TECHNICAL REPORT

SOCIO-ECOLOGICAL AND ECONOMIC VALUATION OF ARTIFICIAL-REEF-DRIVEN RESTORATION OF VAAN ISLAND

GULF OF MANNAR, TAMIL NADU, INDIA

Environment, Climate Change and Forests Department
Tamil Nadu Coastal Restoration Mission
In partnership with
Indian Institute of Technology Madras
Suganthi Devadason Marine Research Institute

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மன்னார் வளைகுடாவில் உள்ள வான் தீவில் செயற்கை பவளப்பாறைகள் மூலம் மேற்கொள்ளப்பட்ட மறுசீரமைப்பிற்கான சமூக சூழலியல் மற்றும் பொருளாதார மதிப்பீடு

S.A. Sannasiraj, Santosh Kumar Sahu, Aman Srivastava,
J.K. Patterson Edward, Deepak S. Bilgi and Akhil Thampi

Tamil Nadu
Coastal Restoration Mission

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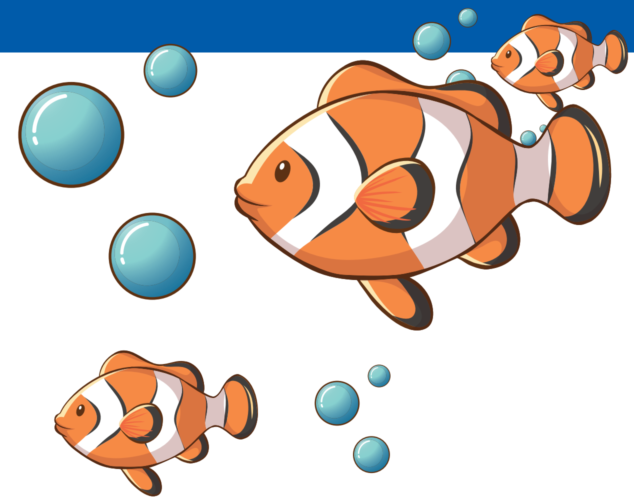

FOREWORD

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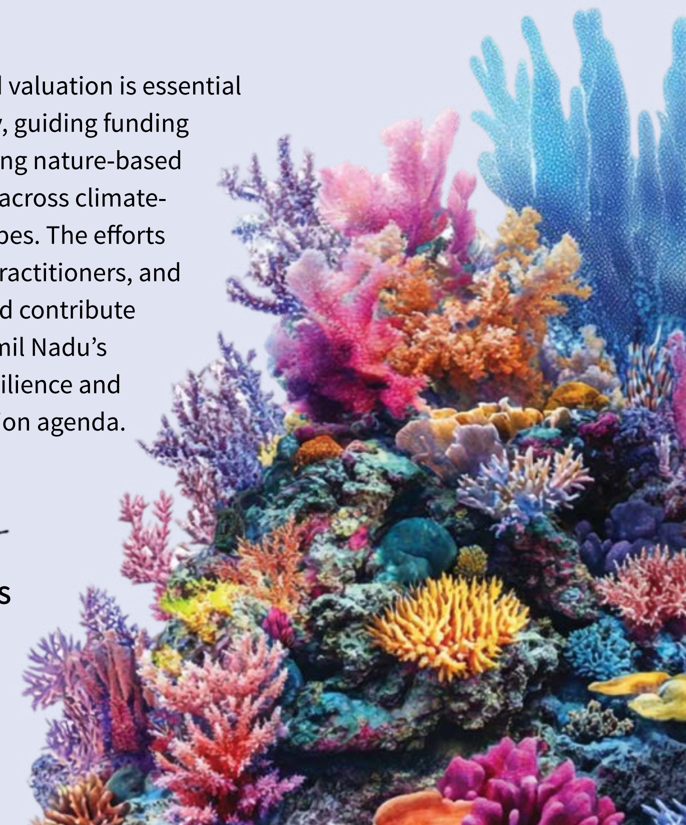
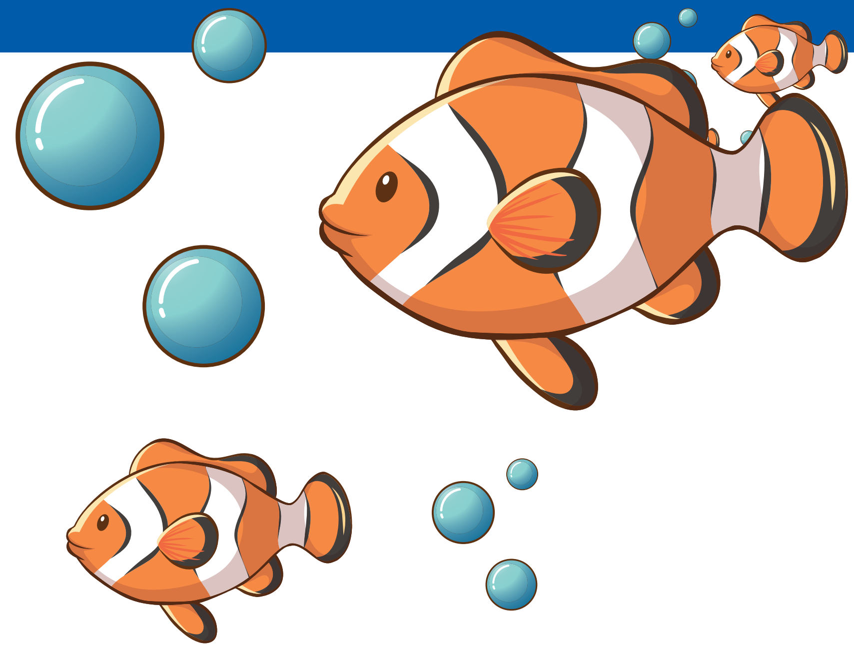
The report on, "Socio-Ecological and Economic Valuation of Artificial Reef–Driven Restoration of Vaan Island, Gulf of Mannar, Tamil Nadu, India," provides a timely assessment of the ecological and economic outcomes of restoring the submerging Vaan Island through artificial reef interventions.

The restoration has strengthened coastal protection, enhanced marine biodiversity, supported fisheries, and sustained local livelihoods. Importantly, this valuation translates ecological gains into economic evidence, enabling clearer cost–benefit understanding and stronger investment rationale.

Such science-based valuation is essential for informing policy, guiding funding decisions, and scaling nature-based coastal restoration across climate-vulnerable landscapes. The efforts of all institutions, practitioners, and researchers involved contribute meaningfully to Tamil Nadu's broader climate resilience and ecosystem restoration agenda.

Supriya Sahu, IAS





PREFACE

The Gulf of Mannar on the southeast coast of India is one of the important biodiversity hotspots of the country, where coral reefs, seagrass meadows, mangrove forests, island ecosystems and other coastal and marine biosystems are abundantly available. These ecosystems offer various ecological and economic benefits. The livelihood of the coastal communities and the protection of the coast along which they live depend on these ecosystems. All of these ecosystems, in spite of their importance, have suffered degradation due to several natural and anthropogenic factors, and in the process all the benefits associated with these systems have also been considerably reduced.

There are 21 uninhabited coral islands in the Gulf of Mannar. They are very important for the coastal people as they protect the mainland coast from erosion apart from providing livelihood through fishery resources. The combination of sea level rise and earlier coral mining activities has caused severe soil erosion on these islands leading to the submergence of two of them. Another island, the Vaan, had also been eroding at a faster rate, and the deployment of multi-purpose artificial reefs helped to mitigate the erosion and enhance the biodiversity around it. Within a decade, the highly successful restoration effort has increased the island's size through soil accretion, enhanced the biodiversity around it and boosted the fishery resources.

This report details, in a comprehensive manner and supported by scientific data, the valuation of the ecological and other direct and indirect benefits in economic perspectives. Based on a seven-component Total Economic Value (TEV) framework, the observed effects of the Vaan Island restoration project are translated into monetary estimates. The framework quantifies: (1) hard-coral habitat accrual, (2) other epibenthic organisms, (3) fisheries enhancement, (4) geomorphic saved area, (5) vegetation and biodiversity, (6) regulating and supporting services, and (7) mainland coastal protection. According to the integrated TEV valuation, the Vaan Island restoration project has yielded a consolidated decadal benefit of ₹62.66 crore (approx. $7.83 million). The TEV analysis validates that the Vaan Island restoration project is not merely an ecological expenditure but a high-value investment in natural infrastructure that generates multifold socio-economic returns over years.

The economic valuation of the project's outcomes clearly shows the good payoff of the artificial reef deployment in Vaan Island. Based on the results, the report makes various recommendations to conserve and restore the remaining eroding islands of the Gulf of Mannar and their degraded coral reefs in order to preserve and improve the associated biodiversity and fishery resources for the benefit of the coastal communities. Nature-based solutions for ecological restoration, like the present one, will help to restore more similar ecosystems in the Gulf of Mannar or other areas in India.

We are grateful to Tmt. Supriya Sahu, IAS, Additional Chief Secretary to Government, Environment, Climate Change and Forest Department (ECCFD), Government of Tamil Nadu (GoTN), who has been the guiding force and inspiration for this challenging but important task, which will help policy makers, funding agencies, conservation managers and researchers in taking up more similar restoration initiatives.

Our thanks are due to State Coastal Zone Development Fund, GoTN, National Adaptation Fund for Climate Change of Ministry of Environment, Forest and Climate Change, Government of India (GoI), Deep Sea Mission of Ministry of Earth Sciences, GoI, and ECCFD, GoTN for the funding support received for the Vaan Island restoration projects and this economics analysis study.

We thank Dr. K Diraviya Raj, Associate Professor at SDMRI, for his coordination and support in providing important primary and published monitoring data available with SDMRI.

The authors express their thanks to Mr. Ganesh Karpenter for the English edits, Dr. Vengadesan, P. for the Tamil translation, Mr. V N Arunkumar for the design and layout of the book and St Joseph's Press, Thiruvananthapuram, for the timely printing.

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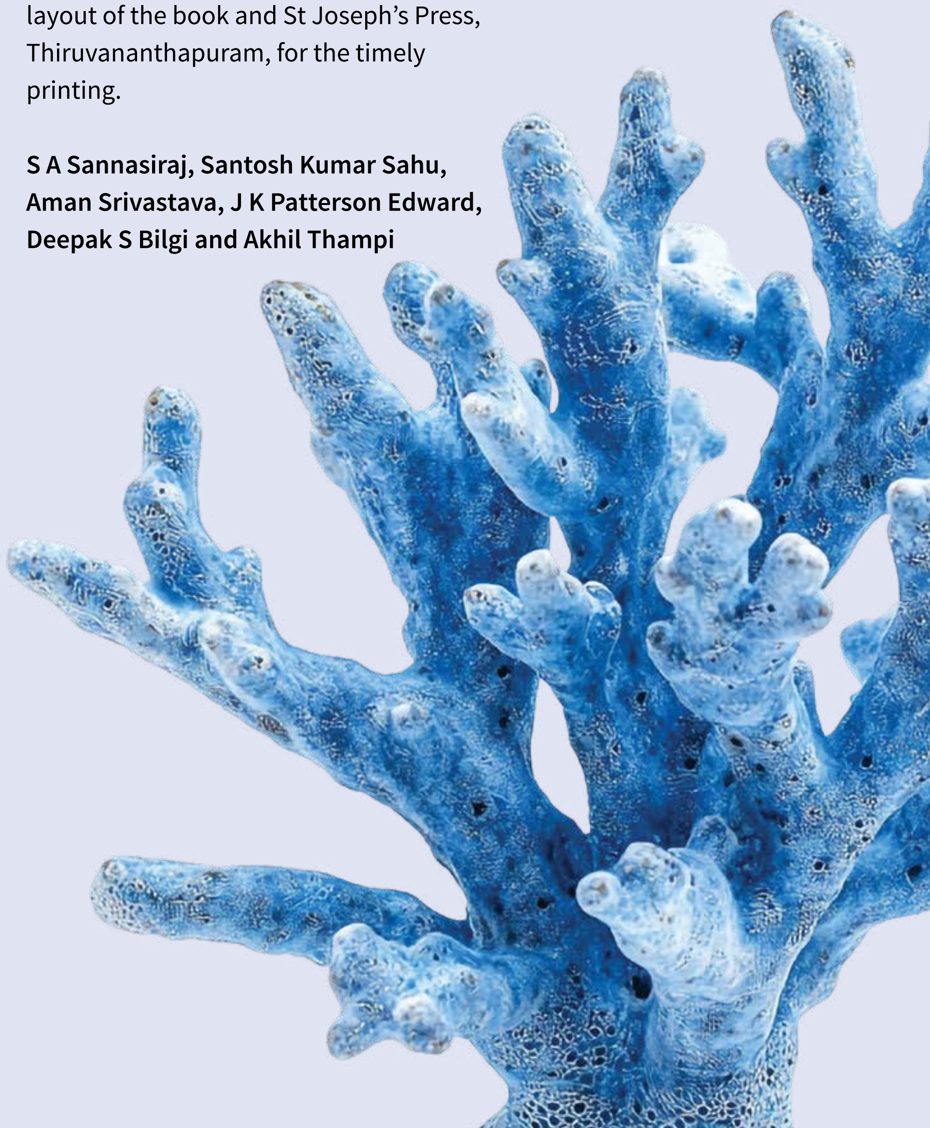


LIST OF ABBREVIATIONS

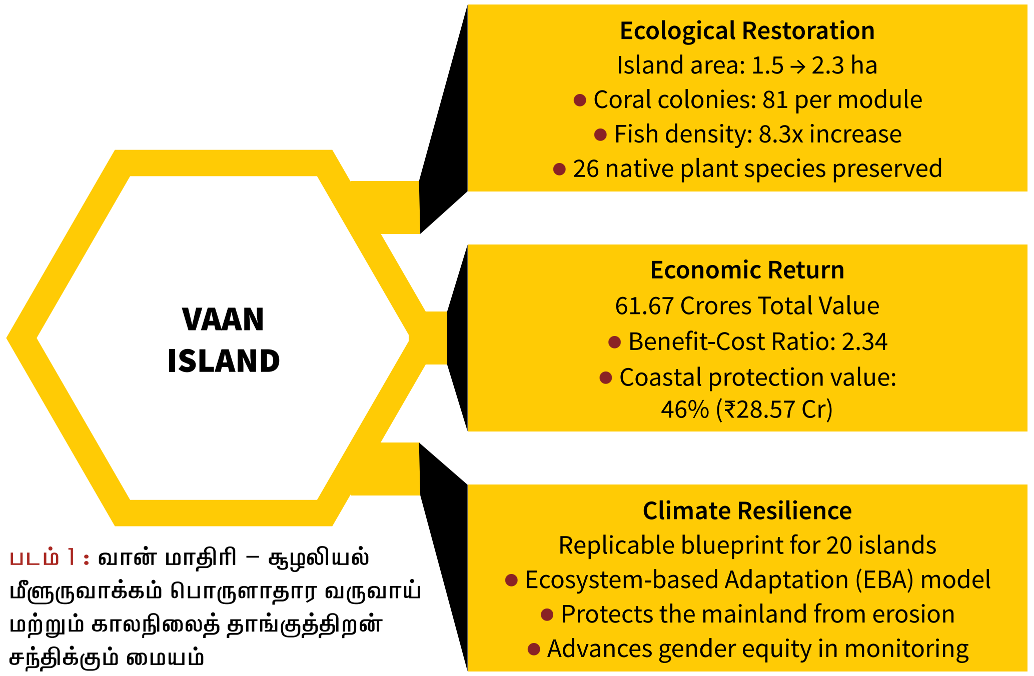
Abbreviation	Full Form
A_{AR}	Artificial Reef Influence Area
AR	Artificial Reef
BCR	Benefit-Cost Ratio
CAGR	Compound Annual Growth Rate
CSI	Cost per Species-Hectare Saved Index
DGPS	Differential Global Positioning System
DSAS	Digital Shoreline Analysis System
DTM	Digital Terrain Model
EbA	Ecosystem-based Adaptation
FV	Future Value
GoMBR	Gulf of Mannar Biosphere Reserve
GoMMNP	Gulf of Mannar Marine National Park
GPS	Global Positioning System
HTL/LTL	High Tide Line / Low Tide Line
IIT Madras	Indian Institute of Technology Madras
M_{ha}	Modules per Hectare
MoEF & CC	Ministry of Environment, Forest and Climate Change
NABARD	National Bank for Agriculture and Rural Development
NDVI	Normalized Difference Vegetation Index
NPV	Net Present Value
PRIMER	Plymouth Routines in Multivariate Ecological Research
PV	Present Value
QGIS	Quantum Geographic Information System
SDR	Social Discount Rate
SDMRI	Suganthi Devadason Marine Research Institute
SIMPER	Similarity Percentages
TEV	Total Economic Value
UVC	Underwater Visual Census
V_{bio}	Vegetation and Biodiversity Valuation
V_{coast}	Mainland Coastal Protection Valuation
V_{coral}	Hard-Coral Habitat Valuation
V_{fish}	Fisheries Valuation
V_{geo}	Counterfactual Geomorphic Saved Area Valuation
V_{org}	Other Epibenthic Organisms Valuation
V_{reg}	Regulating and Supporting Services Valuation
V_{total}	Aggregated Total Economic Value

தொழில்நுட்ப அறிக்கை

மன்னார் வளைகுடாவில் உள்ள வான் தீவில் செயற்கை பவளப்பாறைகள் மூலம் மேற்கொள்ளப்பட்ட மறுசீரமைப்பிற்கான சமூக சூழலியல் மற்றும் பொருளாதார மதிப்பீடு

ஆய்வின் முக்கியக் கருத்துக்கள்

வான் தீவில் பத்து ஆண்டுகளுக்கும் மேலாக மேற்கொள்ளப்பட்ட இந்த ஆய்வு ஒருங்கிணைந்த கடற்கரை மேலாண்மை (Integrated Coastal Management) துறையில் ஒரு முக்கிய மைல்கல்லாக விளங்குகிறது. இந்தத் திட்டத்தின் செயல்பாடு தீவிரமான கடல் அரிப்பால் இழந்த நிலப்பகுதிகளை மீட்டெடுத்ததுடன் மட்டுமல்லாமல் பலதரப்பட்ட சமூக சூழலியல் மற்றும் பொருளாதார நன்மைகளையும் வழங்கியுள்ளது. இந்த வெற்றியின் பலன்கள் ஒன்றோடொன்று இணைந்த மூன்று முக்கிய அலகுகளாக வகைப்படுத்தப்படுகின்றன. அவை (i) சூழலியல் மறுசீரமைப்பு, (ii) பொருளாதார சாத்தியக்கூறுகள் மற்றும் (iii) காலநிலை மீள்தன்மை. கீழ்கண்ட படம் 1–ல் காட்டப்பட்டுள்ளபடி, இந்த மூன்று அலகுகளும் ஒருங்கிணைந்து, நிரூபிக்கப்பட்ட 'வான் தளவமைப்பு' உருவாக்கப்பட்டுள்ளது. இது, சூழலியல் சார்ந்த தகவலமைப்பு அணுகுமுறையை நடைமுறைப்படுத்துவதற்கான ஒரு



