tamil Nadu and Kerala using AHP. The study integrated physical and social parameters—ranging from geomorphology and wave height to population density, to reveal that Kerala is highly susceptible to rising sea levels. The assessment and categorisation of various coastal regions into vulnerability classes highlighted the capacity of AHP to synthesise complex, multi-dimensional data. Regions like Malappuram and Kollam were identified as key districts for future mitigation strategies, highlighting ways the method can be utilised to pinpoint areas of high vulnerability. The findings quantified that 2 % of the coast of Kerala is highly physically vulnerable, and 30 % of the coast is highly socially vulnerable to the impacts of coastal flooding. Fig. 4

Parallel to the coastal assessment, Khan and Jhamnani (2023) explored flood susceptibility in the Idukki district using a GIS-based AHP model. The study identified high-risk flood zones by analysing hydrological, topographical, and geomorphological parameters and prioritised the factors influencing flood susceptibility. Using the AHP model, accurate flood susceptibility maps were produced and classified into five categories: shallow, low, moderate, high, and very high. The mapping showed that over 30 % of the Idukki region was identified as high and very high flood susceptible zones. Furthermore, sensitivity analyses indicated that rainfall, elevation, distance from the river, slope and TWI were the most flooding in Idukki. In contrast, aspect, geology, LULC and soil were identified as less important parameters. Additionally, Naga Kumar et al. (2022) extend the application of MCDM to the coastal vulnerability assessment in Kozhikode district using AHP and GIS. Five key physical variables – geomorphology, coastal slope, shoreline change, mean springtide range and significant wave height were analysed to compute a Coastal Vulnerability Index (CVI). The study used various classification methods in ArcGIS to categorise the CVI values into risk levels; these are Quantile, Equal Interval, Geometric Interval, and Standard Deviation. Geometric Interval classification aligns most with the observed shoreline changes. The results categorise the Kozhikode coast into three risk levels: low, moderate, and high. Approximately 29 % of the coast is identified as high risk, with most of this segment comprising low-lying estuarine and sandy beach areas.

While these studies collectively show the ability of AHP and MCDM methods in flood risk assessment, they have inherent limitations. AHP relies on expert judgment, which introduces potential biases, especially in contexts where quantitative data is scarce. This caveat, coupled with the static nature of AHP and its simplified representation of dynamic flood processes, calls for an integrative approach that combines MCDM with other analytical tools to capture the complexities associated with flooding and provides a very simplified representation of flood processes. The methodology also lacks details on the spatial and temporal resolution of the data used. For instance, FRA commonly uses DEMs, which vary in resolution; for studies within Kerala, DEM resolution varies between 30 m to 90. This coarse resolution fails to capture fine topographic detail. Additionally, flood events are dynamic and evolve, but MCDM approaches use static data layers that do not account for the temporal variations in factors such as rainfall.

4. Discussion

The 47 studies reviewed in this paper were published after the 2018 floods in Kerala. Of the 47 studies, only four mapped the whole state, while the rest focused on detailed technical analysis of a single or a group of basins or districts. However, extreme events and the most severe incidents are known to extend over multiple states or regions; hence, to grasp the full scope of the hazards posed by flooding events, whether urban, riverine or coastal, should evaluate the entire affected zone, i.e., the state. For instance, in 2019, Cyclone Idai caused flooding across Mozambique, Zimbabwe, and Malawi (Mutasa, 2022; Tevera et al., 2021). Moreover, end users of flood maps, such as floodplain managers, are tasked with evaluating asset resilience on a large scale. Therefore, large-scale models can address risks across expansive areas without requiring highly granular and data-heavy models.

Nonetheless, it is likely, and specified in several studies reviewed as a limitation, that high-resolution spatial data is unavailable, with most DEMs ranging between 30 m and 90 m. RS-based approaches, especially SAR, appear to be the most common methodology used for FRA in Kerala. However, the limitations of using SAR in mountainous terrain are seldom discussed in the examined literature. For example, in areas where the terrain is steep, slopes can appear compressed due to foreshortening, affecting the representation of slope in SAR imagery (Amitrano et al., 2024; Giustarini et al., 2016). Additionally, signal scattering is also an issue in mountainous terrain, as the angle of incidence between the radar signal and the surface features can result in scenarios where the signal is reflected away from the sensor or where the signal is scattered in multiple directions (Lu et al., 2013).

The predictive modelling methods presented highlight the use of hydrological and coupled hydrological-hydraulic models. However, 2D and rain-on-grid (RoG) modelling techniques have not been extensively explored for FRA in Kerala, despite rainfall being identified as the primary driver of flood risk in 2018. The potential impact of not exploring these techniques in Kerala, such as inaccurate flood risk assessments, highlights the need for their adoption despite resource constraints. These techniques require significant computational resources, specialised software, and technical expertise, and rely on high-resolution data inputs, which are often lacking. However, without the use of advanced modeling techniques, flood risk assessments may be based on oversimplified methodologies, leading to underestimation or misrepresentation of flood hazards. This misrepresentation of hazards can result in inadequate preparedness and response measures, leaving communities vulnerable to catastrophic flooding.

The overview of various analysis approaches used in Kerala focuses on FRA through statistical, geostatistical, ML, and MCDM techniques. The heavy reliance of the reviewed studies on statistical models and the recent uptake of ML methodologies rarely address their inability to model future scenarios. This limitation underscores the need for advanced modeling techniques that can account for future changes, as statistical models struggle to predict rare extreme events accurately due to limited historical data. The recent update in the use of ML methods highlights the capacity to parse vast datasets and patterns that traditional models overlook. However, this reliance on historical data and expert judgment in methods like MCDM highlights a challenge, i.e. the stochastic nature of weather and anthropogenic impacts on the environment, which introduces uncertainty (Vassoney et al., 2021). Moreover, while quantitative methods such as FFA and the application of copula models provide understanding of (FRA), they are limited by the quality and extent of available data. The adoption of MCDM, particularly AHP, shows an effort to integrate expert opinions with data analysis to validate data using ground truth and local knowledge, but they are static in nature. For instance, flood events are dynamic and evolve, but MCDM approaches use static data layers that do not account for the temporal variations in factors such as rainfall(De Brito and Evers, 2016; Mabrouk and Haoying, 2023).

