Natural Resources for Human Health

eISSN: 2583-1194

Original Research

Received 17 May 2026
Revised 04 July 2026
Accepted 17 July 2026

Natural Resources for Human Health 2026, Vol. 6 (12s): 1342–1359

KEYWORDS:
Island Ecosystems, Parameters, Data Analysis, Ecological Monitoring.

Assessment of Sediment and Water Regimes in Island Ecosystems of the Gulf of Mannar: Implications for Ecological Monitoring

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ABSTRACT: Island ecosystems are highly dynamic, and this study examined sediment and water regimes across four coral islands in the Gulf of Mannar to evaluate their ecological significance. Sediment and water samples were collected from four islands, with sediment analyses covering grain size, calcium carbonate ($CaCO_3$), organic carbon, organic matter, and key water parameters: pH, salinity, temperature, conductivity, dissolved oxygen (DO), turbidity, and total dissolved solids (TDS). Standardized protocols ensured consistency, and data analysis (ANOVA, correlation, regression, Principal Component Analysis (PCA)) was used to assess spatial variability and interrelationships. Sediment composition varied significantly ($p < 0.05$) in terms of sand, silt, clay, calcium carbonate, organic carbon, and organic matter, with regression analysis revealing a positive trend for silt and negative trends for the other components. PCA (KMO = 0.402; Bartlett's $p < 0.0001$) revealed two principal components explaining 87.05% of total variance, with Component 1 linked to sand, organic carbon, and organic matter, and Component 2 to silt, clay, calcium carbonate, and organic matter. Water parameters also varied significantly ($p < 0.05$); conductivity ($r = 0.369$) and temperature ($r = 0.302$) correlated with island location, while temperature was strongly associated with conductivity ($r = 0.478$) and TDS ($r = 0.405$). PCA (Kaiser-Meyer-Olkin (KMO) = 0.563; Bartlett's $p < 0.0001$) identified ionic strength and thermal regime as key environmental drivers. These findings establish critical baseline data, offering a robust framework that demonstrates how sedimentary composition and physicochemical parameters jointly regulate benthic-pelagic interactions and ecosystem resilience. Overall, island-specific sediment and water patterns exert strong control on ecological processes, providing early detection of environmental shifts and strengthening evidence-based adaptive management. The study offers valuable insights for ecological monitoring and conservation within the Gulf of Mannar region.

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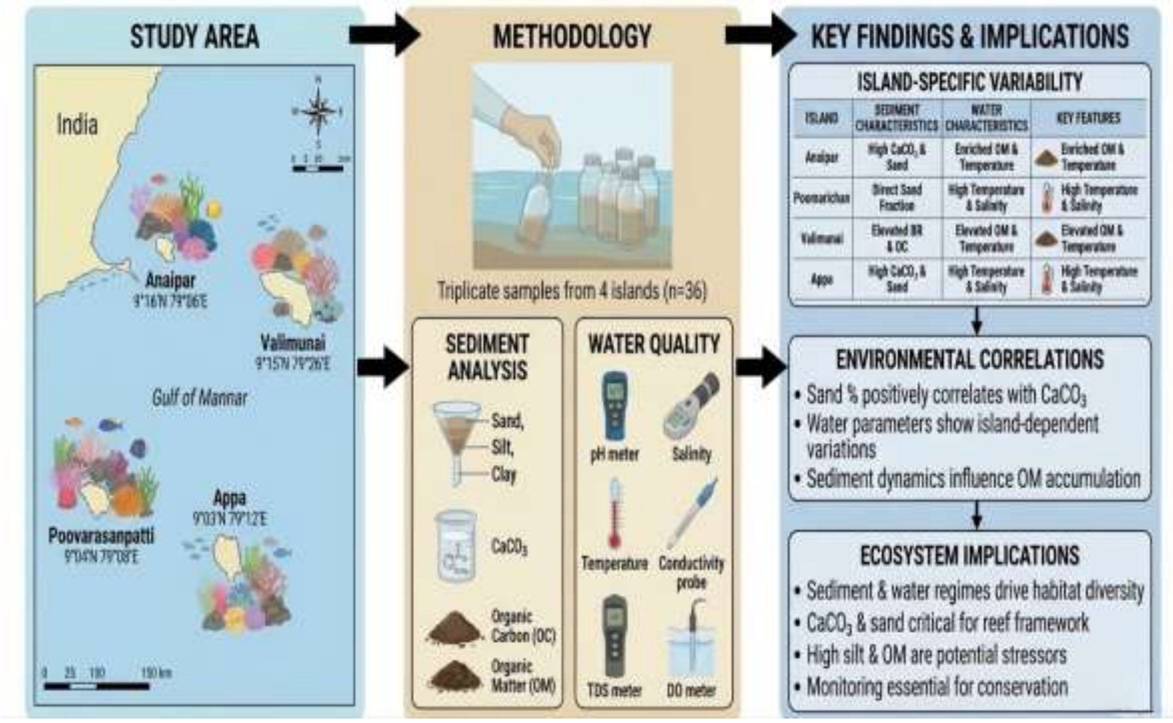
Graphical Abstract



INTRODUCTION

Earth's surface encompasses more than 70% of the seas and oceans, forming the planet's largest biome. The marine ecosystem has an average depth of 3.2 km, shaped by geological processes, chemical and biological events, and environmental transition (Hamid & Yoganandham, 2025; Sandulli *et al.*, 2021). Island ecosystems are fragile systems with unique ecological processes, scarce terrestrial resources, and pronounced vulnerability to environmental change (Whittaker *et al.*, 2007). India has a coastline of about 7500km, with marine patches such as estuaries, lagoons, backwaters, mangroves, salt marshes, coral reefs, offshore waters, and creeks playing a crucial role in ecological balance, supporting fisheries, boosting tourism, and providing livelihoods for coastal communities (Sharma, 2020; Kumar *et al.*, 2013). Among them, the Gulf of Mannar, positioned on the Southeastern coast of India, constitutes a globally significant marine ecosystem of exceptional biodiversity and stands out as a bioregional framework of coastal and shelf ecosystems (Spalding *et al.*, 2007). Marine biodiversity hotspots are increasingly exposed to cumulative pressures from climate change, habitat degradation, and pollution, highlighting the need for integrated monitoring frameworks to enhance ecosystem resilience and conservation effectiveness (Vasileiadou *et al.*, 2024).

The Gulf of Mannar's high-transparency water and well-oxygenated sandy substrate provide favorable conditions for the flourishing of coral assemblages and sensitive benthic organisms (Retnamma *et al.*, 2021). However, Indian Ocean coral reefs demonstrate contrasting responses to thermal stress, with recovery patterns strongly influenced by local environmental conditions that mediate broader climate impacts (Head *et al.*, 2015; Gudka *et al.*, 2016). Excessive fine sedimentation impairs coral health by smothering polyps, limiting light, and altering biogeochemical dynamics (Fabricius *et al.*, 2005; Erftemeijer *et al.*, 2012). Key physical and chemical properties – including temperature, pH, salinity, dissolved oxygen, conductivity, TDS, and turbidity – play pivotal roles in regulating metabolism, structuring species distributions, and sustaining ecosystem productivity (Silambarasan *et al.*, 2013; Retnaningdyah *et al.*, 2023). Recent advances in water-quality assessment demonstrate that monitoring environmental parameters provides critical information for detecting ecological change and supporting coral reef conservation programs (Hondula *et al.*, 2024). In the Gulf of Mannar, sediment fractions such as sand and silt were strongly associated with biodiversity, underscoring the ecological significance of sediment-water regimes in supporting ecological integrity (Ridha *et al.*, 2026). This aligns with broader evidence that natural sediment regimes form a critical foundation for ecosystem management, as they regulate habitat structure, ecological integrity, and long-term resilience (Wohl *et al.*, 2015). Anthropogenic pressures, including overfishing, coral mining, tourism, coastal development, and climate stressors like ocean warming and acidification, collectively threaten the ecological integrity of the Gulf of Mannar islands (Hoegh-Guldberg *et al.*, 2007; Hughes *et al.*, 2017). In the phase of climate change and intensifying human impacts, baseline environmental data are vital for detecting ecological shifts and implementing evidence-based conservation strategies (Mcleod *et al.*, 2010). Complementary studies have also derived seawater quality criteria for copper, cadmium, zinc, and mercury in the coastal and coral reef ecosystems of the Gulf of Mannar, providing ecological thresholds that reinforce the need for integrated monitoring frameworks (Ramakritinan *et al.*, 2026).