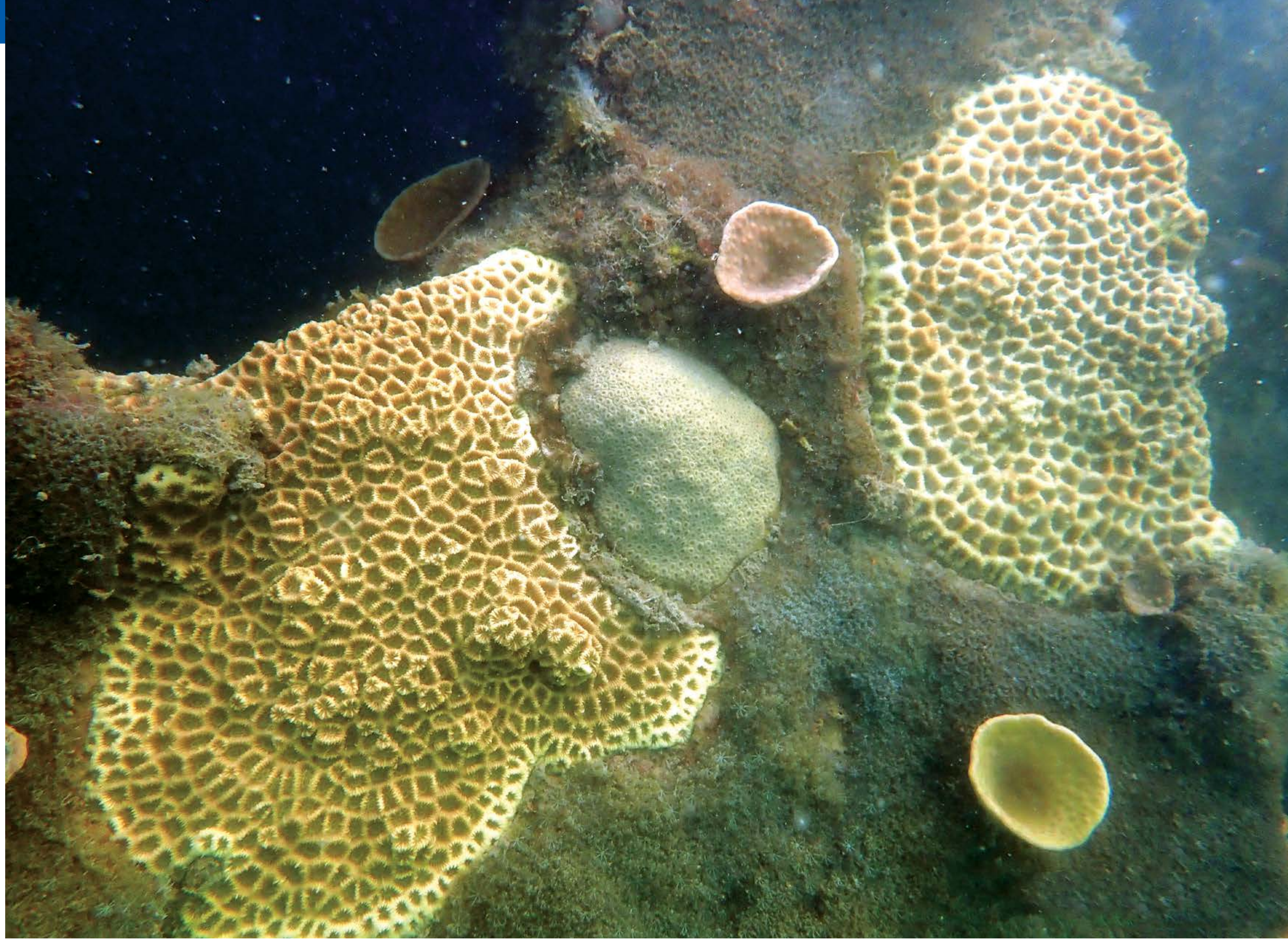
படம் 1 : வான் மாதிரி – சூழலியல் மீளுருவாக்கம் பொருளாதார வருவாய் மற்றும் காலநிலைத் தாங்குத்திறன் சந்திக்கும் மையம்

முழுமையான மற்றும் ஆதார அடிப்படையிலான வழிகாட்டியாக செயல்படுகிறது. கீழே வழங்கப்பட்டுள்ள ஆய்வின் முக்கிய முடிவுகள், இந்தத் திட்டத்தின் அடிப்படை மாற்றத்திறன் கொண்ட விளைவுகளையும் அதனால் உருவாகும் கொள்கை மற்றும் நடைமுறை நிலைகளில் ஏற்படும் தாக்கங்களையும் தெளிவாக எடுத்துக்காட்டுகின்றன.

மூழகிக் கொண்டிருந்த தீவானது மீட்டெடுக்கப்பட்டுள்ளது: 1969 முதல் 2015 வரை வான் தீவானது, 92% அளவிற்கு அரிமாணத்திற்கு உட்பட்டு அதன் பரப்பளவு 20 ஹெக்டேரிலிருந்து வெறும் 1.5 ஹெக்டேராக சுருங்கியது. 10,600 செயற்கை பவளப்பாறைகள் நிறுவப்பட்ட பத்து ஆண்டுகளுக்குப் பிறகு இந்த தீவு நிலைபெற்று அதன் பரப்பளவானது 2.3 ஹெக்டேரைத் தாண்டி விரிவடைந்துள்ளது. இது கடுமையான கரையோர இழப்பு கூட மீளக்கூடியது என்பதற்கான உறுதியான ஆதாரமாக விளங்குகிறது.

மறுசீரமைப்பிற்கான செலவீனங்கள் சுயமாகவும், மேலும் பல மடங்காகவும் ஈடு செய்யப்பட்டுள்ளது: பத்து ஆண்டுகளில் இந்த மறுசீரமைப்பு நடவடிக்கையானது மொத்தமாக 61.67 கோடி (சுமார் $7.34 மில்லியன்) மதிப்புள்ள சமூக – சூழலியல் பயன்களை உருவாக்கியுள்ளது. காலத்திற்கேற்ப சரிசெய்யப்பட்ட முதலீட்டு செலவுடன் ஒப்பிடுகையில் இந்தத் திட்டம் 2.38 என்ற நன்மை – செலவு விகிதத்தை (Benefit-Cost Ratio) கொண்டுள்ளது. இதன் மூலம், இயற்கை அடிப்படையிலான கட்டமைப்புகளில் மேற்கொள்ளப்படும் முதலீடு மிக உயர்ந்த வருவாயை அளிப்பது உறுதி செய்யப்பட்டுள்ளது.

பிரதான நிலப்பகுதி பாதுகாப்பு என்பது மிக முக்கிய பயன்பாடு: கணக்கிடப்பட்ட மொத்த பொருளாதார மதிப்பில் சுமார் பாதி (46%) – 28.56 கோடி. தூத்துக்குடி பகுதியின் கரையோரத்தை கடல் அரிப்பு மற்றும் புயல் அலைகளிலிருந்து பாதுகாப்பதன் மூலம் கிடைக்கிறது. எனவே, தீவுகளை பாதுகாப்பது என்பது பாதிப்புக்குள்ளாகும் சமூகங்களை பாதுகாக்கும் குறிப்பிடத்தக்க மற்றும் செலவு குறைந்த கடற்கரை பாதுகாப்பு முறைகளில் ஒன்றாகும்.



மீன் வளம் எட்டு மடங்காக உயர்ந்து, உள்ளூர் வாழ்வாதாரங்களை வலுப்படுத்தியுள்ளது: பவளப்பாறை சார்ந்த மீன்களின் அடர்த்தி, ஹெக்டேருக்கு 106 தனி உயிர்களிலிருந்து 875 தனி உயிர்கள் வரை உயர்ந்துள்ளது. குறிப்பாக அதிக மதிப்புடைய வணிக முக்கியத்துவம் கொண்ட மீன்களின் எண்ணிக்கை குறிப்பிடத்தக்க அளவில் அதிகரித்துள்ளது. இந்தப் 'பரவலான வளர்ச்சி' நேரடியாக சிறு மீனவர்களின் மீன் பிடிப்பையும் அவர்களின் வருமானத்தையும் அதிகரித்துள்ளது.

செயற்கை பவளப்பாறைகள் ஓராண்டிற்குள் உயிர்ப் பவளப் பாறைகளாக மாறியுள்ளன: நிலைநிறுத்தப்பட்ட பவளப்பாறைகள் இயற்கையான உயிரியல் குடியேற்றத்தை அடைந்து ஒவ்வொரு அலகிலும் 81 பவளக் கூட்டங்களை ஆதரித்ததுடன், பவளமல்லாத கடல் உயிரினங்களில் 6.8 மடங்கு உயர்வையும் ஏற்படுத்தின. இதன் மூலம் கிட்டத்தட்ட மறைந்துவிட்டிருந்த ஒரு சிக்கலான செயல்படும் வாழ்விட

அமைப்பு மீண்டும் உருவாக்கப்பட்டுள்ளது.

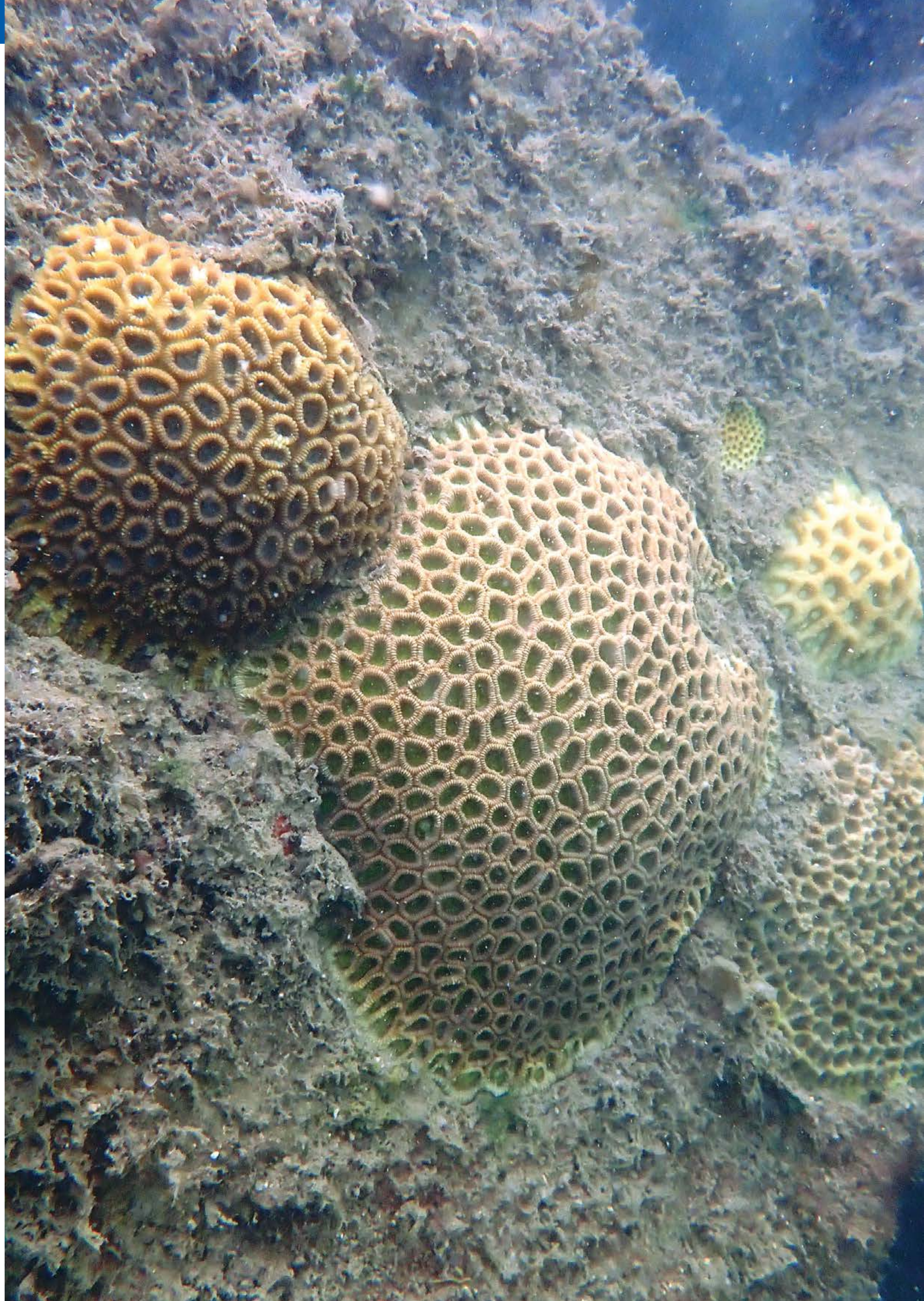
மறைமுக சுற்றுச்சூழல் ஒழுங்குபடுத்தும் சேவைகள் மிகுந்த மதிப்புடையவை: நீர் சுத்திகரிப்பு மணல் படிதல் மற்றும் ஊட்டச்சத்து சுழற்சி போன்ற மறைமுக ஒழுங்குபடுத்தும் சேவைகளின் மதிப்பு மொத்த பொருளாதார மதிப்பின் 24% (15 கோடி) ஆகும். இந்தச் சேவைகள் கடலின் சூழல்நலத்தையும், தீவின் நீண்டகால நிலைத்தன்மையையும் பாதுகாக்கின்றன.

அறிவியல் அடிப்படையிலான வடிவமைப்பு வெற்றிக்கான முக்கிய காரணி : இந்த செயற்கை பவளப்பாறைகள் இந்திய தொழில்நுட்பக் கழகம் சென்னையில் (Indian Institute of Technology Madras) உள்ள பெருங்கடல் பொறியியல் மற்றும் மனிதவியல் மற்றும் சமூகவியல் துறைகள் மேற்கொண்ட எதிரொலி ஆழ அளவையீடு அடிப்படையிலான கடலடித் தளவமைப்பு கணக்கெடுப்பையும் அலை மாதிரிகளையும் கொண்டு, மிக நுட்பமாக கணக்கிட்டு நிலைநிறுத்தப்பட்டன. சரிவக வடிவிலான பவளப்பாறைகளானது அலை ஆற்றலைச் சிறப்பாகச் சிதறடித்ததுடன் மணல் துகள்கள் படிதலையும் மேம்படுத்தியது. இதன் மூலம் பயனுள்ள மறுசீரமைப்பு என்பது அந்தந்த இடத்தின் சூழல் நிலைகளுக்கேற்ற வகையில் வடிவமைக்கப்பட்ட பொறியியல் தீர்வுகளின் தேவையை வலியுறுத்துகின்றது.

பாதிப்புக்கு உள்ளாகி இருக்கின்ற மற்ற 20 தீவுகளுக்கான மறுபயன்பாட்டிற்கு ஏற்ற செயல்திட்டம் : மன்னார் வளைகுடாவில் மேலும் 20 தீவுகள் கடல் அரிப்பால் பாதிக்கப்பட்டு வருகின்றன. அவற்றில் இரண்டுதீவுகள் ஏற்கனவே முழுமையாக மூழ்கியுள்ளன. வடிவமைப்பிலிருந்து கண்காணிப்பு வரை அனைத்தையும் உள்ளடக்கிய 'வான் தளவமைப்பு' யுனெஸ்கோ உயிர்க்கோள காப்பகமாக அறிவிக்கப்பட்ட இந்த பகுதியில் மேலும் இழப்புகளைத் தடுப்பதற்கான தயாரான, ஆதார அடிப்படையிலான செயல்திட்டத்தை வழங்குகிறது.

இது ஒரு காலநிலை மாற்றத்திற்கு எதிரான நடவடிக்கை : இத்திட்டம் இயற்கையாக அமைந்த தடுப்புகளை மீட்டெடுப்பதன் மூலம் கடல் மட்ட உயர்வும் கடுமையான வானிலை நிகழ்வுகளும் ஏற்படுத்தும் பாதிப்புகளை நேரடியாக எதிர்கொள்ள வழிவகை செய்கின்றது. சூழலியல் அடிப்படையிலான தகவமைப்பு அணுகுமுறை ஒரே நேரத்தில் கரையோரங்களை பாதுகாக்கவும், மீன் வளத்தை உயிர்ப்பிக்கவும், உயிரின பல்வகைமையை பாதுகாக்கவும், வலுவான பொருளாதார வருவாயை வழங்கவும் முடியும் என்பதை நிரூபிக்கிறது. இது உலகம் முழுவதும் பாதிப்புக்குள்ளாகும் பகுதிகளுக்கான ஒரு முழுமையான முன்மாதிரியாக விளங்குகிறது.

அனைவரையும் உள்ளடக்கிய மறுசீரமைப்பானது பாலின சமத்துவத்தை முன்னேறக்கூடும் : இந்தத் திட்டத்தின் வெற்றியானது, பவளப் பாறைகள் கணக்கெடுப்பு முதல் கரையோர வரைபடமிடல் மற்றும் உயிரியல் பல்வகைமை பதிவேற்றம் வரை கடல் அறிவியல் மற்றும் கண்காணிப்பு பணிகளில் பெண்களின் பங்கேற்புக்கான புதிய வாய்ப்புகளைத் திறக்கிறது. இத்தகைய முயற்சிகள் விரிவாக்கப்படும் போது, கரையோர பாதுகாப்பில் பெண்களையும் அங்கீகரிக்கப்பட்ட பாதுகாவலர்களாகவும் அறிவுத் தாங்கிகளாகவும் மாற்றும் திறன் கொண்டதாக இத்திட்டம் அமையும்.



THE KEY MESSAGE

The decade-long restoration of Vaan Island represents a landmark achievement in integrated coastal management. The intervention not only reversed severe geomorphic loss but also generated multifaceted socio-ecological and economic returns. The success can be distilled into three interconnected pillars: Ecological Restoration, Economic Viability, and Improved Climate Resilience. As visualized in Fig. 1, these pillars converge to form the proven "Vaan Model"—a holistic, evidence-based blueprint for scaling ecosystem-based adaptation. The following key messages detail the project's transformative outcomes and its implications for policy and practice.

- **A Drowning Island was Rescued.** Vaan Island had suffered an erosion of 92% from 1969 to 2015, shrinking from 20 hectares to just 1.5 hectares. A decade after deploying 10,600 artificial reef modules, the island has stabilized and grown to over 2.3 hectares, which is conclusive proof that severe coastal loss is reversible.

- **Restoration Pays for Itself—Multiple Times Over.** The decade of restoration generated ₹61.67 crores in socio-ecological value. Compared to the time-adjusted investment cost, the project delivers a Benefit-Cost Ratio of 2.34, proving that it is a high-return investment in natural infrastructure.