A key point to address is that FRA benefits when multiple methodologies are integrated, as each approach brings strengths, studies reviewed within the section of predictive modelling based approaches use a combination of methods particularly the combination of remote sensing and hydrological/hydraulic modelling methods. Predictive modelling approaches commonly use LiDAR which generates a Digital Elevation Model essential for modelling. To further this approach of synergising between methods identified within the review, analytical approaches can be used to process large remote sensing data sets to identify patterns such as flood prone areas. Additionally, to support decision making analytical methods can also be used to optimise flood mitigation strategies through optioneering of different cost benefit analysis. Integrating these methods involves a systematic workflow where for example real-time satellite imagery is used for monitoring of spatial overlaps of flood drivers, such as simultaneous precipitation and storm surges and predictive, modelling is used to simulate cascading flood events.

This review acknowledges the potential for selection bias, given the focus on post-2018 studies and excluding non-English language research. Additionally, the evolving nature of flood risk research may have led to the omission of the most current studies that are still in publication at the time of this review.

4.1. Research gaps and future directions

4.1.1. FRA without mitigation

The FRA studies summarised in this review in Kerala have used advanced statistical and ML learning methods to quantify flood risk in Kerala. These studies have been instrumental in highlighting the increasing frequency and intensity of flooding events; however, despite the results generated within these studies, the translation of these findings into specific, localized mitigation actions remains limited.

This gap is characterised by (i) Lack of actionable recommendations for local government and communities regarding specific flood mitigation measures (ii) Insufficient integration of stakeholders across various governance levels in Kerala, resulting in fragmented efforts and a lack of cohesive coordination in flood management and (iii) absence of a clear pathway for incorporating research findings into policy-making and urban/rural planning processes, limiting the translation of research into actionable policies for flood mitigation.

A deficient proportion i.e., five out of the 47 examined studies, provide actionably mitigation strategies based on the findings of their research (Ajin et al., 2019; Aju et al., 2024; Anupriya et al., 2021; Glas, 2023; Vijayachandran and Singh, 2023). This shows a strong bias in research towards using complex risk assessment methods rather than solution-orientated approaches. While sophisticated methods for FRA are crucial and demonstrate scientific rigour, there is a need for more research that bridges the gap between utilising difficult science to quantify risk and translating those findings into actionable strategies. In addition, only 3 out of 44 papers examined the vulnerability associated with the flood risk to physical structures and people. This finding shows that research on FRA in Kerala overlooks an essential component of the disaster risk equation. This oversight also contributed to the lack of actionable recommendations. The low number of papers addressing mitigation and vulnerability suggests a lack of interdisciplinary collaboration where engineering methodologies integrate with social sciences and environmental studies.

4.1.2. Urban flooding and improved urban planning

The issues of increase in urbanization and urban flooding have been frequently featured in the preset studies, especially in cities like Kochi, Thiruvananthapuram, Kozhikode, and Alappuzha. These cities, characterised by their rapid urban expansion, have experienced increased surface runoff and inadequate drainage, exacerbating flood risks. The 2018 floods in Kerala highlighted these vulnerabilities, showing extensive damage from insufficient urban planning and flood management infrastructures. Despite the evident risk, minimal effort is made to understand urban flooding in Kerala, with studies focusing primarily on riverine or coastal flooding. The scarcity of research on urban flooding in Kerala is highlighted because only three out of the 44 reviewed studies directly addressed the quantification of risk to urban infrastructure such as buildings, schools and roads. The lack of studies quantifying these risks to infrastructure is potentially because policymakers and urban planners lack crucial data for informed decision-making on urban development and protection.

This lack of data is evident as only 1 study directly models a critical urban infrastructure, i.e., the piped drainage system, which is critical to managing flood risk (Pradeep, 2022). The vision of transforming Kochi into one of the first sponge cities in India represents a forward-thinking approach; however, the general lack of data for many key infrastructures poses a major hurdle to realising this vision., there is a significant gap in knowledge regarding its urban drainage system (Gupta, 2020). For instance, converting paddy fields and water bodies has caused surface drainage problems in urban areas. However, the lack of drainage or the poor condition of drainage systems in modelling studies is barely acknowledged (Hussain, 2020). Regular flooding in the lower areas and around the backwaters is due to inadequate discharge capacity and blockages of drains at sea outlets. It occurs in the low areas around the backwaters and lower river reaches, a process not represented in the RS, modelling, and AI studies.

It is also reported that most cities have improper sewer systems (mostly clogged), and areas with no sewage system discharge into the nearest open stormwater drains. For instance, Kochi's Sewerage system consists of a sewer network of around 28 km covering a meagre 5 % of the city area. Inadequate sewer systems often overlap with poor stormwater management, where the capacity to manage rainfall events is compromised (Kerala Water Authority, 2022; Trivandrum City Corporation, 2015). This situation increases surface runoff, exacerbating flood risks, especially during heavy rainfall. Discharging sewage into stormwater drains can lead to blockages due to solid waste and sludge accumulation. These blockages reduce the efficiency of drainage systems, further increasing the risk of urban flooding. Another problem for urban flood risk modelling is the enormous obstacle of the lack of data associated with drainage systems. Additionally, although the IMD recently made data from rain gauges available, the temporal resolution of the data is too coarse for urban areas where the concentration time is much finer.

Focusing on the collection and representation of drainage networks in future work is essential, particularly in urban areas with prevalent flooding and water management issues. This is important for accurately predicting flood risks and developing effective and sustainable urban drainage systems. Sustainable urban planning is becoming increasingly important as cities continue to expand and face challenges related to climate change and increased rainfall intensity. Information regarding the drainage system provides essential data that can inform the design of green infrastructure and sustainable urban drainage systems (SUDS) components.

4.1.3. Understanding compound extreme events in Kerala

Compound extreme events, which can occur simultaneously or sequentially, pose a significant threat. These can include consecutive floods in the same area or a combination of extreme events such as a heat wave coinciding with a drought or droughts followed by flash floods. Compound events create impacts greater than the sum of their individual effects and can span multiple areas within a country. In recent years, there has been an increase in the number of such events in Kerala. For instance, in 2024, Kerala experienced a severe drought from March to May, followed by severe flash floods, leading to landslides in several districts.