Global change drivers disproportionately affect small island ecosystems, where constrained space, limited resources, and high exposure to marine variability restrict adaptive capacity (Kench *et al.*, 2009; Nurse *et al.,* 2014). Recent studies emphasize that island biodiversity hotspots require integrated monitoring frameworks that simultaneously assess the terrestrial and marine components to capture ecosystem-level responses (Cramer *et al.*, 2020). The success of marine protected areas in conservation approach hinges on baseline environmental data and ongoing monitoring of ecological indicators (Edgar *et al.*, 2014; Giakoumi *et al.*, 2017). Recent global assessments further demonstrate that long-term monitoring is essential for evaluating conservation outcomes and ecosystem recovery within marine protected areas (Hopf *et al.*, 2024). Evidence-based adaptive management of marine biosphere reserves demands thorough assessment of environmental drivers and their spatial and temporal variability (Abelson *et al.*, 2016; MacNeil *et al.*, 2019). Spatial and temporal variations of physicochemical parameters in the Gulf of Mannar were reported by (Ramasamy *et al.*, 2010; Karuppiah *et al.*, 2011; Baskar *et al.*, 2015; Kathiravan *et al.*, 2017; Sundararajan *et al.*, 2018; Karikalan *et al.*, 2020; Ravichandran *et al.*, 2022).

Despite the ecological importance of the Gulf of Mannar islands, systematic assessments of sediment and water regimes remain limited, particularly in understanding spatial variability and the environmental drivers shaping ecosystem dynamics. This gap constrains our ability to predict ecological responses to anthropogenic pressures and climate change. Contemporary reef monitoring programs increasingly integrate environmental variables, habitat characteristics, and ecological indicators to improve understanding of ecosystem resilience under climate-driven disturbances (Caccarelli *et al.*, 2026). To address this, the present study conducts a comprehensive evaluation of sediment composition and water quality across four representative coral islands. By applying grain size analysis, geochemical characterization, and multivariate statistics, we (1) characterize spatial variability, (2) identify interrelationships among environmental variables, (3) determine principal components explaining environmental variation, and (4) establish baseline data for long-term ecological monitoring. The findings provide critical insights into the factors controlling island ecosystem processes and strengthen the scientific foundation for conservation planning and adaptive management within the Biosphere Reserve framework.

MATERIALS AND METHODS

Study area

Figure 1: Study Area Map

The Gulf of Mannar Biosphere Reserve is recognized as the first marine biosphere reserve in India and Southeast Asia. Due to its exceptional biodiversity, it is often called a 'Biologist's Paradise'. Stretching in the northeast-southwest direction from

Rameswaram Island to Tuticorin, the region covers a distance of approximately 140 km. It is situated between latitudes 8°35'N to 9°25'N and longitudes 78°08'E to 79°30'E. The core zone comprises 21 coral islands off the coast of Tuticorin and Ramanathapuram districts, located 8 km from the mainland, which the Government of India notified as a Marine National Park in 1989. Anaipar, Valimunai, Poovarasanpatti, and Appa Island, which come under the Keelakarai group, have been chosen as the study area. The framework of all these islands comprises calcareous sandstone, sand, dead reefs, and reef flats. In most cases, narrow sandy beaches with coral rubble are commonly seen across the entire island, while a few of them are dominated by a rocky coast. Well-developed fringing coral reefs, along with coral patches, are observed in all 21 islands (Kumaraguru *et al.*, 2006). Coastal sands with silt and clay dominate the soils of these islands.

Table 1: Study Area Coordinates

Name of the island	Longitude	Latitude
Island I - Anaipar	78.69481°E	9.15294°N
Island II - Vali munai	78.73052°E	9.15354°N
Island III - Poovarasanpatti	78.76695°E	9.15413°N
Island IV - Appa	78.82596°E	9.16582°N

Sample collection and analysis of parameters

Extensive fieldwork was conducted in February 2025 across four selected coral islands: Anaipar Island, Valimunai Island, Poovarasanpatti Island, and Appa Island. From each island, triplicate collections of both sediment and water samples were carried out, resulting in a total of 36 samples to ensure data reliability and consistency. Sampling locations were precisely georeferenced using GPS. At each island, samples were obtained from varying depths, ranging from less than 1 meter to 10 meters, with triplicate sets collected at each depth to maintain analytical accuracy. The bottom water samples were collected in pre-cleaned polythene bottles using an Aqua-trap sampler. The water parameters, such as temperature, salinity, pH, dissolved oxygen (DO), conductivity, total dissolved solids (TDS), and conductivity, were measured using a portable multiparameter analyzer in the field itself. The sediment samples were collected using a manually operated Van Veen grab sampler. Coarse grains and coral debris are eliminated from the sediment, and the cleaned samples are packed in properly labeled polyethylene bags. The sediment samples were pretreated for ecological parameter studies.

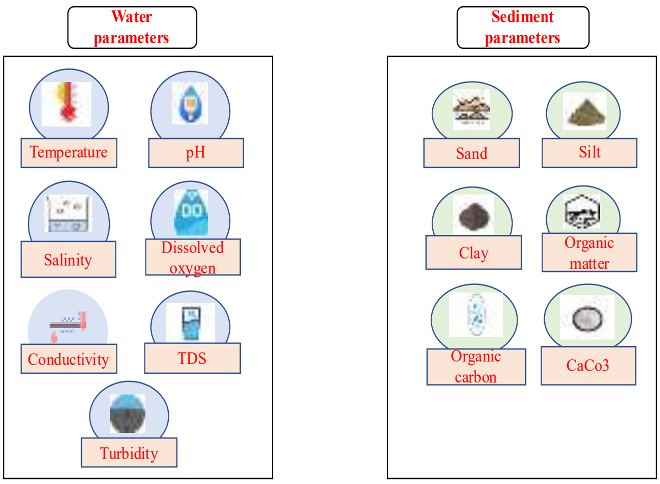


Figure 2: Analysed Water and Sediment Parameters in the Islands

The sand–silt–clay ratio was determined using the method of (Krumbein & Pettijohn, 1938). Oven-dried sediment samples were treated with 0.025 N sodium hexametaphosphate to aid deflocculation. The samples were then wet-sieved through a 230 ASTM mesh (0.063 mm), limiting the washings to 1000 ml. The retained sand was dried and weighed. The filtrate containing silt and clay was collected in a 1-litre cylinder and topped up with the same solution if required. After agitation, a 20-ml sample was pipetted from a 10 cm depth after 2 hours and 3 minutes, dried carefully, and weighed to determine the clay content. The silt fraction was calculated by subtracting the sand and clay weights from the total. All fractions were converted into weight percentages.