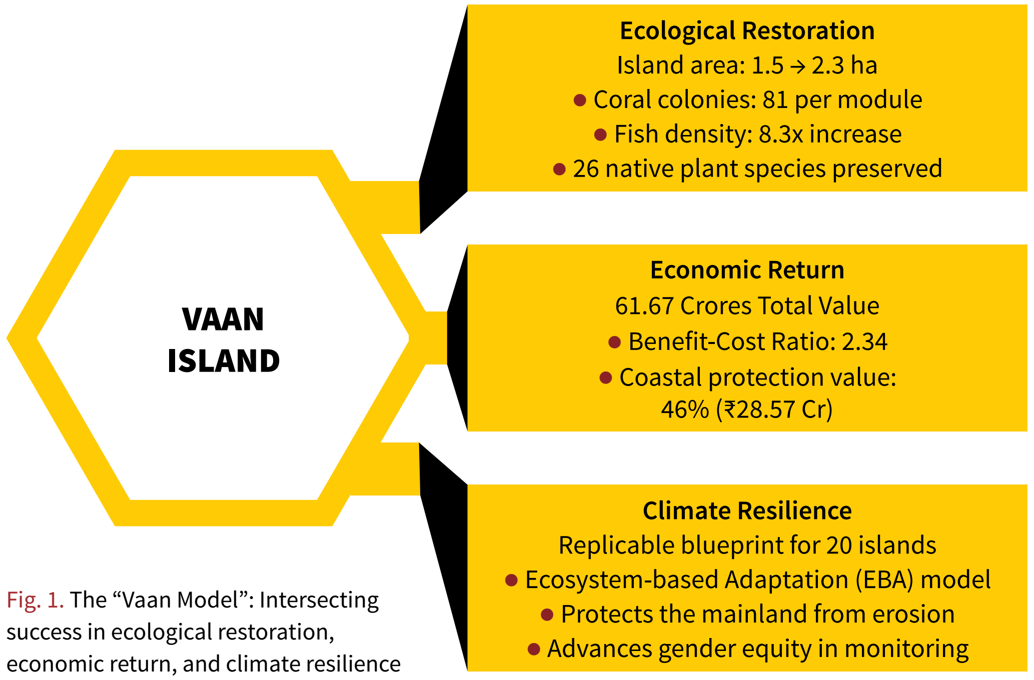


Fig. 1. The "Vaan Model": Intersecting success in ecological restoration, economic return, and climate resilience

The Biggest Winner is the Mainland Coast. Nearly half (46%) of the total economic value, i.e., ₹28.57 crores, comes from protecting the Thoothukudi coastline from erosion and storm surges. Saving offshore islands is one of the most cost-effective forms of coastal defense for vulnerable communities.

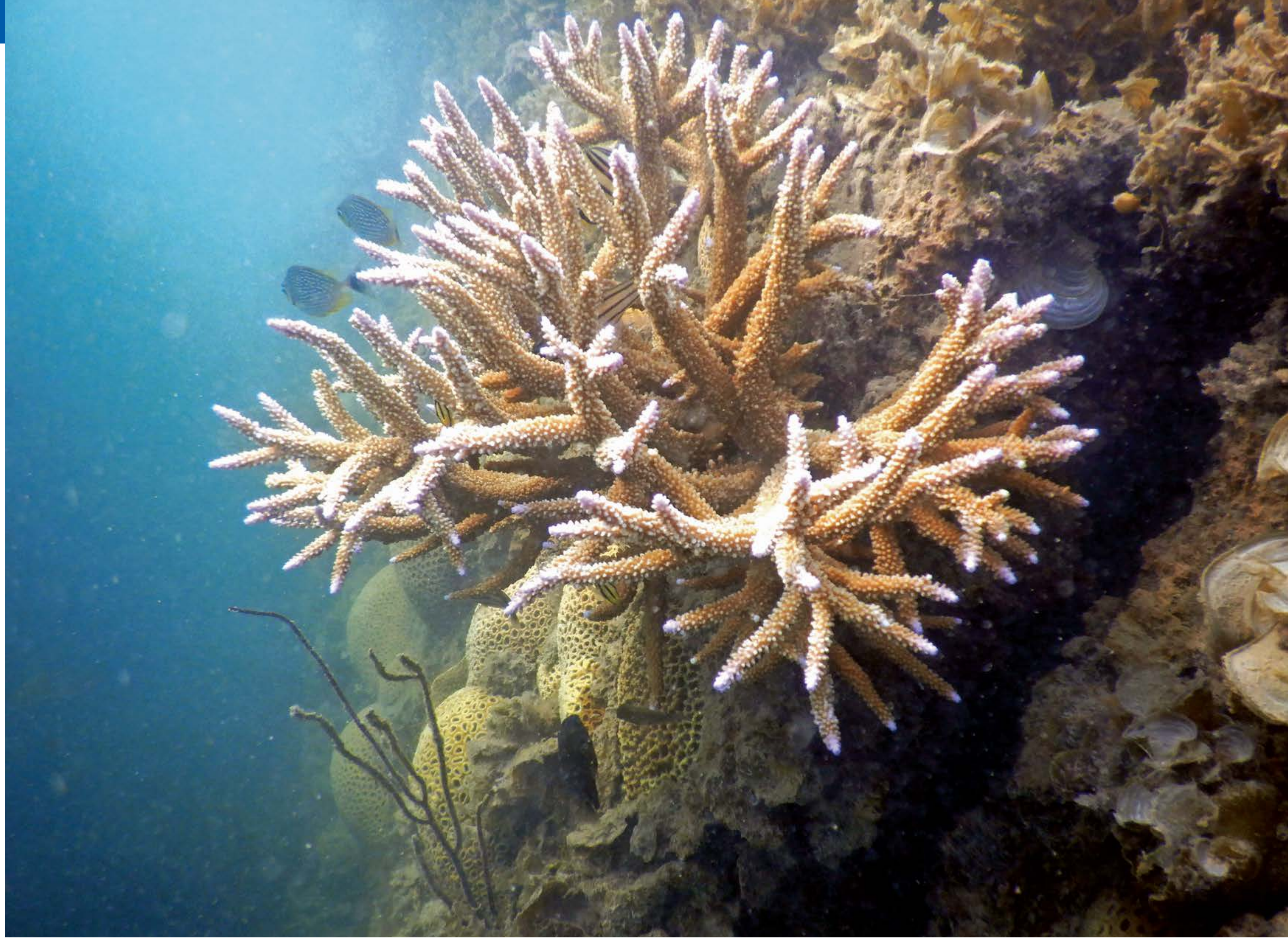
Fish Populations Soared Eightfold, Boosting Local Livelihoods. Reef-associated fish density increased from 106 to 875 individuals per hectare, with a dominance of high-value commercial species. This “spillover” effect directly improves catches and income for small-scale fishers.

Artificial Reefs Become Living Reefs within Years. The modules achieved rapid biological colonization, supporting 81 coral colonies per module and a 6.8-fold increase in non-coral marine life. They effectively rebuilt a complex, functioning habitat where one had nearly vanished.

Beyond Fish: Hidden “Regulating” Services are Hugely Valuable. Functions like water filtration, sediment trapping, and nutrient cycling, often invisible, account for 21.1% of the total value (₹13 crores). These services sustain marine health and long-term island stability.

The Island’s Unique Plant Life was Saved. The stabilization preserved 26 native plant species across dunes, beaches, and salt marshes. This biodiversity has its own value and helps bind the island’s soil, creating a positive feedback loop for resilience.

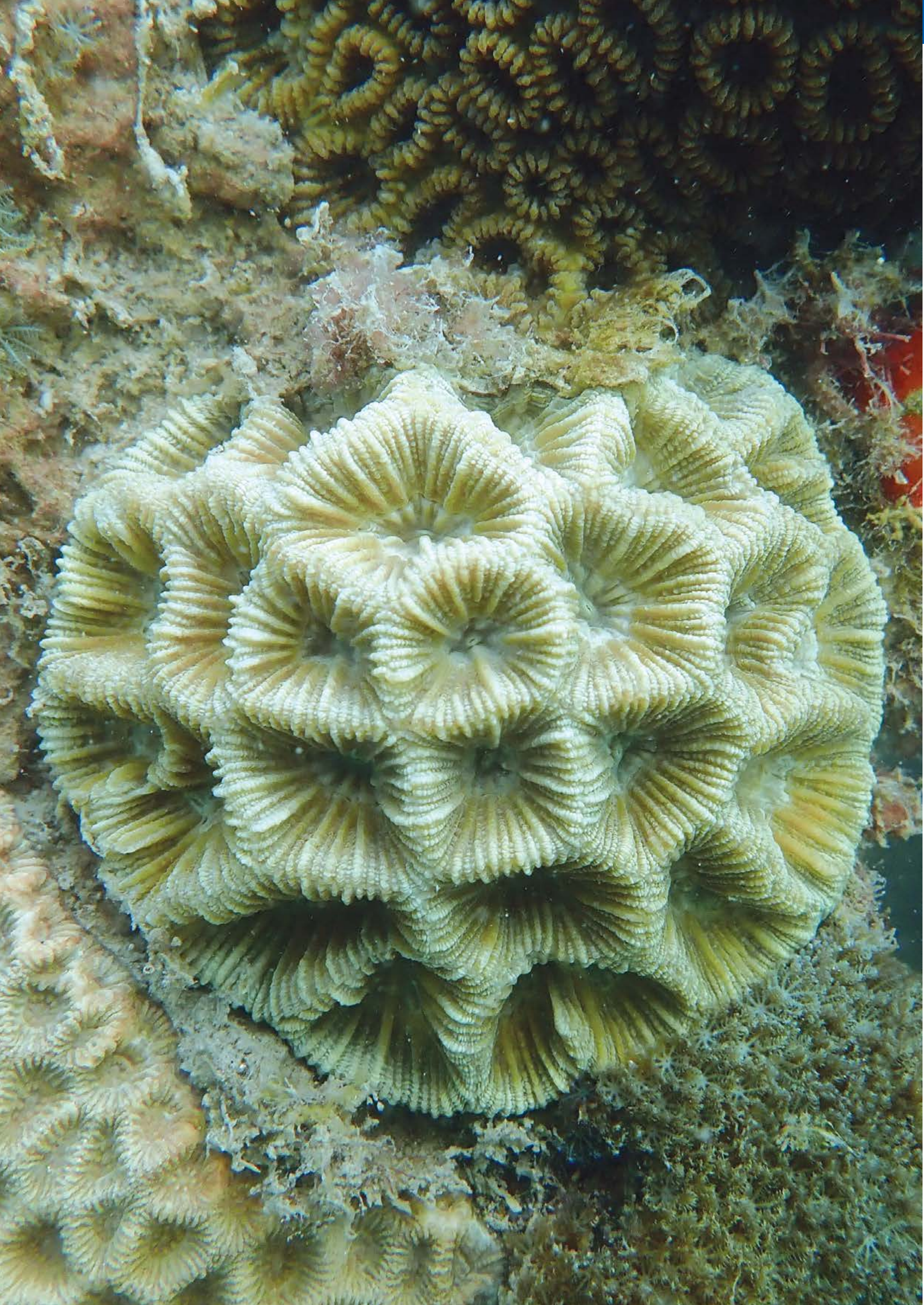
Science-Based Design was Key to Success. The artificial reefs were precisely placed based on detailed bathymetric and wave modeling studies conducted by the Department of Ocean Engineering of IIT (Indian Institute of Technology) Madras. Their trapezoidal shape optimized wave dissipation and sediment trapping, showing that effective restoration requires engineering custom-made to site conditions.



A Replicable Blueprint for 20 other Islands at Risk. The Gulf of Mannar has 20 more eroding islands, two of which have already submerged. The “Vaan Model”—from design to monitoring—provides a ready, evidence-based strategy to prevent further loss across this UNESCO Biosphere Reserve.

This is Climate Adaptation in Action. The project directly counters sea-level rise and extreme weather by restoring natural barriers. It demonstrates how Ecosystem-based Adaptation (EbA) can simultaneously secure coasts, revive fisheries, conserve biodiversity, and deliver strong economic returns—a holistic model for vulnerable regions worldwide.

Inclusive Restoration can Advance Gender Equity. The project’s success opens pathways for women’s participation in marine science and monitoring, from coral surveys to shoreline mapping and biodiversity reporting. When scaled, such initiatives can transform women into recognized stewards and knowledge-holders in coastal conservation.



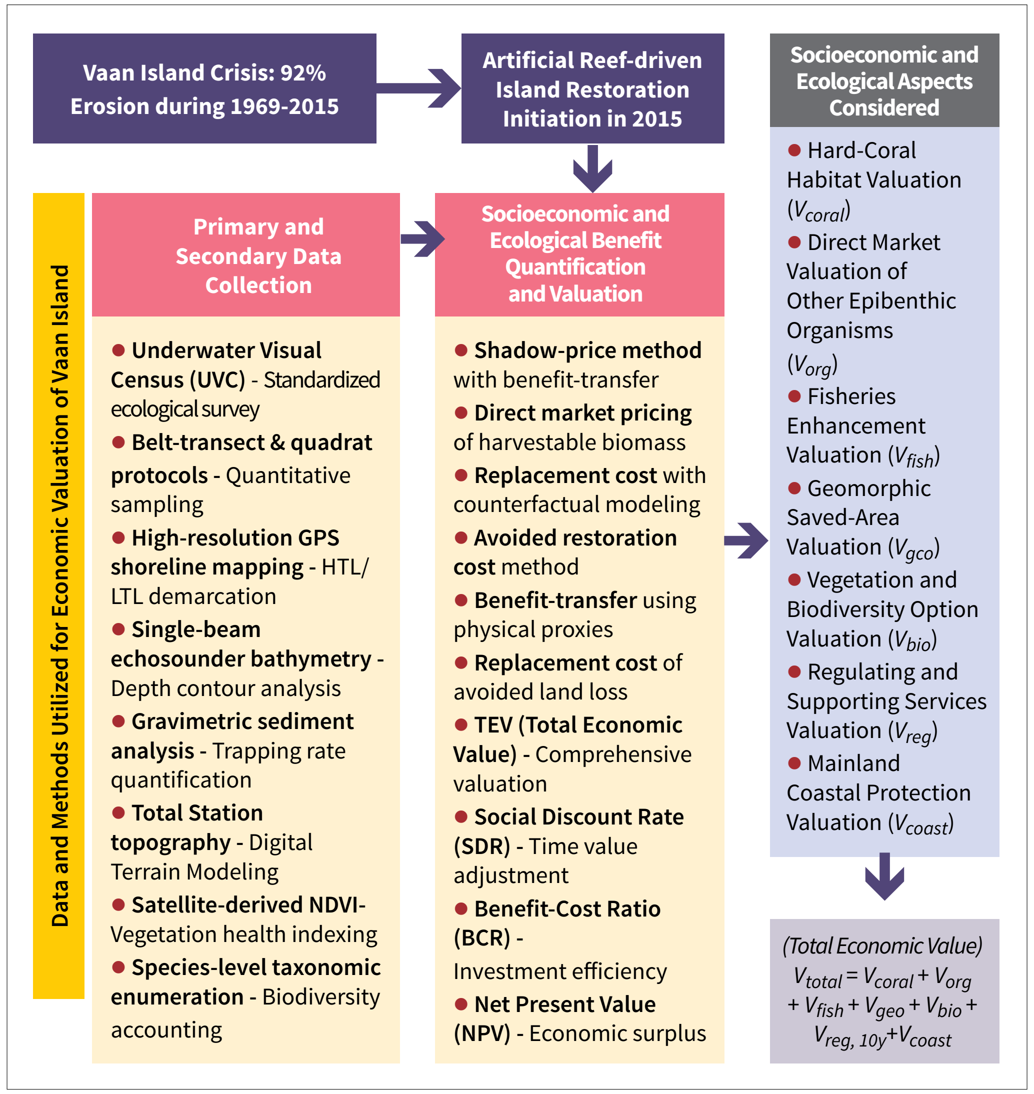
நிர்வாகச் சுருக்கம்

மன்னார் வளைகுடா என்பது ஐக்கிய நாடுகள் கல்வி அறிவியல் பண்பாட்டு நிறுவனம் (UNESCO) மற்றும் ராம்சார் (Ramsar) அமைப்பு ஆகிய நிறுவனங்களால் அங்கீகரிக்கப்பட்ட உலகளவிலான கடல்வாழ் உயிரியல் வள பகுதி ஆகும். இதன் 21 பவள பாறைகளால் சூழப்பட்ட மக்கள் வசிக்காத தீவுகள் தமிழகத்தின் முக்கியமான கடல் சூழலியல் பாதுகாப்பு அமைப்பாகவும், பலதரப்பட்ட உயிரினங்களுக்கான வாழ்விடங்களாகவும், மீன் வள பெருக்கப் பகுதிகளாகவும், மக்கள் நெருக்கமுள்ள கடலோர நிலப் பகுதிகளின் இயற்கை அரண்களாகவும் திகழ்கின்றன. இந்த தீவுக் கூட்டங்களில் ஒன்றான வான் தீவு, தீவிரமான கடல் அரிமாணத்திற்கு உட்பட்டு 1965ஆம் ஆண்டில் இருந்த 20.08 ஹெக்டேர் நிலப்பரப்பு 2015ஆம் ஆண்டில் 1.53 ஹெக்டேராகக் குறைந்ததுடன், மொத்த நிலப்பரப்பின் சுமார் 90 சதவீதத்தை இழந்தது. இந்த இழப்பிற்கு பவளப் பாறைகளை அகழ்தல், பருவ நிலை மாற்றத்தினால் ஏற்பட்ட பவளப்பாறை வெளுத்தல் மற்றும் கடல் நீர் மட்டம் உயர்தல் ஆகியவை காரணங்களாகக் கூறப்படுகின்றன. வான் தீவின் இந்த அதிதீவிர இழப்பானது தனித்துவமான பவளப்பாறைகள் மற்றும் அதனுடன் இணைந்த பல்லுயிர் தன்மைக்கு அச்சுறுத்தலாக அமைவது மட்டுமல்லாமல் பவளப்பாறைகளின் வளம் சார்ந்த ஆயிரக்கணக்கான சிறு மீனவர்களின் வாழ்வாதாரத்திற்கும் அச்சுறுத்தலாக அமைகின்றன. மேலும் இது தூத்துக்குடி பிரதான நிலப் பகுதியின் கடலோர பகுதிகளில் கரையரிப்பையும், சூறாவளி போன்ற கடும் கடல் சீற்றங்களால் ஏற்படும் பாதுகாப்பின்மையையும் அதிகரிக்கிறது.