In recent years, there has been an increase in the number of such events in Kerala, for instance, in 2024, Kerala experienced a severe drought from March to May, followed by severe flash floods in several districts. While significant research has been conducted on individual extreme events such as floods, droughts, and landslides, there is a gap in the study of compound extreme events in Kerala. The 2018 floods in Kerala emphasise the catastrophic potential of compound flooding caused by heavy rainfall, high river discharge, sea level rise, poor land use planning, and inept dam operation. This event combined riverine and coastal flooding, leading to extensive damage. The monsoon brought record-breaking rainfall and overflowing rivers (Turner and Annamalai, 2012; Vijaykumar et al., 2021), with storm surges along the coast exacerbating flooding in urban areas. Coastal cities like Kochi are particularly vulnerable to compound flooding due to their location and inadequate drainage infrastructure. These areas face threats from riverine floods triggered by upstream rainfall and coastal surges (Begmohammadi et al., 2024; Binoy et al., 2023).

The 2018 Kerala floods highlighted the impact of sub-optimal reservoir management practices on flood severity. Rapid water releases from overflowing reservoirs amplified the intensity of downstream flooding, stressing the importance of considering human interventions in natural systems when assessing flood risks. Research into these interactions—specifically, how reservoir operations interact with extreme rainfall and existing hydrological conditions—is crucial for developing strategies to mitigate the risks posed by such compound extreme events, enhancing the resilience of vulnerable communities in Kerala.

Although these are evident risks and increasing frequency of compound extreme events, only three studies have focused on addressing compound risk in Kerala (Anandalekshmi et al., 2019; Ramasamy et al., 2019; Ryan et al., 2020). Addressing this gap in compounded extremes requires models that simulate the interactions between multiple hazards, in-depth case studies of past compound events, and assessments of the cascading effects across different sectors. Additionally, innovative approaches to urban planning and infrastructure development that enhance resilience to compound events and evaluate current disaster preparedness strategies in this context are essential. To address the complexity of compound events several frameworks have been developed such as the IPCC Compound Risk Framework, and the Sendai framework for Disaster risk reductions (Simpson et al., 2023, 2021; UNDRR, 2015). The application of such frameworks expliclity for key contributorss of flooding in Kerala, would inform and create strategies that are tailored to the requirements of the region.

4.1.4. Climate change and flood risk projections in Kerala

Climate change will alter monsoon patterns in South Asia, with implications for increased rainfall intensity and distribution (Turner and Annamalai, 2012). Kerala will see an increase in the frequency and intensity of heavy rainfall events during the monsoon, leading to more severe and unpredictable flooding. According to the Intergovernmental Panel on Climate Change report, the sea level in Kochi will rise by 11 cm by 2030 and 23 cm by 2050 (Calvin et al., 2023; Sreelakshmi et al., 2024). However, despite literature reporting on the impact of climate change on hydrological extremes in Kerala, only four studies included the climate change projects and the effects of climate change in their FRA (Glas, 2023; Mohan and Adarsh, 2023; Reddy and Arunkumar, 2023; Sundar and Kundapura, 2023). An in-depth analysis of future climate scenarios, using climate models and rainfall projection data, is essential to understand the changes and their potential impacts on flood patterns in Kerala. Several flood risk and climate change-related policies and initiatives, such as the Kerala State Action Plan on Climate Change (SAPCC) and Floodplain Zoning Regulations, have all been introduced to reduce the impact of flooding and increase in extreme events within Kerala. While the Kerala State Action Plan on Climate Change (SAPCC) outlines adaptation measures to combat flooding due to climate change, a gap exists in mainstreaming climate resilience into development planning and infrastructure projects.

For instance, in countries such as the UK, Canada, and New Zealand, climate change impact assessments are mandatory part of FRA for obtaining planning permission for new developments ensuring that the potential impacts of climate change, such as increased flooding risk, are considered in the planning and design stages of new infrastructure (Dessai et al., 2022; Doelle and Sinclair, 2019; Memon and Gleeson, 1995). Kerala could introduce similar regulations requiring climate change impact assessments for all new infrastructure projects to ensure that developments are resilient to future flood risks and other climate-related impacts.

5. Conclusions

The studies presented within this review through the use of remote sensing, predictive modelling and analytical approaches indicate that heavy rains during August cause significant surface runoff in the major river basins of Kerala. Initially, the dams acted as a buffer for excess water, but due to the subsequent heavy rainfall, the capacities of the dams were overwhelmed, making it necessary to release the water, worsening flooding downstream. However, other contributing factors include the low elevation of certain areas, the limited design capacity of spillways, and land use changes from wetlands to agriculture and human settlements.

The analysis of the reviewed literature identified three key thematic areas used for FRA in Kerala, i.e., remote sensing, predictive modelling and analytical approaches. However, remote sensing studies, particularly SAR, seldom addressed the limitations of its applications in mountainous terrains. The reliance on basic modelling techniques demonstrates the need for more sophisticated approaches, such as two-dimensional (2D) hydrodynamic and rain-on-grid models, especially in scenarios where the flood risk is attributed to heavy rainfall. Setting the 2018 Kerala floods as a separation point allowed this review to focus on the most current and contextually relevant FRA studies, providing a clear picture of the gaps that may still exist. Although Kerala has suffered from flooding year after year, the vulnerability posed to local communities and infrastructure, even with advances in methodologies and technologies, has not diminished or reduced the risk posed by flood hazards. From the lens of the studies reviewed within this paper, significant effort is made to use and progress methodologies that heavily showcase the complex mathematics to derive outputs and showcase new developments. However, the gaps identified are more related to applying the findings to a wider context that demonstrates the capabilities of the identified FRA methods and findings to actually defend, mitigate, and aid in building resilience for flood risk. To address these challenges, efforts should happen in parallel across multiple fronts, specifically in the following areas:

- The lack of recommendations that translate the FRA findings into policy-making and urban planning is insufficient.
- While urban flooding is consistently acknowledged, data and studies that investigate urban flooding are few.
- Failure to address the catastrophic potential of compound flooding, where multiple sources of flooding converge. Currently, these risks are treated in isolation, missing the cumulative impacts.
- Despite policies like the Kerala SAPCC, integrating climate resilience into development planning is limited in flood risk assessment-related research.

In summary, addressing the identified gaps in flood risk assessment is crucial for enhancing resilience to the growing threat of flooding in Kerala. Once we establish the connection between using complex methods, generating outputs that are applicable and feasible, it becomes essential to place communities at the centre of this process.

CRediT authorship contribution statement

Wright Nigel: Writing – review & editing, Supervision. **Pregnolato Maria:** Writing – review & editing, Writing – original draft. **Debdut Sengupta:** Visualization. **Sreeparvathy Vijay:** Writing – review & editing, Writing – original draft. **Singh Amrie:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2025.102262.

