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# Nature-Based Coastal Restoration for Sea-Level Rise Adaptation and Resilience: A Case Study from Southwest India

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## ABSTRACT

In the Southern coast of India, the Kanyakumari coast is climate-sensitive and fragile in nature, which can increase the vulnerability to climate hazards such as sea level rise, shoreline erosion and coastal floods, tsunamis, and tropical cyclones. This study analyzes the shoreline vulnerability to the impact of sea level rise and evaluates the possibility of nature-based solution as an ecosystem pathway to the coastal region to mitigate the impact of impacts. The study integrates the risk in sea level rise and shoreline assessments with a household survey of 1,653 respondents across 44 coastal villages, complemented by key informant interviews, focus group discussions, and stakeholder consultations conducted during December 2022–February 2023. The perception of the survey indicated that the conventional grey solution remains the dominant adaptation approach (39.2%), followed closely by hybrid approaches integrating grey and green solution measures (38.6%), whereas green solution accounts for 22.2% of current adaptation practices. However, most of the respondents in the coastal region recognized substantial multidimensional benefits of NbS, particularly ecosystem restoration (29.7%), coastal-hazard reduction (26.5%), cost-effective adaptation for sea level rise (24.9%), and enhancement livelihood (14.2%). This study found that the local residents along the coastal region have recognized the importance of green solutions, especially the exposed communities, although persistent knowledge and implementation gaps remain the grey and green solution of sea level rise adaptation. This study aims to implement a green solution to increase the climate resilience to mitigate the impact of sea level rise with the support of indigenous ecological knowledge, participatory governance, and climate-informed coastal-zone management.

**Keywords** Coastal retreat, Kanyakumari, Sea level rise, Shoreline, Nature-based solution.

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## INTRODUCTION

Sea-level rise (SLR) is a significant outcome of climate change, posing a threat to low-lying coastal

areas through flooding, erosion, severe weather events, saltwater intrusion, and the deterioration of ecosystems. In India, around 82,000 km² of coastal regions with low elevation are at risk from SLR, impacting ecosystems, infrastructure, and the livelihoods of nearly 63 million individuals (Das and Swain 2024; Veeran *et al.* 2024; Visvalingam *et al.* 2024; Neumann *et al*. 2015; McGranahan *et al*. 2007). The rate of SLR along the Indian coast is estimated to be between 1.7 and 3.3 mm per year, with some particularly vulnerable areas experiencing rates over 4–5 mm per year (Mondal *et al.* 2021; Qu *et al*. 2023). These challenges underscore the necessity for integrated, science-driven, and socially inclusive adaptation strategies that incorporate resilient infrastructure, ecosystem preservation, policy measures, and community involvement (Tiwari *et al*. 2022, Riera-Spiegelhalder *et al.* 2023).

Nature-based Solutions (NbS) offer a promising approach by mitigating wave energy, erosion, flooding, and storm impacts while promoting sediment accumulation, biodiversity, carbon sequestration, and livelihoods (Jordan and Fröhle 2022; Favero and Hinkel 2024; Santhanam and Kundu 2022; Cahoon *et al*. 2021; Barbier *et al.* 2011). However, their success is contingent upon local ecological, geomorphological, climatic, and socio-economic factors (Sales 2026, (Siddappanavara and Jaganathan 2026).

The Kanyakumari coast is particularly susceptible to SLR and hydro-climatic threats, impacting ecosystems, infrastructure, and coastal populations (Mathew and Agarwala 2025; Swornamma *et al.* 2024; Veeran *et al.* 2022). While hard-engineering solutions are prevalent for shoreline protection, ecosystem-based strategies such as mangrove restoration, salt-marsh rehabilitation, oyster reefs, bamboo barriers, and living breakwaters provide complementary options (Swornamma *et al.* 2026; McQuarrie 2024). However, there is a scarcity of studies evaluating their local feasibility and effectiveness. Consequently, this study formulates an integrated NbS framework for Kanyakumari by assessing SLR-related threats, coastal vulnerability, and ecosystem-based adaptation possibilities to facilitate sustainable and climate-resilient coastal planning(Ghosh and Mistri 2023; Yasmeen *et al.* 2024).

## MATERIALS AND METHODS

### Study Area

The Kanyakumari coastline in Tamil Nadu, India (77°02′–77°35′ E and 8°15′–8°30′ N; Fig. 1) serves as the study area, spanning roughly 1,672 km² and incorporating 44 fishing villages. Over 17% of the district's population lives along this coast. This region is densely populated, with 1,119 people per km², and is known for its dynamic nature and susceptibility to erosion. It is home to ecologically significant resources, growing settlements, and international tourism. The coastline features a variety of landforms, such as beach ridges, bars, dunes, pediplains, meander scars, pediments, inselbergs, brackish-water creeks, deltaic and alluvial plains, and steep slopes. The diverse soils, shaped by marine sedimentation, river processes, and intense tropical weathering, affect land use, agricultural output, and ecosystem resilience (Veeran *et al.* 2024). Fishing communities like Enayam, Muttam, Kodimunai, Colachel, and Neerodi have seen significant shoreline changes, with erosion and accretion rates peaking at 5.01 and 3.77 m per year, respectively (Sam and Gurugnanam 2022). Over 70% of the coastline is deemed highly vulnerable to erosion, posing risks to coastal infrastructure, fisheries-based livelihoods, and local communities. Coastal hazards are exacerbated by extreme events such as tsunamis and tropical cyclones, especially in low-lying areas with sparse protective vegetation.

### Climate Risk, Vulnerability, and Resilience Assessment of the Study Area

The Kanyakumari coastline is increasingly vulnerable to climate threats, such as rising sea levels (SLR) and more severe hydro-meteorological events (Jeganathan *et al.* 2021; Veeran *et al.* 2022 2024; Fig. 2). Over the last twenty years, almost 90% of documented disasters have been linked to climate, including the 2004 tsunami, cyclones, powerful waves, erosion and flooding. The Low Elevation Coastal Zone (LECZ) is densely populated, with approximately 1,106 people per km². A forecasted SLR of about 1.3 mm per year could lead to the permanent flooding of roughly 13 km² with a 1 m rise, impacting over 17% of the LECZ's population by

