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Regular Article

Navigating coastal futures: Harnessing GIS and multi-criteria decision analysis for sustainable resilience in Kerala's vulnerable Shores

Acanga Alfred [a,b], Sreekrishnan Ravi [a], Sabarinath S. [a,*], Maneesha V. Ramesh [a], Hariprasad K.M. [c,**]

[a] Amrita School for Sustainable Futures, Amrita Vishwa Vidyapeetham, Amritapuri, India
[b] Department of Public Adminstration & Management, Lira University, Uganda
[c] Amrita Centre for Wireless Networks and Applicataion, Amrita Vishwa Vidyapeetham, Amritapuri, India

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ABSTRACT

Extreme weather occurrences, particularly in densely populated coastal places like India, cause loss and devastation, hindering disaster preparedness and long-term viability of vulnerable populations. Research shows that hybrid models, such as Bayesian Networks and Coastal Vulnerability frameworks, outperform traditional methods for measuring coastal vulnerability to Sea Level Rise (SLR). However, their extensive geographical coverage has considerable limitations, including data scarcity and challenges in effectively capturing differences in tiny locations. This study uses Geographic Information systems (GIS) and Multi Criteria Decision Analysis (MCDA) to assess coastal vulnerability in two villages in Alappuzha district, Kerala. The parameters used include lithology, elevation, significant wave height, land cover, road network density, and population density. The Coastal Vulnerability Index indicates that site A (27.39/53.7%) is three times more vulnerable than site B (9.13/18%). The results show that lithology limits agricultural lifestyles at both locations. Geology, coastal slope elevation, and wave energy all influence risk exposure. Land use and cover changes have had different causes at each site, resulting in varying socioeconomic consequences. The study emphasizes the need for evidence-based methods that include local ecological knowledge and involve communities to improve coastal resilience in line with the Sustainable Development Goals (SDG). This work contributes to our knowledge of how localized adaptations minimize disaster risk and strengthen resilience in vulnerable coastal communities confronting climate change and socioeconomic pressures.

1. Introduction

The global increase in extreme weather events, such as storm surges and cyclones, has significantly affected livelihoods through amplification of disaster-related loss and damage. Consequently, these trends have resulted in transitions within the disasters discourse with emphasis on enhancing Community Disaster Resilience (CDR) and promoting sustainable futures for communities in fragile and marginal ecological zones such as coastal areas (Shastri et al., 2025). Additionally, these discourse shifts have been reflected across global protocols like the Sendai Framework (2015), which advocates for the swift implementation of Disaster Risk Reduction (DRR) strategies, including early warning systems (Zaidi & Fordham, 2021). However, the diffusion of these global protocols encounters challenges arising from pervasive top-down frameworks employed by state and non-state actors (Theocharidis et al., 2024). These mismatches frequently result in mixed outcomes in disaster management policy and practice that impeded the sustainability of ongoing and future CDR programs. This is critical considering that varying context-based risk drivers, such as vulnerability in Africa and exposure in South Asia, highlight the need for evidence-based and contextually relevant DRR measures (Bündnis Entwicklung Hilft / IFHV, 2023). Additionally, recent research shows that six out of ten people worldwide live within 400 km of a coastline (Ghosh & Mistri, 2021). Moreover, recent estimates from India show that around 340 million people in 66 coastal districts are at risk from hydro-meteorological disasters (Ghosh & Mistri, 2021; Rehman et al., 2021). Furthermore,

* Corresponding author. Amrita School for Sustainable Futures, Amritapuri, Amrita Vishwa Vidyapeetham, India.
** Corresponding author. Amrita Centre for Wireless Networks and Applicataion, Amritapuri, Amrita Vishwa Vidyapeetham, India.
E-mail addresses: am.id.r4ids23039@am.students.amrita.edu, aacanga@lirauni.ac.ug (A. Alfred), am.id.r4ids23051@am.students.amrita.edu (S. Ravi), sabarinaths@am.amrita.edu (S. Sabarinath), maneesha@amrita.edu (M.V. Ramesh), am.en.r4wna25003@am.students.amrita.edu (K.M. Hariprasad).

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projections indicate that by 2050, sea level rise (SLR) could threaten the livelihoods of 5 million people in India (Kulp & Strauss, 2019).

Previous studies such as Dovie and Pabi (2023) linked these global policy-practice mismatches and their adaptation to local contexts with reactive disaster response strategies anchored in economic models like cost-benefit analysis. Consequently, these challenges prompted calls for evidence-based, efficient, cost-effective, and place-based hybrid approaches. This is premised on findings that show that disaster-induced disruptions livelihoods also affect communities' sense of place, place identity and place attachment particularly in the global south (Matovu, Lukambagire, et al., 2024; Tasnuva et al., 2023). These disruptions to sense of place have also been associated with intent and community participation in disaster response exposing at-risk communities to greater disaster loss and damage. It also highlighting the urgent need for developing and implementing place-based adaptation strategies for sea level rise (SLR) in fragile ecologies to cement their sustainable futures. This is reinforced by Durap and Balas (2024) who highlight the effectiveness of hybrid models such as Bayesian Networks (BN) and Coastal Vulnerability (CV) frameworks over traditional Coastal Vulnerability Index (CVI) methods. The BN-CV frameworks analyze geomorphological features and oceanic dynamics to pinpoint vulnerabilities in different beach types. These findings are essential for developing sustainable strategies for the study locations, particularly in light of current initiatives like the Tsunami Readiness Program, which aims to enhance disaster preparedness and evacuation. However, challenges persist in integrating local parameters such as integration of risk, vulnerability, resilience indicators, methodological suitability, accounting for cascading uncertainties from intra-scalar ecological interactions and customizing policy frameworks to address specific contexts. These gaps are particularly amplified within data scarce contexts. Therefore addressing these challenges will enhance CDR efforts across scales.

One of the key outcomes after the 2004 Indian Ocean Tsunami was that its scale and scope reshaped disaster discourse and policy emphasizing the need for Early Warning Systems (EWS) and community resilience projects such as the Tsunami Ready Community Program throughout afflicted countries (Harvan et al., 2025; Indukala et al., 2024; Pal et al., 2023; Ramesh, 2014; Skidmore & Cohon, 2023). While there has been proliferation of hybrid EWS and DRR models after the Indian Ocean Tsunami, data-scarce locations such as Kerala's coastline continue to lack integrated risk assessments that account both human and physical components. Furthermore, the broad scope coverage of these models usually obscures micro-level distinctions between surrounding regions, which have distinct geophysical and socio-economic features. This gap emphasizes the importance of reviewing existing techniques to identify site-specific variations and provide locally grounded insights that can better influence disaster resilience measures. This study aims to fill that gap and support federal and state initiatives in India to enhance CDR for coastal communities under the Tsunami Readiness Program. This study focuses on two villages near Alappad that experienced the highest death toll during the 2004 tsunami (Pal et al., 2023). It employs Geographic Information System (GIS) tools and Multi-Criteria Analysis (MCDA) to present and analyze data to inform selection of alternative pathways for each site (Abdullah et al., 2021; Barzehkar et al., 2021; Skidmore & Cohon, 2023). The aims of this study were to.

1. Use GIS to generate analytical Maps for each study site
2. Calculate the Coastal Vulnerability for each study site
3. Adopt Multi-Criteria Analysis (MCDA) based approaches and draw from existing related studies to propose sustainability pathways (policy and practice) for each study site

1.1. Conceptual background

Sustainable futures and sustainability of resilience building strategies at grassroots levels stems from the resilience theory. At its core, the concept of resilience (adaptive capacity) remains contentious arising from its multidisciplinary roots. For instance, material and ecological sciences link resilience to the properties of materials, like ductility, and the ability of ecosystems to absorb shocks while maintaining stability (Aldunce et al., 2014; Holling, 1973). This perspective can be seen in the recovery (bounce-back) framing of adaptation within recent discourses. However, a drawback of this framing of adaptation lies in its presumption that materials and ecosystems will necessarily return to the previous levels of normalcy. Additionally, it also overlooks the potential altering effects of external stressors on the structure of materials and ecosystems. For instance, Hallegatte et al. (2020) found a bidirectional predictor-outcome relationship between poverty and vulnerability. Their findings indicate that the poor have lower adaptive capability (resilience) and face greater exposure and vulnerability to extreme weather events. This binary view obscures embodied contextual and cultural community ecological disaster knowledge within at-risk ecologies. This is amplified by framings of vulnerability that associate it with at-risk communities' "ignorance of the risks, lack of awareness, indolence, or laziness in seeking better living conditions" (Chavez-Rodriguez, 2024, p. 12). These framings are limited considering that vulnerability, especially within the global South, arises from structural limitations such as inadequate state action on disaster preparedness, mitigation, and response (Huang, 2018). This lack of action heightens their exposure to hazards and weakens their ability to adapt.