இந்த அறிக்கை வான் தீவில் மேற்கொள்ளப்பட்ட குறிப்பிடத்தக்க மீட்டெடுப்பு நடவடிக்கையின் பத்தாண்டு கால சமூக சுற்றுச்சூழல் மற்றும் பொருளாதார மதிப்பீட்டை [2015–2025] விளக்குகிறது. காலநிலை மாற்றத்திற்கான தேசிய தழுவல் நிதியம் (NAFCC) மற்றும் தமிழ்நாடு மாநில கடலோர நிதியம் ஆகியவற்றின் கீழ் நிதியளிக்கப்பட்ட இந்த திட்டத்தின் மூலம் 10,600 தனித்துவமாக வடிவமைக்கப்படட் சரிவக வடிவிலான செயற்கை (AR - Artificial Reef) பவளப்பாறைகள் தீவைச் சுற்றி நிலைநிறுத்தப்பட்டன. இந்த அறிக்கையின் இரண்டு முக்கிய நோக்கங்கள் (1) இந்த திட்டத்தினால் ஏற்பட்ட புவியியல், சூழலியல் மற்றும் நீரியக்கவியல் போன்ற உயிர் இயற்பியல் அளவுருக்களில் ஏற்பட்ட மீட்பை கணக்கிடுதல், (2) இந்த இயற்கை சார்ந்த தீர்வு திட்டத்தினால் ஏற்பட்ட பல பரிமாணப் பயன்களின் மொத்த பொருளாதார மதிப்பு (Total Economic Value - TEV) திட்டச் செலவுகளை விட குறிப்பிடத்தக்க அளவில் அதிகமாக உள்ளது என்பதை கண்டறிதல் ஆகும். இந்த ஆய்வு, பண்பு சார்ந்த வெற்றி அளவுகோள்களை மட்டும் சாராமல், ஆதார அடிப்படையிலான ஒரு வலுவான மாதிரியை உருவாக்குவதை நோக்கமாகக் கொண்டது. இந்த மாதிரி,

மன்னார் வளைகுடாவில் மண் அரிப்புக்கு உள்ளாகி வரும் 21 தீவுகளில் சூழலியல் சார்ந்த தகவமைப்பு நடவடிக்கைகளை மேலாண்மை மற்றும் வியூக ரீதியான அளவூட்டலுக்காக வழிகாட்டுவதாகும்.

இந்த மதிப்பீடு, பத்து ஆண்டுகளாக மேற்கொள்ளப்பட்ட முதன்மை கண்காணிப்பு தரவுகளையும், மேம்பட்ட பொருளாதார மதிப்பீட்டு முறைகளையும் இணைத்த ஒருங்கிணைந்த பல்துறை அணுகுமுறையை அடிப்படையாகக் கொண்டது (படம் 1-ஐ காண்க). இந்த மதிப்பீட்டிற்கு கடலின் அடிமண் மேற்பரப்பில் வாழக்கூடிய உயிரினங்கள் (எபிபென்தோஸ்) மற்றும் மீன் கூட்டங்களைப் பற்றிய ஆண்டுதோறும் மேற்கொள்ளப்பட்ட நீர்மூழ்கி வாகன காட்சி கணக்கெடுப்புகள் (UVCs), உயர் தெளிவு புவியிடங்கட்டி மூலம் கரையோர வரைபடமிடல், எதிரொலி ஆழ அளவி மூலம் கடலடித் தளவமைப்பு (bathymetry) படிவு பிடிப்பு கருவிகளால் (sediment traps) அளவீடுகள், மேலும் தாவர ஆய்வுக்காக மின்னணு தியோடலைட் (total station) நிலவமைப்பு தரவுகள் மற்றும் செயற்கைக்கோள் மூலம் பெறப்பட்ட இயல்பாக்கப்பட்ட வேறுபாடு தாவரக் குறியீடு (NOV) தரவுகள் ஆகியவை முதன்மை தரவுகளாக பயன்படுத்தப்பட்டன. இந்த செயல்



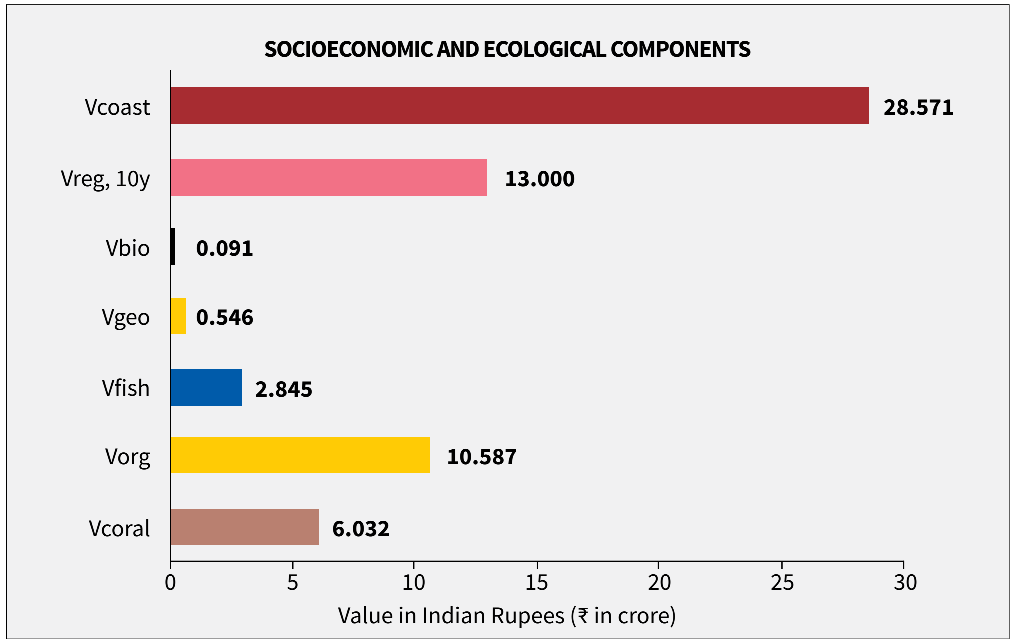
படம் 1. வான் தீவில் செயற்கை பவளப்பாறைகள் மீளமைப்பு மதிப்பீட்டிற்கான செயல்முறை கட்டமைப்பு

திட்டத்திற்கு முந்தைய கரையரிப்பு மாற்றப் போக்குகளைப் புரிந்துகொள்ள, 1969-ஆம் ஆண்டை அடிப்படையாகக் கொண்ட வரலாற்று நிலைகள் இந்திய நில அளவைத் துறையின் நிலவரைபடங்கள் (toposheets) மற்றும் செயற்கைக்கோள் படங்களை பயன்படுத்தி மீள் உருவாக்கம் செய்யப்பட்டன.

மேற்கண்ட தரவுகளின் அடிப்படையில் உயிர் இயற்பியல் அளவுருக்களின் மாற்றத்திறனை பண மதிப்பீடுகளாக மாற்றுவதற்காக ஏழு காரணிகளை கொண்ட மொத்த பொருளாதார மதிப்பீடு கட்டமைப்பு ஒன்று உருவாக்கப்பட்டது. இந்த கட்டமைப்பானது (1) கடின பவளப் பாறை வாழிட திரள்களின் வளர்ச்சி, (2)அடிமண் மேற்பரப்பில் வாழும் உயிரினங்கள், (3) மீன்வள மேம்பாடு, (4)புவியியல் ரீதியாக பாதுகாக்கப்பட்ட பகுதிகள், (5) தாவர வளம் மற்றும் உயிரியல் பல்வகைமை, (6) சூழல் ஒழுங்குபடுத்தல் மற்றும் ஆதரிக்கும் சேவைகள், மற்றும் (7) கரையோர பாதுகாப்பு ஆகிய காரணிகளை மதிப்பீடு செய்கின்றது.

இந்த மதிப்பீடானது நேராக சந்தைப்படுத்துதல் (அறுவடை செய்யக் கூடிய உயிரிப் பொருட்கள்), மாற்றுச் செலவு முறைகள் (நிலம் மற்றும் தாவரங்களை மீள் உருவாக்கம் செய்ய ஆகும் செலவிற்கு தவிர்த்தல்), நேரடிப் பலன் பரிமாற்றம் (சந்தைப்படுத்த முடியாத சேவைகள்) ஆகிய முறைகள் கலந்து மேற்கொள்ளப்பட்டது. மேலும் ஒன்றோடொன்று இணைந்துள்ள கூறுகளுக்கிடையேயான காரணிகள் இருமுறை கணக்கிடப்படாதவாறு இருப்பது உறுதி செய்யப்பட்டது.

பத்து ஆண்டுகள் மேற்கொள்ளப்பட்ட கண்காணிப்பின் முடிவுகள், அளவிடப்பட்ட அனைத்து பரிமாணங்களிலும் இந்த திட்டம் மிகுந்த வெற்றியடைந்ததை உறுதிப்படுத்துகின்றன (படம் 2-ஐ காண்க). புவியியல் கோணத்தில் செயற்கை பவளப்பாறைகள் நிறுவப்பட்ட பின்னர், தீவின் உயர் ஓத (high-tide) கரையோரப் பகுதிகள் நிலைப்படுத்தப்பட்டு, நீண்ட காலமாக தொடர்ந்துவந்த அதி தீவிர கரையோர அரிப்பு கட்டுப்படுத்தப்பட்டு



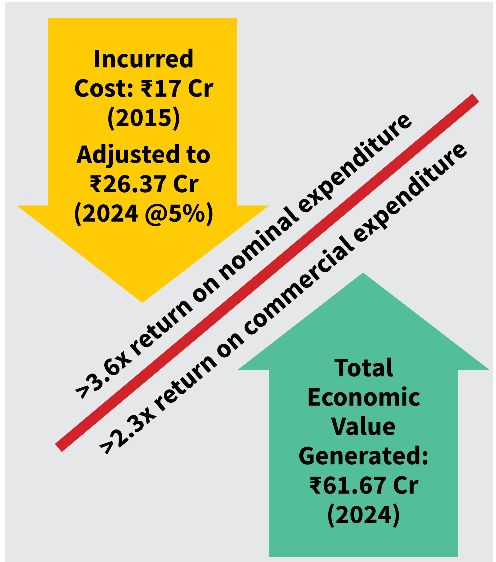
படம் 2. வான் தீவில் அமைக்கப்பட்ட செயற்கை பாறை (AR) மீளமைப்பிலிருந்து பெறப்பட்ட மொத்த பொருளாதார மதிப்பின் கூறுவாரியான பிரிப்பு

(குறிப்பு : (1) Vcoral – பவள வாழ்விடம், (2) Vorg - கடலின் அடிமண் மேற்பரப்பில் வாழும் உயிரினங்கள், (3) Vfish - மீன்வள பரவல் (spillover), (4) Vgeo - தீவின் பாதுகாக்கப்பட்ட புவியியல் பரப்பளவு, (5) Vbio - நில வாழ்வுத் தாவரங்கள் மற்றும் உயிரியல் பல்வகைமை தாங்குத்தன்மை, (6) Vreg, 10y - பத்து ஆண்டுகளுக்கு ஒருங்கிணைந்த ஒழுங்குமுறை மற்றும் ஆதரவு சேவைகள், மற்றும் (7) Vcoast - பிரதான நிலப்பகுதியில் உள்ள உட்கட்டமைப்புகளுக்கான கடற்கரை பாதுகாப்பு)

நிறுத்தப்பட்டது. அதன் விளைவாக மொத்தமாக நிகர மண் சேர்ப்பு ஏற்பட்டது.

இதன் விளைவாக தீவின் பரப்பளவானது 1.53 ஹெக்டேரிலிருந்து அதிகபட்சமாக 2.30 ஹெக்டேராக உயர்ந்தது. கடலடித் தளவமைப்பு அளவீடுகள் குறிப்பிடத்தக்க ஆழக் குறைவை காட்டின. உதாரணமாக, வடமேற்கு மணல் திட்டில் ஆழம் 2.5 மீட்டரிலிருந்து 1 மீட்டருக்கும் குறைவாக மாறியது. இது AR அமைப்புகள் காரணமாக அலைகளின் ஆற்றல் குறைதல், மணல் படிதலும் ஏற்பட்டதன் விளைவாகும். சராசரியாக, மண் படிதல் விகிதம் தினமும் சுமார் 200 கிலோ கிராம்/சதுர மீட்டர் ஆக பதிவானது. சூழலியல் ரீதியாக AR தொகுதிகள் கடல்வாழ் உயிரினங்கள் பல்வகையாகவும் விரைவாகவும் குடியேறுவதற்கு உதவின.

குறிப்பாக, 2015ஆம் ஆண்டில் இல்லாத கடின பவளப்பாறைகள் (hard corals) 2024 ஆம் ஆண்டுக்குள் ஒவ்வொரு AR தொகுதியிலும் சராசரியாக 81.33 பவளக் கூட்டங்களாக உயர்ந்ததுடன், ஒரு ஹெக்டேருக்கு சுமார் 1,14,989 பவளக் கூட்டங்கள் வளரக்கூடிய நிலை உருவானது. மேலும் பவளமல்லாத, அடித்தள உயிரினங்கள் (molluscs, sponges, ascidians) போன்றவற்றின் அடர்த்தி 6.8 மடங்காக உயர்ந்து காணப்பட்டது. இந்த உயர் வாழ்விட மேம்பாடு காரணமாக, பவளப்பாறை சார்ந்த மீன் இனங்கள் வேகமாக அதிகரித்தன. மீன் அடர்த்தி ஒரு ஹெக்டேருக்கு 105.75 இலிருந்து 875.25 ஆக உயர்ந்து, சுமார் 8.3 மடங்கு அதிகரித்தது. இதில் கொண்டல் மீன் (Lutjanidae) மற்றும் விலை மீன் (Lethrinidae) போன்ற வணிக முக்கியத்துவம் வாய்ந்த மீன் குடும்பங்கள் ஆதிக்கம் செலுத்துகின்றன. மேலும் நிலைப்படுத்தப்பட்ட பகுதியில், 26 உள்ளூர் நில வாழ் தாவர இனங்கள் பாதுகாக்கப்பட்டன.



படம் 3. வான் தீவில் அமைக்கப்பட்ட செயற்கை பவளப்பாறை மீளமைப்பின் செலவு – பயன் சமநிலை

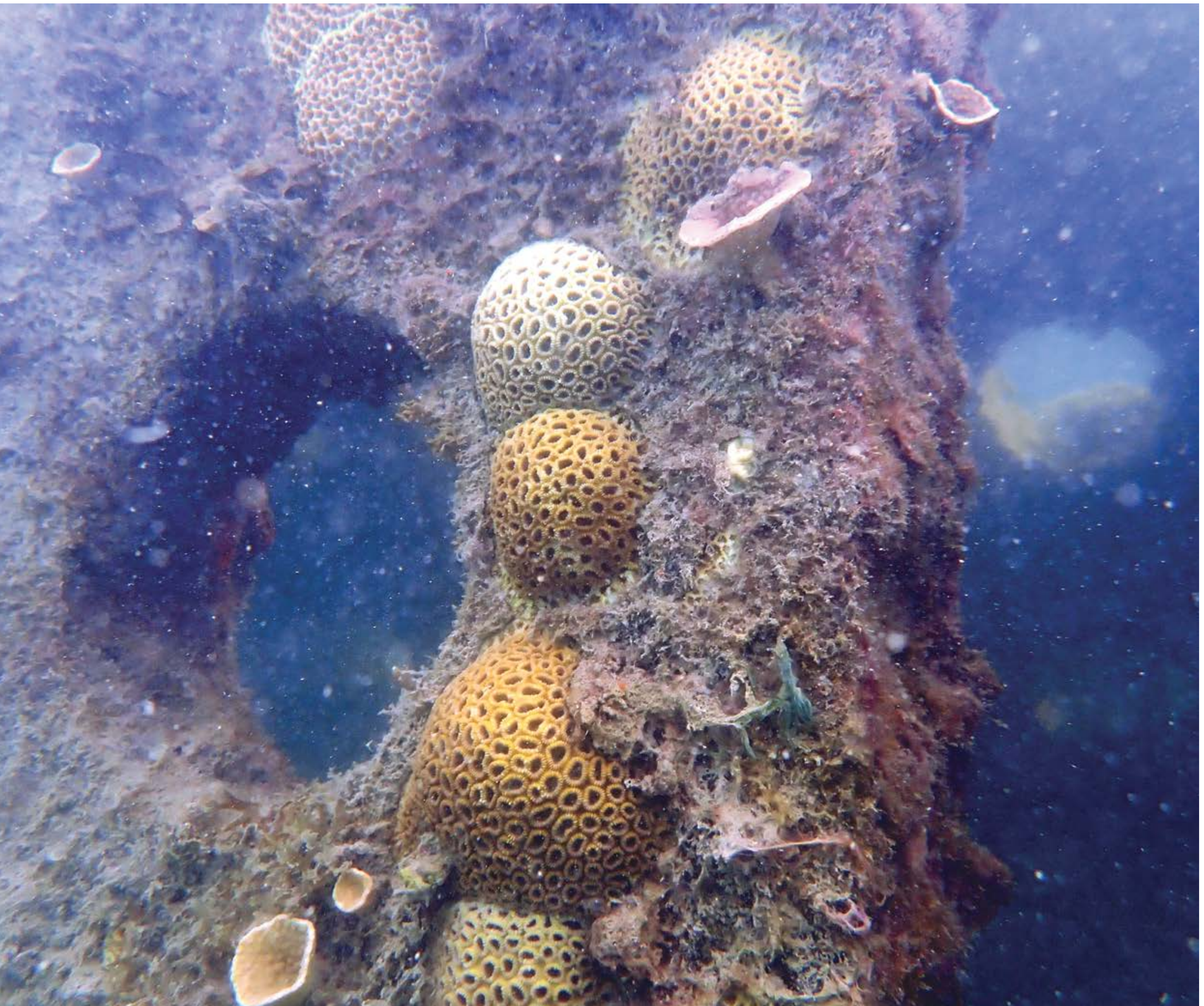
ஒருங்கிணைந்த மொத்த பொருளாதார மதிப்பு மதிப்பீட்டின் அடிப்படையில், செயற்கை பவளப்பாறைகள் நிறுவப்பட்டதன் மூலம் பத்து ஆண்டுகளில் கிடைத்த ஒருங்கிணைந்த நன்மை சுமார் 61.67 கோடி ($7.34 மில்லியன்) என கணக்கிடப்பட்டது (படம் 3–ஐ காண்க). இதில் பிரதான நிலப்பகுதி கடற்கரை பாதுகாப்பு மிகப்பெரிய பங்காக 45.58%ஐ (28.56 கோடி) கொண்டதாகவும், அதனைத் தொடர்ந்து பத்து ஆண்டுகளுக்கான ஒருங்கிணைந்த ஒழுங்குமுறை சேவைகள் 23.94% (15.00 கோடி) எனவும் கணக்கிடப்பட்டுள்ளது.

கடலின் அடிமண் மேற்பரப்பில் வாழும் உயிரினங்கள் மற்றும் மீன்வளம் தொடர்பான நேரடி பயன்பாட்டு மதிப்புகள் மொத்த மதிப்பின் சுமார் 30%ஐ குறிப்பிடத்தக்க வகையில் பங்களித்துள்ளன.