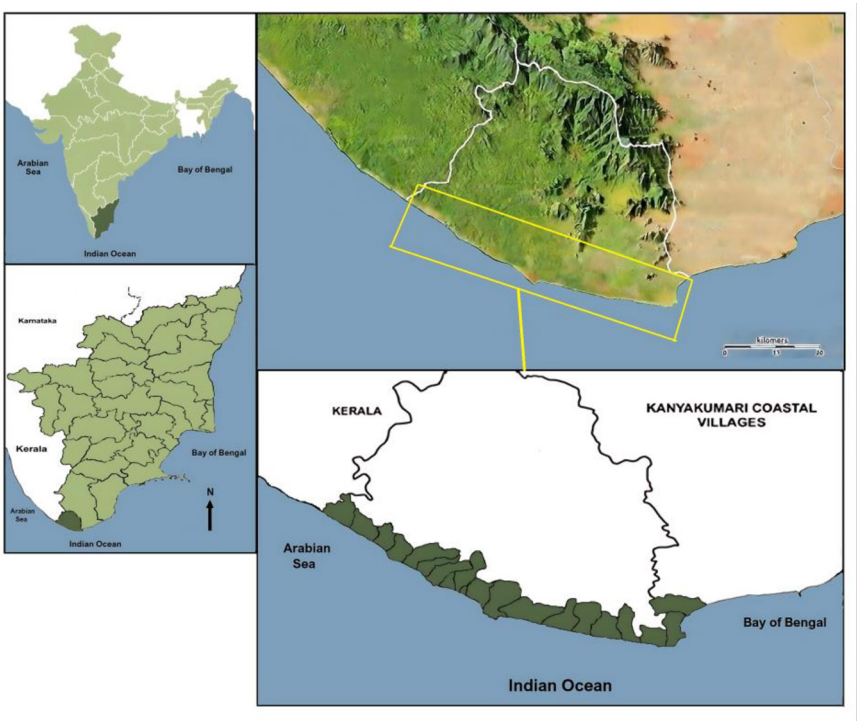


**Fig. 1.** Location of the study area, the coast of Kanyakumari district, Tamil Nadu, India.

2100 (Natesan and Parthasarathy, 2010; Swornamma *et al.* 2026). Approximately 70% of the Southwestern coast is highly susceptible to erosion, with some villages experiencing rates of 3–5 m per year (Sekar




**Fig. 2.** Major Drivers of Coastal Vulnerability and Environmental Degradation in Kanyakumari District. **(A)** Shoreline erosion in the Vallavilai coastal village, **(b)** High-Energy Wave Regimes and Coastal Erosion in Thengapattinam, **(c)** Impacts of beach sand mining on coastal stability and erosion in Rajakkamangalam, **(d)** Plastic pollution in Enayam coastal village.

**Table 1.** Composition of stakeholders surveyed from December 2022 to February 2023.

| Stakeholder group | Respondents (%) |
|---|---|
| Local residents | 54.7 |
| Students and teachers | 27.5 |
| Community leaders | 11.4 |
| Policymakers | 3.8 |
| Climate experts | 2.6 |
| Total | **100** |

*et al*. 2024; Nguyen *et al.* 2022). Additionally, SLR exacerbates seawater intrusion and deteriorates groundwater quality (Sangeetha *et al.* 2020). These challenges underscore the necessity for adaptation strategies that are locally specific, ecosystem-based, cost-efficient, and community-focused.

Indigenous knowledge held by coastal communities is a valuable asset that can enhance climate adaptation when combined with scientific evaluations and participatory planning processes. This research employed Key Informant Interviews (KIIs), household surveys, focus group discussions, and stakeholder consultations to evaluate perceptions of sea-level rise (SLR), coastal vulnerability, and the relevance of Nature-based Solutions (NbS) along the Kanyakumari coast (A and Maity 2024; Martín *et al.* 2020; Brillinger *et al.* 2021; Wijsman and Berbés-Blázquez 2022 Chrisben Sam and Gurugnanam 2023). A survey of stakeholders, conducted from December 2022 to February 2023, involved local residents (54.7%), students and teachers (27.5%), community leaders (11.4%), policymakers (3.8%), and climate experts (2.6%), (Table 1). The use of standardized protocols and the triangulation of both quantitative and qualitative data improved the assessment's reliability and facilitated the evaluation of locally suitable shoreline protection and climate-resilient adaptation strategies (Lacambra S *et al.* 2024).

## RESULTS AND DISCUSSION

### Findings

In a survey conducted among 1,653 households across 44 fishing villages along the Kanyakumari coast, researchers evaluated the vulnerability to sea-level rise (SLR) and explored ecosystem-based adaptation strategies. Communities identified as vulnerable exhibited a higher percentage of elderly and dependent individuals, smaller family units, and lower levels of education. Approximately 80% of those surveyed rely on marine resources for their livelihoods, heightening their susceptibility to climate-related hazards. The risk evaluation considered both natural and human-induced threats, along with exposure and vulnerability metrics, to assess community-level risk and resilience (Chilton *et al.* 2021; Mathew and Agarwala 2025). Participants pointed to SLR, the increasing frequency and severity of tropical cyclones, degradation of coastal ecosystems, infrastructure weaknesses, shoreline erosion, and saltwater intrusion as significant climate-related challenges. The results underscore the necessity for suitable coastal protection strategies, incorporating both ecosystem-based solutions and hard-engineering approaches, to mitigate coastal exposure and vulnerability to emerging climate threats.

### Analysis of the household survey on sea-level-rise vulnerability in Kanyakumari coastal villages

The household survey reveals a significant awareness of complex coastal-climate risks among the villages in Kanyakumari (Fig. 3). Shoreline erosion has a considerable impact on livelihoods, income, assets, household well-being, and living standards (Gusha *et al*. 2026). Sea-level rise (SLR) and tropical cyclones emerged as the most prevalent hazards in all 44 villages surveyed, followed by land loss (42 villages), ecosystem degradation (41 villages), and infrastructure risks (41 villages) (Fig. 3a). These results suggest that coastal vulnerability arises from the interplay of gradual SLR with cyclone-induced flooding, shoreline instability, and ongoing land and ecosystem degradation. Seawater intrusion and coastal inundation, reported by 44% and 46% of respondents, respectively, are additional factors impacting freshwater resources, settlements, and livelihoods. Respondents expressed strong preferences for policy support, engineering protection, and financial assistance, while ecosystem restoration and community participation were less recognized, highlighting a lack of awareness and institutional backing for nature-based adaptation (Hallegatte *et al*. 2011; Wamsler *et al.* 2020). These findings underscore the necessity for integrated coastal resilience strategies

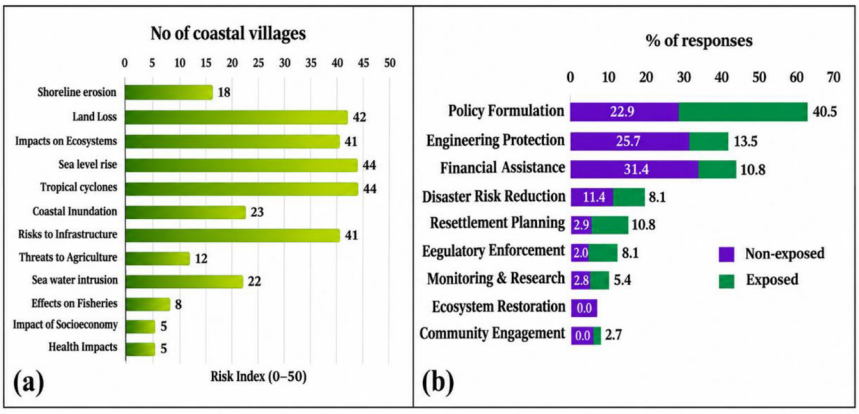


**Fig. 3. (a)** Household Vulnerability to Sea-Level Rise: Evidence from 44 Coastal Villages and, **(b)** Environmental Degradation in Kanyakumari District.

that combine ecosystem-based adaptation, resilient infrastructure, livelihood protection, financial mechanisms, and participatory governance (Fig. 3b).