In contrast, psychology, psychiatry, and humanities disciplines approach resilience from an individual perspective, viewing it as a bidirectional process that fosters resistance, recovery, and a return to pre-disaster normalcy (Aldunce et al., 2014; Abramson et al., 2015). This perspective looks at the individual as an actor within an environment from which they are detached and have agency. Thus this distinction of the individual from the environment allows for better understanding of why levels of resilience and adaptation across individuals and communities might differ. Additionally, the Socio-Ecological Systems (SES) framework suggests that resilience encompasses adaptive capacity rooted in agency, self-organization, and critical reflexivity (Jozaei et al., 2022; Mochizuki et al., 2018; Hung et al., 2016; Adger et al., 2005). The bounce-forward school and similar frameworks, such as Disaster Risk Reduction and Climate Change Adaptation, emerge from this perspective, emphasizing adaptability, transformation, and social learning (Graveline & Germain, 2022; Amirzadeh & Barakpour, 2021; Brunetta et al., 2019).

Drawing from these discussions above, CDR, as used in this article, is derived from the SES perspective and refers to a community's ability to withstand shocks without undermining its functioning, fidelity, and structural qualities, while preserving its inherent capacity for adaptation, learning, and transformation. This perspective is critical avoids the dualistic approach of the capacity school of thought within the disasters discourse that excessively focused on victimhood of at-risk communities while disregarding their agency. This is crucial given that viewing vulnerability as static restricts its relevance over time and in different contexts. Based on this observation and the brief discussion above, a circular multilevel feedback loop diagram was developed (see Fig. 1 below).

The model above links ecological, psychological, and social systems to address the pervasive victimhood-based framing of vulnerability rooted in the dualistic view. It also emphasizes the agency, contextual knowledge, and social learning of at-risk communities, particularly those in coastal regions of the global south. This model also places CDR as the central node along with defining it as a community's ability to withstand external stressors while maintaining functionality, reflexivity, and agility (transformation potential). The model integrates psychological, social, and ecological aspects of resilience from the literature. The other nodes sit on the periphery for the following reasons. The bounce-back paradigm emphasizes stability in physical and environmental conditions after a hazard. The psychological lens focuses on the

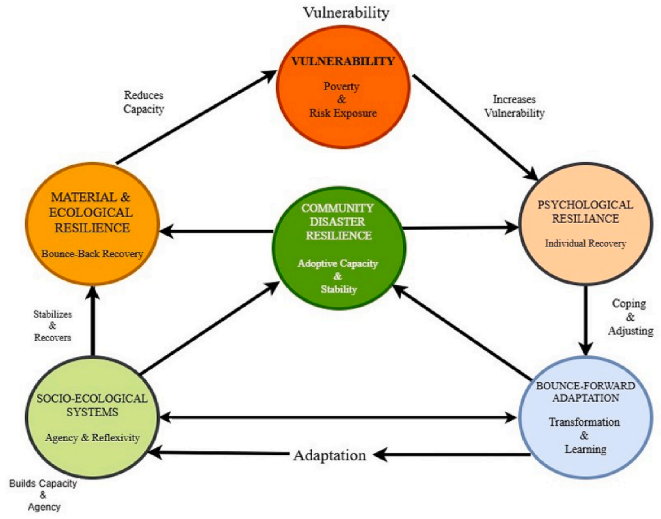


Fig. 1. Conceptual model showing interaction of vulnerability, resilience & adaptation.
Source: Authors' creation from literature

behavioral and emotional aspects of individual recovery. The social-ecological systems lens connects human and environmental systems through self-organization and reflexivity. The bounce-forward framing of adaptation focuses on post-hazard transformation and innovation. These nodes link the vulnerability at the top of the model to the adaptive capacity at the bottom. Structural limitations, such as poverty and exposure to hazards, restrict community adaptive capacity. On the contrary, community agency and resource stock boost their resilience and ability to transform. The loops show that a community's level of vulnerability negatively impacts its adaptive capacity, while the level of adaptive capacity is shaped by agency and learning. CDR enables adaptation and transformation, while adaptation reduces vulnerability, which in turn enhances CDR.

2. Study areas

Ward 18 in Arattupuzha Gram Panchayat is considered as Site A for this study. It is located between 76° 24′ and 76° 26′E and 9° 15′ and 9° 13′N. TM Chira village in Pithuppally Panchayat and taken to be Site B for this study. It is located between 76° 28′ and 76° 29′E and 9° 8′ and 9° 7′N. Both sites A and B are located within Karthikappally Taluk in Alappuzha District, Kerala, India. The taluk ranks as the third most populated in the district, contributing 19% of the total population. The taluk recorded a population density of 1832 persons per sq. Km in 2011. Fig. 2 illustrates the study locations within the broader geographical context of India and Kerala.

3. Methods

Recent studies emphasize the need for context-specific and evidence-based policies to improve DRR and CDR for sustainable livelihoods. Additionally, prior studies have also emphasized the centrality of Decision Support Tools (DSTs), such as GIS and Multi-Criteria Decision Analysis (MCDA), in enhancement of enhance disaster management especially in coastal ecosystems (Barzehkar et al., 2021). Relatedly, scholars, including Abdullah et al. (2021), describe MCDA as a comprehensive approach that integrates qualitative and quantitative methods to evaluate, rank, and select solutions for real-world challenges. This process identifies choices, organizes alternative solutions, prioritizes problems, and establishes descriptive parameters. It includes defining alternatives, formulating criteria, and assessing the performance of all or some alternatives based on these criteria. Thereafter, suggestions about potential future scenarios for each site are made based on data and inferences from prior studies. ArcGIS platform was used to process data obtained from various sources to produce analytical maps in line with the first study objective. The downloaded datasets were processed using ArcGIS Pro to create outputs such as elevation and land use-land cover maps. A comprehensive outline and discussion of the data sources and related parameters used is outlined in section 3.1 below. This study also draws on insights from previous research to evaluate the Coastal Vulnerability Index (CVI) for both locations (Barzehkar et al., 2021; Mullick et al., 2019). This information is vital for developing resilience and formulating protective action plans and strategies for community resilience. Fig. 3 illustrates the flow of the methods used in the study.

3.1. Data sourcing

The data used for this study was obtained from relevant databases. The databases include the U.S Geological Survey (USGS)'s Earth Explorer from which Digital Elevation Maps in the Shuttle Radar Topography Mission (SRTM) format were obtained. The same database was used to derive Normalized Difference in Vegetation Index Tiff files and lithology Tiff files. Data in the form of Geotiff files from the Environmental Systems Research Institute (Esri)'s Online Sentinel-2 Land Cover Explorer at a 10-m resolution was obtained to create Land Use Land

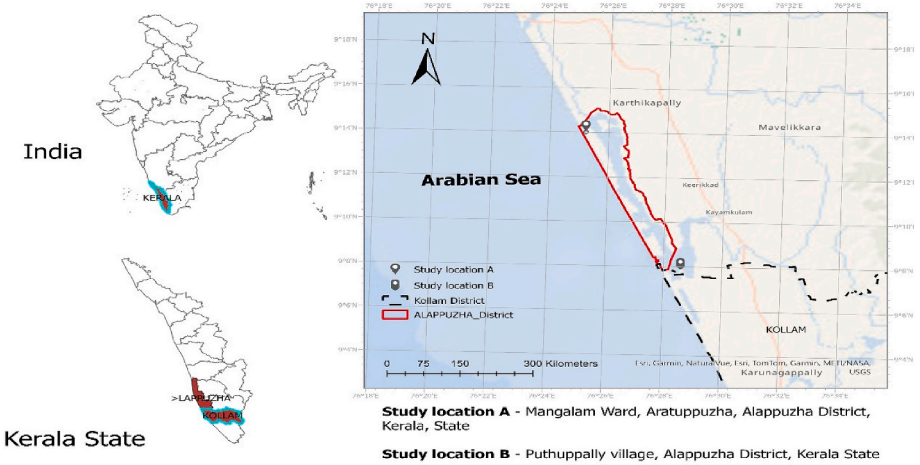


Fig. 2. Map showing study locations.
Source: Authors' creation using ArcGIS Pro

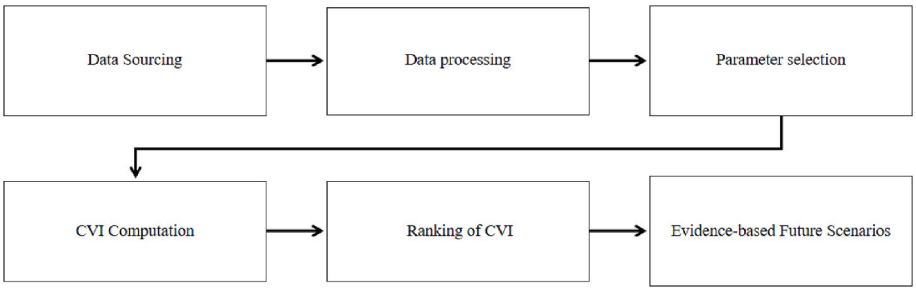


Fig. 3. Methodological flow diagram.
Source: Authors' own creation

Cover maps. Table 1 provides a summary of the obtained datasets.