Organic matter content was estimated using the modified method (Walkley, 1947), following (Jackson, 1958). A 0.5 g portion of dried, 200 µm-sieved sediment was placed in a 500-ml Erlenmeyer flask. To this, 10 ml of 1N $K_2Cr_2O_7$ and 20 ml of concentrated H_2SO_4 containing Ag_2SO_4 were added. The mixture was gently swirled and allowed to stand for 30 minutes. Next, 200 ml of distilled water, 10 ml of 85% H_3PO_4, 0.2 g NaF, and 15 drops of diphenylamine indicator were added. The solution was then titrated with 0.5 N ferrous ammonium sulfate until a one-drop endpoint (brilliant green) was reached. A blank titration was run for each batch. Organic matter (%) was calculated using equation 1:

$$\mathbf{OM\ (\%) = 10(S - T) \times F} \longrightarrow \quad \textbf{(Eq.1)}$$

Where,
S = blank titration volume (ml)
T = sample titration volume (ml)
F = factor (1.03 for 0.5 g sample)

Calcium carbonate content was determined using the volumetric method of (Hutchinson & MecLennan, 1947). A 5 g sediment sample was treated with 100 ml of 1N HCl and left to react for 1 hour under a watch glass with occasional stirring. After settling, 20 ml of the supernatant was pipetted into a flask, and six to eight drops of bromothymol blue were added. The excess acid was titrated with 1N NaOH to a blue endpoint. A blank titration was also performed. Calcium carbonate (%) was calculated using equation 2:

$$\mathbf{CaCO_3\ (\%) = (Blank - Sample\ Titre) \times 5} \longrightarrow \quad \textbf{(Eq.2)}$$

Data analysis

The values of sedimentation and water parameters from the four islands were presented as means with standard errors. One-way ANOVA was employed to identify significant differences in sedimentation and water characteristics across islands. Additionally, Pearson correlation analysis (r) was conducted to determine significant relationships among the sedimentation and water parameters. To further explore the relationships between the islands and environmental parameters, multiple linear regression analysis was performed, treating the islands as dependent variables and the sedimentation and water parameters as independent variables. Principal Component Analysis (PCA) was also applied to examine the interrelationships and loading factors among the variables. All statistical analyses were carried out using SPSS version 22 and PAST version 3 software.

RESULTS

Effect of the island on different sedimentation characteristics

The mean values of sand ranged from 30 ± 2.49 to 53 ± 3.62 among four islands. Similarly, the mean values of silt ranged from 8.9 ± 1.11 to 25.9 ± 4.5, clay ranged from 35 ± 2.9 to 48 ± 1.6, Calcium carbonate ranged from 44 ± 3.48 to 59.08 ± 0.80, organic carbon ranged from 0.18 ± 0.01, and the organic matter ranged from 0.32 ± 0.02 to 0.82 ± 0.04. In addition, the study showed that all sedimentation parameters were significantly different among the four islands, indicating that the islands showed different content and compositions of the sediment parameters and biogeochemical characteristics.

Table 2: Sedimentation Characteristics of Island Ecosystems. Means in a column and Std. error with the ANOVA test values. Significant differences were presented ***p< 0.001, and the degrees of freedom.

Sample area	Sand (%)	Silt (%)	Clay (%)	Calcium Carbonate (%)	Organic Carbon (%)	Organic Matter (%)
Island I	42 ± 1.76	8.9 ± 1.11	48 ± 1.6	55 ± 1.68	0.26 ± 0.02	0.43 ± 0.03
Island II	51 ± 4.91	13.7 ± 2.7	35 ± 2.9	49 ± 1.52	0.48 ± 0.02	0.82 ± 0.04
Island III	30 ± 2.49	25.9 ± 4.5	41 ± 2.4	59 ± 0.80	0.18 ± 0.01	0.32 ± 0.02
Island IV	53 ± 3.62	9.2 ± 0.81	36 ± 2.7	44 ± 3.48	0.19 ± 0.03	0.33 ± 0.04
ANOVA test (F, p)	**$F_{3, 35}$ = 9.28*** **	**$F_{3, 35}$ = 8.65*** **	**$F_{3, 35}$ = 6.02*****	**$F_{3, 35}$ = 9.26*****	**$F_{3, 35}$ = 42.4*****	**$F_{3, 35}$ = 42.01*****

Correlation between island sedimentation and different physicochemical characteristics

Island sedimentation was significantly related to physicochemical properties (adjusted multiple regression R^2 = 0.572; F6,29=6.48; P =0.0002). Silt showed a positive trend, but other variables, such as clay, calcium carbonate, organic carbon, and organic matter, showed significant negative trends across the four islands (P < 0.05). Correlation analysis revealed positive associations between silt and calcium carbonate, and between sand and clay (P < 0.001). Organic matter and organic carbon were highly positively correlated with each other (p < 0.0001). However, silt and calcium carbonate, and sand with clay were positively correlated with islands (P < 0.001), and the organic matter and organic carbon were highly positively correlated with islands (P < 0.0001; Table 3)

Table 3: Correlation between Sedimentation Characteristics and Islands

Sediment	Islands	Sand	Silt	Clay	Calcium carbonate	Organic Carbon
Sand	0.091					
Silt	0.144	-0.711***				
Clay	-0.395*	-0.567***	-0.142			
Calcium Carbonate	-0.292	-0.351*	0.397*	0.037		
Organic carbon	-0.430**	0.203	-0.080	-0.125	-0.103	
Organic matter	-0.421*	0.204	-0.073	-0.137	-0.104	0.999***

Multiple linear regression

Multiple linear regression also revealed similar results, indicating that the sedimentation parameters of clay, calcium carbonate, organic carbon, and organic matter were significantly related to islands (Table 4).

Table 4: Multiple Linear Regression Showing the Relationship between Islands (dependent variables and Different Sedimentation Characteristics (independent variables).

Variables	Slope	Error	Intercept	Error	r	p
Sand	1.0778	2.0142	41.5	5.5162	0.091382	0.596
Silt	1.3222	1.5622	11.111	4.2784	0.14365	0.403
Clay	-3.1	1.236	47.944	3.3848	-0.39514	0.017
Calcium Carbonate	-2.1389	1.1997	57.444	3.2855	-0.2924	0.084
Organic carbon	-0.050667	0.018236	0.405	0.049943	-0.43014	<0.01
Organic matter	-0.085625	0.031649	0.69247	0.086674	-0.42089	<0.01

Principal Component Analysis

The suitability of the dataset for factor analysis was evaluated using the Kaiser-Meyer-Olkin (KMO) measure and Bartlett's Test of Sphericity. The KMO value of 0.402, which falls below the commonly accepted threshold of 0.6, indicates inadequate overall sampling adequacy and suggests that the correlations among the sedimentation variables across the four islands are suboptimal. However, Bartlett's Test of Sphericity yielded a statistically significant result (Chi-Square = 352.15, $p < 0.0001$), indicating the presence of strong interrelationships among the variables. Despite the low KMO value, the significant outcome of Bartlett's test supports the existence of patterned relationships, thereby justifying the use of Principal Component Analysis (PCA) to explore and extract meaningful underlying dimensions within the dataset.

Table 5: KMO and Bartlett's sphericity tests by PCA

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.402
Bartlett's Test of Sphericity	Approx. Chi-Square	352.149
	df	21
	Sig.	.000

The results of the PCA show that Component Axis 1 and Component Axis 2 were significantly correlated, and the variance of Axis 1 was 62.73%, and the variance of Axis 2 was 24.32%, suggesting that island ecosystems were significantly correlated with sedimentation parameters. The primary component 1 showed a significant positive correlation between island and sand, organic carbon, and organic matter. The primary component 2 showed a significant positive correlation between island and silt, clay, calcium carbonate, organic carbon, and organic matter, whereas the primary component 3 showed a significant negative correlation with clay (Table 6).

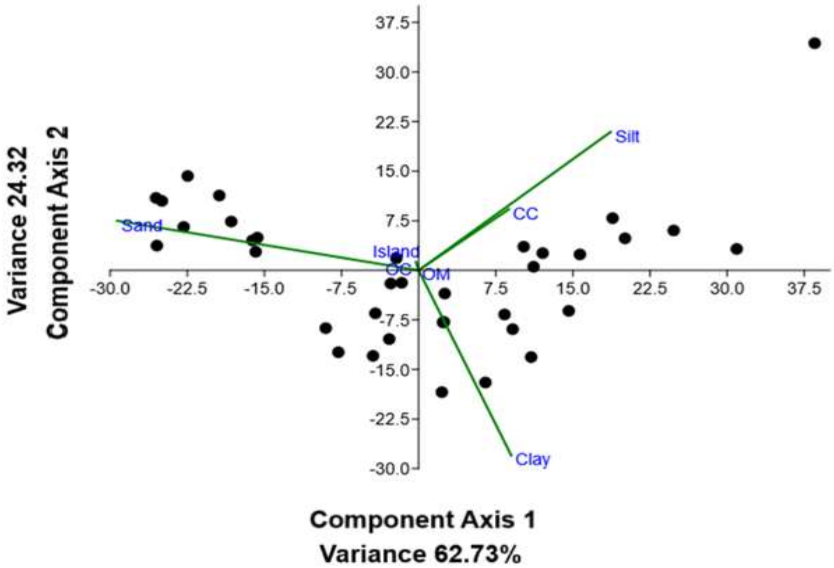


Figure 3: Principal Component Analysis (PCA) of the Correlation of Loading Factors between Islands and Sedimentation Characteristics

Table 6: Principal Component Analysis on the Correlation Matrix between the Island and Sedimentation Characteristics

Component Matrix[a]			
	Component		
	1	2	3
Island		-0.697	
Sand	0.647	-0.667	
Silt	-0.508	0.445	0.679
Clay		0.493	-0.772
CC		0.537	
OC	0.856	0.423	
OM	0.855	0.418	
Extraction Method: Principal Component Analysis.			