The survey also uncovered a growing perception of household climate vulnerability and susceptibility, with 92.6% and 92.7% of respondents, respectively, noting increases (Fig. 4a). Meanwhile, 90.1% reported enhanced climate resilience, indicating active coping and adaptation at the household level. This simultaneous increase in vulnerability and resilience illustrates a resilience–vulnerability paradox, suggesting that current adaptive capacity may not sufficiently counteract escalating coastal hazards (Fig. 4b). Consequently, the results emphasize the need for coordinated, multi-level adaptation that integrates ecosystem-based approaches, resilient infrastructure, institutional support, and community-based risk governance (Tota *et al.* 2026).

## Analysis of adaptation practices and the benefits of Nature-based Solutions (NbS) for sea-level rise

The household survey reveals that grey infrastructure is the most frequently employed adaptation strategy for addressing shoreline erosion and sea-level rise (SLR) impacts, with 39.2% of respondents favoring it. This is closely followed by hybrid methods at 38.6%, and green/Nature-based Solutions (NbS) at 22.2% (Fig. 5). While grey solutions offer immediate protection against erosion and powerful waves, they can interfere with sediment transport, exacerbate downstream erosion, and necessitate ongoing maintenance as SLR accelerates. The relatively low uptake

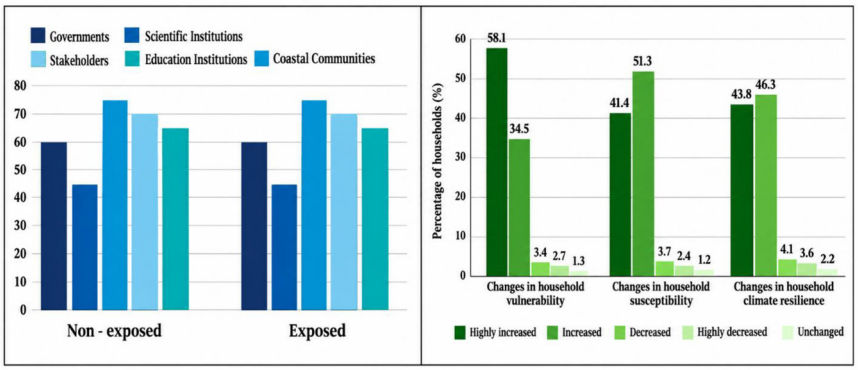


**Fig. 4. (a)** Comparative assessment of household vulnerability to coastal hazards in exposed and non-exposed coastal villages, **(b)** The Coastal resilience–vulnerability paradox: Household-level evidence of rising susceptibility and adaptive capacity.

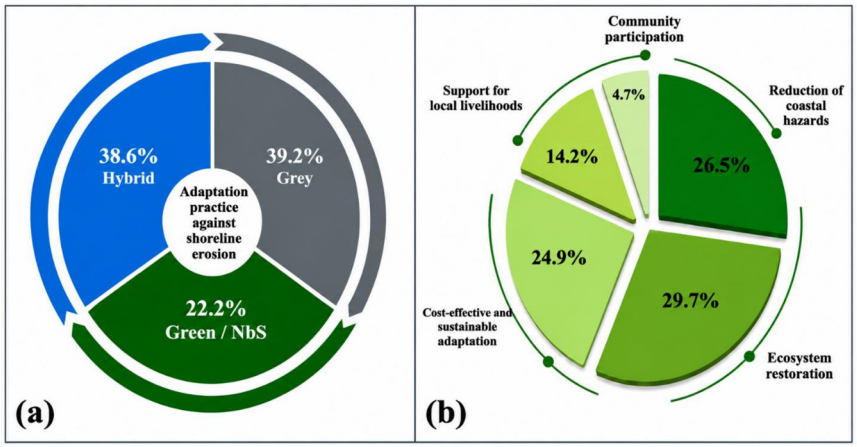


**Fig. 5 (a)** Shoreline erosion adaptation strategies and coastal resilience measures for the study area, **(b)** Household perceptions of Nature-Based Solutions (NbS) for coastal adaptation and resilience.

of NbS underscores a gap in both implementation and awareness, despite their long-term ecological and climate resilience advantages (Cohn *et al.* 2021). Conversely, the strong inclination towards hybrid approaches suggests an increasing acceptance of integrating engineered defenses with ecosystem restoration to mitigate coastal risks.

Respondents highlighted several advantages of NbS, such as ecosystem restoration (29.7%), reduction of coastal hazards (26.5%), cost-effective SLR adaptation (24.9%), and support for livelihoods (14.2%) (Fig. 5b). These insights indicate a gradual transition from traditional engineering solutions to integrated coastal resilience strategies that include mangrove restoration, wetland conservation, and living shorelines (Sarker *et al.* 2024; Ayassamy 2025). However, adaptation decisions are still shaped by local knowledge, economic viability, and community preferences. Awareness of NbS was slightly greater among communities exposed to coastal hazards compared to those not exposed. About 32.3% of respondents from exposed villages viewed NbS as effective, compared to 28.7% from non-exposed villages, while "somewhat effective" responses were 32.8% and 30.4%, respectively (Fig. 6). On the other hand, rejection rates were higher in non-exposed villages (13.3%) than in exposed ones (9.3%) (Table 2). This suggests that direct exposure to coastal hazards may enhance acceptance of ecosystem-based adaptation, although ongoing uncertainty points to persistent gaps in awareness and confidence regarding the effectiveness of NbS.

Overall, the findings illustrate that SLR impacts arise from the interplay of social, ecological, and economic factors, leading to land inundation, livelihood disruption, infrastructure damage, displacement, biodiversity loss, and ecosystem degradation. Effective coastal adaptation thus necessitates community-level ecosystem protection and sustainable livelihood strategies, supported by participatory governance (Arkema *et al*. 2017). A locally tailored NbS framework should incorporate community involvement, scientific expertise, policy backing, multi-level governance, and dedicated funding mechanisms (Roy *et al*. 2023; Fan *et al.* 2018). A hybrid governance approach, combining bottom-up and top-down strategies, can further ensure that adaptation measures are tailored to site-specific socio-economic, ecological,

**Table 2.** Categorical comparison of perceived Nature-based Solutions (NbS) effectiveness in exposed and non-exposed coastal villages.

| Response category | Exposed villages (%) | Non-exposed villages (%) | Difference (pp) |
|---|---|---|---|
| Effective | 32.3 | 28.7 | +3.6 |
| Somewhat effective | 32.8 | 30.4 | +2.4 |
| Rejection of NbS | 9.3 | 13.3 | −4.0 |

**Note:** Difference = exposed villages − non-exposed villages; pp = percentage points. Values represent survey-based perceptions, not measured pre-/post-restoration outcomes.