பணத்தின் கால மதிப்பை கருத்தில் கொண்டு மேற்கொள்ளப்பட்ட துல்லியமான செலவு நன்மை பகுப்பாய்வு (cost benefit analysis) அடிப்படையில், வாய்ப்பு செலவுடன் சரிசெய்யப்பட்ட திட்டச் செலவு 26.37 கோடி (2015–இல் செய்யப்பட்ட 17 கோடி செலவு, 5% சமூக தள்ளுபடி விகிதத்தில் சரிசெய்யப்பட்டது) என கணக்கிடப்பட்டது. ஆனால், இந்த திட்டத்தின் சரிசெய்யப்பட்ட, நன்மை – செலவு விகிதம் (Adjusted Benefit - Cost Ratio) 2.34 மற்றும் 35.3 கோடி என்ற மிக வலுவான நேர்மறை நிகர தற்போதைய மதிப்பானது (Net Present Value), இந்தத் திட்டம் மிக உயர்ந்த பொருளாதார செயல்திறன் கொண்டதாகவும், பொது முதலீட்டிற்கு சிறந்த வருவாயை அளிப்பதாகவும் உள்ளதை தெளிவாக நிரூபிக்கிறது.

இந்த பத்து ஆண்டுகால ஆய்வானது, வான் தீவின் செயற்கை பவளப்பாறைகள் அடிப்படையிலான மீட்பு நடவடிக்கை, ஒரு மாற்றத்தை ஏற்படுத்தும் வெற்றியாக அமைந்துள்ளது என்பதை உறுதியான ஆதாரங்களுடன் நிறுவுகின்றது. திட்டமிட்டு வடிவமைக்கப்பட்ட இயற்கை அடிப்படையிலான தீர்வானது, பாதுகாக்கப்பட்ட பகுதி கட்டமைப்பின் கீழ் கடுமையான கரையோர அரிப்பை திறம்பட மாற்றி அமைத்ததுடன், கடல் வாழிடங்களை மீளுருவாக்கி, மீன்வள உற்பத்தித் திறனை உயர்த்தியுள்ளது. முக்கியமாக, மொத்த பொருளாதார மதிப்பு பகுப்பாய்வு, இத்தகைய நடவடிக்கைகள் வெறும் சூழலியல் செலவுகள் அல்ல என்பதை உறுதிப்படுத்துகிறது. மாறாக, கரையோர பாதுகாப்பு மூலம் தவிர்க்கப்பட்ட இழப்புகள் மற்றும் சூழலியல் ஒழுங்குபடுத்தும் செயல்பாடுகள் தொடர்ச்சியாக வழங்கும் பயன்கள் ஆகியவற்றின் மூலம் பலமடங்கு சமூக–பொருளாதார வருவாயை உருவாக்கும் உயர்மதிப்புடைய இயற்கை கட்டமைப்பு முதலீடுகளாக அவை விளங்குகின்றது. இந்த “வான் தளவமைப்பு” சூழலியல் மீட்பு காலநிலைத் தகவமைப்பு மற்றும் பொருளாதார பகுத்தறிவு ஆகியவற்றை திறம்பட இணைத்து, மீளப் பயன்படுத்தக் கூடிய ஆதாரப்பூர்வமான ஒரு மாதிரியை வழங்குகிறது.

சூழலியல் மற்றும் பொருளாதார வெற்றிகளை அடிப்படையாகக் கொண்டு, ஒருங்கிணைந்த செயற்கை பவளப்பாறைகள் நிறுவல் மற்றும் மொத்த பொருளாதார மதிப்பு கண்காணிப்பு நடைமுறையை ஒரு தரப்படுத்தப்பட்ட மாநிலக் கொள்கையாக உடனடியாக ஏற்றுக்கொள்ள பரிந்துரைக்கப்படுகிறது. இந்த அணுகுமுறை, மன்னார் வளைகுடா கடல் தேசியப் பூங்காவில் கடுமையாக அரிப்புக்கு உள்ளாகி வரும் மீதமுள்ள தீவுகளை பாதுகாக்கும் நோக்கில் பயன்படுத்தப்பட வேண்டும் என்பதை வலியுறுத்துகிறது. மேலும் திட்டமிட்ட மற்றும் கட்டுப்படுத்தப்பட்ட முறையில் இதனை விரிவாக்குவதும் அவசியமாகும். இந்தத் திட்டமிட்ட விரிவாக்கம், இப்பகுதியின் தனித்துவமான உயிரிசைவை பாதுகாக்கவும், கரையோர சமூகங்களின் வாழ்வாதாரங்களை உறுதிப்படுத்தவும், மேலும் காலநிலை மாற்றத்தின் வேகமாக அதிகரிக்கும் தாக்கங்களுக்கு எதிராக கரையோரத்தை வலுப்படுத்தவும் அத்தியாவசியமானதாகும்.



EXECUTIVE SUMMARY

The Gulf of Mannar, a UNESCO (United Nations Educational, Scientific and Cultural Organization) Biosphere Reserve and Ramsar site, is a globally significant marine biodiversity hotspot. Its 21 uninhabited coral islands serve as critical ecological sentinels, providing habitat for diverse species, serving as fisheries nurseries, and forming natural breakwaters that protect the densely populated mainland coast of Tamil Nadu. Vaan Island, among these, experienced catastrophic erosion, losing 92% of its landmass from 20.08 hectares in 1969 to a mere 1.53 hectares by 2015. This alarming decline was driven by decades of coral mining, climate-change-mediated mass bleaching events, and relative sea-level rise. The imminent submergence of Vaan Island not only threatened a unique coral reef and associated biodiversity but also jeopardized the livelihoods of thousands of small-scale fishers dependent on reef-associated resources, and exposed the Thoothukudi coastline to increased erosion and storm-surge vulnerability.

This report presents a comprehensive, decadal socio-ecological and economic assessment (2015–2025) of a landmark restoration intervention at Vaan Island. Funded under the National Adaptation Fund for Climate Change (NAFCC) and the Tamil Nadu State Coastal Fund, the project deployed 10,600 specially designed trapezoidal artificial reef (AR) modules around the island's periphery. The study's primary objectives were twofold: first, to rigorously quantify the biophysical recovery across geomorphic, ecological, and hydrodynamic parameters; and second, to determine whether the multi-dimensional benefits of this nature-based solution, captured through a holistic Total Economic Value (TEV) framework, demonstrably exceeded the costs. The investigation aimed to move beyond qualitative success metrics and provide a robust, evidence-based model to inform adaptive management and strategic scaling of ecosystem-based adaptation across the Gulf of Mannar's 21 eroding islands.

The assessment is founded on an integrated, multi-disciplinary methodology combining decade-long primary monitoring with advanced economic valuation (see Fig. 1). Primary field datasets included annual underwater visual censuses (UVCs) of epibenthic communities and fish assemblages, high-resolution GPS (Global Positioning System) shoreline mapping, single-beam echosounder bathymetry, sediment-trap measurements, and total-station topography coupled with satellite-derived NDVI (Normalized Difference Vegetation Index) for vegetation analysis. Historical baselines from 1969 were reconstructed using Survey of India toposheets and satellite imagery to contextualize pre-intervention erosion trajectories.

Building on this empirical foundation, a

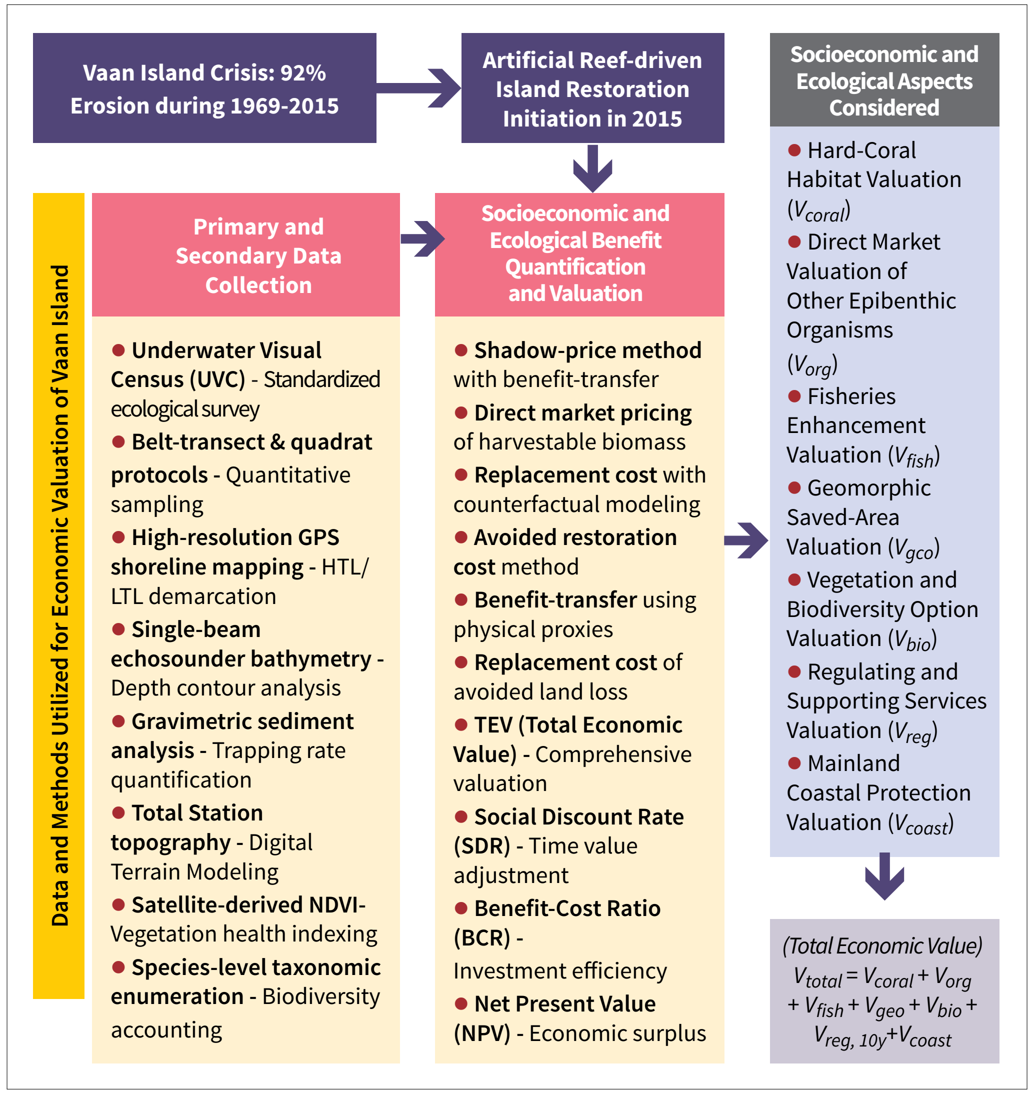


Fig. 1. Methodological Framework for Vaan Island AR Restoration Valuation.

seven-component Total Economic Value (TEV) framework was developed to translate the observed biophysical changes into monetary estimates. The framework quantified values for: (1) hard-coral habitat accrual, (2) other epibenthic organisms, (3) fisheries enhancement, (4) geomorphic saved area, (5) vegetation and biodiversity, (6) regulating and supporting services, and (7) mainland coastal protection. Valuation employed a mix of direct market pricing (for harvestable biomass), replacement cost methods (for avoided reconstruction of land and vegetation), and benefit-transfer approaches (for non-market ecosystem services), eliminating double-counting across the interconnected components.

The results from ten years of monitoring confirm the intervention as a resounding success across all measured dimensions (see Fig. 2). Geomorphically, the AR deployment halted the chronic erosional trend, stabilizing the island's high-tide line area and enabling net accretion, with the area increasing from 1.53 ha to a maximum observed extent of 2.30 ha. Bathymetric surveys showed significant shallowing (e.g., from 2.5 m to <1 m in the northwest spit), driven by AR-induced wave energy dissipation and sediment trapping, with measured sedimentation rates averaging ~20 mg/cm²/

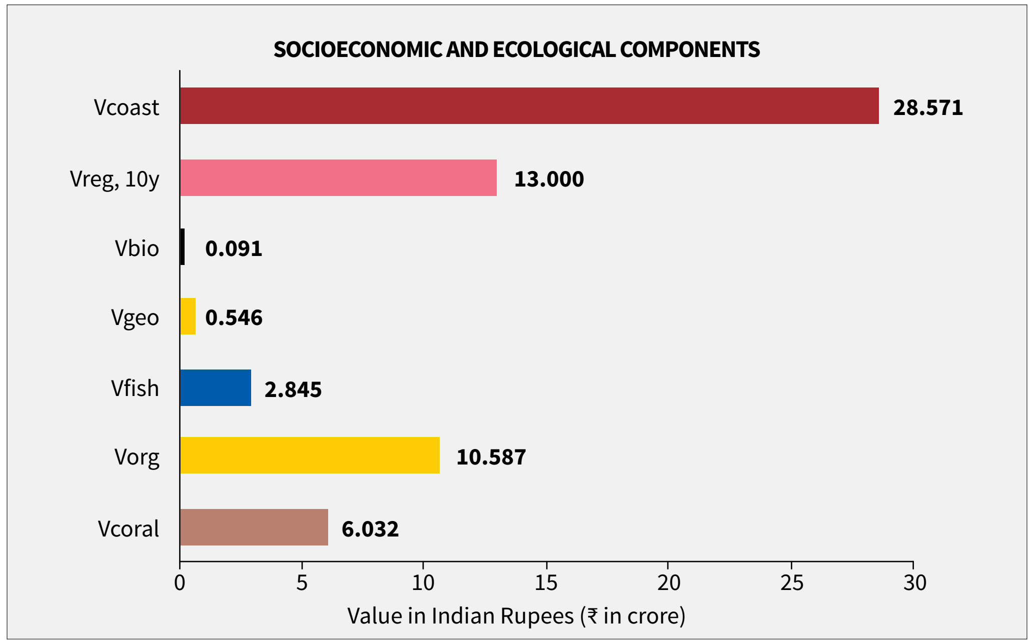
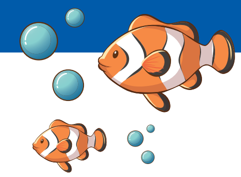


Fig. 2. Component-wise breakdown of total economic value (V_{total} = ₹61.67 crore) from Vaan Island AR restoration: Absolute values highlighting the primacy of V_{coast} (₹28.57 Cr), followed by $V_{reg,10y}$ (₹13 Cr), V_{org} (₹10.60 Cr), V_{coral} (₹6.03 Cr), V_{fish} (₹2.85 Cr), V_{geo} (₹0.55 Cr), and V_{bio} (₹0.09 Cr). Proportional contributions showing dominance of mainland coastal protection (V_{coast}, 45.58%) and regulating services ($V_{reg,10y,}$ 23.94%), with provisioning (29.16%) and stock values (1.33%).

[Note: (1) V_{coral}: coral habitat, (2) V_{org}: epibenthic organism, (3) V_{fish}: fisheries spillover, (4) V_{geo}: geomorphic saved area of island, (5) V_{bio}: terrestrial vegetation and biodiversity resilience, (6) $V_{reg,10y:}$ regulating and supporting services cumulatively across a decade, and (7) V_{coast}: coastal protection for mainland infrastructure]

day. Ecologically, the AR modules facilitated rapid and diverse colonization. Hard coral density on the modules rose from zero in 2015 to 81.33 colonies per module by 2024, supporting an estimated 114,989 colonies per hectare. This habitat formation corresponds to a valuation of ₹6.03 crore (Vcoral). Non-coral epibenthic organisms (molluscs, sponges, ascidians, etc.) showed a 6.8-fold increase in density, contributing a direct market value of ₹10.59 crore (Vorg). This habitat complexity supported an explosive growth in reef-associated fish assemblages, with density surging from 105.75 to 875.25 individuals per hectare—an 8.3-fold increase dominated by commercially valuable families such as Lutjanidae and Lethrinidae—yielding a fisheries enhancement value of ₹2.84 crore (Vfish). The geomorphic stabilization of the island platform itself represents a saved-area value of ₹0.54 crore (Vgeo), while the preservation of terrestrial vegetation—comprising 26 native species across diverse landforms—on the stabilized platform is valued at ₹0.09 crore (Vbio). The valuation breakdown highlights the predominance of protective and regulatory services: mainland coastal protection accounted for the largest share at 46.3% (₹28.57 crore), followed by the ten-year cumulative value of regulating and supporting services (Vreg) at 21.1% (₹13 crore). Direct-use values from epibenthos and fisheries accounted for 21.8% (₹13.43 crore) of the total value, underscoring the project's multidimensional socio-ecological returns.

Furthermore, the integrated TEV valuation yielded a consolidated decadal benefit of ₹61.67 crores attributable to the AR intervention (see Fig. 3). A rigorous cost-benefit



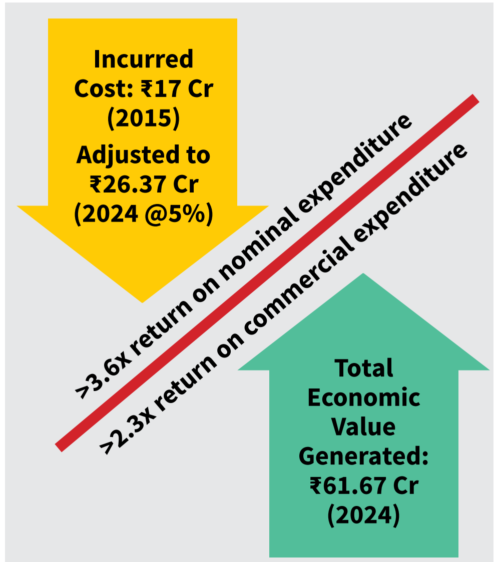


Fig. 3. Cost-Benefit balance of Vaan Island AR restoration: Scale visualization comparing ₹17 Cr of incurred cost (2015, adjusted to ₹26.37 Cr 2024 @5%) against ₹61.67 Cr of total economic value generated (2024), demonstrating a benefit-cost ratio (BCR) of 3.6x (nominal) and 2.3x (adjusted @5%) returns versus commercial alternatives, with an NPV of ₹35.3 Cr.

analysis, accounting for the time value of money, shows that against an opportunity-cost-adjusted project cost of ₹26.37 crores (2015 expenditure of ₹17 Cr adjusted at a 5% social discount rate), the project delivers an Adjusted Benefit-Cost Ratio of 2.34 and a strongly positive Net Present Value of ₹35.3 crores. This demonstrates exceptional economic efficiency and a high return on public investment.

This decadal study provides conclusive evidence that the artificial reef-driven restoration of Vaan Island is a transformative success. The project has proven that strategically engineered nature-based solutions can effectively reverse severe coastal erosion, rebuild marine habitats, and improve fisheries productivity within a protected area framework. Crucially, the TEV analysis validates that such interventions are not merely ecological expenditures but are high-value investments in natural infrastructure that generate multifold socio-economic returns, primarily through avoided losses (coastal protection) and sustained ecosystem regulatory functions. The "Vaan Island Model" successfully bridges ecological restoration, climate adaptation, and economic rationale, thereby yielding a replicable, evidence-based blueprint.