3.2. Data parameters and sub parameters

Previous studies have established scalar measurements of coastal vulnerability, typically using either a two-tier or a three-tier scale. The three-tier scale assesses coastal vulnerability based on geomorphological, physical, and socioeconomic parameters (Theocharidis et al., 2024). Researchers widely recognize the Coastal Characteristics Vulnerability Index (CCVI), Coastal Forcing Vulnerability Index (CFVI), and Socioeconomic Vulnerability Index (SEVI) as key sub-criteria within this three-tier framework (Bagdanavičiūtė et al., 2019; Barzehkar et al., 2021; Mullick et al., 2019).

Theocharidis et al. (2024) emphasize the significance of natural parameters (metrics) such as lithology, slope, elevation, significant wave height, proximity to the coast, distance to rivers, and shoreline alteration as essential sub-parameters in the two-tier scale method. They also consider socioeconomic factors like land cover, road network density, population density, tourist numbers, public awareness, and designated conservation areas/cultural heritage. Three sub parameters were selected from natural and socioeconomic parameters drawn from relevant literature to create a consistent 5-point scale to evaluate coastal vulnerability (Gadgil et al., 2011; Theocharidis et al., 2024; Yahia Meddah et al., 2023).

It is worth noting that limited data on visitor numbers, designated conservation areas, and public awareness initiatives, while justifying their omission as sub parameters, significantly narrows the social criteria available for evaluating the Coastal Vulnerability Index (CVI) in this study. This is aligned with recent field research by Shancy and Muthulakshmi (2024) in the Alappuzha district that underscored that customized disaster education programs can reduce demographic disparities in disaster awareness and response while also strengthening community resilience.

The evaluation of analytical maps obtained from ArcGIS and assignment of weights in the results section was guided by the contents in the table above (Table 2).

Table 1
Databases used for sourcing data.

Dataset Used	Spatial resolution	Parameters Derived
Environmental Systems Research Institute (ESRI)'s Online Sentinel-2 Land Cover Explorer	10 m	LULC
USGS SRTM-DEM	30 m	Elevation
Open Street Map		Road network & point data
Bhukosh		Lithology
Environmental Systems Research Institute (ESRI)'s Online Sentinel-2 Land Cover Explorer	5 m	NDVI
Open Street Map		Population density
Copernicus ERA 5 wave data	0.25° × 0.25°	Wave Height

Source: authors' creation

3.3. Measurement of Coastal Vulnerability Index

A review DSTs and indices for effective coastal planning and management by Barzehkar et al. (2021) and Hoque et al. (2019) highlighted that Coastal Vulnerability Index (CVI) quantitatively assesses coastal vulnerability and can be catalytic in development of adaptation pathways. Relatedly, Enríquez-Hidalgo et al. (2025) argue that DSTs provide multi-factor and multi-scenario options that can improve the selection of adaptation pathways. However, these tools are confined to specific contexts, which may restrict the reproducibility of findings in other settings. This limitation is well addressed by the usage of multi-criteria decision analysis (Abdullah et al., 2021).

This study employed six sub-parameters to assess vulnerability in both sites, drawing on the work of Gornitz et al. (1994) and Shaw, Taylor, Forbes, Ruz, and Solomon (1994), who evaluated flood risk levels in connection to sea level rise and livelihood vulnerability. In this study, assignment of risk scores for each sub parameter was guided by analysis of the ArcGIS derived maps against the criteria outlined in Table 2. Thereafter, the CVI was calculated as the square root of the geometric mean or the square root of the risk scores/weights of sub parameters divided by the total number of sub parameters used for the study as indicated in equation (1) in section 3.3.1 below. This technique ensures that all study parameters contribute adequately to the overall CVI.

3.3.1. Calculation and normalization of CVI

This study adopted equation (1) below to calculate the CVI. Arising from reliance on six sub parameters for this study, the range of the resultant CVI would lie between 0.408 and 51 (Enríquez-Hidalgo et al., 2025). Lower CVI scores correspond with lower vulnerability while higher CVI scores correspond with greater levels of vulnerability.

$$\text{Coastal Vulnerability Index} = \sqrt[2]{\frac{(a \times b \times c \times d \times e \times f)}{6}} \quad (1)$$

Where a = lithology, b = elevation, c = significant wave height, d = land cover, e = road network density, and f = population density.

While CVI scores have their intrinsic utility, inter-scalar variances often present challenges in replicability in decision making across contexts. This therefore calls for normalization of CVI scores. Normalization was achieved in two ways, the first being transformation of the CVI scores into a 5-point scale that was later read against Table 3. This was accomplished through the use equation (2). This was accomplished by dividing the received CVI score by the maximum score of 51 and multiplying the resultant fraction by 5. Secondly, the CVI scores were transformed into percentages using equation (3). To enhance comparisons for readers not grounded in statistics, this transformation was attained by dividing the CVI by the highest score of 51 and multiplying the obtained fraction by 100.

Table 2
Parameters, sub parameters and their indicators.

Parameters	Sub Parameters	Indicator/Score Ranking scale				
		Very Low (1)	Low (2)	Moderate (3)	High (4)	Very High (5)
Natural Parameters	Lithology	Volcanic	Metamorphic	Sedimentary Rock	Consolidated dune	Sand plains
	Elevation (% slope)	≥ 12	8 - 12	4 – 8	2 – 4	<2
	Significant Wave Height in Metres (m)	≤03.5	03.5 – 0.70	0.70 – 1.05	1.05 – 1.70	>1.70
Socioeconomic parameters	Land cover	Tree Cover	Shrub land, bare soil	Crop land, grassland	Herbaceous wetland	Built-up
	Road network Density	≤2	2 – 5	5 – 10	10 – 15	>15
	Population density (persons per sq. km)	<200	200 – 350	350 – 450	450 – 600	>600

Source: Adapted from Gadgil et al. (2011); Theocharidis et al. (2024) & Yahia Meddah et al. (2023).

Table 3
Futures chart developed from Literature.

Strategies to address SLR	*Range of CVI Score*[a]	Temporal dimensions			Suitable Sites for application
		Short Term	Mid Term	Long Term	
Hard Engineering	≥3	Ideal	Ideal	No	Open Coasts, estuaries & deltas
Soft Engineering	3 to 4	Ideal	Ideal	No	Open Coast
Nature-Based Solutions	>4	Start	Ideal	Ideal	Deltas & estuaries
Enhancing Status quo	≤2	Ideal	Phase out	No	Built-up areas with low SLR
Managed Retreats	≥3	Plan	Ideal	Ideal	All coastal zones especially where adaptive capacity is low
Hybridized Approaches	≥2	Ideal	Ideal	Ideal	Based on context and evidence

[a] CVI Scores range from 1 – Very Low to 5 – Very High.
Source: Adapted from (Enríquez-Hidalgo et al., 2025)

(Calculated CVI score / 51) * 5 (2)

(Calculated CVI score / 51) * 100 (3)

3.4. MCDA based criteria to suggest possible futures

Table 3 showcases a 5-point rating system designed by the study to explore potential futures for each research area, inspired by Enríquez-Hidalgo et al. (2025).

4. Results

4.1. Lithology

Understanding lithology and its characteristics, such as erodibility, plays a crucial role in CDR programming and land use planning within coastal ecologies vulnerable to SLR. For this study, data obtained from Bhukosh was processed using ArcGIS software to create lithological and geological maps of the study areas. Analytical maps of the lithological profile (panel C, Fig. 4) indicate that the western coast of India, where the two study sites are located, contains Ultisol soils. According to a USGS study (1999), Utisol soils result from extensive weathering and leaching, are often thin, contain both coarse and fine-grained sand particles, are acidic, and overlay a clay-enriched sublayer that frequently holds mineral deposits like iron, quartz, and kaolinite. Additionally, Krishnan et al. (1996) noted that areas with these soils typically have fairly deep water tables, overly drained sandy soils, gently sloping beaches, and moderate levels of soil erosion. These findings indicate that Utisol soils have a limited ability to support agricultural livelihoods. Therefore, taking these attributes into consideration and mapping them against the criteria laid out in Table 2, both sites received a rating of 5 out of 5, indicating very high livelihood vulnerability.