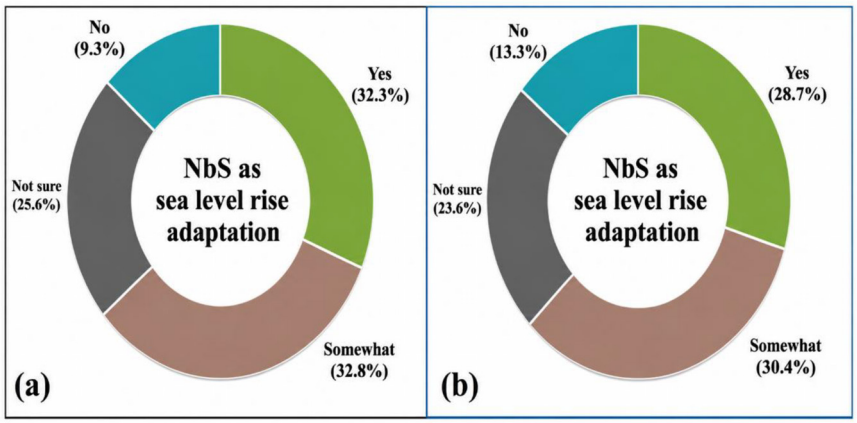


**Fig. 6.** **(a)** Nature based solutions for SLR adaptation in exposed coastal villages in the study area, **(b)** Nature based solutions for SLR adaptation in non -exposed coastal villages in the study area.

and climatic conditions, thereby enhancing long-term coastal resilience (Wang *et al.* 2025).

## Integrating NbS for climate-resilient shoreline management and coastal adaptation

Coastal erosion along the Kanyakumari shoreline is influenced by rising sea levels, cyclonic events, powerful waves, and shifts in littoral dynamics (Krishna *et al.* 2023). Significant erosion is observed in areas such as Kovalam, Murungavilai, Mandaikadu, Enayamputhenthurai, Sanguthurai, Chothavilai, Midalam and Muttom (Abijith *et al*. 2023). Due to the limitations of seawalls and groynes, sustainable alternatives can be found in nature-based and eco-engineering strategies. Restoring mangroves in the Thamirabarani, Pazhayar, and Manakudy regions can help reduce wave energy and encourage sediment build-up, while Ipomoea pes-caprae, wetlands, and marshes can help stabilize beaches and mitigate storm effects (Sánchez-Núñez *et al*. 2019; Pande and Nayak 2013). Measures such as sand-dune restoration, artificial reefs, beach nourishment, and sediment management can enhance these efforts in at-risk areas (Joy and Gopinath 2021; Escudero *et al.* 2020; Finkl and Walker 2018). By integrating mangroves, dunes, wetlands, and salt marshes, the impacts of cyclones and floods can be minimized, while also supporting carbon storage, biodiversity, and local livelihoods. Therefore, Kanyakumari should adopt a proactive approach to ecosystem-based and hybrid adaptation in line with CRZ and climate-policy frameworks (Veeran *et al*. 2024; Kausher *et al.* 2025).

## Harnessing NbS to build climate resilience against seawater intrusion

Kanyakumari's coastal communities are increasingly experiencing seawater intrusion, driven by factors such as rising sea levels, excessive groundwater extraction, powerful waves, shoreline erosion, and inadequately designed coastal infrastructure (Hussain and Javadi 2016; Vinayaraj *et al*. 2011; Swornamma *et al.* 2024). The relative sea-level rise is approximately 1.8 mm per year, with seawater reaching up to 750 meters inland in regions like Colachel, Kadiyapattinam, Mandaikadu, and Vaniyakudy. This saline intrusion has compromised groundwater and freshwater resources, including shallow wells, creeks, and the AVM canal, impacting irrigation, agriculture, drinking water supply, and coastal livelihoods.

To mitigate these challenges, sustainable groundwater management and Nature-based Solutions (NbS) can be employed. These include controlling groundwater extraction within a 5 km coastal buffer, implementing rainwater harvesting, recycling wastewater, and enhancing aquifer recharge (Lazarova *et al.* 2011). Preserving natural sand dunes in areas like Ra-

**Table 3.** NBS for Coastal Adaptation Plan for sea level rise in Kanyakumari coast.

| Indicator | Description | Affected villages | Nature best solution (NbS) |
|---|---|---|---|
| Coastal Protection | Shoreline erosion | Sanguthurai, Chothavilai, and Midalam Muttom | • Plant native mangrove species in affected area<br>• Beach nourishment to stabilized shorelines<br>• Restoration of sand dunes to safeguard against erosion<br>• Raising habitat and infrastructure above flood level in low-lying areas |
| Disaster risk Management | Tropical cyclone and floods | Entire coastal villages in the study area | • Integrating green engineering with NbS will improve coastal defense<br>• Revitalize the community- led initiatives of deteriorated mangroves<br>• Restoration of wetland and sand dunes<br>• Agroforestry within inducted coastal hinterlands<br>• Disaster preparedness, hazard mapping, and cyclone warning |
| Wetland Management | Mangrove ecosystem | Manakudy and Rajakkamangalam | • Rehabilitation of mangrove forests and community-led mangrove nurseries<br>• Cultivate negative climate-resilient mangrove species<br>• Expanded mangrove ecosystems as marine protected areas (MPAs)<br>• Promote sustainable livelihoods for the local community in the mangrove forest area |
| Coastal Management | Sand dunes | Chothavilai, Pallamthurai, Sanguthurai, Periakadu, Chinnavilai, Rajakka mangalam and Muttom | • Planting black pine forests on the edges of the dunes<br>• Ecotourism and recreation activities<br>• "Sand Engine" model<br>• Community-driven initiative to plant native and drought-tolerant species |
| Water Management | Sea water intrusion | Azhikal, Pillithoppu, Colachel and Muttom | • Develop adaptive stormwater management<br>• Remove coastal defence structures<br>• Sand dunes function as natural rainwater harvesting system practices<br>• Restoration of the natural coastal buffers<br>• Rainwater harvesting, water recycling systems, and drought mitigation techniques |
| Off shore Management | Coral reef | Enayam, Kovalam, Puthenthope | • Coral gardening<br>• Artificial reefs<br>• Integrated coastal management<br>• Implement watershed management |
| Sustainable agriculture | Coconut crop | Entire Kanyakumari coastal villages | • Climate risk management like early warning systems, climate-resilient genotypes and crop insurance<br>• Coconut-based farming systems (CBFS)<br>• Coconut orchards protect against storms and cyclones.<br>• Salt-tolerant coconut crops<br>• Effective irrigation systems |
| Sustainable Tourism | Coastal tourism | Kanyakumari Sanguthurai Muttom, Kovalam Beach | • Restoration of wetlands and dunes promotes tourism<br>• Mitigate erosion and the loss of biodiversity<br>• Encourage tourists to participate in restoration efforts<br>• Swach Bharat Campaign |

jakkamangalam, Periyakadu, and Muttom can serve as hydrogeological barriers against seawater intrusion (Stuyfzand 2017). Additionally, restoring mangroves, salt marshes, and native coastal vegetation such as Spinifex littoreus can help reduce wave energy, stabilize shorelines, and safeguard coastal aquifers (Dabalà *et al*. 2023; Jay 2021). Other measures should involve improving drainage and flood management, limiting development in high-risk zones, restoring coastal buffers, and selectively redesigning rigid structures to reinstate natural sediment and hydrological processes (Schoonees *et al.* 2019; Dewi *et al.* 2023). Hybrid interventions and the restoration of the AVM canal can further enhance freshwater security and bolster




**Fig. 7(a)** Mangrove restoration for enhancing coastal resilience in the Manakudy coastal villages, **(b)** Community-led mixed vegetation restoration for enhancing shoreline resilience in the Rajakkamangalam coastal belt, **(c)** Enhancing coastal resilience through Ipomoea pes-caprae–NbS for sand-beach erosion Mitigation at Pillaithoppu coastal village, **(d)** Restoring coastal resilience through Indian screw pine planting for shoreline erosion mitigation in Ganapathypuram coastal village.

long-term coastal resilience.