Based on the unequivocal technical, ecological, and economic success documented herein, it is recommended that the integrated AR deployment and TEV monitoring protocol be immediately adopted as a standardized state policy and scaled systematically to protect the remaining critically eroding islands within the Gulf of Mannar Marine National Park. This strategic scaling is imperative to safeguard the region's unique biodiversity, secure the livelihoods of coastal communities, and fortify the coastline against the accelerating impacts of climate change.

Keywords: Artificial Reef (AR); Coastal Restoration; Total Economic Value (TEV); Ecosystem-Based Adaptation (EbA); Gulf of Mannar; Socio-Ecological Valuation; Climate Resilience; Benefit-Cost Analysis (BCA)

THE KEY RECOMMENDATIONS

The Vaan Island restoration delivers a proven, scalable blueprint for Gulf of Mannar resilience, validated by a TEV of ₹61.67 Cr exceeding costs (BCR 1.97–3.63). Table 1 operationalizes this success across stakeholders, prioritizing policy formalization, mandatory TEV adoption, data-driven management, and inclusive scaling to protect 20 remaining eroding islands (two of which have already submerged) while advancing gender equity and global EbA leadership.

The demonstrable success of the Vaan Island artificial reef (AR) project provides a robust, evidence-based platform to guide future policy, management, and investment. The following recommendations are targeted at specific stakeholders to translate these findings into implementable strategies for scaling resilience across the Gulf of Mannar Biosphere Reserve (GoMMNP) and analogous vulnerable coastal systems.

I. For Policymakers and National/State Funding Agencies (MoEF&CC, NABARD, TN Dept. of Environment):

■ **Institutionalize and scale the "Vaan Model":** Formalize the integrated AR deployment protocol, viz., combining detailed bathymetric/hydrodynamic studies, purpose-designed modules, and a long-term TEV monitoring framework,

Table 1. Stakeholder-specific priority recommendations for scaling the Vaan Island artificial reef restoration model.

Stakeholder	Priority Recommendations for Vaan Island	Expected Outcome
Policy Makers	1. Formalize the "Vaan Model" as state policy 2. Mandate TEV in coastal projects	Scalable restoration across the other 20 islands
Park Management	3. Integrate TEV into monitoring 4. Create "Priority Intervention Atlas"	Data-driven conservation decisions
Research Institutions	5. Develop regional valuation coefficients 6. Study long-term feedback	Stronger economic justification
International Bodies	7. Showcase as a global EbA exemplar Facilitate South-South exchange	Global replication of the model
Private Sector	9. "Adopt-an-Island" partnerships	CSR/ESG alignment with measurable impact
All Stakeholders	10. Gender-responsive design in scaling	Inclusive, equitable conservation

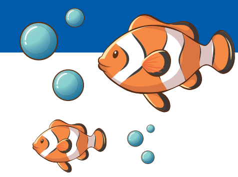
as the standard operating procedure for climate adaptation funding in coastal and marine protected areas. Establish a dedicated, ring-fenced "Reef-Island Resilience Fund" to finance the sequential restoration of the remaining critically eroding islands in the GoMMNP, prioritizing those identified as being on the verge of submergence.

■ **Mandate Socio-Economic Valuation in Project Appraisal:** Require that proposals for coastal resilience projects include a comprehensive Total Economic Value (TEV) framework from the outset, as demonstrated in this study. This moves beyond cost-effectiveness analysis to capture the full spectrum of non-market benefits (coastal protection, biodiversity, regulating services), which this report proves constitute the majority of economic return, thereby justifying larger investments in nature-based solutions.

II. For the GoMMNP Management and Forest Department:

■ **Adopt the AR-TEV Framework as a Core Monitoring Tool:** Integrate the seven-component TEV assessment methodology into the long-term ecological monitoring program of the Biosphere Reserve. This will transform monitoring data from purely biological indicators into powerful socio-economic metrics that can communicate the Park's value to finance and planning departments in a language they understand.

■ **Develop a "Priority Intervention Atlas":** Utilize the methodologies from this study (e.g., historical shoreline analysis, wave modelling) to conduct a vulnerability assessment of all 21 islands. Create a geospatial atlas ranking islands by erosion risk, ecological value, and protective value for the mainland coast. This atlas will provide a science-based blueprint for directing the limited conservation resources to the most critical and high-return sites.



■ **Strengthen Enforcement through Demonstrated Value:** Use the findings of this report, particularly the quantified fisheries spillover and massive coastal protection value, in community outreach and stakeholder engagement. Demonstrating how a protected "no-take" zone actively sustains adjacent fisheries and protects coastal communities can build stronger local stewardship and support for enforcement.

III. For Research Institutions and Academia (IITs, National Institutes, Universities):

■ **Refine and Standardize Valuation Coefficients:** Conduct targeted research to develop region-specific, peer-reviewed benefit-transfer values for key ecosystem services (e.g., coral habitat value, regulating service flows per hectare) in the Indian and Southeast Asian context. This will reduce uncertainty in future valuations and increase the defensibility of economic analyses for policymakers.

■ **Investigate Second-Order Ecological and Geomorphic Feedbacks:** Initiate research on the long-term biogeomorphic evolution of AR-stabilized islands. Key questions include: the role of vegetation accretion in further stabilizing sediments, the genetic connectivity of AR coral populations with natural reefs, and the optimal AR configuration for maximizing biodiversity versus coastal protection under different wave regimes.

IV. For National and International Conservation Bodies (UNDP, GEF, IUCN):

■ **Champion the Project as a Global EbA Exemplar:** Showcase the Vaan Island restoration as a world-leading case study in Ecosystem-based Adaptation (EbA) within marine protected areas. Its success provides a tangible model for simultaneously achieving three of the UN Sustainable Development Goals (SDGs), namely SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land). Advocate for its replication in small island states and other climate-vulnerable coastal nations with fringing reef systems.

■ **Facilitate South-South Knowledge Exchange:** Create platforms (workshops, fellowships, technical manuals) for sharing the technical designs, monitoring protocols, and economic valuation methodologies with practitioners and scientists in regions facing similar challenges, such as the Caribbean, Southeast Asia, and the Pacific Islands.

V. For Corporate CSR and Philanthropic Foundations:

■ **Partner for "Adopt-an-Island" Resilience Programs:** Forge innovative public-private-philanthropic partnerships to fund the restoration of individual islands within the GoMMNP portfolio. The compelling BCR and clear valuation breakdown furnished in this report provide a strong investment thesis for CSR funds dedicated to climate action and biodiversity, yielding measurable, high-impact outcomes aligned with global ESG (Environmental, Social, and Governance) commitments.

VI. For Funders on Gender-Responsive Reef-Island Restoration:

The Vaan Island model presents a powerful opportunity to operationalize the IKI Gender Strategy. The project's seven valuation components provided multiple entry points for advancing gender justice, moving beyond simple participation toward trans-

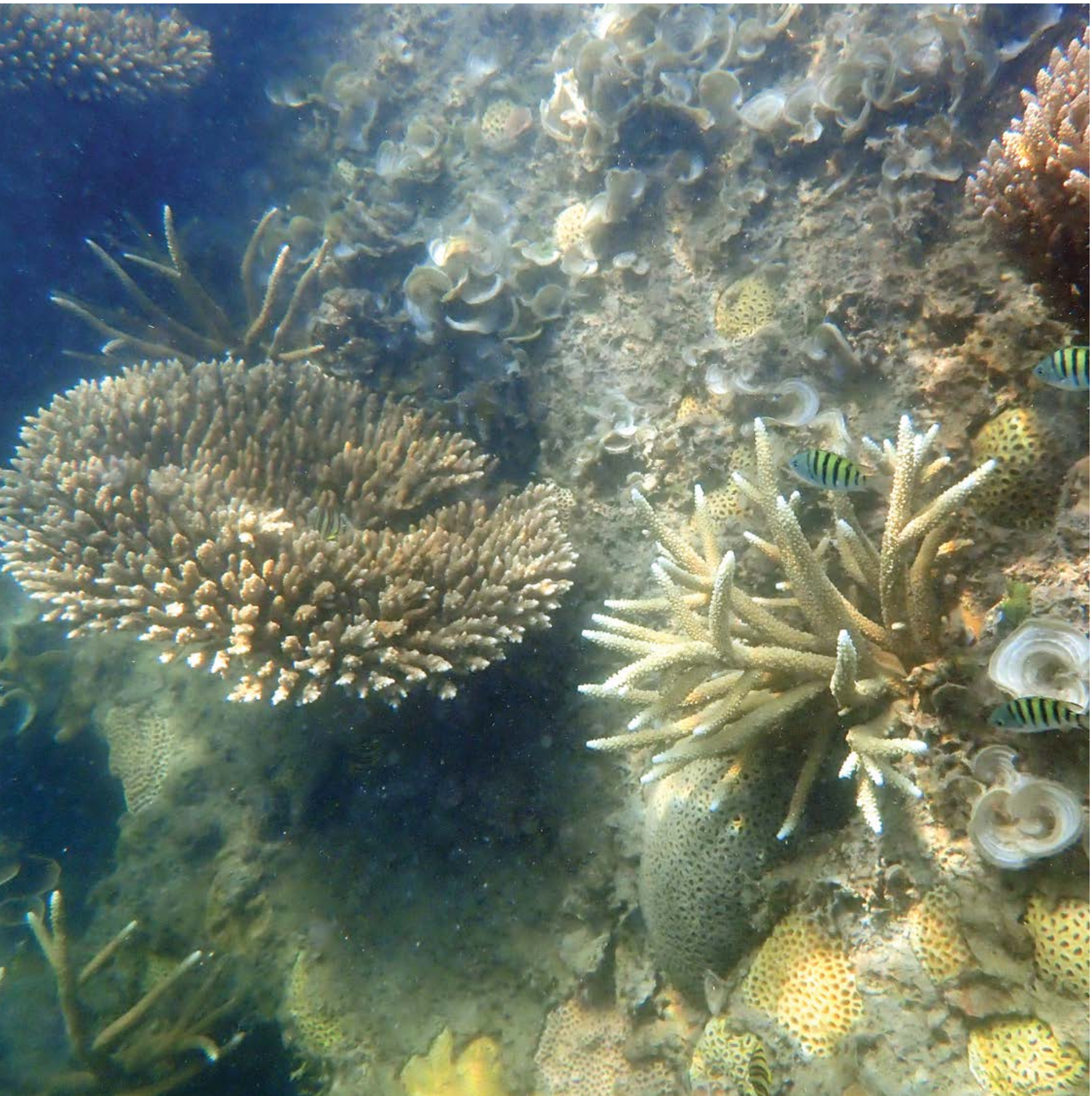
Table 2. Gender integration analysis of Vaan Island TEV framework: Pathways for IKI (International Climate Initiative) strategy alignment

Dimension	Gender-Responsive Actions	Gender-Transformative Potential	IKI Continuum Alignment*
Hard-Coral Habitat (V_{coral})	Train women in non-invasive coral monitoring and data collection.	Establish women-led research cooperatives for reef monitoring and citizen science reporting within buffer zones.	Sensitive → Transformative
Non-Coral Epibenthos (V_{org})	Document women's traditional knowledge of epibenthic species for monitoring protocols.	Create women-managed databases and knowledge repositories for conservation planning.	Blind → Responsive → Transformative
Fisheries Spillover (V_{fish})	Provide women fish vendors with safe landing center spaces and processing training.	Form women-led fisheries monitoring groups tracking spillover effects for co-management advocacy.	Transformative
Geomorphic Stabilization (V_{geo})	Employ women in remote sensing and shoreline change analysis.	Position women as lead analysts in island resilience assessments shared with the park authorities.	Responsive → Transformative
Vegetation and Biodiversity (V_{bio})	Train women SHGs in NDVI monitoring and vegetation health surveys.	Develop women-led biodiversity reporting platforms for GoMMNP decision-making.	Transformative
Regulating Services (V_{reg})	Collect gender-disaggregated data on water quality benefits for households.	Enable women to co-design community monitoring of regulating services for adaptive management.	Responsive → Transformative
Mainland Coastal Protection (V_{coast})	Assess erosion protection benefits for women-owned coastal assets.	Advocate for women's leadership in Park buffer zone resilience committees using Vcoast valuation.	Highly Transformative

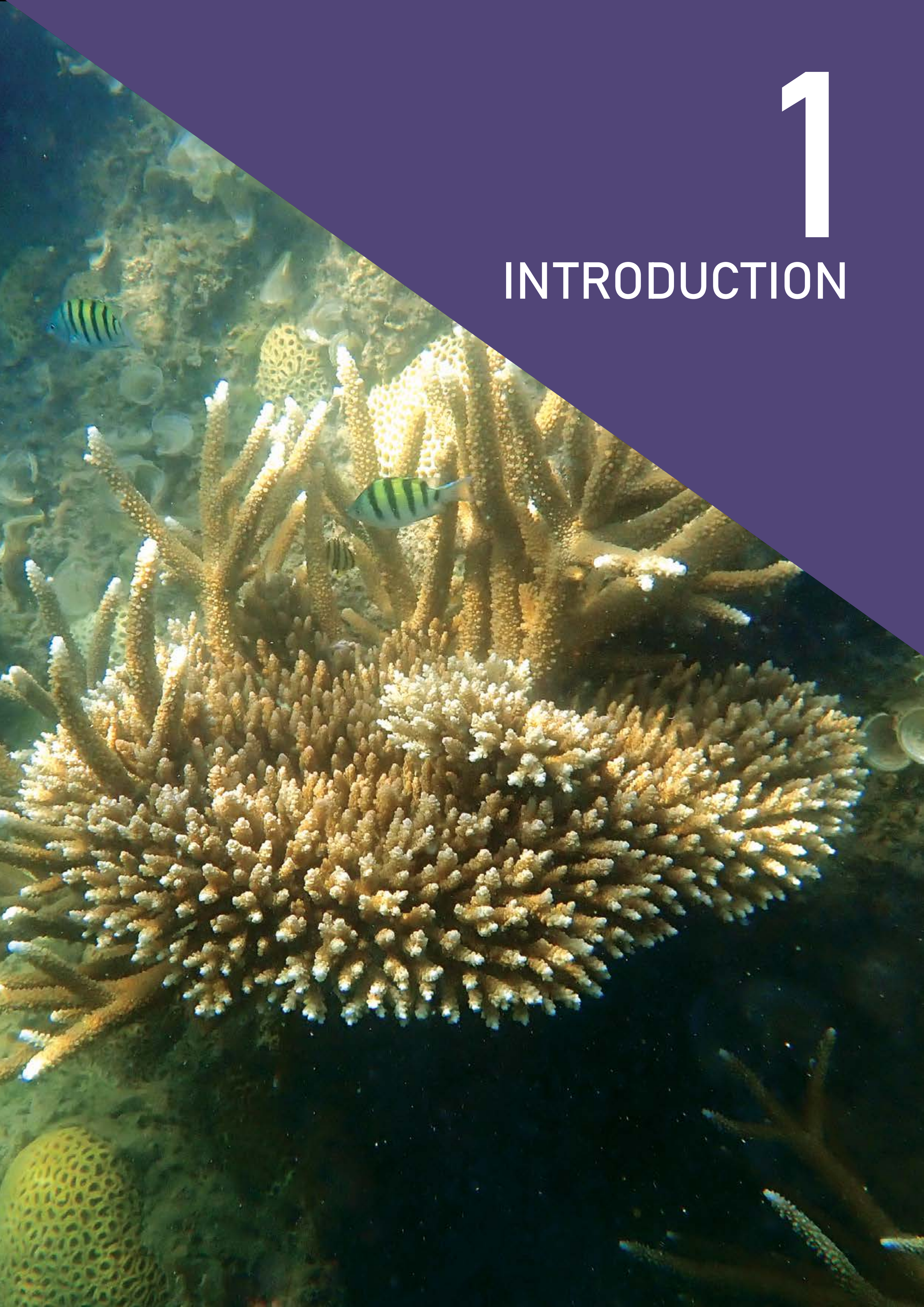
*[*Note: The framework progresses from gender-blind (ignoring women's roles) → gender-sensitive (including women in monitoring) → gender-responsive (addressing practical data collection needs) → gender-transformative (positioning women as knowledge authorities, decision influencers, and conservation leaders within GoMMNP's protected boundaries through research, monitoring, and advocacy roles).]*

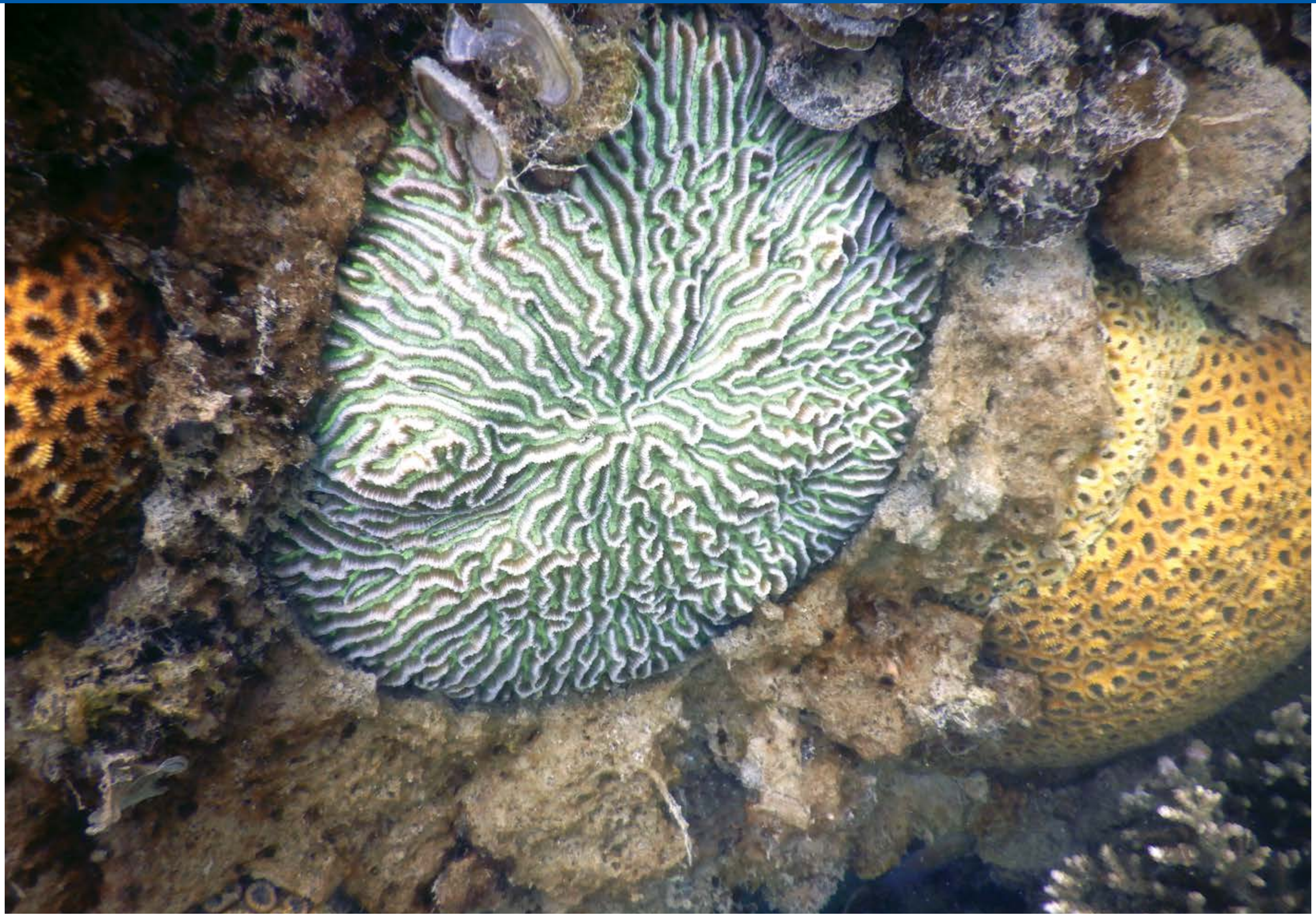
formative change. Table 2 analyzes each dimension, demonstrating how the project's framework can be utilized to meet IKI's objectives for effective, equitable climate and biodiversity action.