Data availability

Data will be made available on request.

References

Abe, G., Erinjery Joseph, J., 2015. Changes in streamflow regime due to anthropogenic regulations in the humid tropical Western Ghats, Kerala State, India. J. Mt Sci. 12, 456–470.

Ajin, R.S., Loghin, A.-M., Vinod, P.G., Jacob, M.K., 2019. Flood hazard zone mapping in the tropical Achankovil river basin in Kerala: a study using remote sensing data and geographic information system. J. Wetl. Biodiv 9, 45–58.

Aju, C.D., Achu, A.L., Prakash, P., Raicy, M.C., Reghunath, R., 2024. An integrated statistical-geospatial approach for the delineation of flood-vulnerable sub-basins and identification of suitable areas for flood shelters in a tropical river basin, Kerala. Geosystems Geoenvironment 3, 100251.

Alexander, A.A., Thampi, S.G., Chithra, N.R., 2018. Development of hybrid wavelet-ANN model for hourly flood stage forecasting. ISH J. Hydraul. Eng. 24, 266–274. https://doi.org/10.1080/09715010.2017.1422192.

Amitrano, D., Di Martino, G., Di Simone, A., Imperatore, P., 2024. Flood detection with SAR: a review of techniques and datasets. Remote Sens. https://doi.org/10.3390/rs16040656.

Amitrano, D., Di Martino, G., Iodice, A., Riccio, D., Ruello, G., 2018. Unsupervised rapid flood mapping using sentinel-1 GRD SAR images. IEEE Trans. Geosci. Remote Sens. 56, 3290–3299. https://doi.org/10.1109/TGRS.2018.2797536.

Anandalekshmi, A., Panicker, S.T., Adarsh, S., Muhammed Siddik, A., Aloysius, S., Mehjabin, M., 2019. Modeling the concurrent impact of extreme rainfall and reservoir storage on Kerala floods 2018: a Copula approach. Model Earth Syst. Environ. 5, 1283–1296. https://doi.org/10.1007/s40808-019-00635-6.

Anju, B., Drissia, T.K., Nowshaja, P.T., 2021. One dimensional hydrodynamic modelling of pamba river for identifying the flood vulnerability. IOP Conference Series: Materials Science and Engineering. IOP Publishing, 012023.

Anupriya, A., Reeba, T., Anoop, R., 2021. Flood modelling and breach analysis of karuvannur river in kerala state. IOP Conf. Ser. Mater. Sci. Eng. 1114, 012027. https://doi.org/10.1088/1757-899x/1114/1/012027.

Aruldoss, M., Lakshmi, T.M., Venkatesan, V.P., 2013. A survey on multi criteria decision making methods and its applications. Am. J. Inf. Syst. 1, 31–43.

Athira, S., Katpatal, Y.B., Londhe, D.S., 2022. Flood modelling and inundation mapping of Meenachil River using HEC-RAS and HEC-HMS software. International Conference on Climate Change and Ocean Renewable Energy. Springer, pp. 113–130.

Begmohammadi, A., Wirasaet, D., Lin, N., Dietrich, J.C., Bolster, D., Kennedy, A.B., 2024. Subgrid modeling for compound flooding in coastal systems. Coast. Eng. J. https://doi.org/10.1080/21664250.2024.2373482.

Binoy, S., Jyoma, J.P., Adarsh, S., Siddik, A.M., Nourani, V., Alisha, A., Sreeshma, T., 2023. Flood risk analysis and mapping under compound hazards: a copula approach for tropical coastal district of Alappuzha, India. J. Hydro Environ. Res. 46, 60–71.

Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P. W., Trisos, C., … Hauser, M., 2023. Lee, H., Romero, J. (Eds.), IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team. IPCC, Geneva, Switzerland.

Ceballos, B., Lamata, M.T., Pelta, D.A., 2016. A comparative analysis of multi-criteria decision-making methods. Prog. Artif. Intell. 5, 315–322.

Chen, J., Shi, X., Gu, L., Wu, G., Su, T., Wang, H.M., Kim, J.S., Zhang, L., Xiong, L., 2023. Impacts of climate warming on global floods and their implication to current flood defense standards. J. Hydrol. (Amst.) 618. https://doi.org/10.1016/j.jhydrol.2023.129236.

Chithra, K., Binoy, B.V., Bimal, P., 2022. Spatial mapping of the flood-affected regions of northern Kerala: a case study of 2018 Kerala Floods. J. Indian Soc. Remote Sens. 50, 677–688. https://doi.org/10.1007/s12524-021-01485-5.

Chithra, K., Binoy, B.V., Bimal, P., 2024. Modeling flood susceptibility on the onset of the Kerala floods of 2018. Environ. Earth Sci. 83. https://doi.org/10.1007/s12665-023-11412-1.

Costabile, P., Macchione, F., 2015. Enhancing river model set-up for 2-D dynamic flood modelling. Environ. Model. Softw. 67, 89–107. https://doi.org/10.1016/j.envsoft.2015.01.009.

De Brito, M.M., Evers, M., 2016. Multi-criteria decision-making for flood risk management: A survey of the current state of the art. Nat. Hazards Earth Syst. Sci. 16, 1019–1033. https://doi.org/10.5194/nhess-16-1019-2016.

Dessai, S., Fowler, H.J., Hall, J.W., Mitchell, D.M., 2022. UK climate risk assessment and management. Clim. Risk Manag 37, 100440.

Devi, A.B., Deka, D., Aneesh, T.D., Srinivas, R., Nair, A.M., 2022. Predictive modelling of land use land cover dynamics for a tropical coastal urban city in Kerala, India. Arab. J. Geosci. 15. https://doi.org/10.1007/s12517-022-09735-7.

Dhanabalan, S.P., Abdul Rahaman, S., Jegankumar, R., 2021. Flood monitoring using Sentinel-1 sar data: A case study based on an event of 2018 and 2019 Southern part of Kerala. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. 44 37–41.

Dhiman, R., VishnuRadhan, R., Eldho, T.I., Inamdar, A., 2019. Flood risk and adaptation in Indian coastal cities: recent scenarios. Appl. Water Sci. https://doi.org/10.1007/s13201-018-0881-9.

Dixit, A., Sahany, S., Rajagopalan, B., Choubey, S., 2022. Role of changing land use and land cover (LULC) on the 2018 megafloods over Kerala, India. Clim. Res 89, 1–14.