## Integrating coastal zone management by NbS to enhance climate resilience for shoreline erosion

Coastal wetlands face threats from rising sea levels, yet mangroves offer natural defense for shorelines and aid in carbon storage, with an average rate of 210 g $m^{-2}$ $yr^{-1}$ (Sasmito *et al.* 2016; Chmura *et al.* 2003). Although the rocky and high-energy coast of Kanyakumari restricts widespread mangrove growth, restoration efforts in protected estuaries like Manakudy, Rajakkamangalam, Thengapattinam, and Kadiapattinam can boost flood defense, carbon sequestration, groundwater replenishment, biodiversity, and shoreline stability (Chow 2018). To sustain salinity and sediment dynamics, it is crucial to restore tidal connectivity and eliminate hydrological barriers (Balwan and Kour 2021; David *et al.* 2016). Species resilient to climate change, such as Avicennia marina, A. officinalis, Rhizophora mucronata, and Acanthus ilicifolius, can aid restoration efforts, alongside natural regeneration, protected zones, zoning regulations, and monitoring through remote sensing (Awazi 2025; Nath *et al.* 2023; Zhao and Liu 2020). Enhancing coastal protection and supporting fisheries, biodiversity, and local livelihoods can be achieved through mangrove restoration, bamboo dykes, and wetland rehabilitation.

Coconut cultivation along the western coast of Kanyakumari is increasingly at risk due to erosion, cyclones, flooding, and saltwater intrusion (Swornamma *et al.* 2024). A sea level rise of 1 meter could submerge over 20% of coastal coconut farms (Natesan and Parthasarathy 2010). By integrating coconut agroforestry with salt-resistant plants, windbreaks, mangroves, and wetlands, soil stability, moisture retention, and groundwater recharge can be enhanced. Agricultural resilience can be further bolstered through early-warning systems, climate-resilient crop varieties, crop insurance, and climate-risk management strategies (Faria *et al.* 2026; Saravanan *et al.* 2023). Table 3 provides a summary of site-specific Nature-based Solutions (NbS) strategies.

## Empowering negative inhabitants through local leadership for coastal climate resilience

Successful implementation of Nature-based Solutions (NbS) hinges on robust institutional backing, clear

governance, active community involvement, and heightened public awareness. The involvement of local communities, leaders and indigenous knowledge is crucial for coastal adaptation that suits local needs (Onwubiko and Aheto 2026). In areas like Manakudy, Rajakkamangalam, Colachel and Kadiapattinam, engaging communities in mangrove restoration and ecosystem management can bolster long-term resilience (Fig. 7). Additionally, integrating mangroves with bio-seawalls or offshore reefs can enhance wave reduction (Perricone *et al.* 2023). Although educational levels are high at 82.02%, only 20.7% of the population is aware of the impacts of coastal climate change (IPCC 2021; Veeran *et al.* 2022). Therefore, to enhance community-driven NbS efforts, there is a need for focused awareness campaigns, training, coastal conservation initiatives, and better access to climate finance and technical resources (Conti *et al*. 2021; Niu *et al*. 2023; Vicarelli *et al.* 2024).

## CONCLUSION

The evaluation of sea-level rise (SLR) along the Kanyakumari coast indicates significant vulnerability due to the interplay of geomorphological and socio-economic elements, underscoring the importance of comprehensive adaptation strategies. Current hard-engineering solutions, such as seawalls, groynes, and breakwaters, might offer limited defense but could also impact coastal livelihoods and social fairness. In this climate-sensitive environment, Nature-based Solutions (NbS) present a viable option by boosting shoreline resilience, restoring ecosystem functions, promoting livelihood diversification, and decreasing reliance on hard infrastructure. Combining NbS with traditional ecological knowledge and participatory coastal governance can enhance socio-ecological resilience and adaptive capacity. Consequently, the study offers a scientific foundation for crafting equitable, location-specific adaptation strategies to tackle sea-level rise, erosion, cyclones, and coastal flooding while fostering sustainable coastal development in Kanyakumari.

### REFERENCES


Abijith, D., Saravanan, S., & Sundar, P. K. S. (2023). Coastal vulnerability assessment for the coast of Tamil Nadu, India—a geospatial approach. *Environmental Science and Pollution Research*, 30 (30), 75610—75628. https://doi.org/10.1007/s11356-023-27686-8

Arkema, K. K., Griffin, R., Maldonado, S., Silver, J., Suckale, J., & Guerry, A. D. (2017). Linking social, ecological and physical science to advance natural and nature-based protection for coastal communities. *Annals of the New York Academy of Sciences*, 1399 (1), 5—26. https://doi.org/10.1111/nyas.13322

Awazi, N. P. (2025). Southern Africa's Coast: Mangroves for Resilience in the Face of Climate Change. In Building Climate Resilient Communities Along Africa's Coasts: The Role of Mangroves (pp, 101–121). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-90843-9_5

Ayassamy, P. (2025). Mangroves as a nature-based solution and a tool for coastal resilience. Wetlands, 45 (6), 89. https://doi.org/10.1007/s13157-025-01971-3

Balwan, W. K., & Kour, S. (2021). Wetland-an ecological boon for the environment. *East African Scholars Journal of Agriculture and Life Sciences,* 4(3), 38—48.