To this end, the most critical overarching recommendation is to shift the paradigm from viewing interventions like the Vaan Island AR project as isolated conservation efforts to recognizing them as strategic investments in critical natural infrastructure. The evidence is now clear: protecting and restoring these reef-island systems is not merely an ecological imperative but a fiscally sound, cost-effective strategy for safeguarding coastal economies, communities, and biodiversity against climate change. The responsible path forward is to systematically replicate this proven model where it is needed most.



1
INTRODUCTION





The Gulf of Mannar lies along the southeast coast of India, in the state of Tamil Nadu, extending from Rameswaram to Kanniyakumari, and covering an area of about 10,500 sq km. The Gulf of Mannar is rich in biodiversity with a total of 4,223 reported species (Balaji et al., 2012), including 181 seaweed species, 158 arthropod species, mollusks, 1,147 finfishes, 28 sea cucumber species, 11 sea snake species, 5 sea turtle species, 290 birds, 7 marine mammals (Balaji et al., 2012) and 132 species of corals (Edward et al., 2023). The rich biodiversity of the Gulf of Mannar is primarily due to the presence of dynamic marine habitats, including coral reefs, seagrass meadows, mangrove forests, sand dunes, seaweed beds, coral islands, and oyster beds. These coastal and marine ecosystems, along with the associated biodiversity in the Gulf of Mannar, provide direct and indirect livelihood to thousands of small-scale fisherfolk. The coastal population along the Gulf of Mannar is very dense; the number of fishing families living on the coast was 98,457 in 2005, increasing to 110,667 in 2016 (CMFRI-DoF, 2020), an increase of about 12%. It is obvious that this has further increased since then. The livelihood of the coastal communities depends to a great extent on the reef-associated fishery resources.

Recognizing the importance of the Gulf of Mannar's resources, the government has taken protection measures at various levels to safeguard marine life and the livelihood of dependent fishermen. The Gulf of Mannar was declared as the Gulf of Mannar Biosphere Reserve (GOMBR) in 1989 by the Government of India, and the GOMBR was declared as a Ramsar site in 2022. There are 21 uninhabited coral islands in the Gulf of Mannar between Rameswaram and Tuticorin running in a stretch parallel to the mainland coast at distances ranging from 140 m to 9.3 km. In 1986, the Government of Tamil Nadu declared the 21 islands (Fig. 1.1) and the surrounding waters of the Gulf of Mannar as the Gulf of Mannar Marine National Park (GoMMNP), covering an area of 560 sq km, and designated it as a 'no-go' and 'no-take' zone. This protection of the islands and surrounding waters is to conserve the delicate marine life sheltered by the island ecosystems.

The coral reefs of the Gulf of Mannar are among the country's four major reef areas, with significant associated biodiversity. Fringing coral reefs are observed around these islands, playing key ecological and economic roles that benefit coastal communities (Edward et al., 2023). The rich biodiversity of the Gulf of Mannar is primarily due to these shallow-water coral reefs that have naturally developed around the islands. Islands provide a calm environment for coral survival and growth, and the corals, in turn, provide the sand necessary for the islands. Commercially and ecologically important fish of the Gulf of Mannar use the calm reef environment around the islands for feeding and breeding. Thus, the islands and surrounding reef areas act as nursery grounds for fish, and the spill-over fish are used by dependent coastal communities for their livelihood. The loss of coral reefs and islands would rob the coastal communities in the Gulf of Mannar of their livelihood options.

The islands of the Gulf of Mannar protect the mainland coast from erosion and thus protect the properties of coastal communities. The islands also serve as shelter for fishermen during rough weather seasons, saving their lives, and their absence would be a huge loss. Further, islands provide homes to various terrestrial and marine organisms, without which these organisms would vanish. Hence, protecting and restor-

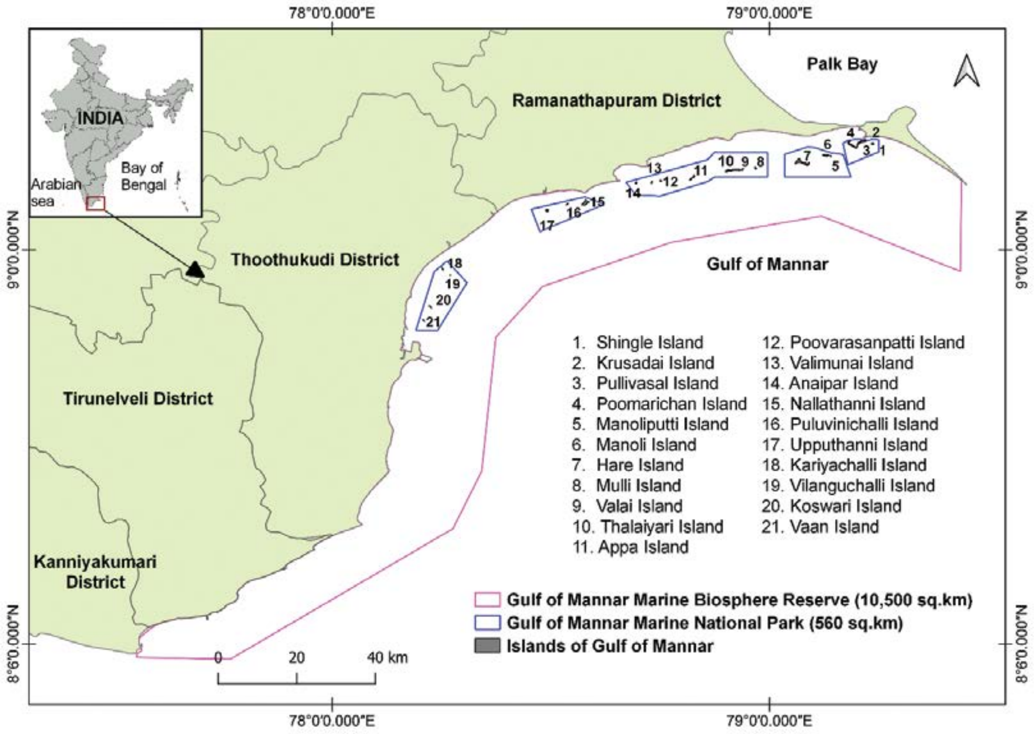


Fig. 1.1. Map showing the boundaries of the Gulf of Mannar Biosphere Reserve and the Gulf of Mannar Marine National Park, including the 21 islands

ing eroding islands means conserving associated biodiversity and preserving other ecological and economic benefits. Two of the 21 islands (Vilanguchalli in the Tuticorin region and Poovarasanpatti in the Keelakarai region) were submerged a few decades ago due to continuous coral mining before 2004 and rising sea levels. Further, climate-change-mediated mass coral bleaching events have caused significant damage to the corals of the Gulf of Mannar during the past two decades. Coral reefs act as natural barriers to reduce the speed of waves and currents, and thus reduce soil erosion on the islands. The significant loss of coral reefs around the Gulf of Mannar islands has reduced this natural coastal protection, exposing the islands to coastal erosion. Apart from the two submerged islands, some of the remaining islands are also in a critical zone of severe erosion and on the verge of submergence.

Vaan Island is one of the 21 uninhabited coral islands of the Gulf of Mannar. The island area was 20.08 ha in 1969, and it decreased to 16 ha as per the Gulf of Mannar Marine National Park Notification in 1986. The island area continued to decrease due to the combined effects of coral mining and sea level rise, and dwindled to 2.33/1.53 ha at low and high tide, respectively, in December 2015 (Asir et al. 2020). The Union Ministry of Environment and Forest (MoEF&CC), under the National Adaptation Fund for Climate Change, National Bank for Agriculture and Rural Development (NABARD), and Tamil Nadu Department of Environment, initiated steps to protect the eroding island and its ecosystem by deploying specially designed multipurpose artificial reef modules. Based on the fine-resolution bathymetry and wave dynamic studies carried out by Indian Institute of Technology (IIT) Madras, 10,600 trapezoidal artificial reef modules were deployed around the island by Suganthi Devadason Marine Research Institute (SDMRI). The trapezoidal artificial

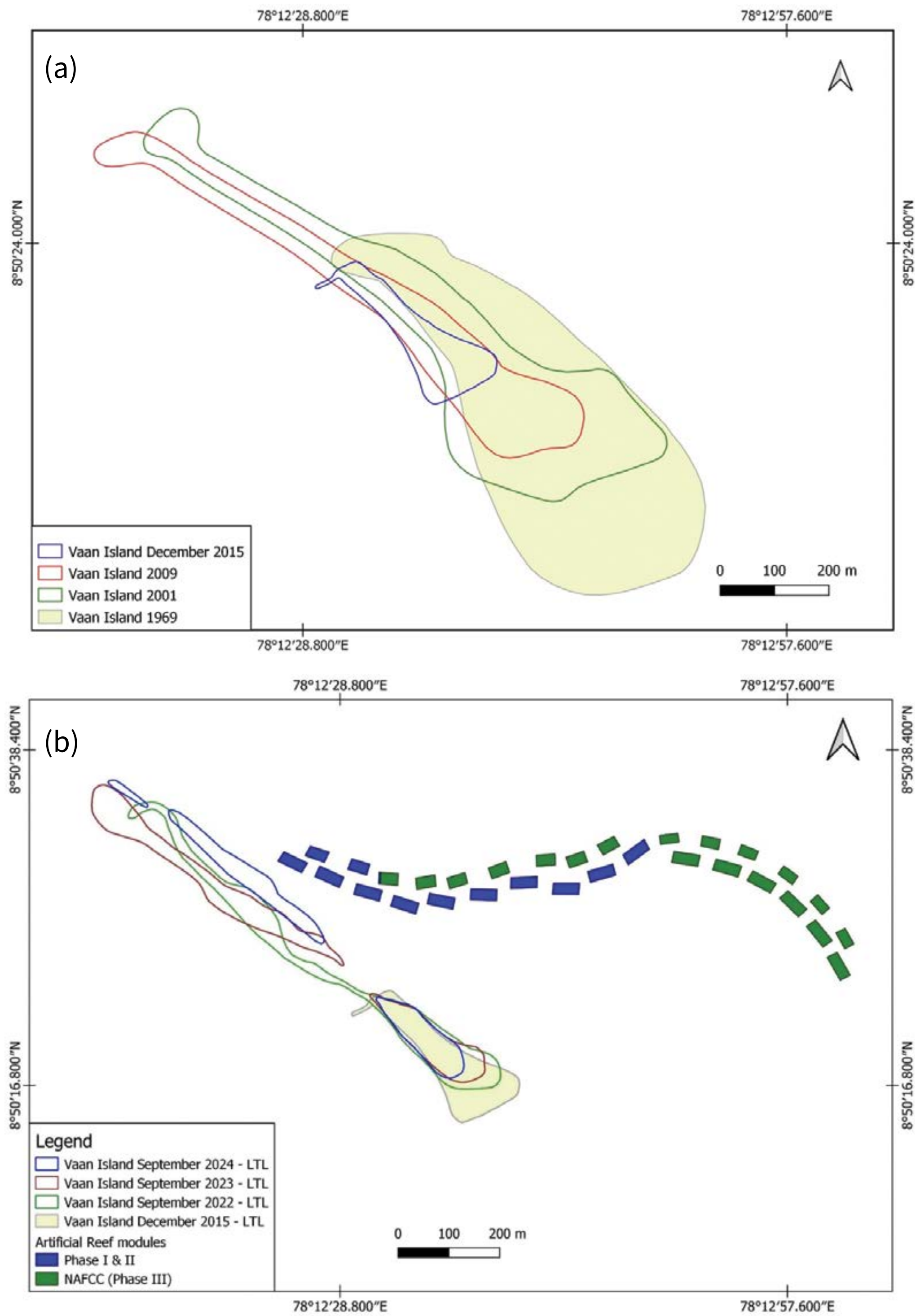


Fig. 1.2. Morphological variation of Vaan Island (a) before and (b) after the deployment of Artificial Reef modules

reefs are efficient at dissipating wave energy and encouraging sediment deposition. The deployed modules have also provided shelter to numerous epibenthic organisms, including corals, and have helped to enhance fish abundance. Figure 1.2 shows the morphological evolution of Vaan Island before and after the deployment of Artificial Reef modules.

The present report has been prepared to provide a decadal assessment (2015–2025)

of the deployment of artificial reef modules to stabilize the critically eroded Vaan Island in the Gulf of Mannar. The island had lost 92% of its area since 1969 due to coral mining, bleaching, and sea-level rise, which threatened its ecological role as a coral refuge and fisheries nursery, as well as its function as a mainland protective barrier. Although post-deployment monitoring confirms visible geomorphic stabilization and epifaunal colonization, a need was felt for a rigorous, multi-dimensional evaluation of project's success. Existing assessments of coastal restoration often focus narrowly on short-term structural outcomes, failing to capture the broader social and economic returns necessary for policy and scaling decisions. To address this gap, this analysis employs a comprehensive Total Economic Value (TEV) framework, quantifying benefits across seven interconnected components derived from primary biophysical monitoring: (1) coral habitat accrual reversing biotic homogenization, (2) improved epibenthic productivity supporting local livelihood, (3) direct fisheries enhancement, (4) sustained geomorphic integrity reducing island submergence risk, (5) terrestrial vegetation and biodiversity resilience, (6) regulating and supporting services via sediment trapping, shoaling, and hydrodynamics, and (7) direct coastal protection for mainland infrastructure. This integrated approach translates a decade of ecological recovery into defensible socio-economic indicators, providing the evidence base required for adaptive management and strategic investment. Therefore, the primary objectives are to quantify biophysical recovery and to determine if TEV benefits exceed costs. The secondary goals include validating long-term efficacy using historical baselines, benchmarking against regional values, and providing replicable strategies for ecosystem-based adaptation across the region's other eroding islands. The present study provides a quantitative model for evidence-based policy since qualitative monitoring cannot justify investment in nature-based coastal resilience.

2 MATERIALS AND METHODOLOGY

This chapter delineates the multi-method empirical foundation and integrated economic valuation framework for assessing artificial reef (AR)-driven restoration outcomes at Vaan Island from 2015 to 2025. Section 2.1 details primary field datasets, including underwater visual censuses for epibenthos and fishes, GPS shoreline mapping, echosounder bathymetry, sediment traps, total-station topography/NDVI vegetation, and secondary historical baselines (1969–2015), alongside QGIS/PRIMER processing protocols spanning pre-deployment, deployment, and decadal monitoring phases. Section 2.2 presents the seven-component total economic value (TEV) structure comprising coral habitat, epibenthos, fisheries, geomorphic, biodiversity, regulating, and protection valuations, operationalized via shadow pricing, direct markets, replacement costs (including mainland coastal protection via DSAS-informed counterfactual erosion), and benefit transfers, with Equations. 2.1–2.17 linking biophysical proxies to scenario-calibrated monetary estimates without double-counting.

2.1. Data Collection, Sources, and Time Frame

Comprehensive datasets spanning ecological, geomorphic, bathymetric, sedimentary, and fisheries parameters, including underwater visual censuses (UVC), GPS shoreline mapping, echosounder bathymetry, sediment traps, total-station topography/NDVI vegetation, and historical baselines (1969–2015), were compiled from primary field surveys by SDMRI and secondary records to quantify artificial reef (AR)-driven restoration outcomes at Vaan Island (2015–2025). These were supplemented by datasets from recently published peer-reviewed studies documenting Vaan Island erosion dynamics, AR deployment effects, epibenthic succession, and geomorphic stabilization in the Gulf of Mannar (Raj et al., 2015; Jayanthi et al., 2020; Asir, et al., 2020; Edward et al., 2020; Mathews et al., 2021; Edward et al., 2023; Edward et al., 2025).

2.1.1. Primary Field Datasets

Epibenthic communities were assessed through annual Underwater Visual Census (UVC) conducted on randomly selected AR modules (n=618–1,200 per module per year) from both inner (1 m height, ~2 m depth) and outer (2 m height, ~3 m depth) layers, employing standard belt-transect and quadrat protocols (0.25–1 m^2 area). Taxa enumeration included 19 hard coral genera (e.g., *Pocillopora, Turbinaria;* density increasing from 0 to 81.33 no./module) and over 40 non-coral epibenthic groups, with molluscs dominant (2.36→19.36 no./module), alongside sponges, hydroids, ascidians, echinoderms, and octocorals. Surveys were conducted annually from October 2015 to December 2024, following the post-monsoon period.

Fish assemblages were surveyed using Underwater Visual Census (UVC) along 250 m^2 belt transects around AR clusters (n=4 per site in 2016 and 2024), recording species-level counts for 79 taxa across 26 families, with density increasing from 69.83 to 1,698 no./250 m^2, dominated by Lutjanidae (*Lutjanus* spp.), Scaridae (*Scarus ghobban*), and Lethrinidae; biomass was estimated via length-weight allometry from Fish Base. Surveys were conducted in July 2016 and December 2024.

Island morphology, specifically high and low tide line (HTL/LTL) areas, was monitored using handheld GPS (Garmin eTrex 30, ±3 m accuracy) to track shorelines (n=50+ points per visit), georeferenced to DGPS benchmarks, with monthly surveys conducted post-AR deployment; areas were computed via QGIS polygonization across

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the 1969–2025 series (20.08→3.15 ha LTL). Surveys were conducted from December 2015 to September 2025, on a bi-monthly to monthly basis.

Bathymetry was surveyed using a single-beam echosounder (Humminbird, 200 kHz) coupled with DGPS (Sokkia GRX1, ±2 cm accuracy), collecting 500–1,000 soundings per 50×50 m grid across the spit area; contours (0.5–4 m) were interpolated in Surfer software, tracking shoaling from 2.5 m to <1 m in the northwest spit region. Surveys were conducted annually from December 2015 to January 2025.

Sedimentation rates were measured using 10 sediment traps (0.01 m^2 mouth area, 0.3 m height) deployed 0.5 m above the seabed at 2–3 m depth across the AR field, with tri-monthly retrieval from November 2017 to October 2025; rates ranged from 9.6–39.48 $mg/cm^2/day$ (mean ~20 $mg/cm^2/day$), determined via gravimetric analysis following 60 µm sieving. Surveys were conducted seasonally over this period.