Effect of islands on different water parameters

The mean pH values ranged from 7.66 ± 0.04to 7.84 ± 0.02 across the four islands. Similarly, salinity ranged from 29.44 ± 0.32to 31.37 ± 1.08, conductivity from 52.92 ± 0.83to56.49 ± 1.08, temperature from 31.13 ± 0.35°C to 32.08 ± 0.46°C, TDS from 39.90 ±0.22 to 40.37 ± 0.55, DO from 8.70 ± 0.22to 9.06 ± 0.16, and turbidity from 4.67 ± 0.47 to 6.11 ± 1.37. The results indicated that all measured water quality parameters differed significantly among the four islands (Table 7).

eISSN: 2583-1194

Table 7 Water parameters of Island Ecosystems. Means in a column and Std. error with the ANOVA test values. Significant differences were observed at *p*< 0.05, with the corresponding degrees of freedom reported.

Sample area	**pH**	**Salinity (‰)**	**Conductivity (mS/cm)**	**Temperature (°C)**	**TDS (g/L)**	**DO (mg/L**	**Turbidity (NTU)**
Island I	7.78 ± 0.05	29.79 ± 0.42	52.92± 0.83	31.13 ± 0.35	39.9 ± 0.22	8.72 ± 0.14	6.11 ± 0.87
Island II	7.82 ± 0.04	29.44 ± 0.32	53.96 ± 0.66	31.59 ± 0.03	39.14 ± 0.22	8.83 ± 0.08	6.11 ± 1.37
Island III	7.84 ± 0.02	31.37± 1.08	53.14 ± 1.08	31.21 ± 0.09	40.32 ± 0.39	9.06 ± 0.16	4.67 ± 0.47
Island IV	7.66 ± 0.04	30.62± 0.46	56.49 ± 1.08	32.08 ± 0.46	40.37 ± 0.55	8.7 ± 022	5.22 ± 0.91
ANOVA Test (F, p)	**$F_{3,35}$ = 3.713***	**$F_{3,35}$ = 1.795**	**$F_{3,35}$ = 3.07***	**$F_{3,35}$ = 2.12**	**$F_{3,35}$ = 2.294**	**$F_{3,35}$ = 1.05**	**$F_{3,35}$ = 0.544**

Correlation between island sedimentation and different water characteristics

Table 8: Correlation between Island Ecosystems and Water Parameters

Variables	**Island**	**pH**	**Salinity**	**Conductivity**	**Temperature**	**TDS**	**DO**
pH	-0.277						
Salinity	0.251	-0.026					
Conductivity	0.369*	-0.305	0.207				
Temperature	0.302*	-0.027	-0.053	0.478**			
TDS	0.247	-0.025	0.410**	0.405**	0.1088		
DO	0.036	0.184	0.196	-0.054	-0.087	0.074	
Turbidity	-0.164	-0.098	-0.105	0.223	0.291*	0.024	-0.065

A Pearson correlation analysis of water parameters (Table 8) across the islands showed certain significant ecological associations. Conductivity (r = 0.369, *p*< 0.05) and temperature (r = 0.302, p < 0.05) revealed a moderate positive and significant correlation with island location. There is no meaningful relationship between island and pH, salinity, TDS, DO, or turbidity (|r| ≤ 0.25, p > 0.05). Temperature is found to have a strong coupling with conductivity (r = 0.478, *p*< 0.01) and TDS (r = 0.405, *p*< 0.01). TDS also increases with increasing salinity (r = 0.410, *p*< 0.01), while turbidity shows a weaker but significant affinity with temperature (r = 0.291, p < 0.05). By contrast, dissolved oxygen exhibits only weak, non-significant associations with all other parameters, inferring well-mixed, oxygen-replete conditions across the study area. These trends highlight that ionic strength and thermal regime dominate the islands, while variations in pH, DO, turbidity, and absolute salinity remain within acceptable ecological limits. Overall, the correlation matrix highlights that islands are embedded within water masses characterized by elevated conductivity and temperature, with moderate turbidity and stable oxygen levels. These conditions may influence benthic-pelagic coupling and nutrient fluxes in the islands.

Multiple linear regression

Multiple linear regression further illustrated similar results, indicating the ecological relevance of the water parameters across the islands. More prominently, conductivity and temperature were found to be the significant predictors in the islands (Table 9).

Table 9: Multiple Linear Regression Showing the Relationship between Island (dependent variables and Different Water Parameters (independent variables)

Variables	Slope	Error	Intercept	Error	r	p
pH	-0.033	0.019598	7.8583	0.053672	-0.27744	0.101
Salinity	0.44222	0.29241	29.2	0.80079	0.25106	0.1396
Conductivity	0.98889	0.42662	51.656	1.1683	0.36941	0.027
Temperature	0.24556	0.13283	30.889	0.36378	0.30221	0.073
TDS	0.25778	0.1733	39.289	0.4746	0.24718	0.146
DO	0.015556	0.073571	8.7889	0.20148	0.036237	0.834
Turbidity	-0.41111	0.42269	6.5556	1.1576	-0.16453	0.338

Principal Component Analysis

The suitability of the dataset for factor analysis was evaluated using the Kaiser-Meyer-Olkin (KMO) measure and Bartlett's Test of Sphericity. The KMO value of 0.563, which falls below the commonly accepted threshold of 0.6, indicates inadequate overall sampling adequacy and suggests that the correlations among the water parameters across the four islands are suboptimal. However, Bartlett's Test of Sphericity yielded a statistically significant result (Chi-Square = 44.008, $p < 0.0001$), indicating the presence of strong interrelationships among the parameters. Despite the low KMO value (Table 10), the significant outcome of Bartlett's test supports the existence of patterned relationships, thereby justifying the use of Principal Component Analysis (PCA) to explore and extract meaningful underlying dimensions within the dataset.

Table 10: KMO and Bartlett's sphericity tests by PCA

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.563
Bartlett's Test of Sphericity	Approx. Chi-Square	44.008
	df	28
	Sig.	0.28

Principal Component Analysis (PCA) revealed that Component Axis 1 accounted for 44.70% of the total variance, primarily driven by conductivity, salinity, and TDS. These variables exhibited strong positive loadings, indicating their co-variation and dominant role in differentiating island environments. Component Axis 2 explained 22.9% of the variance, with turbidity showing a negative correlation, suggesting contrasting ecological conditions. The spatial distribution of sample points across the biplot highlights the environmental heterogeneity among the islands.