Doelle, M., Sinclair, A.J., 2019. The new IAA in Canada: from revolutionary thoughts to reality. Environ. Impact Assess. Rev. 79, 106292.

Drissia, T.K., Jothiprakash, V., Anitha, A.B., 2019a. Flood frequency analysis using L moments: a comparison between at-site and regional approach. Water Resour. Manag. 33, 1013–1037.

Drissia, T.K., Jothiprakash, V., Anitha, A.B., 2019b. Statistical classification of streamflow based on flow variability in west flowing rivers of Kerala, India. Theor. Appl. Clim. 137, 1643–1658.

Dwivedi, C.S., Pampattiwar, S.T., Pandey, A.C., Parida, B.R., Mitra, D., Kumar, N., 2023. Characterization of the coastal vulnerability in different geological settings: a comparative study on Kerala and Tamil Nadu Coasts Using FuzzyAHP. Sustainability 15. https://doi.org/10.3390/su15129543.

Dykstra, S.L., Dzwonkowski, B., 2020. The propagation of fluvial flood waves through a backwater-estuarine environment. Water Resour. Res. 56. https://doi.org/10.1029/2019WR025743.

Eslaminezhad, S.A., Eftekhari, M., Mahmoodizadeh, S., Akbari, M., Haji Elyasi, A., 2021. Evaluation of tree-based artificial intelligence models to predict flood risk using GIS. Iran. -Water Resour. Res. 17, 174–189.

Giustarini, L., Hostache, R., Kavetski, D., Chini, M., Corato, G., Schlaffer, S., Matgen, P., 2016. Probabilistic flood mapping using synthetic aperture radar data. IEEE Trans. Geosci. Remote Sens. 54, 6958–6969. https://doi.org/10.1109/TGRS.2016.2592951.

Glas, V., 2023. Application of the FAST Flood Simulation Model for Local Risk-informed Decision-making on Flood Risk Reduction - A Case Study of Pamba Basin. University of Twent, Kerala, India.

Guo, K., Guan, M., Yu, D., 2021. Urban surface water flood modelling-a comprehensive review of current models and future challenges. Hydrol. Earth Syst. Sci. https://doi.org/10.5194/hess-25-2843-2021.

Gupta, K., 2020. Challenges in developing urban flood resilience in India. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 378. https://doi.org/10.1098/rsta.2019.0211.

Hill, B., Liang, Q., Bosher, L., Chen, H., Nicholson, A., 2023. A systematic review of natural flood management modelling: approaches, limitations, and potential solutions. J. Flood Risk Manag. https://doi.org/10.1111/jfr3.12899.

Hoq, M.S., Raha, S.K., Hossain, M.I., 2021. Livelihood vulnerability to flood hazard: understanding from the flood-prone haor ecosystem of Bangladesh. Environ. Manag. 67, 532–552. https://doi.org/10.1007/s00267-021-01441-6.

Hunt, K.M.R., Menon, A., 2020. The 2018 Kerala floods: a climate change perspective. Clim. Dyn. 54, 2433–2446. https://doi.org/10.1007/s00382-020-05123-7.

Hussain, S., 2020. Planning challenges and implications of sponge city concept in managing urban Floods in Kerala. Int. J. Res. Eng. Sci. ISSN 8, 29–35.

Indian Meteorological Department, 2023. Administrative Profile: Climate Status of Environment related issues: Kerala ENVIS Centre, Ministry of Environment and Forests, Govt. of India [WWW Document]. URL ⟨http://kerenvis.nic.in/Database/CLIMATE_829.aspx⟩ (Accessed 8.1.24).

Jacinth Jennifer, J., Saravanan, S., Abijith, D., 2022. Integration of SAR and multi-spectral imagery in flood inundation mapping–a case study on Kerala floods 2018. ISH J. Hydraul. Eng. 28, 480–490.

Jacob, X.K., Bisht, D.S., Chatterjee, C., Raghuwanshi, N.S., 2020. Hydrodynamic modeling for flood hazard assessment in a data scarce region: a case study of Bharathapuzha River Basin. Environ. Model. Assess. 25, 97–114.

Jeslin, A.J., Sumam, K.S., 2021. Upstream flood hydrograph prediction of Chalakkudy River. IOP Conference Series: Materials Science and Engineering. IOP Publishing, 012030.

Jha, M.K., Afreen, S., 2020. Flooding urban landscapes: analysis using combined hydrodynamic and hydrologic modeling approaches. Water 12. https://doi.org/10.3390/w12071986.

Jodhani, K.H., Patel, D., Madhavan, N., 2023. A review on analysis of flood modelling using different numerical models. Mater. Today Proc. 80, 3867–3876. https://doi.org/10.1016/j.matpr.2021.07.405.

Jones, A., Kuehnert, J., Fraccaro, P., Meuriot, O., Ishikawa, T., Edwards, B., Stoyanov, N., Remy, S.L., Weldemariam, K., Assefa, S., 2023. AI for climate impacts: applications in flood risk. NPJ Clim. Atmos. Sci. 6, 63.

Joy, J., Kanga, S., Singh, S.K., 2019. Kerala Flood 2018: flood mapping by participatory GIS approach, Meloor Panchayat. Int. J. Emerg. Technol. 10, 197–205.

Kerala Water Authority, 2022. Comprehensive sewerage system in Kochi Corporation-DPR for construction of 5 MLD STP. Netw. Allied Compon. Elamkulam Amrut 2, 0.

Khan, Z.A., Jhamnani, B., 2023. Development of flood susceptibility map using a GIS-based AHP approach: a novel case study on Idukki district, India. J. Spat. Sci. 1–34.

Kourtis, M.I., Bellos, V., Tsihrintzis, V.A., 2017. Comparison of 1D-1D and 1D-2D urban flood models, in: 15th Internation Conference on Environmental Science and Technology.

Kousky, C., Kunreuther, H., LaCour-Little, M., Wachter, S., 2020. Flood risk and the U.S. housing market. J. Hous. Res. 29, S3–S24. https://doi.org/10.1080/10527001.2020.1836915.

Krebs, G., Kokkonen, T., Valtanen, M., Setälä, H., Koivusalo, H., 2014. Spatial resolution considerations for urban hydrological modelling. J. Hydrol. 512, 482–497. https://doi.org/10.1016/j.jhydrol.2014.03.013.