Barbier, E. B., Hacker, S. D., Kennedy, C., Koch, E. W., Stier, A. C., & Silliman, B. R. (2011). The value of estuarine and coastal ecosystem services. *Ecological monographs,* 81 (2), 169—193. https://doi.org/10.1890/10-1510.1

Brillinger, M., Henze, J., Albert, C., & Schwarze, R. (2021). Integrating nature-based solutions in flood risk management plans: A matter of individual beliefs ? *Science of the Total Environment*, 795, 148896. https://doi.org/10.1016/j.scitotenv.2021.148896

Cahoon, D. R., McKee, K. L., & Morris, J. T. (2021). How plants influence resilience of salt marsh and mangrove wet lands to sea-level rise. *Estuaries and Coasts*, 44 (4), 883—898. https://doi.org/10.1007/s12237-020-00834-w

Chilton, D., Hamilton, D. P., Nagelkerken, I., Cook, P., Hipsey, M. R., Reid, R., Sheaves, M., Waltham, N. J., & Brookes, J. (2021). Environmental flow requirements of estuaries: Providing resilience to current and future climate and direct anthropogenic changes. *Frontiers in Environmental Science*, 9, p, 764218. https://doi.org/10.3389/fenvs.2021.764218

Chrisben Sam, S., & Gurugnanam, B. (2023). End point rate analysis and estimation along the Southwest coast of Kanyakumari, Tamil Nadu, using geospatial techniques. *International Journal of Environmental Science and Technology*, 20 (7), 7463—7476. https://doi.org/10.1007/s13762-022-04374-7

Chmura, G. L., Anisfeld, S. C., Cahoon, D. R., & Lynch, J. C. (2003). Global carbon sequestration in tidal, saline wetland soils. Global Biogeochemical Cycles, 17(4), n/a–n/a. https://doi.org/10.1029/2002GB001917

Chow, J. (2018). Mangrove management for climate change adaptation and sustainable development in coastal zones. *Journal of Sustainable Forestry*, 37 (2), 139—156. https://doi.org/10.1080/10549811.2017.1339615

Cohn, J. L., Copp Franz, S., Mandel, R. H., Nack, C. C., Brainard, A. S., Eallonardo, A., & Magar, V. (2021). Strategies to work towards long-term sustainability and resiliency of nature-based solutions in coastal environments: A review and case studies. *Integrated Environmental Assessment and*

*Management*, 18 (1), 123—134. https://doi.org/10.1002/ieam.4484

Conti, M. E., Battaglia, M., Calabrese, M., & Simone, C. (2021). Fostering sustainable cities through resilience thinking: The role of nature-based solutions (NBSS): Lessons learned from two Italian case studies. *Sustainability*, 13 (22), 12875. https://doi.org/10.3390/su132212875

Dabalà, A., Dahdouh-Guebas, F., Dunn, D. C., Everett, J. D., Lovelock, C. E., Hanson, J. O., Buenafe, K. C. V., Neubert, S., & Richardson, A. J., (2023). Priority areas to protect mangroves and maximise ecosystem services. *Nature Communications*, 14 (1), p, 5863. https://doi.org/10.1038/s41467-023-41333-3

Das, A., & Swain, P. K. (2024). Navigating the sea level rise: Exploring the interplay of climate change, sea level rise, and coastal communities in India. *Environmental Monitoring and Assessment,* 196 (11), 1010. https://doi.org/10.1007/s10661-024-13191-z

David, C. G., Schulz, N., & Schlurmann, T. (2016). Assessing the application potential of selected ecosystem-based, low-regret coastal protection measures. In Ecosystem-based disaster risk reduction and adaptation in practice (pp, 457—482). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-43633-3_20

Dewi, S. P., Kurniati, R., & Ristianti, N. S. (2023). Revealing community capacity for applying rain water harvesting in Semarang coastal areas. *Local Environment*, 28 (11), 1410—1427. https://doi.org/10.1080/13549839.2023.2221891

Escudero, M., Mendoza, E., & Silva, R. (2020). Micro sand engine beach stabilization strategy at Puerto Morelos, Mexico. *Journal of Marine Science and Engineering*, 8 (4), 247. https://doi.org/10.3390/jmse8040247

Fan, J., Wang, Q., Wang, Y., Chen, D., & Zhou, K. (2018). Assessment of coastal development policy based on simulating a sustainable land-use scenario for L iaoning C oastal Z one in C hina. Land Degradation & Development, 29 (8), 2390—2402. https://doi.org/10.1002/ldr.3013

Faria, F., Alam, M. S., Sultana, R., & NUR, M. N. (2026). Integrated Climate-Resilient climate resilient Management in Bangladesh: Policy, Practice and Implications. *Chinese Journal of Urban and Environmental Studies*, 14 (01), 2650003. https://doi.org/10.1142/S234574812650003X

Favero, F., & Hinkel, J. (2024). Key Innovations in Financing Nature-Based Solutions for Coastal Adaptation. Climate, 12 (4), 53. https://doi.org/10.3390/cli12040053

Finkl, C. W., & Jesse Walker, H. (2018). Beach nourishment. In Encyclopedia of Coastal Science (pp, 1—17). Springer, Cham. https://doi.org/10.1007/978-3-319-48657-4_35-2

Ghosh, S., & Mistri, B. (2023). Cyclone-induced coastal vulnerability, livelihood challenges and mitigation measures of Matla–Bidya inter-estuarine area, Indian Sundarban. Natural Hazards, 116 (3), 3857—3878. https://doi.org/10.1007/s11069-023-05840-2

Gusha, M., Mhuru, M., Chitengedza, M., Sabarinath, S., & Ramesh, M. V. (2026). Promoting livelihood diversification in vulnerable rural coastal communities in India. *World Development Perspectives*, 42, 100771. https://doi.org/10.1016/j.wdp.2026.100771

Hallegatte, S., Lecocq, F., & De Perthuis, C. (2011). Designing climate change adaptation policies: An economic frame work. World Bank policy research working paper, (5568). https://ssrn.com/abstract=1761894

Hussain, M. S., & Javadi, A. A. (2016). Assessing impacts of sea level rise on seawater intrusion in a coastal aquifer with sloped shoreline boundary. *Journal of Hydro-environment Research*, 11, 29—41. https://doi.org/10.1016/j.jher.2016.01.003

Intergovernmental Panel on Climate Change. (2021). Climate Change 2021: The Physical Science Basis. Cambridge University Press.

Jay, K. R. (2021). Investigating the role of dune grasses, carbon storage, and marine nutrient subsidies to the functions and services of US Central Atlantic coastal dune ecosystems.

Jeganathan, A., Andimuthu, R., & Kandasamy, P. (2021). Climate risks and socio-economic vulnerability in Tamil Nadu, India: A. Jeganathan *et al*. *Theoretical and Applied Climatology*, 145 (1), 121—135. https://doi.org/10.1007/s00704-021-03595-z

Jordan, P., & Fröhle, P. (2022). Bridging the gap between coastal engineering and nature conservation ? A review of coastal ecosystems as nature-based solutions for coastal protection. *Journal of Coastal Conservation*, 26 (2), 4. https://doi.org/10.1007/s11852-021-00848-x

Joy, A., & Gopinath, A. (2021). The application of reefs in shoreline protection. Handbook of ecological and ecosystem engineering, 295—315. https://doi.org/10.1002/9781119678595.ch16

Kausher, A. H. M., Rahman, A., & Anindita, M. (2025, November). Moribund Delta Management in a Changing Climate: The Case of South-Western Delta in Bangladesh. In International Conference on Water and Environmental Engineering (pp, 866—878). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-032-18708-6_77

Krishna, P. S., Aboobacker, V. M., Ramesh, M., & Nair, L. S. (2023). Remotely induced storm effects on the coastal flooding along the Southwest coast of India. Oceanologia, 65 (3), 503—516. https://doi.org/10.1016/j.oceano.2023.03.003