The geological map (panel D, Fig. 4) shows that the rocks beneath the area from Alappuzha district to Kollam district, which includes both study locations, belong to three geological periods: Quaternary (Q), Neogene (N), and Permian-Carboniferous (pC). This aligns with earlier research by Douglas Steinshouer et al. (1971, p. 97). Since both study locations are located entirely within the Q zone, which has specific soil properties described in the lithology section above, this article will not

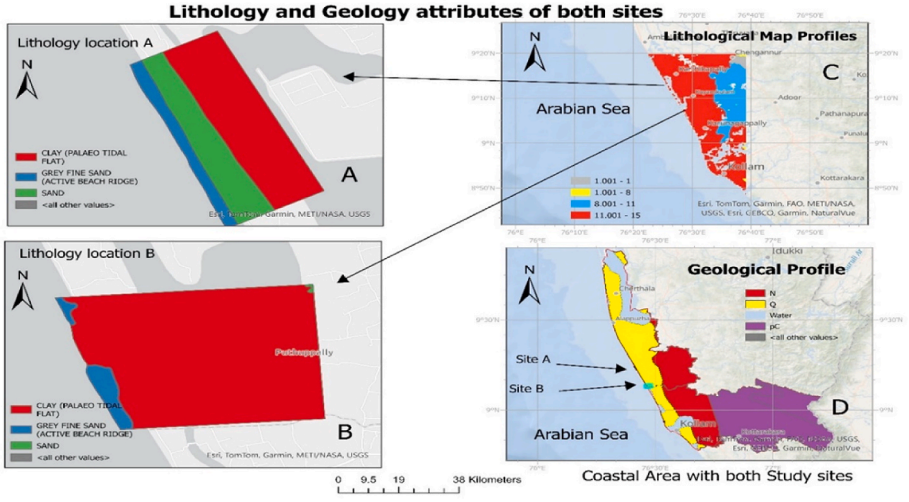


Fig. 4. Lithology and Geology Map of study areas.
Source: Authors' creation from ArcGIS

discuss the N and pC zones.

Though the results indicate that both study sites are situated within the same lithological and geological zone, salient differences exist within the lithological profiles of both sites (see panels A & B, Fig. 4). Site A features more sand deposits, while Site B has a higher concentration of clay deposits. These variations pose unique challenges for disaster preparedness and response. For instance, Site B is at greater risk of flooding, whereas Site A is more prone to erosion and accretion, affecting the livelihoods of fishing communities in different ways. Previous studies (Culshaw et al., 1991; FOGED, 1987) highlight the importance of analyzing the geotechnical properties of quaternary soils to develop secure and cost-effective civil engineering solutions. This approach aims to improve sustainable livelihoods for coastal communities facing vulnerabilities due to climate change and significant human-induced land use changes. During the Monsoon season, fishing livelihoods in coastal communities face disruptions. Consequently, these communities turn to alternative sources of income, such as sand mining. However, when sand mining occurs alongside rising sea levels, it can trigger negative consequences like flooding. This flooding further disrupts livelihoods and increases disaster risk (Matovu, Brouwer, et al., 2024; Matovu, Lukambagire, et al., 2024).

4.2. Coastal elevation and surface features

Studies by Arun Kumar and Kunte (2012) and Mahmood et al. (2020) associate coastal elevation and slope with the levels of vulnerability to SLR and land subsidence within coastal areas. Drawing from Gadgil et al.'s (2011) slope categorization for India, this study developed a five-point scale for slope evaluation (Table 2). Additionally, 30 m elevation DEM data from USGS' Earth Explorer was processed using surface analytical tools embedded in ArcGIS to create contour, aspect, and slope maps as shown in Fig. 5.

The contour elevation maps show that both sites are less than 50 m above sea level. Additionally, the slope aspect maps indicate that the beaches at both locations slope toward the water bodies. Specifically, for both sites, the slopes toward the backwaters run from east to north, while those near the Arabian Sea slope from west to south. Given that a sea wall runs parallel to the Arabian Sea, these slope aspects suggest that wave energy may be causing beach erosion at both sites. Regarding slope gradient, site A features a slope ranging from 1 to 6%, indicating a gently sloping landscape, except for the sea wall, which exceeds a 6% slope. In contrast, site B's main feature is the sea wall, while the rest of the site has a slope of less than 4%.

When these observations are mapped against the criteria laid out in Table 2, they confirm that both sites are highly vulnerable due to their low altitude and gently sloping land into water bodies, resulting in a vulnerability score of 4 out of 5 for each location.

4.3. Significant wave height

Recent studies emphasize how wave activity disrupts low-lying coastal communities (Bagdanavičiute et al., 2015; López Royo et al., 2016) with scholars associating significant wave height as a predictive tool for monitoring SLR and flood risk. In a longitudinal study, Anusree and Kumar (2024) compared significant wave height results from buoys in the Arabian Sea with ERA5 data, finding negligible differences for India's western coast. They noted that significant wave height during the southern Monsoon around Goa peaked at 5.85 m, supporting earlier findings by Kumar and Anand (2004), which reported a wave height of 6 m. Utilizing a point between both study sites, data for wind wave and swell data was extracted from the Copernicus Climate Change Service Climate Data Store (2023). To enhance the analysis, the extraction criteria was limited to ERA5's hourly data at four-hourly intervals from May to August, covering the years 2010 to 2024. The extracted data was analyzed using the Adoption and Panoply tools to create Fig. 6.

Fig. 6 shows a maximum wave height of 4.3 m at the chosen location between the two study sites during the monsoon season. When applied to Table 2, this result underscores a significantly high vulnerability level for both locations. Additionally, Fig. 6 portrays many peak wave heights exceeding the 1.7 threshold needed for a vulnerability score of 5. Since this point represents both sites, each location received a parameter score of 5/5. However, actual vulnerability levels differ, with site A, located directly by the sea, experiencing greater exposure to the direct impacts of wave energy. Site B on the other hand is further inland and next to an estuary.

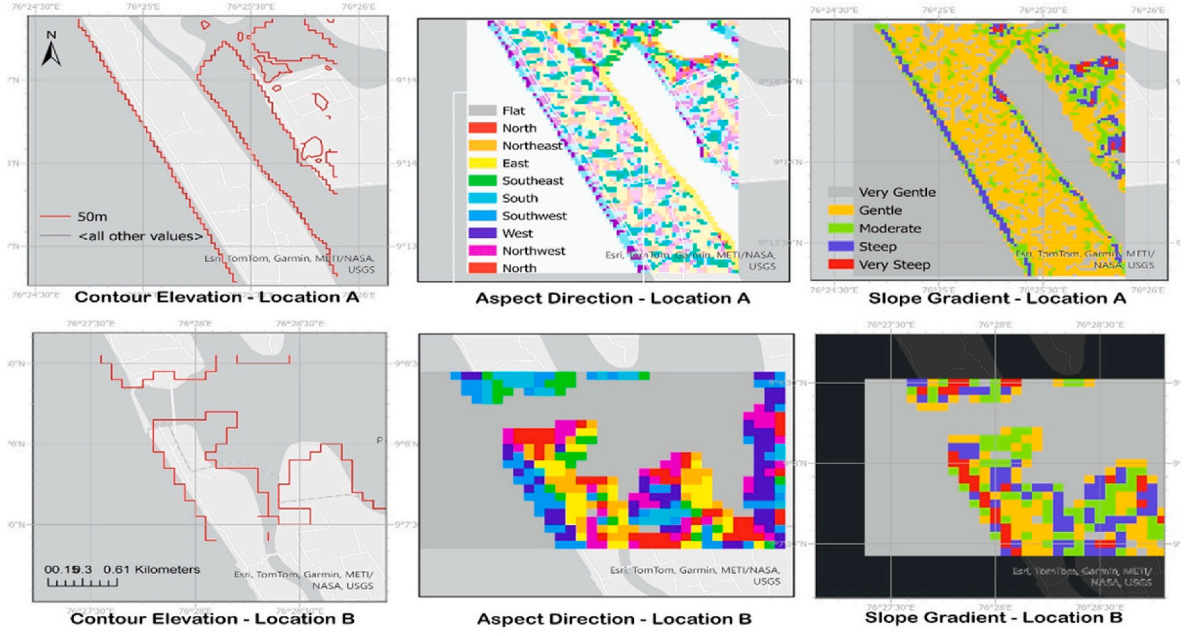


Fig. 5. Surface feature comparisons of study sites.
Source: Authors' creation in ArcGIS Pro