Kulithalai Shiyam Sundar, P., Kundapura, S., 2023. Spatial mapping of flood susceptibility using decision tree–based machine learning models for the vembanad lake system in Kerala, India. J. Water Resour. Plan Manag. 149. https://doi.org/10.1061/jwrmd5.wreng-5858.

Kulk, G., Sathyendranath, S., Platt, T., George, G., Suresan, A.K., Menon, N., Evers-King, H., Abdulaziz, A., 2023. Using multi-spectral remote sensing for flood mapping: a case study in Lake Vembanad, India. Remote Sens. 15, 5139.

Kumar, S., Jayarajan, K., 2021. Flood mapping and vulnerability assessment using geospatial techniques: a case study of Lower Periyar River Basin, Kerala. Recent Technologies for Disaster Management and Risk Reduction: Sustainable Community Resilience & Responses. Springer, pp. 107–120.

Kumar, A., Khosa, R., Gosian, A.K., 2023. A framework for assessment of flood conditions using hydrological and hydrodynamic modeling approach. Water 15. https://doi.org/10.3390/w15071371.

Lal, P., Prakash, A., Kumar, A., Srivastava, P.K., Saikia, P., Pandey, A.C., Srivastava, P., Khan, M.L., 2020. Evaluating the 2018 extreme flood hazard events in Kerala, India. Remote Sens. Lett. 11, 436–445. https://doi.org/10.1080/2150704X.2020.1730468.

Lin, B., Wicks, J.M., Falconer Dsc, R.A., Adams, K., 2005. Integrating 1D and 2D hydrodynamic models for flood simulation. Water Manag. 19–25.

Lu, J.S., Han, X., Bertoni, H.L., 2013. The influence of terrain scattering on radio links in hilly/mountainous regions. IEEE Trans. Antennas Propag. 61, 1385–1395. https://doi.org/10.1109/TAP.2012.2231919.

Lyngwa, R.V., Nayak, M.A., 2021. Atmospheric river linked to extreme rainfall events over Kerala in August 2018. Atmos. Res. 253. https://doi.org/10.1016/j.atmosres.2021.105488.

Mabrouk, M., Haoying, H., 2023. Urban resilience assessment: a multicriteria approach for identifying urban flood-exposed risky districts using multiple-criteria decision-making tools (MCDM). Int. J. Disaster Risk Reduct. 91. https://doi.org/10.1016/j.ijdrr.2023.103684.

Mallouk, A., Lechgar, H., Malaainine, M.E., Rhinane, H., 2016. A multicriteria approach with GIS for assessing vulnerability to flood risk in urban area (case of Casablanca city, Morocco). in: Lecture Notes in Electrical Engineering. Springer Verlag, pp. 257–266. https://doi.org/10.1007/978-3-319-30301-7_27.

Mangukiya, N.K., Mehta, D.J., Jariwala, R., 2022. Flood frequency analysis and inundation mapping for lower Narmada basin, India. Water Pr. Technol. 17, 612–622. https://doi.org/10.2166/wpt.2022.009.

Memon, P.A., Gleeson, B.J., 1995. Towards a new planning paradigm? Reflections on New Zealand's resource management act. Environ. Plann B Plann Des. 22, 109–124.

Mignot, E., Li, X., Dewals, B., 2019. Experimental modelling of urban flooding: a review. J. Hydrol. 568, 334–342. https://doi.org/10.1016/j.jhydrol.2018.11.001.

Modi, A., Nair, T.M.B., Remya, P.G., Harikumar, R., Srinivas, K., Srinivas, G., 2021. The role of anomalous oceanic features on enhancing flooding duration in Kuttanad region, Kerala (India). J. Earth Syst. Sci. 130. https://doi.org/10.1007/s12040-021-01599-x.

Mohan, M.G., Adarsh, S., 2023. Dynamic flood frequency analysis for west flowing rivers of Kerala, India. Water Secur 19. https://doi.org/10.1016/j.wasec.2023.100137.

Mohanty, M.P., Mudgil, S., Karmakar, S., 2020. Flood management in India: a focussed review on the current status and future challenges. Int. J. Disaster Risk Reduct. https://doi.org/10.1016/j.ijdrr.2020.101660.

Mohanty, M.P., Sherly, M.A., Karmakar, S., Ghosh, S., 2018. Regionalized design rainfall estimation: an appraisal of inundation mapping for flood management under data-scarce situations. Water Resour. Manag. 32. https://doi.org/10.1007/s11269-018-2080-8.

Mohapatra, P.K., Singh, R.D., 2003. Flood management in India. Flood Probl. Manag. South Asia 131–143.

Mutasa, C., 2022. Revisiting the impacts of tropical cyclone Idai in Southern Africa. in: Climate Impacts on Extreme Weather. Elsevier, pp. 175–189.

Naga Kumar, K.C.V., Deepak, P.M., Basheer Ahammed, K.K., Rao, K.N., Gopinath, G., Dinesan, V.P., 2022. Coastal vulnerability assessment using Geospatial technologies and a Multi-Criteria Decision Making approach–a case study of Kozhikode District coast, Kerala State, India. J. Coast. Conserv. 26 (3), 16.

Nanditha, J.S., Mishra, V., 2024. Projected increase in widespread riverine floods in India under a warming climate. J. Hydrol. (Amst.) 630, 130734.

Nath, D., 2024. Why do landslides occur, and what triggered the tragedy in Wayanad. Indian Express.

Nkwunonwo, U.C., Whitworth, M., Baily, B., 2020. A review of the current status of flood modelling for urban flood risk management in the developing countries. Sci. Afr. https://doi.org/10.1016/j.sciaf.2020.e00269.

Parvathy, S., Thomas, R., 2021. Impact of urbanization on flooding in chalakudy river. IOP Conf. Ser. Mater. Sci. Eng. 1114, 012025. https://doi.org/10.1088/1757-899x/1114/1/012025.

Peel, M.C., Blöschl, G., 2011. Hydrological modelling in a changing world. Prog. Phys. Geogr. 35, 249–261. https://doi.org/10.1177/0309133311402550.

Peng, J., Zhang, J., 2022. Urban flooding risk assessment based on GIS- game theory combination weight: A case study of Zhengzhou City. Int. J. Disaster Risk Reduct. 77. https://doi.org/10.1016/j.ijdrr.2022.103080.

Pradeep, A., 2022. Risk Assessment of rainstorm waterlogging in Kollam city based on Mike+ 1D drainage Modelling. National Institute of Technology, Kurukshetra.