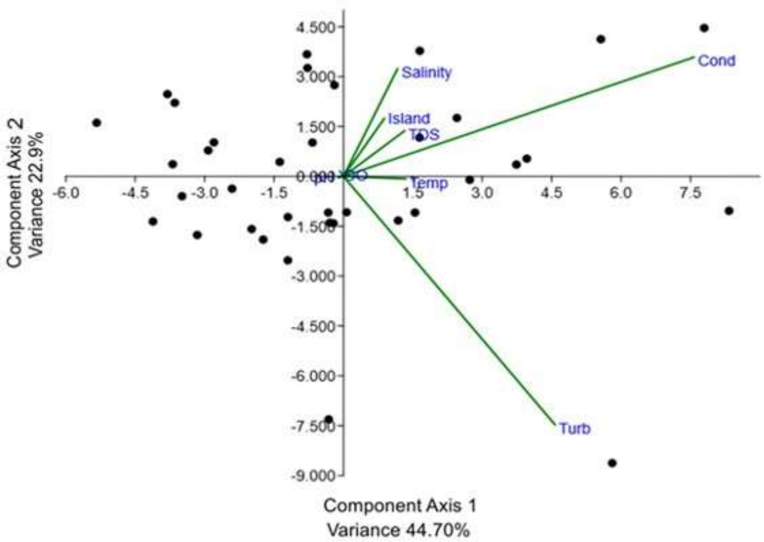


Figure 4: Principal Component Analysis (PCA) of the Correlation of Loading Factors between Islands and Water Parameters

Table 11: Principal Component Analysis on the Correlation Matrix between Islands and Water Parameters

Component Matrix[a]

	Component		
	1	2	3
Island	.663		
pH	-.408		.626
Salinity	.439	.648	
Conductivity	.832		
Temperature	.576	-.447	
TDS	.611		
DO		.545	.442
Turbidity		-.586	.525

Extraction Method: Principal Component Analysis.

Principal Component Analysis (PCA) revealed that Component Axis 1 accounted for 44.70% of the total variance, primarily driven by conductivity, temperature, TDS, and island location. These variables exhibited strong positive loadings, indicating their co-variation and dominant role in differentiating island environments. Component Axis 2 explained 22.9% of the variance, with notable loadings of salinity, DO, and turbidity signifying biogeochemical conditions. Component axis 3 captured pH-driven variation alongside DO and turbidity, suggesting site-specific dynamics (Table 11). The spatial distribution of sample points across the biplot highlights the environmental heterogeneity among the islands.

DISCUSSION

The present study revealed significant spatial variability in sediment characteristics across the four islands of the Gulf of Mannar, with sand content ranging from 30 ± 2.49 to 53 ± 3.62, silt from 8.9 ± 1.11 to 25.9 ± 4.5, and clay from 35 ± 2.9 to 48 ± 1.6 and this substantial inter-island heterogeneity in sediment texture reflects the complex interplay of hydrodynamic processes, biological activities, and geomorphological characteristics unique to each island ecosystem. Similar spatial heterogeneity in sediment distribution has been documented in other island ecosystems, where substrate variability significantly influences biodiversity and ecosystem functioning (Romoth *et al.*, 2023; Zeppilli *et al.*, 2018). The observed variations likely result from differences in wave energy regimes, current patterns, proximity to mainland sediment sources, and local reef structural complexity among the study islands, which influence sediment deposition patterns and habitat heterogeneity in coral reef ecosystems (Bartzke *et al.*, 2025; Biggs *et al.*, 2026).

Calcium carbonate content in the studied islands ranged from 44 ± 3.48 to 59.08 ± 0.80, indicating substantial biogenic carbonate production despite varying environmental pressures. This carbonate fraction represents accumulated skeletal remains from corals, coralline algae, mollusks, foraminifera, and other calcifying organisms that form the foundation of reef island ecosystems. Recent research has highlighted that coral reefs account for more than 25% of total calcium carbonate buried in marine sediments globally. Making them critical components of the global carbon cycle (Jones *et al.*, 2015; Eyre *et al.*, 2018). The significant differences in Calcium carbonate content among the four islands suggest varying levels of reef productivity, community structure, and calcification rates. Reef-derived carbonate production plays a vital role in sustaining reef structure and supporting island persistence, with variations in nutrient availability contributing to differences in calcification rates and ecosystem development (Lange & Benkwitt, 2024). Organic carbon 0.18 ± 0.01 to 0.48 ± 0.02 and organic matter 0.32 ± 0.02 to 0.82 ± 0.04 values fall within typical ranges for tropical reef sediments, reflecting the oligotrophic nature of these environments. Inter-island variability indicates differences in primary productivity, organic matter sources, and degradation rates. The organic carbon content in marine sediments serves as a crucial indicator of ecosystem productivity and benthic community condition. In carbonate-rich reef settings, carbonate-associated organic matter (CAOM), bound to carbonate sediments, represents a dynamic component of coastal carbon cycling (Zeller *et al.*, 2024), with implications for long-term ecosystem resilience.

The sediment textural characteristics observed across the four islands, with notable variations in sand, silt, and clay fractions, have profound implications for benthic habitat quality, infaunal community structure, and biogeochemical processes. Sediment grain size influences porosity, permeability, oxygen penetration depth, nutrient cycling rates, and the distribution of benthic organisms (Thrush *et al.*, 2013; Romoth *et al.*, 2023). Experimental studies have shown that elevated sediment loads, particularly when combined with thermal stress, can negatively affect coral physiological performance and reef ecosystem health (Good *et al.*, 2025). The predominance of sand in some islands versus higher silt-clay content in others creates distinct microhabitat conditions that support different ecological communities. The interplay between calcium carbonate content, organic matter, and sediment texture creates unique biogeochemical environments on each island. High carbonate content can buffer pH fluctuations, supporting calcifying organisms and mitigating ocean acidification impacts (Eyre *et al.*, 2018; Bice *et al.*, 2025). Such heterogeneity strengthens ecosystem resilience by ensuring that environmental stressors do not uniformly affect all islands. The significant inter-island differences in sedimentation characteristics identified in this study underscore the necessity for inter-specific monitoring and management strategies within the Gulf of Mannar Biosphere Reserve. Sediment characteristics can serve as sensitive indicators of environmental change, integrating signals from multiple stressors including pollution, sedimentation, fishing impacts, and climate change effects (McIlroy *et al.*, 2024). The baseline data provided by this study enable the detection of future changes in sediment regimes that may signal ecosystem degradation or recovery. For instance, shifts in sediment texture may indicate altered hydrodynamic conditions or sediment supply, changes in organic carbon could reflect variations in productivity or pollution inputs, and declining calcium carbonate content might signal reduced calcification or enhanced dissolution due to ocean acidification.

The present study revealed significant spatial heterogeneity in water quality parameters across the four island ecosystems, with pH values ranging from 7.66 ± 0.04 to 7.84 ± 0.02, indicating slightly alkaline conditions typical of marine environments. These narrow pH variations suggest a stable carbonate buffering capacity crucial for maintaining calcifying benthic communities including foraminifera (Uthicke *et al.*, 2014). Temperature variations 31.13 ± 0.35to 32.08 ± 0.46 and conductivity (52.92 ± 0.83 to 56.49 ± 1.08) showed significant correlations with island location ($r = 0.302$ and $r = 0.369$, respectively, $p < 0.05$). The strong positive correlation between conductivity and temperature suggests that thermal stratification and evaporative processes regulate ionic strength around these islands. Camp *et al.*, (2015) demonstrated that such thermal-conductivity coupling drives microhabitat differentiation in tropical marine systems, influencing benthic community structure. The multiple linear regression results confirm that conductivity and temperature are primary predictors of island environmental differentiation. Dissolved oxygen concentrations remained uniformly high 8.70 ± 0.22 to 9.06 ± 0.16 across all islands, indicating well-oxygenated, wave-mixed conditions that support diverse aerobic benthic communities (Hughes *et al.*, 2017). Turbidity values 4.67 ± 0.47 to 6.11 ± 1.37 were relatively low, suggesting minimal anthropogenic disturbance and optimal light conditions for symbiont-bearing organisms (Fabricius *et al.*, 2005).