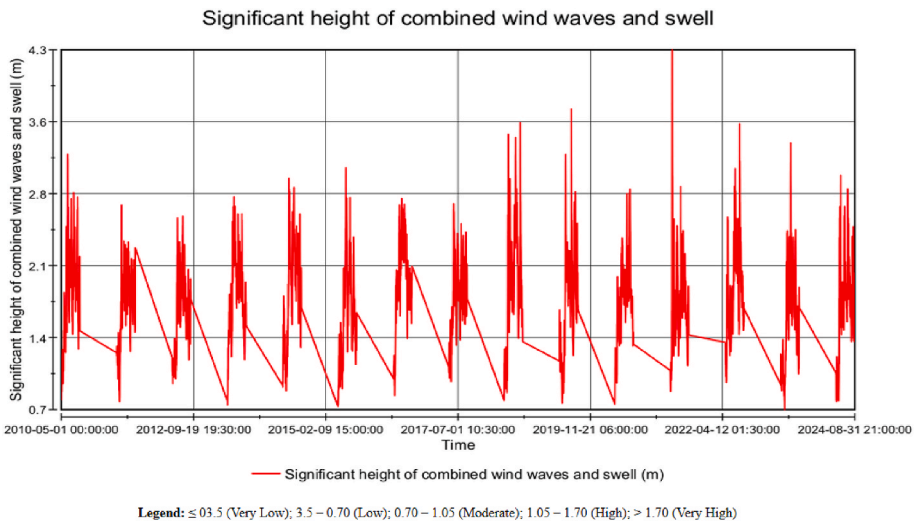


Fig. 6. Four Hourly variations in Wind wave and swell between May and August for 2010 – 2024.
Source: Reanalysis of data from Copernicus database

4.4. Land cover

Evidence from studies such as Tasnuva et al. (2023), Ding et al. (2019), Huang (2018), and Sudha Rani et al. (2015) have associated human-induced land use changes with cascading disaster losses in coastal communities and fragile ecosystems. Utilizing data for Kollam and Alappuzha districts from USGS covering the years 2017 to 2023, land use and land cover (LULC) maps were obtained from ArcGIS Pro as illustrated in Fig. 7 below.

To give context to the land use and land cover changes occurring at both sites, an analysis of the same was done across Kollam and Alappuzha districts of Kerala for the period 2017 to 2023. This analysis is presented by panels A, D, and G. They reveal that human settlement is the primary driver of changes in LULC followed by agriculture and vegetation. They also reveal that notable changes occurred in the northeastern region of Alappuzha district and the southeastern area of Kollam district. Additionally, they also reveal emergence of built-up areas within water bodies that belies the practice of swamp reclamation that increases the risk of flood hazards.

The LULC changes across site A for the period 2017 to 2023 are shown in panels B, E, and H. They reveal a significant increase in built-up areas. Expansion of built-up areas and agricultural areas at the expense of vegetation and barren areas across panels B to E suggests land reclamation efforts. For example, the floating solar farm in the backwaters aims to reduce energy poverty, but it is also a site where barren patches in panel B, are replaced by built up space in panel E and eventually agricultural land along with additional barren land in panel H. These human induced changes amplify flood risk for people residing close to the backwaters. Additionally, across panels B, E & H, the expansion of built up spaces almost erases a water body mass at the bottom right corner of all panels. Furthermore, decline in vegetation cover is visible across all the same panels.

Changes in LULC at site B for the period 2017 to 2023 are presented by panels C, F, and I. They reveal that during this period there was significant loss in vegetation cover and water body masses at the expense of built up space. This is visible in the lower right sections of all panels. However, a notable revelation is that loss of vegetation in the area south of the estuary in the backwaters is neither caused by expansion of built up space nor or agricultural areas. Instead, this decline likely stems from saltwater intrusion resulting from the creation of a break in the coast line to connect the back waters to the Arabian sea.

To corroborate the above findings, additional data from ESRI's living Atlas website was accessed and examined. In this additional analysis, water bodies such as seas and backwaters were excluded to gain insights into LULC changes. This led to the creation of Fig. 8.

Previous studies underscore a strong connection between high population density and vulnerability to coastal hazards (Enríquez-Hidalgo et al., 2025; Skidmore & Cohon, 2023; Theocharidis et al., 2024). In densely populated coastal areas, the provision of public goods and utilities, such as complex sanitation systems, often leads to land subsidence due to excessive groundwater extraction. This issue worsens because of optimism bias, where people tend to overestimate the reliability of grey infrastructure like seawalls (Aldrich & Meyer, 2015; Nicholls et al., 2021). As a result, when the findings were applied to Table 2 and previous research, both locations were assigned a parameter score of 5/5, which indicates a high level of risk.

To further reinforce the risk assessments above, Normalized Difference in Vegetation Index data from USGS' Earth Explorer for November 2023 was processed in ArcGIS Pro to assess how urban growth affects livelihoods. The results from the analysis performed in ArcGIS are presented in Frame 1 of Fig. 9 using a five-color coding system to illustrate the extent of plant changes, with red signifying the most pronounced changes attributable to variations in LULC. The findings show that in 2023, the most significant changes in vegetation occurred to the northeast of site A and along the edges of site B, following a northeast to southwest direction.

Additionally, satellite images for both sites were obtained from Esri's Online Sentinel-2 Land Cover Explorer for February 11, 2025 to validate the output from ArcGIS. The obtained images were juxtaposed in Microsoft PowerPoint program and presented in Fig. 9.

The results in frame 2 show that plants at both locations experienced significant water stress evident from their greenish-yellow coloration. In contrast, rich green tones, indicating healthy, non-water-stressed plants, appear farther from the water bodies, except for a mangrove forest in the lower right quadrant of panel B. Brown patches, which signify bare earth, are visible close to the shoreline and near the backwaters. This observation may support earlier findings linking erosion to intense wave energy and saltwater intrusion (Ravi et al., 2026).

4.5. Road network density

Prior studies such as McLaughlin et al. (2002) and Mahapatra et al. (2015) show that higher road density increases vulnerability to various hazards. This vulnerability arises from factors such as increased vehicular traffic, dense populations, and other socio-demographic elements that can amplify adverse effects of hazards, as seen during