Lacambra, S. C. L., Spencer, T., Munera, C., Pizarro, V., Lozano-Rivera, P., Esquivel, C., & Cardona, O. D. (2024). Coastal ecosystems contribution to climate adaptation and disasters risk management in the tropical Americas. Nature-Based Solutions, 5, 100112. https://doi.org/10.1016/j.nbsj.2024.100112

Lazarova, V., Emsellem, Y., Paille, J., Glucina, K., & Gislette, P. (2011). Water quality management of aquifer recharge using advanced tools. *Water Science and Technology*, 64 (5), 1161—1168. https://doi.org/10.2166/wst.2011.418

Maity, R. (2024). Coastal vulnerability considering combined effect of tropical cyclones and future sea level rise. *Journal of Coastal Conservation*, 28 (3), 1—17. https://doi.org/10.1007/s11852-024-01055-0

Martín, E. G., Giordano, R., Pagano, A., Van Der Keur, P., & Costa, M. M. (2020). Using a system thinking approach to assess the contribution of nature based solutions to sustainable development goals. *Science of the Total Environment*, 738, 139693. https://doi.org/10.1016/j.scitotenv.2020.139693

Mathew, V., & Agarwala, N. (2025). Impact of climate change on coastal communities and security. *Maritime Technology and Research*, 7 (4), 277917—277917. https://doi.org/10.33175/mtr.2025.277917

McGranahan, G., Balk, D., & Anderson, B. (2007). The rising tide: Assessing the risks of climate change and human settlements in low elevation coastal zones. *Environment and Urbanization*, 19 (1), 17—37. https://doi.org/10.1177/0956247807076960

McQuarrie, F. (2024). Harnessing Oyster Shells for Sustainable Coastal Restoration, Resilience and Ecosystem Enhancement. https://digitalcommons.newhaven.edu/capstones/1

Mondal, I., Thakur, S., Ghosh, P., & De, T. K. (2021). Assessing the impacts of global sea level rise (SLR) on the mangrove forests of Indian Sundarbans using geospatial technology. Geographic information science for land resource management, 209—227. https://doi.org/10.1002/9781119786375.ch11

Natesan, U., & Parthasarathy, A. (2010). The potential impacts of sea level rise along the coastal zone of Kanyakumari District in Tamilnadu, India. *Journal of Coastal Conservation*, 14 (3), 207—214. https://doi.org/10.1007/s11852-010-0103-6

Nath, A., Koley, B., Choudhury, T., Saraswati, S., Ray, B. C., Um, J. S., & Sharma, A. (2023). Assessing coastal land-use and land-cover change dynamics using geospatial techniques. *Sustainability*, 15(9), 7398. https://doi.org/10.3390/su15097398

Neumann, B., Vafeidis, A. T., Zimmermann, J., & Nicholls, R. J. (2015). Future coastal population growth and exposure to sea-level rise and coastal flooding-a global assessment. *PloS one*, 10 (3), e0118571. https://doi.org/10.1371/journal.pone.0131375

Nguyen, N. T., Friess, D. A., Todd, P. A., Mazor, T., Lovelock, C. E., Lowe, R., Gilmour, J., Chou, L. M., Bhatia, N., Jaafar, Z., & Tun, K., (2022). Maximizing resilience to sea-level rise in urban coastal ecosystems through systematic conservation planning. *Landscape and Urban Planning*, 221, p.104374. https://doi.org/10.1016/j.landurbplan.2022.104374

Niu, Y., Abdullayev, V., Alyar, A. V., & Kamran, A. T. (2023). Resilience and adaptation to climate change: Community-based strategies in coastal regions. *Estidamaa*, 2023, 36—43. https://orcid.org/0009-0005-1283-7347

Onwubiko, C. C., & Aheto, D. W. (2026). Perceptions and Awareness on the Perceived Effectiveness of Nature-Based Solutions in Selected Coastal Communities of Rivers State, Nigeria. *Coasts*, 6 (1),7. https://doi.org/10.3390/coasts6010007

Pande, A., & Nayak, G. N. (2013). Understanding distribution and abundance of metals with space and time in estuarine mudflat sedimentary environment. *Environmental Earth Sciences*, 70 (6), 2561—2575. https://doi.org/10.1007/s12665-013-2298-y

Perricone, V., Mutalipassi, M., Mele, A., Buono, M., Vicinanza, D., & Contestabile, P. (2023). Nature-based and bioinspired solutions for coastal protection: An overview among key ecosystems and a promising pathway for new functional and sustainable designs. *ICES Journal of Marine Science*, 80 (5), 1218—1239. https://doi.org/10.1093/icesjms/fsad080

Qu, Y., Jevrejeva, S., & Palanisamy, H. (2023). Are Near-Coastal Sea Levels Accelerating Faster Than Global during the Satellite Altimetry Era ? *Atmosphere*, 14 (10), 1573. https://doi.org/10.3390/atmos14101573

Riera-Spiegelhalder, M., Campos-Rodrigues, L., Ensenado, E. M., Dekker-Arlain, J. D., Papadopoulou, O., Arampatzis, S., & Vervoort, K. (2023). Socio-economic assessment of ecosystem-based and other adaptation strategies in coastal areas: A systematic review. *Journal of Marine Science and Engineering*, 11 (2), 319. https://doi.org/10.1016/j.marpol.2014.09.013

Roy, P., Pal, S. C., Chakrabortty, R., Chowdhuri, I., Saha, A., & Shit, M. (2023). Effects of climate change and sea-level rise on coastal habitat: Vulnerability assessment, adaptation strategies and policy recommendations. *Journal of Environmental Management*, 330, 117187. https://doi.org/10.1016/j.jenvman.2022.117187

Sales, V. G. (2026). Sea Level Rise: Scientific Evidence, Socio-Economic Realities, and Adaptation Challenges for Coastal Communities. *Sea Level Rise*, 17.

Sam, S. C., & Gurugnanam, B. (2022). Coastal transgression and regression from 1980 to 2020 and shoreline forecasting for 2030 and 2040, using DSAS along the Southern coastal tip of Peninsular India. *Geodesy and Geodynamics*, 13 (6), 585—594. https://doi.org/10.1016/j.geog.2022.04.004

Sánchez-Núñez, D. A., Bernal, G., & Mancera Pineda, J. E. (2019). The relative role of mangroves on wave erosion mitigation and sediment properties. *Estuaries and Coasts*, 42 (8), 2124—2138. https://doi.org/10.1007/s12237-019-00628-9

Sangeetha, A., Kumar, P., & Rahman, D. (2020). Assessment of seawater intrusion into shallow coastal aquifer in Kanyakumari District, Tamilnadu, India. *International Journal*, 9 (3), 3006—3014.