PCA revealed that Component Axis 1 (44.70% variance) represents a conductivity-TDS-temperature gradient driven by evaporative concentration, while Component Axis 2 (22.9% variance) reflects salinity-turbidity dynamics. This multi-dimensional environmental heterogeneity creates distinct microhabitats among islands (Anthony *et al.*, 2015). The observed environmental gradients have significant implications for benthic-pelagic coupling and nutrient dynamics. Island IV, exhibiting the high conductivity (56.49 ± 1.08) and temperature (32.08 ± 0.46), represents the most environmentally distinct system, potentially creating thermal stress conditions affecting calcification and species composition (Schmidt *et al.*, 2011). The strong correlations between TDS, salinity, and conductivity indicate that dissolved solid concentrations are driven by physical evaporative processes rather than biological inputs (Sippo *et al.*, 2016). These baseline water quality characterizations provide essential reference conditions for monitoring climate change impacts. Recent observations from major coral reef systems indicate that extreme thermal events can rapidly alter reef condition, emphasizing the need for continuous environmental monitoring and robust baseline datasets (Caccarelli *et al.*, 2026). At coral reefs, the study by Hughes *et al.*, (2017) emphasized that tropical island ecosystems are particularly vulnerable to warming and altered hydrological regimes. The significant temperature-conductivity relationships observed suggest these systems may experience amplified environmental stress under future climate scenarios, potentially affecting benthic community resilience.

In addition to these observations, recent studies further reinforce the ecological significance of sediment-water regimes in the Gulf of Mannar. Patterson Edward *et al.* (2024) documented long-term coral reef decline and emphasized the need for adaptive management approaches, which complement the present findings identifying ionic strength and thermal regime as dominant environmental drivers. Saha et al. (2024) highlighted the importance of maintaining a balance between fisheries productivity and ecosystem health, underscoring the value of baseline sediment and water quality information for sustainable resource management. Kanaga *et al.* (2025) developed a Resource Vulnerability Index (RVI) framework demonstrating the usefulness of quantitative indicators for evaluating ecosystem resilience, aligning with the present regression analyses that identified sediment composition and conductivity as significant factors shaping island-specific environmental conditions. Collectively, these studies support the growing recognition that integrated environmental monitoring is essential for understanding ecosystem dynamics and strengthening conservation strategies in the Gulf of Mannar.

The present study provides valuable baseline data on sediment and water regimes in selected Gulf of Mannar islands; its scope is constrained by limited spatial and temporal coverage, methodological reliance on classical techniques, and absence of biological integration. Future research should expand sampling across seasons and islands, incorporate advanced analytical methods, and integrate ecological indicators with anthropogenic pressure assessments to strengthen conservation planning.

Further, research has been planned to focus on correlating sediment and water parameters with benthic community structure, which would illuminate specific habitat requirements and enable habitat suitability modeling for key species, supporting predictive conservation strategies and ecosystem management.

CONCLUSION

This study demonstrates that sediment and water regimes in the Gulf of Mannar islands exhibit significant spatial variability, with distinct biogeochemical and physicochemical signatures across sites. Sediment composition differed markedly in sand, silt, clay, calcium carbonate, organic carbon, and organic matter, with multivariate analyses revealing strong interrelationships and two principal components driving variability. Water parameters also showed island-specific differences; pH, salinity, temperature, conductivity, TDS, DO, and turbidity collectively shaped ecological conditions. Temperature and conductivity emerged as dominant predictors, strongly correlated with TDS and salinity, while turbidity and pH reflected localized processes. Together, these findings establish critical baseline data, demonstrating that sedimentary composition and physicochemical parameters jointly regulate benthic-pelagic interactions and ecosystem resilience. The detection of sediment and water indicators provides a robust framework for ecological monitoring, offering early detection of environmental shifts. Island-specific monitoring and management approaches are recommended to address the unique characteristics and vulnerabilities of each island ecosystem. However, the study is limited to four islands and a single sampling season, underscoring the need for expanded temporal and spatial coverage. Future research should integrate biological indicators with physicochemical monitoring to strengthen conservation planning. The baseline data provided by this study establishes a foundation for long-term ecological monitoring and adaptive management in the Gulf of Mannar Biosphere Reserve, contributing to the conservation of this globally significant marine protected area.

Acknowledgements

The authors hereby acknowledge heartfelt thanks to DST-FIST, New Delhi, for the infrastructure provided and PSGR Krishnammal College for Women, Coimbatore, Tamil Nadu, India, for providing constant support to the work.

Statements and Declarations

Author contribution

Punitha Selvam: Conceptualization, Methodology, Software, Formal analysis, Writing – Original draft

Mohanraj T: Writing – Review & editing

Nandhitha Srinivasan: Methodology, Formal analysis

Sheeba Maxwalt: Writing – Review & editing, Supervision, Project Administration

All authors read and approved the final manuscript.

Funding

No funding was received for conducting this study.

Consent to participate

Not applicable.

Consent to publish

Not applicable.

Conflict of interest

The authors declare that there are no conflicts of interest in competing financial or personal relationships that could have appeared to influence the work reported in this work.

Data availability

All data generated or analysed during this study are included in this published article.

REFERENCES

[1] Abelson, A., Halpern, B. S., Reed, D. C., Orth, R. J., Kendrick, G. A., Beck, M. W., ... & Nelson, P. A. (2016). Upgrading marine ecosystem restoration using ecological-social concepts. *BioScience*, *66*(2), 156-163. https://doi.org/10.1093/biosci/biv171

[2] Anthony, K. R., Marshall, P. A., Abdulla, A., Beeden, R., Bergh, C., Black, R., ... & Wear, S. (2015). Operationalizing resilience for adaptive coral reef management under global environmental change. *Global change biology*, *21*(1), 48-61. https://doi.org/10.1111/gcb.12700

[3] Bartzke, G., Hebbeln, D., & Huhn, K. (2025). Hydro-and sediment dynamics in a cold-water coral reef: insights from a 3D numerical model. *Frontiers in Marine Science*, *12*, 1654625. https://doi.org/10.3389/fmars.2025.1654625

eISSN: 2583-1194

[4] Baskar, K., Sridhar, S. G. D., Sivakumar, T., Hussain, S. M., & Maniyarasan, S. (2015). Temporal variation of physico-chemical parameters and ostracoda population, off Rameswaram, Gulf of Mannar, southeast coast of Tamil Nadu, India. *Journal of the Geological Society of India*, *86*(6), 663-670.

[5] Biçe, K., Myers Stewart, T., Waldbusser, G. G., & Meile, C. (2025). The effect of carbonate mineral additions on biogeochemical conditions in surface sediments and benthic–pelagic exchange fluxes. *Biogeosciences*, *22*(3), 641-657. https://doi.org/10.5194/bg-22-641-2025

[6] Biggs, T. W., Messina, A. M., & Storlazzi, C. D. (2026). Waves, watersheds, and sediment in a coral reef embayment: Towards parsimonious models of accumulation and composition. *Estuarine, Coastal and Shelf Science*, 109952. https://doi.org/10.1016/j.ecss.2026.109952

[7] Camp, E. F., Edmondson, J., Doheny, A., Rumney, J., Grima, A. J., Huete, A., & Suggett, D. J. (2019). Mangrove lagoons of the Great Barrier Reef support coral populations persisting under extreme environmental conditions. *Marine Ecology Progress Series*, *625*, 1-14. https://doi.org/10.3354/meps13073

[8] Ceccarelli, D. M., Emslie, M. J., Logan, M., Bray, P., Campili, A. R., Cantin, N., ... & Stephenson, B. (2026). Substantial impacts from the 2024 summer reverse five years of coral cover gains on the Great Barrier Reef. *Coral Reefs*, 1-15. https://doi.org/10.1007/s00338-026-02829-8

[9] Cramer, K. L., O'Dea, A., Leonard-Pingel, J. S., & Norris, R. D. (2020). Millennial-scale change in the structure of a Caribbean reef ecosystem and the role of human and natural disturbance. *Ecography*, *43*(2), 283-293. https://doi.org/10.1111/ecog.04722

[10] Edgar, G. J., Stuart-Smith, R. D., Willis, T. J., Kininmonth, S., Baker, S. C., Banks, S., ... & Thomson, R. J. (2014). Global conservation outcomes depend on marine protected areas with five key features. *Nature*, *506*(7487), 216-220. https://doi.org/10.1038/nature13022

[11] Erftemeijer, P. L., Riegl, B., Hoeksema, B. W., & Todd, P. A. (2012). Environmental impacts of dredging and other sediment disturbances on corals: a review. *Marine pollution bulletin*, *64*(9), 1737-1765. https://doi.org/10.1016/j.marpolbul.2012.05.008