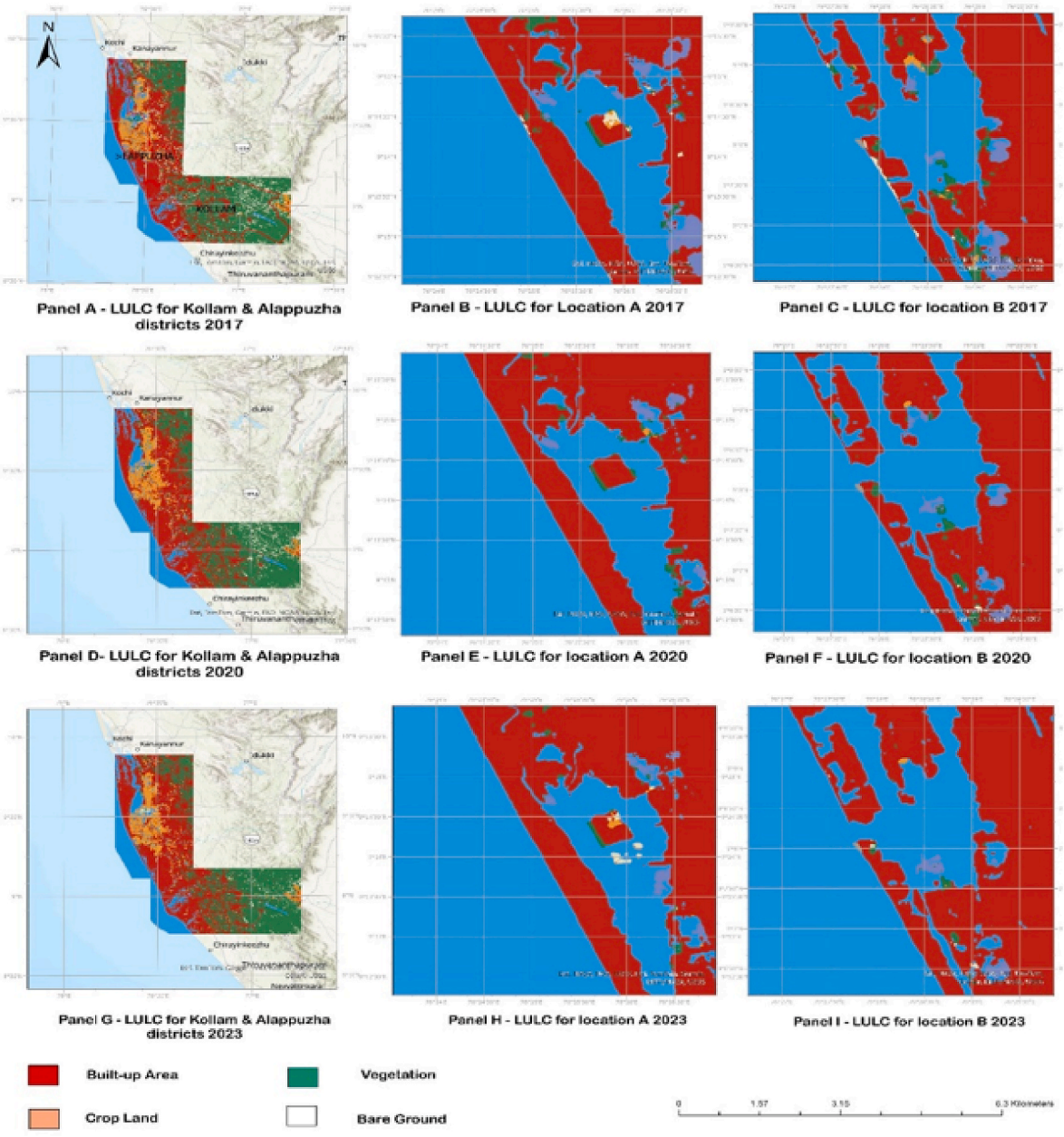


Fig. 7. Visualization of Land Use Land Cover changes from 2017 to 2023.

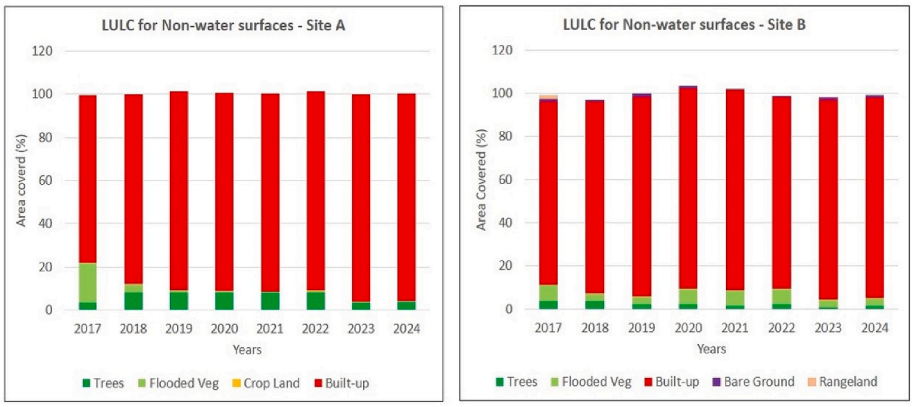
COVID-19 pandemic (Yahia Meddah et al., 2023). Additionally, low road density complicates emergency disaster responses and mass evacuations. Road density data for major roads within the study areas, acquired from Open Street Maps on February 26, 2025, was analyzed in Arc GIS Pro to produce Fig. 10. Color coding was employed to signify susceptibility levels, with yellow denoting the lowest and red the highest.

The results indicate that site A, despite the presence of the main coastal highway linking Kollam to Kochi, has a lower road density than site B. Relatedly, the results also highlight a red hue along the main roads at site A signaling high vulnerability. This vulnerability stems from two primary issue: the first being the proximity of settlements to the high tide line in contravention of the Coastal Hazard Zone (CHZ) notifications of 2019. Secondly, destruction resulting from geophysical hazards such as tsunamis not only poses a threat to houses at site A but could lead to debris blocking the road and hindering evacuation efforts. In contrast, site B's high vulnerability is limited to the bottom right half. This disparity in the road network likely stems from legal restrictions on settlement, as outlined in the Indian Forest Act (1927) and the Biological Diversity Act (2002), which limit human settlement in areas with government fisheries and mangrove forests.

When these results were ranked against the criteria outlined in Table 2, and based on the considerations briefly highlighted above, site A was assigned a moderate risk score of (3/5) and site B a very low risk (1/5) to site B.

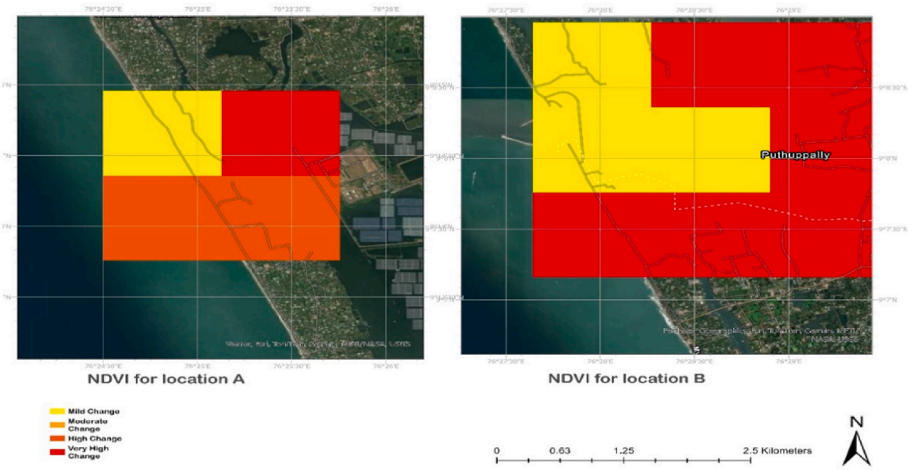
4.6. Population density

Studies highlight the importance of considering population density in disaster management, particularly in coastal areas (Enríquez-Hidalgo et al., 2025; McLaughlin et al., 2002; Skidmore & Cohon, 2023). This research utilized Open Street Maps data, focusing on point data as a proxy for population density due to the small size of both sites. The method assumes that point density effectively reflects the concentration



Frame 1 Frame 2

Fig. 8. Temporal analysis of LULC for areas typically not covered by water across both study location.
Source: ESRI data transformed by authors in MS-Excel



Frame 1



NDVI for Site A NDVI for Site B

Frame 2

Fig. 9. Frame 1 Mapping NDVI at November 2023 using USGS Data.
Frame 2 Esri derived NDVI of study sites as of February 2025.

of residences in a specific location on a map, offering a clearer representation than line data. Analyzing this data from Open Street Maps in ArcGIS Pro led to the creation of Fig. 11, where color coding indicates population density levels—grey for the lowest density and red the