Santhanam, H., & Kundu, S. K. (2022). Nature-based solutions (NbS) for sustainable development of the resource base and ecosystem services of marine and coastal ecosystems of India. In Blue-Green Infrastructure Across Asian Countries: Improving Urban Resilience and Sustainability ity (pp, 337—356). Singapore: Springer Singapore. https://doi.org/10.1007/978-981-16-7128-9_15

Saravanan, S., Abijith, D., Kulithalai Shiyam Sundar, P., Reddy, N.M., Almohamad, H., Al Dughairi, A. A., Al-Mutiry, M., & Abdo, H. G. (2023). Multi-Criterion Analysis of Cyclone Risk along the Coast of Tamil Nadu, India—A Geospatial Approach. *ISPRS International Journal of Geo-Information*, 12 (8), p. 341. https://doi.org/10.3390/ijgi12080341

Sarker, M. M. H., Martinez-Hernandez, A. G., Vásquez, J. R., Rivadeneyra, P., & Raimondo, S. (2024). Coastal Infrastruc-

ture and Climate Change adaptation in Bangladesh: Ecosystem services insights from an integrated SES-DAP SIR framework (No. 17.2024). Working Paper. https://hdl.handle.net/10419/300343

Sasmito, S. D., Murdiyarso, D., Friess, D. A., & Kurnianto, S. (2016). Can mangroves keep pace with contemporary sea level rise ? A global data review. *Wetlands Ecology and Management*, 24 (2), 263—278. https://doi.org/10.1007/s11273-015-9466-7

Schoonees, T., Gijón Mancheño, A., Scheres, B., Bouma, T. J., Silva, R. C. C. D. S., Schlurmann, T., & Schüttrumpf, H. (2019). Hard structures for coastal protection, towards greener designs. *Estuaries and Coasts*, 42(7), 1709—1729. https://doi.org/10.1007/s12237-019-00551-z

Sekar, L. G., Androws, X., Annaidasan, K., Kumar, A., Kannan, R., Muthusankar, G., & Balasubramani, K. (2024). Assessment of shoreline changes and associated erosion and accretion pattern in coastal watersheds of Tamil Nadu, India. *Natural Hazards Research,* 4 (2), 231—238. https://doi.org/10.1016/j.nhres.2023.09.008

Siddappanavara, P. M., & Jaganathan, A. (2026). Effectiveness and Scalability of Coastal Nature-based Solutions under Climate Impact Drivers: A Systematic Review. *Evolving Earth*, 100108. https://doi.org/10.1016/j.eve.2026.100108

Stuyfzand, P. J. (2017). Observations and analytical modeling of freshwater and rainwater lenses in coastal dune systems. *Journal of Coastal Conservation*, 21 (5), 577—593. https://doi.org/10.1007/s11852-016-0456-6

Swornamma, J. B. R., Balasubramaniyan, M., & Veeran, Y. (2026). Implications of Sea-Level Rise on the Coastal Villages of Kanyakumari District, Tamil Nadu, India: A Geospatial Perspectives. *Journal of the Indian Society of Remote Sensing*, 54 (2), 791—804. https://doi.org/10.1007/s12524-025-02344-3

Swornamma, J. B. R., Veeran, Y., & Balasubramaniyan, M. (2024). Policy planning and practical implementations of coastal adaptation strategies to reduce the impact of sea level rise in the coastal region of Kanyakumari District, Tamil Nadu, India. *Regional Studies in Marine Science*, 74, 103538. https://doi.org/10.1016/j.rsma.2024.103538

Tiwari, A., Rodrigues, L. C., Lucy, F. E., & Gharbia, S. (2022). Building climate resilience in coastal city living labs using ecosystem-based adaptation: A systematic review. *Sustainability*, 14 (17), 10863. https://doi.org/10.3390/su141710863

Tota, W., Maulud, K. N. A., Noor, N. M., Ariffin, E. H., & Ahmad, A. (2026). Systematic literature review on climate change adaptation strategies of coastal communities in Southeast Asia. *Climate Research*, 96, 1—14. https://doi.org/10.3354/cr01766

Veeran, Y., John Bose, R. S., & Kandasamy, S. (2022). Local Knowledge of Coastal Population to Sea Level Rise and Climate Change–A Case Study in Fishermen Community, Kanyakumari District, Tamil Nadu, India. *Journal of Climate Change*, 8(2), 23-34. https://doi.org/10.3233/JCC220011

Veeran, Y., Swornamma, J. B. R., & Balasubramaniyan, M. (2024). Implications of sea-level rise on the coastal villages of Kanyakumari District, Tamil Nadu, India: A geospatial perspectives. https://doi.org/10.21203/rs.3.rs-4501167/v1

Vicarelli, M., Sudmeier-Rieux, K., Alsadadi, A., Shrestha, A., Schütze, S., Kang, M.M., Leue, M., Wasielewski, D., & Mysiak, J., (2024). On the cost-effectiveness of Nature-based Solutions for reducing disaster risk. *Science of The Total Environment*, 947, p, 174524. https://doi.org/10.1016/j.scitotenv.2024.174524

Vinayaraj, P., Johnson, G., Dora, G. U., Philip, C. S., SanilKumar, V., & Gowthaman, R. (2011). Quantitative estimation of coastal changes along selected locations of Karnataka, India: A GIS and remote sensing approach. http://drs.nio.org/drs/handle/2264/3985

Visvalingam, G., Krishnaraj, S., Andiyappan, R. K., Kamalapathy, R., Datchanamourthy, S. V., & Lagudu, S. (2024). Understanding the impact of climate-induced sea level rise on groundwater inundation in a low-lying coastal area: A numerical simulation in Southeast India. *Regional Studies in Marine Science*, 70, 103401. https://doi.org/10.1016/j.rsma.2024.103401

Wamsler, C., Alkan-Olsson, J., Björn, H., Falck, H., Hanson, H., Oskarsson, T., Simonsson, E., & Zelmerlow, F., (2020). Beyond participation: When citizen engagement leads to undesirable outcomes for nature-based solutions and climate change adaptation. *Climatic Change*, 158 (2), pp, 235—254. https://doi.org/10.1007/s10584-019-02557-9

Wang, H., Han, B., Wu, T., Leung, F., & Ren, Y. (2025). Pre--adopting new urban areas to climate change with coastal nature-based solutions. *Ecological Indicators*, 177, 113693. https://doi.org/10.1016/j.ecolind.2025.113693

Wijsman, K., & Berbés-Blázquez, M. (2022). What do we mean by justice in sustainability pathways ? Commitments, dilemmas, and translations from theory to practice in nature-based solutions. *Environmental Science & Policy*, 136, 377—386. https://doi.org/10.1016/j.envsci.2022.06.018

Yasmeen, A., Pumijumnong, N., Arunrat, N., Punwong, P., Sereenonchai, S., & Chareonwong, U. (2024). Nature-based solution for coastal erosion protection in the muddy coasts: Empirical perceptibility from the Upper Gulf of Thailand. Ocean & Coastal Management, 259, 107488. https://doi.org/10.1016/j.ocecoaman.2024.10748

Zhao, L., & Liu, F. (2020). Land-use planning adaptation in response to SLR based on a vulnerability analysis. Ocean & Coastal Management, 196, 105297. https://doi.org/10.1016/j.ocecoaman.2020.105297