[12] Eyre, B. D., Cyronak, T., Drupp, P., De Carlo, E. H., Sachs, J. P., & Andersson, A. J. (2018). Coral reefs will transition to net dissolving before end of century. *Science*, *359*(6378), 908-911. https://doi.org/10.1126/science.aao1118

[13] Fabricius, K. E. (2005). Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. *Marine pollution bulletin*, *50*(2), 125-146. https://doi.org/10.1016/j.marpolbul.2004.11.028

[14] Giakoumi, S., Scianna, C., Plass-Johnson, J., Micheli, F., Grorud-Colvert, K., Thiriet, P., ... & Guidetti, P. (2017). Ecological effects of full and partial protection in the crowded Mediterranean Sea: a regional meta-analysis. *Scientific reports*, *7*(1), 8940. https://doi.org/10.1038/s41598-017-08850-w

[15] Good, A. M., Epps, A., Coberly, M., Rodgers, K. S., Prouty, N. G., Storlazzi, C. D., & Bahr, K. D. (2025). Impact of warming and suspended terrigenous sediment on the Hawaiian reef coral Montipora capitata. *Coral Reefs*, *44*(6), 2065-2081. https://doi.org/10.1007/s00338-025-02752-4

[16] Gudka, M., Obura, D., Mwaura, J., Porter, S., Yahya, S., & Mabwa, R. (2018). Impact of the 3rd global coral bleaching event on the Western Indian Ocean in 2016. *Global coral reef monitoring network (GCRMN)/Indian ocean commission*, 67. https://doi.org/10.13140/RG.2.2.32306.71365

[17] Hamid, N., & Yoganandham, S. T. (2025). An Introduction to Marine Ecosystem: Environmental and Economic Impacts. In *Recent Trends in Marine Toxicological Assessment* (pp. 3-14). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-75713-6_1

[18] Head, C. E., Bonsall, M. B., Koldewey, H., Pratchett, M. S., Speight, M., & Rogers, A. D. (2015). High prevalence of obligate coral-dwelling decapods on dead corals in the Chagos Archipelago, central Indian Ocean. *Coral Reefs*, *34*(3), 905-915. https://doi.org/10.1007/s00338-015-1307-x

[19] Hoegh-Guldberg, O., Mumby, P. J., Hooten, A. J., Steneck, R. S., Greenfield, P., Gomez, E., ... & Hatziolos, M. E. (2007). Coral reefs under rapid climate change and ocean acidification. *science*, *318*(5857), 1737-1742. https://doi.org/10.1126/science.1152509

[20] Hondula, K. L., König, M., Grunert, B. K., Vaughn, N. R., Martin, R. E., Dai, J., ... & Asner, G. P. (2024). Mapping water quality in nearshore reef environments using airborne imaging spectroscopy. *Remote Sensing*, *16*(11), 1845. https://doi.org/10.3390/rs16111845

[21] Hopf, J. K., Quennessen, V., Ridgway, J., Barceló, C., Caltabellotta, F. P., Farnsworth Hayroyan, S., ... & White, J. W. (2024). Ecological success of no-take marine protected areas: using population dynamics theory to inform a global meta-analysis. *Ecological Applications*, *34*(7), e3027. https://doi.org/10.1002/eap.3027

[22] Hughes, T. P., Barnes, M. L., Bellwood, D. R., Cinner, J. E., Cumming, G. S., Jackson, J. B., ... & Scheffer, M. (2017). Coral reefs in the Anthropocene. *Nature*, *546*(7656), 82-90. http://doi.org/10.1038/nature22901

[23] Hutchinson M, MecLennan K (1947) In: Piper CS (ed) Soil and plant analysis. Interscience, New York, p 368.

[24] Jones, R., Ricardo, G. F., & Negri, A. P. (2015). Effects of sediments on the reproductive cycle of corals. *Marine Pollution Bulletin*, *100*(1), 13-33. https://doi.org/10.1016/j.marpolbul.2015.08.021

[25] Kanaga, V., Rajakumar, M., Jawahar, P., & Britanicy, A. (2025). *Estimation of Marine Resource Vulnerability Index for the Gulf of Mannar Coast, Tamil Nadu*. *Indian Journal of Animal* Research, 1–6. https://doi.org/10.18805/IJAR.B-5498

[26] Karikalan, R., Bangaru Priyanga, S., & Rakkiannan, S. (2020). Textural Analysis of Coastal Sediments in Mandapam area, Gulf of Mannar Coast, Tamilnadu, India. *Infokara Research*, *9*(3), 780-790.

[27] Karuppiah, T., Balakrishnan, G., Peyail, S., Theivasigamani, A., Anil, K. S., Ramachandran, K., ... & Srinivasan, N. (2011). Studies on the physico-chemical characteristic and nutrients in the Kottakudi Estuary of Thirupulani, Ramanathapuram-District, South East Coast of India. *Aquaculture, Aquarium, Conservation & Legislation*, *4*(3), 313-319. http://www.bioflux.com.ro/aacl

[28] Kathiravan, K., Natesan, U., & Vishnunath, R. (2017). Spatio-temporal variability of hydro-chemical characteristics of coastal waters of Gulf of Mannar Marine Biosphere Reserve (GoMMBR), South India. *Applied Water Science*, *7*(1), 361-373. https://doi.org/10.1007/s13201-014-0251-1

[29] Kench, P. S., Smithers, S. G., McLean, R. F., & Nichol, S. L. (2009). Holocene reef growth in the Maldives: evidence of a mid-Holocene sea-level highstand in the central Indian Ocean. *Geology*, *37*(5), 455-458. https://doi.org/10.1130/G25590A.1

[30] Krumbein, W. C., & Pettijohn, F. J. (1938). Manual of sedimentary petrology. *Appleton, Century, and Crofts, New York*, 549.

[31] Kumar, P. S., & Khan, A. B. (2013). The distribution and diversity of benthic macroinvertebrate fauna in Pondicherry mangroves, India. *Aquatic biosystems*, *9*(1), 15. https://doi.org/10.1186/2046-9063-9-15

[32] Kumaraguru, A. K., Joseph, V. E., Marimuthu, N., & Wilson, J. J. (2006). Scientific information on Gulf of Mannar-A bibliography. http://eprints.cmfri.org.in/id/eprint/6766

[33] Lange, I. D., & Benkwitt, C. E. (2024). Seabird nutrients increase coral calcification rates and boost reef carbonate production. *Scientific Reports*, *14*(1), 24937. https://doi.org/10.1038/s41598-024-76759-2

[34] MacNeil, M. A., Mellin, C., Matthews, S., Wolff, N. H., McClanahan, T. R., Devlin, M., ... & Graham, N. A. (2019). Water quality mediates resilience on the Great Barrier Reef. *Nature Ecology & Evolution*, *3*(4), 620-627. https://doi.org/10.1038/s41559-019-0832-3

[35] McIlroy, S. E., Guibert, I., Archana, A., Chung, W. Y. H., Duffy, J. E., Gotama, R., ... & Baker, D. M. (2024). Life goes on: Spatial heterogeneity promotes biodiversity in an urbanized coastal marine ecosystem. *Global Change Biology*, *30*(4), e17248. https://doi.org/10.1111/gcb.17248

[36] Mcleod, E., Hinkel, J., Vafeidis, A. T., Nicholls, R. J., Harvey, N., & Salm, R. (2010). Sea-level rise vulnerability in the countries of the Coral Triangle. *Sustainability Science*, *5*(2), 207-222. https://doi.org/10.1007/s11625-010-0105-1

[37] Nurse, L. A., McLean, R. F., Agard, J., Briguglio, L. P., Duvat-Magnan, V., Pelesikoti, N., ... & Webb, A. (2014). Small islands. *Climate change 2014: Impacts, adaptation, and vulnerability. Part B: Regional aspects. Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change*, pp-1613. https://hal.science/hal-01090732v1

[38] Patterson Edward, J. K., Naganathan, V., Mathews, G., Diraviya Raj, K., Asir, N. G. G., Bilgi, D. S., Ashok Kumar, T. K., & Sudhakar, B. J. (2024). *Coral reefs of the Gulf of Mannar, Tamil Nadu, India: Decadal changes in status and management paradigms*. Environment, Climate Change and Forests Department, Government of Tamil Nadu & Suganthi Devadason Marine Research Institute. https://sdmri.in/wp-content/uploads/2024/07/Coral-reefs-of-the-Gulf-of-Mannar-Tamil-Nadu-India_Summary-Report-2023.pdf

[39] Ramakritinan, C. M., Anand, M., Palanikumar, L., Singh, M., Manikandan, S., Jayanthi, G., ... & Subramanian, B. R. (2026). Derivation of seawater quality criteria for copper, cadmium, zinc, and mercury for the coastal and coral reef ecosystems

of Gulf of Mannar, India: CM Ramakritinan et al. *Journal of Earth System Science*, *135*(2), 98. https://doi.org/10.1007/s12040-026-02795-3

[40] Ramasamy, P., & Karikalan, R. (2010). Distribution and percentage of heavy minerals in coastal geomorphological landforms in Palk Strait. Southeast Coast of India. *Middle-East Journal of Scientific Research*, *5*(1), 49-53.