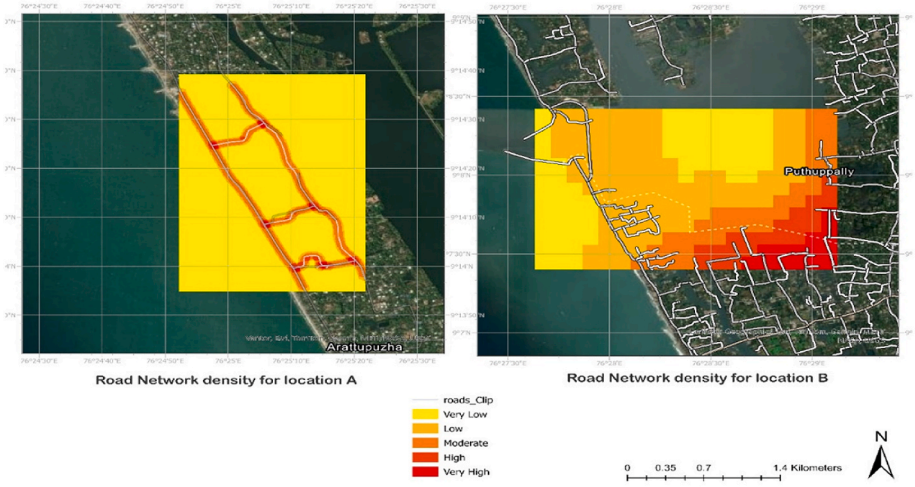


Fig. 10. Road density maps.
Source: Authors' creation from ArcGIS

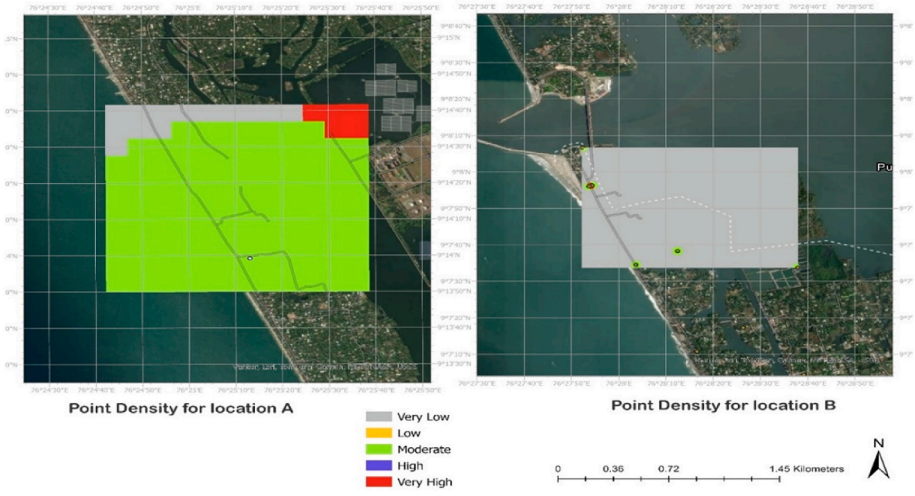


Fig. 11. Point density map.
Source: Authors' creation from ArcGIS

highest.

The results indicate that site A has a moderate population density, with a densely populated northeastern area. In contrast, site B shows a low population density. The 2011 District Census Handbook confirms these findings, ranking Alappuzha as the second highest in population density in Kerala state (Directorate of Census Operations, 2011). These results also partially align with the LULC analysis. However, a limitation of using point density in this study is that it does not account for the number of residents in each household. Mapping the results against the criteria in Table 2 assigned a vulnerability score of 3/5 to Site A and 1/5 to Site B. Table 4 summarizes the scores for the various parameters used in this study.

Table 4
Summary of CVI sub parameters for both sites.

Parameters	Study location A Scores	Study location B Scores
Lithology	5	5
Elevation (m)	4	4
Significant Wave Height (m)	5	5
Land cover	5	5
Road network Density	3	1
Population density	3	1

Source: Authors' own creation

4.7. Calculation of CVI

The CVI scores for each study site were calculated using the equations presented earlier and are summarized into Table 5 below.

5. Discussion

The findings reveal that despite possessing a similar lithological profile, it present different risk scenarios for each of the study sites; erosion at site A and flood risk at site B. These findings align Mukhopadhyay and Karisiddaiah's (2014) study on the processes and

Table 5
Summary of CVI scores.

Parameter	Site A	Site B	Equation used
Coastal Vulnerability Index (CVI) Score	27.39	9.13	1
Normalized CVI (5 point scale)	2.69	0.89	2
Normalized CVI (Percentage scale)	53.7%	18%	3

Source: Authors' own creation

landforms along India's coasts. The study revealed variations between the east and west coasts particularly with reference to different origins of present landforms with their origins tracing to rocks, sediment, and corals. Additionally, the study points out common features along the eastern coast, including long sandy beaches with dunes, large lagoons, and expansive deltas such as the Sundarbans (mangrove wetland). Along the western coast, the study identified common features as narrower and more indented landscape, characterized by rocky protrusions, intermittent sand bays, and estuaries. The similarities between prior studies and the findings of this study underscore different livelihood and sustainability pathways for communities at each site. For instance, deltas along the eastern coast such as the Sundabans boosts eco-tourism and supports activities such as crab farming, enhance agricultural livelihoods. Parallels from these findings can be realized at site B that already has a mangrove forest. Contrarily, the sandy soil along the western coast, particularly at site A, are likely to promote compensatory livelihood pathways like sand mining that heighten flood risk and ultimately reduce the adaptive capacities. Relatedly, the continued reliance of communities at both sites on fisheries and external supplies such as piped water to support their livelihoods implies that in lieu of alternative livelihoods, disaster-induced disruptions can result in adverse social upheaval.

A notable finding of this study is that low elevation and proximity to the sea significantly increase vulnerability to SLR through accelerating shoreline changes at both sites. These observations support earlier findings by Mohanty et al. (2016), who used satellite data and the Bruun Rule to determine the shoreline change rate (SCR). Their study sought to assess the implications of SLR and coastal slope aspects for coastal erosion across mainland India from 1989 to 2001. The findings of that study revealed that SLR and coastal slope significantly altered shorelines particularly in West Bengal (70%), Kerala (65%), Gujarat (60%), and Odisha (50%). These findings underscore the centrality of SCR in the sustainable usage of coastal ecologies particularly densely populated ones. Drawing from these findings, uptake of apt mitigation and anticipatory actions anchored in contextual realities can avert erosion at site A along with flooding and saltwater intrusion at site B. These efforts can be strengthened through effective community engagement and leveraging local ecological knowledge to design adaptive coastal erosion and resilience building strategies.

Another key finding from this study was that significant wave height and wave energy act as mediators of accretion and erosion at both sites. The results of this study are consistent with earlier ones such as Kumar et al. (2018), who investigated inter-annual fluctuations in significant wave height all across the Indian mainland using data from 1998 to 2012. A notable finding of that study was that despite the prevalence of tropical cyclones causing variations in wave height between 3.65 and 7.36 m, wave heights along India's western coast were approximately 20% higher than those along the eastern coast. These variations were significant during the Asian summer Monsoon (June to September). Another finding of that study was that wave heights increased by around 0.7-2.5 cm every year. These prior results highlight the role of tracking variances in wave height considering that uptick in wave heights present complex scenarios for both sites in this present study. Through extending the high tide line farther inland, these wave height induced changes affect the scope of the CRZ. For instance by extending the CRZ-III farther inland, it adversely affects future infrastructure developments and assimilates previously safe infrastructure resulting in unintended legal and financial costs through relocation of newly created at-risk communities. These disruptions of communities' sense of meaning and place can present serious complications for CDR resilience particularly when communities refuse to relocate in risky areas such as site A necessitating counter measures rooted in combination of political will, effective community buy-in and adequate funding.

While anthropogenic changes to land use and land cover have been linked to rapid expansion of urban settlements across both sites at the cost of vegetation, a unique trade-off is revealed by this study at site B where saltwater intrusion depletes vegetation cover. These findings are supported by Nath et al. (2023) whose study relied on geospatial techniques to evaluate the eastern coast of India over a 43-year period, from Subarnarekha (Orissa) to the Rasulpur estuaries (1975-2018). The results of that study demonstrated that human activities such as urban settlements and tourism-based livelihoods resulted in land use land cover changes through expansion of built-up regions, sand areas, vegetation and soil areas. Additionally, their study revealed that while erosion was common along both the eastern and western coasts, inundation was a key driver along the western coast and expansion of shallow water areas along the eastern one. Relatedly, Tripathi et al. (2022) employed satellite imagery to examine six districts in Odisha between 1990 and 2018. Their findings revealed that the intensification of agricultural and socioeconomic activities negatively impacted the supply of ecosystem services and the long-term management of coastal ecosystems. Therefore, the findings from prior studies uncover an established link between densely populated coastal areas such as the narrow ones of western India and cascading effects of human and climate change induced changes in land use and land cover. These insights underscore the need for evidence-based and proactive strategies for disaster risk reduction to counter risk drivers that are not always synergetic in nature.

A key finding of this present study was that the road network density of a given location serves as a critical mediator particularly during emergencies. While it is generally accepted that an inverse link exists between a location's road network and its vulnerability (Nigam et al., 2024), the layout of the roads and other factors such as absence of community awareness of evacuation routes can adversely affect this link. Additionally, established legal frameworks such as the Coastal Regulation Zone Regulation notice (2019) not only establishes four levels of Coastal Regulation Zonation (CRZ), but explicitly bans the development of permanent homes inside CRZ-III sites located less than 200 m from the high tide line owing to their significant exposure and vulnerability. This implies that the buildings along the major highway at site A and a significant portion of the village lie within CRZ-III. Therefore, efforts to enhance the road network, disaster proof existing structures development of new infrastructures to enhance livelihoods and reduce risk of the community will involve a lot of political brinkmanship and community involvement. Local governance measures will need to find a balance between enforcement of legal provisions such as Coastal Regulation Zonation (CRZ) that regulates development along the coast with communities that refuse to relocate. Additionally, legal provisions that gazette areas planted with mangrove as protected sites could also elicit community resistance of nature-based solutions. Both scenarios could further heighten the vulnerability of site A. While site B has a relatively denser network of roads, the main road running from Kochi to Trivandrum is also within the CRZ-III that could pose significant challenges to evacuation in case of hazards like tsunamis that block this road.