Pramanick, N., Acharyya, R., Mukherjee, Sandip, Mukherjee, Sudipta, Pal, I., Mitra, D., Mukhopadhyay, A., 2022. SAR based flood risk analysis: a case study Kerala flood 2018. Adv. Space Res. 69, 1915–1929. https://doi.org/10.1016/j.asr.2021.07.003.

Rajindas, K.P., Shashikala, A.P., 2021. Development of hybrid wave transformation methodology and its application on Kerala Coast, India. J. Earth Syst. Sci. 130. https://doi.org/10.1007/s12040-021-01612-3.

Ramasamy, S.M., Gunasekaran, S., Rajagopal, N., Saravanavel, J., Kumanan, C.J., 2019. Flood 2018 and the status of reservoir-induced seismicity in Kerala, India. Nat. Hazards 99, 307–319. https://doi.org/10.1007/s11069-019-03741-x.

Reddy, N.V.J., Arunkumar, R., 2023. Development of flood inundation maps for the Chaliyar Basin, Kerala under climate change scenarios. Water Pr. Technol. 18, 2372–2383. https://doi.org/10.2166/wpt.2023.148.

Rentschler, J., Salhab, M., Jafino, B.A., 2022. Flood exposure and poverty in 188 countries. Nat. Commun. 13. https://doi.org/10.1038/s41467-022-30727-4.
Rohtash, L.N.T., Thakural, L.N., Choudhary, M.K., Tiwari, D., 2018. Rainfall runoff modeling using SWAT model for Chaliyr basin Kerala India. J. Int. Sci. Res. 8.
Rubinato, M., Nichols, A., Peng, Y., Zhang, J. min, Lashford, C., Cai, Y., peng, Lin, P. zhi, Tait, S., 2019. Urban and river flooding: Comparison of flood risk management approaches in the UK and China and an assessment of future knowledge needs. Water Sci. Eng. 12, 274–283. https://doi.org/10.1016/j.wse.2019.12.004.
Ryan, C., Trigg, M.A., Adarsh, S., 2020. An investigation into the impact of reservoir management Kerala floods 2018: A case study of the Kakki reservoir. IOP Conference Series: Earth and Environmental Science. Institute of Physics Publishing. https://doi.org/10.1088/1755-1315/491/1/012005.
Sabitha, N.M., Thampi, S.G., Kumar, D.S., 2023. Application of a distributed hydrologic model to assess the impact of climate and land-use change on Surface Runoff from a small urbanizing Watershed. Water Resour. Manag. 37, 2347–2368.
Sahu, S., Suresh, H., Murthy, I., Ravindranath, N., 2015. Mangrove area assessment in India: implications of Loss of Mangroves. J. Earth Sci. Clim. Change 06. https://doi.org/10.4172/2157-7617.1000280.
Saravanan, S., Abijith, D., Reddy, N.M., KSS, P., Janardhanam, N., Sathiyamurthi, S., Sivakumar, V., 2023. Flood susceptibility mapping using machine learning boosting algorithms techniques in Idukki district of Kerala India. Urban Clim. 49. https://doi.org/10.1016/j.uclim.2023.101503.
Simpson, N.P., Mach, K.J., Constable, A., Hess, J., Hogarth, R., Howden, M., Lawrence, J., Lempert, R.J., Muccione, V., Mackey, B., New, M.G., O'Neill, B., Otto, F., Pörtner, H.O., Reisinger, A., Roberts, D., Schmidt, D.N., Seneviratne, S., Strongin, S., van Aalst, M., Totin, E., Trisos, C.H., 2021. A framework for complex climate change risk assessment. One Earth. https://doi.org/10.1016/j.oneear.2021.03.005.
Simpson, N.P., Williams, P.A., Mach, K.J., Berrang-Ford, L., Biesbroek, R., Haasnoot, M., Segnon, A.C., Campbell, D., Musah-Surugu, J.I., Joe, E.T., Nunbogu, A.M., Sabour, S., Meyer, A.L.S., Andrews, T.M., Singh, C., Siders, A.R., Lawrence, J., van Aalst, M., Trisos, C.H., 2023. Adaptation to compound climate risks: a systematic global stocktake. iScience 26. https://doi.org/10.1016/j.isci.2023.105926.
Singh, V., Lohani, A.K., Jain, S.K., 2022. Reconstruction of extreme flood events by performing integrated real-time and probabilistic flood modeling in the Periyar river basin, Southern India. Nat. Hazards 112, 2433–2463. https://doi.org/10.1007/s11069-022-05272-4.
Sivadasan, M., 2004. Mangroves of Kerala, India. J. Indian Assoc. Angiosperm Taxon. 14.
Snehil, Goel, R., 2020. Flood damage analysis using machine learning techniques, in: procedia computer science. Elsevier B. V. 78–85. https://doi.org/10.1016/j.procs.2020.06.011.
Sonu, T.S., Mohammed Firoz, C., Bhagyanathan, A., 2022. The impact of upstream land use land cover change on downstream flooding: a case of Kuttanad and Meenachil River Basin, Kerala, India. Urban Clim. 41. https://doi.org/10.1016/j.uclim.2022.101089.
Sood, A., Smakhtin, V., 2015. Revue des modèles hydrologiques globaux. Hydrol. Sci. J. 60, 549–565. https://doi.org/10.1080/02626667.2014.950580.
Sreelakshmi, M., Balachandran, S., Abdurazak, F., Gopinath, G., Joseph, S., 2024. From perils to preparedness: decoding coastal hazard risks on Kerala's central coast through the IPCC framework. Nat. Hazards. https://doi.org/10.1007/s11069-024-06543-y.
Stephens, S.A., Paulik, R., Reeve, G., Wadhwa, S., Popovich, B., Shand, T., Haughey, R., 2021. Future changes in built environment risk to coastal flooding, permanent inundation and coastal erosion hazards. J. Mar. Sci. Eng. 9. https://doi.org/10.3390/jmse9091011.
Sundar, P.K.S., Kundapura, S., 2023. Spatial mapping of flood susceptibility using decision tree–based machine learning models for the Vembanad Lake System in Kerala, India. J. Water Resour. Plan Manag 149, 04023052.
Tayefi, V., Lane, S.N., Hardy, R.J., Yu, D., 2007. A comparison of one- and two-dimensional approaches to modelling flood inundation over complex upland floodplains. Hydrol. Process 21, 3190–3202. https://doi.org/10.1002/hyp.6523.