[41] Rathje. (1959). Jackson, ML: Soil chemical analysis. Verlag: Prentice Hall, Inc., Englewood Cliffs, NJ. 1958, 498 S. DM 39.40. https://doi.org/10.1002/jpln.19590850311

[42] Ravichandran, M., Devi, N. R., Rasheeq, A. A., Muthusamy, A., Subbiah, S., Kumar, B. P., ... & Arumugam, A. (2022). Spatiotemporal dynamics of physicochemical and sediment parameters in Gulf of Mannar waters, Southeast coast of India. *Regional Studies in Marine Science*, *56*, 102603. https://doi.org/10.1016/j.rsma.2022.102603

[43] Retnamma, J., Kalathil, B. K., Loganathan, J., Chinnadurai, K., Gupta, G. V. M., Chakraborty, K., & Sahu, K. C. (2021). Why the Gulf of Mannar is a marine biological paradise?. *Environmental Science and Pollution Research*, *28*(45), 64892-64907. https://doi.org/10.1007/s11356-021-15530-w

[44] Retnaningdyah, C., Arisoesilaningsih, E., Vidayanti, V., & Febriansyah, S. C. (2023). Community structure and diversity of benthic macroinvertebrates as bioindicators of water quality in some waterfall ecosystems, Bawean Island, Indonesia. *Biodiversitas: Journal of Biological Diversity*, *24*(1). https://doi.org/10.13057/biodiv/d240144

[45] Ridha, H., Sukumaran, S., Manikandan, B., & Thampan, A. K. (2026). Advancing biodiversity assessment of marine protected areas by identifying ecologically critical sites and species. *Ocean & Coastal Management*, *272*, 107981. https://doi.org/10.1016/j.ocecoaman.2025.107981

[46] Romoth, K., Darr, A., Papenmeier, S., Zettler, M. L., & Gogina, M. (2023). Substrate heterogeneity as a trigger for species diversity in marine benthic assemblages. *Biology*, *12*(6), 825. https://doi.org/10.3390/biology12060825

[47] Saha, D., Kumar, D. S., Krishnan, P., Mukherjee, R., Vidhyavathi, A., Maheswari, M., & Vijayabhama, M. (2024). Balancing nets and lives: A socio-ecological analysis of sustainable fisheries on the Indian coast of the Gulf of Mannar. *Sustainability*, *16*(20), 8738. https://doi.org/10.3390/su16208738

[48] Sandulli, R., Ingels, J., Zeppilli, D., Sweetman, A. K., Hardy Mincks, S., Mienis, F., & Chin-Lin, W. (2021). Extreme benthic communities in the age of global change. *Frontiers in Marine Science*, *7*, 609648. https://doi.org/10.3389/fmars.2020.609648

[49] Schmidt, C., Heinz, P., Kucera, M., & Uthicke, S. (2011). Temperature‐induced stress leads to bleaching in larger benthic foraminifera hosting endosymbiotic diatoms. *Limnology and Oceanography*, *56*(5), 1587-1602. https://doi.org/10.4319/lo.2011.56.5.1587

[50] Sharma, V. Marine Biodiversity Along the Indian Coastline. https://doi.org/10.31426/ijamsr.2020.3.12.3958

[51] Silambarasan, A., Sivaraj, S., Muthuvelu, S., Bharathidasan, V., & Murugesan, P. (2016). Influence of environmental parameters on abundance and diversity of phytoplankton in Pichavaram mangroves, southeast coast of India. *Indian J Geo-Marine Sci*, *45*(4), 591-602.

[52] Sippo, J. Z., Maher, D. T., Tait, D. R., Holloway, C., & Santos, I. R. (2016). Are mangroves drivers or buffers of coastal acidification? Insights from alkalinity and dissolved inorganic carbon export estimates across a latitudinal transect. *Global Biogeochemical Cycles*, *30*(5), 753-766. https://doi.org/10.1002/2015GB005324

[53] Spalding, M. D., Fox, H. E., Allen, G. R., Davidson, N., Ferdaña, Z. A., Finlayson, M. A. X., ... & Robertson, J. (2007). Marine ecoregions of the world: a bioregionalization of coastal and shelf areas. *BioScience*, *57*(7), 573-583. https://doi.org/10.1641/B570707

[54] Sundararajan, S., Kamalakannan, B., Karthikeyan, R., Khadanga, M. K., & Jena, B. K. (2018). Journal of Marine Science: Research & Development. https://doi.org/10.4172/2155-9910.1000252

[55] Thrush, S. F., Hewitt, J. E., Lohrer, A. M., & Chiaroni, L. D. (2013). When small changes matter: the role of cross‐scale interactions between habitat and ecological connectivity in recovery. *Ecological Applications*, *23*(1), 226-238. https://doi.org/10.1890/12-0793.1

[56] Uthicke, S., Liddy, M., Nguyen, H. D., & Byrne, M. (2014). Interactive effects of near-future temperature increase and ocean acidification on physiology and gonad development in adult Pacific sea urchin, Echinometra sp. A. *Coral Reefs*, *33*(3), 831-845. https://doi.org/10.1007/s00338-014-1165-y

[57] Vasileiadou, K., Chatzinikolaou, E., Klayn, S., Pavloudi, C., & Reizopoulou, S. (2024). Marine biodiversity hotspots–challenges and resilience. *Frontiers in Marine Science*, *11*, 1338242. https://doi.org/10.3389/fmars.2024.1338242

[58] Walkley, A. (1947). A critical examination of a rapid method for determining organic carbon in soils—effect of variations in digestion conditions and of inorganic soil constituents. *Soil science*, *63*(4), 251-264.

[59] Whittaker, R. J., & Fernández-Palacios, J. M. (2007). *Island biogeography: ecology, evolution, and conservation*. Oxford university press. https://doi.org/10.1093/oso/9780198566113.001.0001

[60] Wohl, E., Bledsoe, B. P., Jacobson, R. B., Poff, N. L., Rathburn, S. L., Walters, D. M., & Wilcox, A. C. (2015). The natural sediment regime in rivers: Broadening the foundation for ecosystem management. *BioScience*, *65*(4), 358-371. https://doi.org/10.1093/biosci/biv002

[61] Zeller, M. A., Van Dam, B. R., Lopes, C., McKenna, A. M., Osburn, C. L., Fourqurean, J. W., ... & Böttcher, M. E. (2024). The unique biogeochemical role of carbonate-associated organic matter in a subtropical seagrass meadow. *Communications Earth & Environment*, *5*(1), 681. https://doi.org/10.1038/s43247-024-01832-7

[62] Zeppilli, D., Leduc, D., Fontanier, C., Fontaneto, D., Fuchs, S., Gooday, A. J., ... & Fernandes, D. (2018). Characteristics of meiofauna in extreme marine ecosystems: a review. *Marine Biodiversity*, *48*(1), 35-71. https://doi.org/10.1007/s12526-017-0815-z