Relatedly, evidence from prior studies reveal an established inverse relationship between the optimal use of its stock of resources and ecosystem service provisioning arising from its population density of a location (Nigam et al., 2024). Additionally, Prusty and Farooq (2020) highlight that India's Coastal Zones, with an estimated population density of 80 persons per sq. Km, have twice the global density for coastal areas. These foreground the centrality of population density in shaping the livelihoods of communities, particularly those inhabiting fragile coastal ecologies. These prior results provide a crucial watershed considering that Alappuzha district is the second most densely populated in Kerala state and yet it accounts for only 6% of the state's population (Directorate of Census Operations, 2011). Additionally, official census statistics for Alappuzha district (Directorate of Census Operations, 2011) show decadal percentage population changes from 2001 to 2011 across Kerala state (4.9), Alappuzha district (0.9), and Karthikappally Taluk (−0.2). These statistics raise critical particularly considering that while Alappuzha district has a low population growth

rate, the population density of Karthikappally Taluk (1832 persons per sq. km) exceeds that of Alappuzha district (1,504) by 22% and is more than double that of the Kerala state (860). The findings of this study indicate that Site A has a moderate population density, and Site B has a low density. However, they are not entirely in agreement with the use of point data which might be a drawback for this study. That notwithstanding, the results from this study and prior ones underscore the role population density plays in shaping unique prospects for sustainable management of coastal ecologies. For instance site A that has a relatively higher density and located within CRZ-III, future community disaster resilience programing will lean toward encouraging relocation or emigration unlike site B which might still have capacity to host more people as it is relatively away from CRZ-III.

For example, as illustrated in Fig. 12 from site A, post-tsunami reconstruction prioritized vertical evacuation through construction of flat top houses. However, this approach overlooked local architectural expertise, the potential risk arising from wave energy and shoreline alterations. Consequently, the houses that were built were not only within the CRZ-III, but eventually ended up dilapidated, inhabitable and abandoned as seen in Fig. 12. Therefore, it is essential to create comprehensive disaster management frameworks that monitor shoreline alterations, wave height, and anticipated SLR. This can be strengthened by leveraging current predictive and AI-driven technologies to provide critical evidence. These measures will facilitate informed infrastructure planning, focusing on the expansion of road network density and building developments, while also enhancing emergency preparedness, especially in high-risk locations such as site A. At site B, it is essential to establish robust infrastructure that adheres to building codes and CRZ regulations while facilitating swift emergency response.

In order to close the policy-practice gap, the following section offers suggestions for policy and practice for each research site based on a contextually grounded discussion that synthesizes findings from previous relevant studies throughout India's coastlines with the current study's findings.

6. Policy and practice recommendations for resilient futures

Sustainable livelihoods are crucial as they address multiple sustainable development goals such as SDG 1, 2, 3, 5, 8, 10 and 12. To mitigate the issues of erosion and flood risk at both study sites, a need arises to put in place an integrated coastal zone management framework supported by sand mining and nature-based solution regulations. This will, in part, address livelihood disruptions stemming from lithology, saltwater intrusion, sand mining, and limited sea access during monsoon months while promoting ecosystem conservation. Additionally, targeted investment in nature-based solutions, particularly in keystone species such mangroves, is essential for enhancing coastal resilience. Considering existing legal frameworks that designate mangrove forests as conservations sites and likely to attract community pushback, adopting participatory approaches can leverage indigenous ecological knowledge and enhance uptake of place enhancement measures by communities. For example, planting palm trees and seagrass at Site A may offer more viable nature-based solutions that sustain the livelihoods of local communities as they address the challenge of low productivity in Utisols and erosion. Reinforcement of the existing grey engineering solutions could also serve as an effective stop-gap measures (Long et al., 2024; Theocharidis et al., 2024) particularly at site A. These proposals can be anchored on existing programs like the Mahatma Gandhi National Rural Employment Guarantee Scheme (MGNREGS) and self-help groups, which focus on addressing multidimensional poverty (Kaur et al., 2019) through supporting participatory skills diversification and retooling initiatives.

At site B, a combination of soft engineering and targeted financing to expand nature based solutions could support livelihoods. This can be attained through community based conservation programs for the existing mangrove forest, promotion of crab farming and training in ecotourism. Additionally, the nearby fisheries department can train community members in aquaculture as an alternative livelihood particularly during the monsoon when the sea is inaccessible. This approach could foster local stewardship and bolster conservation efforts (Acanga et al., 2025; Mehta et al., 2021; Pandey et al., 2021).

Recent findings indicate that unregulated coastal development may contribute to land subsidence (El Shinawi et al., 2022) and fail to deliver on the goal of sustainable cities and communities. Coupled with other anthropogenic land use and land cover changes, this underscores the need for better management strategies in urban planning that align with CRZ guidelines and population dynamics. At site A, which is entirely situated within CRZ-III, it is imperative that future infrastructure developments incorporate stricter enforcement of applicable building codes to effectively reduce hazard risk exposure. The existing frameworks can be reinforced by guidelines that necessitate the implementation of home proofing as an interim solution, alongside the creation of participatory strategies aimed at addressing the strong emotional ties to place and encourage emigration/relocation. Strong attachment to place can pose considerable challenges to the relocation of communities, particularly in light of the substantial resistance encountered with past post-tsunami relocation initiatives (RAMACHANDRAN, 2018). In this context, utilizing social capital and



Fig. 12. Evidence from site A.
Source: Taken by first author during prior field visit

community networks is crucial for mitigating vulnerabilities and enhancing resilience at site A that was previously affected by a tsunami (Acanga et al., 2026a; Acanga et al., 2026b).

Enlisting critical stakeholders, such as the National Disaster Management Authority at federal and state levels, along with academic institutions and research organizations, can enhance community resilience in both locations. The implementation of this approach will improve the collection, monitoring, analysis, and dissemination of essential data on land use changes, shoreline dynamics, and ecosystem health. This will support the development of participatory adaptive management strategies. Routine engagement of community members in disaster drills can reinforce these efforts. Decentralizing risk education in the formal schooling system at both sites is also important.

7. Conclusion and recommendations for future research

The study highlights the urgent need for context-specific and evidence-based disaster risk reduction (DRR) strategies to enhance community disaster resilience (CDR) in coastal areas of India, particularly in light of increasing vulnerability due to climate change and anthropogenic pressures. By employing Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA), the research identifies significant disparities in vulnerability between two coastal sites, emphasizing the critical role of local ecological knowledge and community engagement in developing adaptive strategies. The findings underscore the importance of integrating socio-ecological systems frameworks that account for both structural limitations and community agency, advocating for a shift from reactive to proactive disaster management approaches. Policy recommendations include the implementation of nature-based solutions, improved infrastructure planning, and the promotion of sustainable livelihoods, all aimed at fostering resilience and mitigating the impacts of extreme weather events. Ultimately, the study calls for a collaborative approach involving local communities, stakeholders, and policymakers to create sustainable futures for vulnerable coastal populations.

Arising from this study, the under listed recommendations are made to guide future research.

1. It is recommended that future studies explore the integration of local ecological, social, and economic factors in the formulation of context-specific disaster risk reduction strategies to effectively tackle unique vulnerabilities.
2. It is suggested for future studies to focus on integrating local parameters and community-specific data into hybrid models, like Bayesian Networks. This approach could enhance the accuracy and applicability of risk assessments, ultimately guiding policy and practice more effectively.
3. It is necessary to conduct studies that explore the dynamics underlying the interactions between social, ecological, and economic systems in coastal communities. This research should focus on identifying factors that enhance adaptive capacity and resilience within at-risk communities.
4. Future studies should focus on assessing the effects of infrastructure-led development on the vulnerability of coastal regions and explore strategies for optimal disaster-proof urban planning.

CRediT authorship contribution statement

Acanga Alfred: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Sreekrishnan Ravi:** Writing – review & editing, Validation, Conceptualization. **Sabarinath S.:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis. **Maneesha V. Ramesh:** Writing – review & editing, Supervision, Software, Formal analysis. **Hariprasad K.M.:** Writing – review & editing, Visualization, Validation, Investigation, Data curation, Conceptualization.

Ethics and declaration

Ethical Approval is not applicable to this manuscript.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Declaration of the use of AI assisted technologies

During the preparation of this work the authors used QuillBot to enhance the readability of the work and spell checking. The authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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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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