Teng, J., Jakeman, A.J., Vaze, J., Croke, B.F.W., Dutta, D., Kim, S., 2017. Flood inundation modelling: a review of methods, recent advances and uncertainty analysis. Environ. Model. Softw. https://doi.org/10.1016/j.envsoft.2017.01.006.
Tevera, D., Sibanda, M., Mamba, S.F., Tivana, L.D., 2021. Assessment of cyclone Idai floods on local food systems and disaster management responses in Mozambique and Zimbabwe. Cyclones in Southern Africa: Volume 3: Implications for the Sustainable Development Goals 59–68.
Thakur, P.K., Ranjan, R., Singh, S., Dhote, P.R., Sharma, V., Srivastav, V., Dhasmana, M., Aggarwal, S.P., Chauhan, P., Nikam, B.R., 2020. Synergistic use of remote sensing, GIS and hydrological models for study of august 2018 Kerala floods. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. 43 1263–1270.
Tiwari, V., Kumar, V., Matin, M.A., Thapa, A., Ellenburg, W.L., Gupta, N., Thapa, S., 2020. Flood inundation mapping-Kerala 2018; Harnessing the power of SAR, automatic threshold detection method and Google Earth Engine. PLoS One 15. https://doi.org/10.1371/journal.pone.0237324.
Trivandrum City Corporation, 2015. City Disaster Management Plan.
Turner, A.G., Annamalai, H., 2012. Climate change and the South Asian summer monsoon. Nat. Clim. Change 2 (8), 587–595.
UNDRR (United Nations Office or Disaster Risk Reduction), 2015. Sendai Framework for Disaster Risk Reduction 2015 - 2030.
Unnithan, S.L.K., Biswal, B., Rüdiger, C., 2020b. Flood inundation mapping by combining GNSS-R signals with topographical information. Remote Sens. https://doi.org/10.3390/RS12183026.
Unnithan, S.L.K., Biswal, B., Rüdiger, C., 2020a. Flood inundation mapping by combining GNSS-R signals with topographical information. Remote Sens. 12. https://doi.org/10.3390/RS12183026.
Unnithan, S.L.K., Biswal, B., Rüdiger, C., Dubey, A.K., 2024. A novel conceptual flood inundation model for large scale data-scarce regions. Environ. Model. Softw. 171. https://doi.org/10.1016/j.envsoft.2023.105863.
Vanama, V.S.K., Rao, Y.S., Bhatt, C.M., 2021. Change detection based flood mapping using multi-temporal Earth Observation satellite images: 2018 flood event of Kerala, India. Eur. J. Remote Sens 54, 42–58. https://doi.org/10.1080/22797254.2020.1867901.
Vanama, V.S.K., Shitole, S., Khati, U., Rao, Y.S., 2020. Split-Window Based Flood Mapping with L-Band ALOS-2 SAR Images: A Case of Kerala Flood Event in 2018. IGARSS 2020-2020 IEEE International Geoscience and Remote Sensing Symposium. IEEE, pp. 4742–4745.
Varughese, A., 2020. Modelling stream flow using swat model: a case study of Thuthapuzha river Basin, Kerala. Int. J. Farm Sci. 10, 86–95.
Vassoney, E., Mammoliti Mochet, A., Desiderio, E., Negro, G., Pilloni, M.G., Comoglio, C., 2021. Comparing multi-criteria decision-making methods for the assessment of flow release scenarios from small hydropower plants in the Alpine Area. Front Environ. Sci. 9. https://doi.org/10.3389/fenvs.2021.635100.
Venkatesh, B., Chandramohan, T., Purandara, B.K., Jose, M.K., Nayak, P.C., 2018. Modeling of a river basin using SWAT model. Hydrologic modeling Select Proceedings of ICWEES-2016. Springer, pp. 707–714.
Vijayachandran, L., Singh, A.P., 2023. Flood risk assessment in the Karamana river basin, Kerala, using HEC-RAS. Environ. Monit. Assess. 195. https://doi.org/10.1007/s10661-023-11450-z.
Vijaykumar, P., Abhilash, S., Sreenath, A.V., Athira, U.N., Mohanakumar, K., Mapes, B.E., Chakrapani, B., Sahai, A.K., Niyas, T.N., Sreejith, O.P., 2021. Kerala floods in consecutive years - Its association with mesoscale cloudburst and structural changes in monsoon clouds over the west coast of India. Weather Clim. Extrem 33. https://doi.org/10.1016/j.wace.2021.100339.
Vincent, A.M., Parthasarathy, K.S.S., Jidesh, P., 2023. Flood susceptibility mapping using AutoML and a deep learning framework with evolutionary algorithms for hyperparameter optimization. Appl. Soft Comput. 148. https://doi.org/10.1016/j.asoc.2023.110846.
Vishnu, C.L., Rani, V.R., Sajinkumar, K.S., Oommen, T., Bonali, F.L., Pareeth, S., Thrivikramji, K.P., McAdoo, B.G., Anilkumar, Y., Rajaneesh, A., 2020. Catastrophic flood of August 2018, Kerala, India: Study of partitioning role of lineaments in modulating flood level using remote sensing data. Remote Sens Appl. 20. https://doi.org/10.1016/j.rsase.2020.100426.
Vishnu, C.L., Sajinkumar, K.S., Oommen, T., Coffman, R.A., Thrivikramji, K.P., Rani, V.R., Keerthy, S., 2019. Satellite-based assessment of the August 2018 flood in parts of Kerala, India. Geomat. Nat. Hazards Risk.
Vojinovic, Z., Tutulic, D., 2009. On the use of 1d and coupled 1d-2d modelling approaches for assessment of flood damage in urban areas. Urban Water J. 6, 183–199. https://doi.org/10.1080/15730620802566877.

Yaduvanshi, A., Singh, R., Kumar, R., 2022. Population changes and sustainability of energy drive cooling demand related risks in urbanized India. Energy Build. 260. https://doi.org/10.1016/j.enbuild.2022.111891.
Yahaya, S., Ahmad, N., Abdalla, R.F., 2010. Multicriteria analysis for flood vulnerable areas in Hadejia-Jama'are River Basin, Nigeria. Eur. J. Sci. Res.
Yazdandoost, F., Bozorgy, B., 2008. Flood risk management strategies using multi-criteria analysis. Proc. Inst. Civ. Eng. Water Manag. 161, 261–266. https://doi.org/10.1680/wama.2008.161.5.261.