Topography and vegetation were surveyed using a Total Station (Sokkia FX 105, 5″ accuracy) to generate Digital Terrain Models (DTM) with 2017 baseline data (average elevation 0.9 m); NDVI was derived from Landsat/Sentinel-2 imagery (2017–2024) and classified into barren, low, medium, and high vegetation cover, dominated by foreshore herbs and shrubs (*Ipomoea pes-caprae, Sesuvium portulacastrum*; 26 species total). Surveys were conducted biannually from September 2017 to 2024.

2.1.2. Secondary Historical Data and Data Processing

Secondary data provided essential pre-AR baselines for contextualizing restoration impacts. Historical island morphology was reconstructed from Survey of India toposheets (1969: 20.08 ha), Marine National Park notifications (1986: 16 ha baseline), and Google Earth imagery (2001–2015), establishing an erosion trajectory from 20.08 ha to 1.53 ha HTL by December 2015—a net loss of 92% over 46 years driven by coral mining and hydrodynamic forcing. The pre-deployment hydrodynamic context was informed by IIT-Madras wave modelling, which identified optimal AR siting at 2–3 m depth contours under northeast monsoon conditions (significant wave height Hs = 1–2 m, with the dominant direction from SE–NE).

All spatial datasets were processed in QGIS 3.28 (WGS84/UTM Zone 43N projection) for georeferencing, shoreline digitization, and area calculations via polygonization. Community structure analyses were conducted using PRIMER v7 and PAST 4.03, with SIMPER used to assess taxon contributions to dissimilarity and ANOSIM used to test for epibenthic/fish assemblage shifts across years. The integrated time frame spans the pre-AR baseline (2015), the deployment phase (December 2015–February 2019), and decadal post-deployment monitoring (2016–2025), to facilitate before–and–after assessment of AR efficacy.

2.2. Economic Valuation Framework

The economic valuation framework integrates seven components, viz., hard-coral habitat (V_{coral}), other epibenthic organisms (V_{org}), fisheries (V_{fish}), geomorphic saved area (V_{geo}), vegetation/biodiversity (V_{bio}), regulating/supporting services (V_{reg}), and coastal protection (V_{coast})—linking the observed ecological indicators to monetary estimates via direct market pricing, replacement costs, and benefit-transfer methods. Direct market values (V_{org}, V_{fish}) apply ex-vessel prices to harvestable biomass; replacement costs (V_{geo}, V_{bio}, V_{coast}) quantify avoided restoration expenditures for stabilized land and vegetation and utilize the information on land prices around the Thoothukudi coast stretch; and non-market estimates (V_{coral}, V_{reg}) derive shadow prices and service flows from reef valuation meta-analyses, avoiding double-counting across use/non-use categories.

2.2.1. Hard-Coral Habitat Valuation (V_{coral})

The ecological valuation of hard-coral habitat (V_{coral}) employed a shadow-price methodology (Patterson, 2008) to apportion reef ecosystem-service benefits to live coral biomass, treating ARs as production factors for habitat-supported services (fisheries enhancement, biodiversity maintenance, and coastal protection). The effective AR influence area was defined as A_{AR}=13 ha, representing the aggregated ecological footprint of 10,600 modules (physical footprint = 2.65 ha), which accounted for per-module halo effects on flow, sediment trapping, and biota (r = 15 m) (Reeds et al., 2018; Pondella et al., 2022). This was computed using Eq. 2.1 and from Fig. 2.1:

$A_{eff} \propto$ (Artificial Reef Units, Halo Radius) …(2.1a)

$A_{eff} = k \times N \times \pi r^2 = 0.017 \times 10{,}600 \times 3.14 \times 15^2 \approx 13$ ha …(2.1b)

where N = 10,600 modules, r = 15 m (conservative halo radius), and k = 0.017 (overlap factor for dense clusters; obtained from Figure 2.1), yielding module density $M_{ha} = 10{,}600 \div 13 = 815$ modules ha^{-1}.

Annual coral biomass per hectare was derived using Eq. 2.2:

$B_{ha,t} = D_t \times M_{ha} \times W$ …(2.2)

with D_t is observed hard-coral density (no. module−1, 2015–2024) and W=0.5 kg colony−1 (mean skeletal mass for small–medium Indo-Pacific genera) (Peirano et al., 2001; Fisher, 2023). The 2024 biomass $B_{ha,2024}$ served as the shadow-price denominator. Reef ecosystem-service values (V_{reef}) were obtained via benefit transfer from global/SE Asian meta-analyses (low/mid/high: 15,000; 100,000; 200,000 USD ha−1 yr−1) (Laurans et al., 2013; Okubo & Onuma, 2015; Cannas et al., 2019; Ottaviani, 2020; Suggett et al., 2024), converted at 1 USD = ₹80 (2015–2024 average), targeting fisheries, protection, and biodiversity. Unit shadow prices were calculated using Eq. 2.3:

Fig. 2.1. Demonstrated is the area of influence due to the deployed artificial reef (AR) by considering the conservative halo radius of 15 meters around the ARs in the vicinity of Vaan Island.

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$$P_{mid} = \frac{V_{reef,mid}}{B_{ha,\,2024}} \qquad \ldots(2.3)$$

$$V_{coral,ha,t} = B_{ha,t} \times P_{mid} \qquad \ldots(2.4)$$

with mid-case (P_{mid}) adopted for time-series applications. Annual habitat values $V_{coral,ha,t}$ were then calculated using Eq. 2.4 and scaled to A_{AR} = 13 ha, attributing proportional reef benefits to AR coral accumulation without overlap with direct fisheries valuation.

2.2.2. Direct Market Valuation of Other Epibenthic Organisms (V_{org}) and Fisheries (V_{fish})

Direct market (Remoundou et al., 2009) values were estimated for (i) harvest-relevant epibenthic organisms other than hard corals and (ii) reef-associated fishes supported by the AR field. For other epibenthic taxa, the same AR influence area A_{AR} = 13 ha and module density M_{ha} = 815 modules ha^{-1} were used as in the hard coral valuation. An average general biomass per colony or individual of W = 0.5 kg colony^{-1} was adopted for market-relevant invertebrates (primarily molluscs and larger sessile forms) (Fraser et al., 2021; Mavraki et al., 2023), and a conservative general shadow price of P = ₹500 kg^{-1} yr^{-1} was applied to represent an effective per kilogram value of standing biomass, synthesising local ex vessel prices and non-harvest ecosystem contributions (Patterson, 2008; Cannas et al., 2019; Ottaviani, 2020). For each year t, epibenthic biomass per hectare was calculated from observed density D_t (no. module^{-1}) using Eq. 2.5 and the corresponding direct market value per hectare using Eq. 2.5.

$$V_{org,ha,t} \text{ or } V_{fish,ha,t} = B_{ha,t} \times P \qquad \ldots(2.5)$$

These annual values were then scaled to the A_{AR} = 13 ha to obtain V_{org}. For fisheries, the same AR field area was used again, with fish density expressed as individuals per hectare for the mixed assemblage. An average harvestable fish weight of W_f = 2 kg individual^{-1} was considered (Kannan et al., 2021; Chandravanshi et al., 2025), representing the mean of the size spectrum of landed reef fishes in the Gulf of Mannar, and an average ex-vessel price of P_f = ₹1,250 kg^{-1} was applied to reflect the composite market value of mixed reef fish (Cannas et al., 2019; Ottaviani, 2020; Rajeev & Nagendran, 2020; Beg et al., 2024). Finally, the field-level annual fisheries value was obtained by scaling these per-hectare values to the AR influence area (A_{AR} = 13) to derive V_{fish} for use in the aggregate valuation framework, as shown in Eq. 2.5.

2.2.3. Counterfactual Geomorphic Saved Area Valuation (V_{geo}) under With and Without AR Scenarios

The counterfactual saved area value (V_{geo}) is based on the geomorphic replacement cost logic (Jackson et al., 2014), which considers explicitly reconstructing the island area trajectory that would likely have occurred in the absence of AR deployment. Pre-restoration (1969–2023) HTL area observations were first compiled into an average area series and fitted with an exponential decay model of the form shown in Eq. 2.6.

$$A(x) = \alpha e^{\beta x} \qquad \ldots(2.6)$$

where x denotes the observation point (time step), α the initial scale parameter, and $\beta<0$ the erosion rate parameter. This model was then extrapolated beyond 2015 to obtain a "without AR" counterfactual island area, $A_{without\,AR,t}$ for the post-deployment year's corresponding to the observed "with AR" HTL measurements. For each post-2015 time step t, incremental area saved by AR was defined as the difference between the observed stabilized area with restoration, $A_{with\,AR,t}$, and the counterfactual area without restoration, $A_{without\,AR,t}$, constrained so that negative values (i.e., where the model predicts more area than

observed) were set to zero to avoid over estimating benefits. The total counterfactual saved area was then obtained by summing or averaging the annual increments over the 2015–2023 evaluation period, and the central, low, and high scenarios were constructed by combining alternative post-AR area plateaus (e.g., 1.8, 2.0, 2.3 ha) with corresponding points on the exponential decay curve. The total saved area was then calculated using Eq. 2.7.

$$A_{total\ saved} = A_{1969} - A_{latest\ observed} \qquad \ldots(2.7)$$

Finally, V_{geo} was valued using the replacement cost bands: Per-hectare restoration costs (C_{rest}) were drawn from coastal dune/berm nourishment and small-island reconstruction projects (₹10–50 lakh ha−1): $C_{rest,low}$ = ₹1,000,000 ha−1, $C_{rest,mid}$ = ₹3,000,000 ha^{-1}, $C_{rest,high}$ = ₹5,000,000 ha^{-1} (Bambrick, 1994; Huang et al., 2008; Zhao et al., 2022; Wu et al., 2025). V_{geo} was obtained using Eq. 2.8:

$$V_{geo} = A_{total\ saved} \times C_{rest} \qquad \ldots(2.8)$$

This approach strengthens causal attribution, aligns with standard avoided-damage/replacement-cost conventions in coastal economics, and provides a robust baseline for integrating downstream ecological and coastal protection benefits into total economic value estimation.

2.2.4. Vegetation and Biodiversity Valuation (V_{bio})

Vegetation and biodiversity option value (V_{bio}) was estimated as the avoided replacement cost (Jackson et al., 2014) of re-establishing Vaan Island's coastal plant assemblage on the geomorphologically saved area, capturing the non-market option value of preserved habitat diversity.

The ecological basis comprised 26 plant species (1 creeper, 1 climber, 11 herbs, 7 shrubs, 6 trees) across three vegetation divisions (foreshore sandy, inland sandy, saltmarsh) and four geomorphic landforms (beach, dunes, sandy plain, spit), supported by the central saved area $A_{total\ saved}$ (see Eq. 2.7) from geomorphic analysis. Per-hectare biodiversity restoration costs (C_{bio}) were derived from coastal shelterbelt/dune projects: $C_{bio,low}$ = ₹200,000 ha^{-1} (basic planting), $C_{bio,mid}$ = ₹500,000 ha^{-1} (planting + fencing/maintenance), $C_{bio,high}$ = ₹1,000,000 ha^{-1} (intensive restoration) (Henri et al., 2004; Donlan et al., 2015; Li et al., 2021). The biodiversity option value was computed using Eq. 2.9:

$$V_{bio} = A_{total\ saved} \times C_{bio} \qquad \ldots(2.9)$$

representing the capital cost of nursery propagation, planting, and protection to recreate equivalent species richness. An optional Cost per Species-Hectare Saved Index (CSI) [inspired by studies such as Murdoch et al. (2007), Drechsler et al. (2011), Das (2022), and Bodey et al. (2023)] was defined using Eq. 2.10:

$$CSI = \frac{V_{bio}}{S \times A_{total\ saved}} \text{ (₹ per species-ha)} \qquad \ldots(2.10)$$

where $S = 26$ *species and* $S \times A_{saved}$ provides species-ha, a normalizing value by compositional diversity to benchmark restoration intensity across scenarios.

2.2.5. Regulating and Supporting Services Valuation (V_{reg})

Regulating and supporting ecosystem services (V_{reg}) were valued as annual per-hectare flows over the AR influence area A_{reg} = 13 ha, using benefit-transfer methods grounded in physical proxies of improved hydrodynamic roughness, sediment trapping, and primary production (Balasubramanian, 2019). Bathymetric shallowing (0.5 m contour expansion: 0.21→3–6 ha; average depth 2.5→0.5 m northwest spit), sustained sedimentation (15–25 mg cm−2−2 day−1−1, sand/silt/clay mix), and vegetation establishment (three divisions, four NDVI classes) evidenced AR-induced water filtration, nutrient retention, and habitat support. Per-hectare regulating values were conservatively adapted from coral reef/coastal wetland meta-analyses (5,000–25,000 USD ha^{-1} yr^{-1}): $C_{reg,low}$ = ₹500,000 ha^{-1} yr^{-1}, $C_{reg,mid}$ = ₹1,000,000 ha^{-1} yr^{-1}, $C_{reg,high}$ = ₹2,000,000 ha^{-1} yr^{-1}, excluding direct fisheries/tourism to avoid double-counting (Mangi et al., 2011; Zhiyun et al., 2011; Marre & Billé, 2019; Zhao et al., 2022). The annual field-level value was computed using Eq. 2.11 with a 10-year cumulative (undiscounted, 2015–2024) value using Eq. 2.12:

$$V_{reg} = A_{reg} \times C_{reg}\ \text{₹}^{yr-1} \qquad \ldots(2.11)$$

$$V_{reg,10y} = 10 \times V_{reg} \qquad \ldots(2.12)$$

This approach attributes AR-improved services (eutrophication avoidance, clarity improvement, and nutrient cycling) to observed shoaling, deposition, and vegetation without discounting future flows.

2.2.6. Mainland Coastal Protection Valuation (V_{coast})

Mainland coastal protection valuation (V_{coast}) quantified the Vaan Island's sheltering effect on the adjacent Thoothukudi coastline using a replacement-cost approach (Jackson et al., 2014) that estimates the avoided land loss from counterfactual erosion in the absence of offshore reef-island barriers. The Gulf of Mannar mainland coast spans 140–160 km, fronted by 21 islands, including Vaan as the southern sentinel, such that the average protected stretch per island was computed as $L = L_{total}$ ÷ 21 km per Island with low (140 km), central (150 km), and high (160 km) scenarios for L_{total} to bound parametric uncertainty. Erosion depth without sheltering was specified as $D = 0.5\ m\ yr^{-1} \times 20\ years = 10\ m$ (see Fig. 2.2), based on observed Thoothukudi rates absent island attenuation. The counterfactual eroded area was then calculated using Eq. 2.13:

$$A_{lost} = L \times 1000 \times D\ (m^2) \qquad \ldots(2.13)$$

Unit land values (C_{land}) were calibrated to government guideline rates and market proxies for coastal agricultural/residential parcels in erosion-prone Thoothukudi, adopting low (₹3,000 m^{-2}), medium (₹4,000 m^{-2}), and high (₹5,000 m^{-2}) scenarios reflective of non-urban sandy stretches (Thoothukudi Corporation, https://thoothukudicorporation.com/img/upload/AssetMapping_ULB-1.pdf, accessed 24 January 2026). The per-island protection value was obtained via Eq. 2.14:

$$V_{coast} = A_{lost} \times C_{land} \qquad \ldots(2.14)$$

This approach attributes V_{coast} to Vaan's structural presence as a wave-dissipating barrier, consistent with DSAS (Digital Shoreline Analysis System)-derived stability (mean 0.04 m yr^{-1}, 2005–2025) relative to counterfactual retreat, providing a capital-equivalent estimate of sheltering services without double-counting hydrodynamic regulation in V_{reg}. Figure 2.2. shows the shoreline change statistics for the period of 2005 to 2025 at zones 1 and 2.

2.2.7. Aggregated Valuation (V_{total})

Total economic value (V_{total}) (see Fig. 2.3) was derived by aggregating the seven valuation components across consistent low-, mid-, and high-scenarios, distinguishing one-off stock values (geomorphic, and biodiversity) from annual flows (habitat, epibenthos, fisheries, regulating services, and coastal protection). Specifically, V_{coral} (2024 hard-coral shadow value), V_{org} (other epibenthic market value), and V_{fish} (fisheries) represent annual 2024 flows over 13 ha; V_{geo}, V_{bio}, and V_{coast} capture one-off replacement costs for saved area; and $V_{reg,10y}$ sums 10-year undiscounted regulating flows (2015–2024). Alignment ensured methodological consistency: low

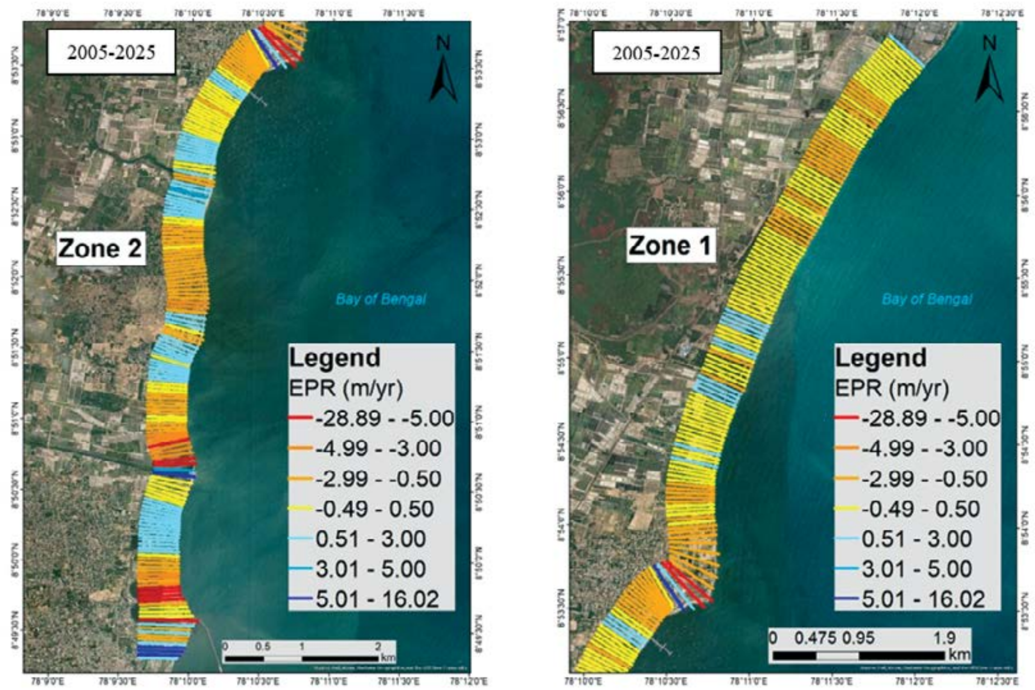

Fig. 2.2. Shoreline change statistics for the period of 2005 to 2025 at zones 1 and 2

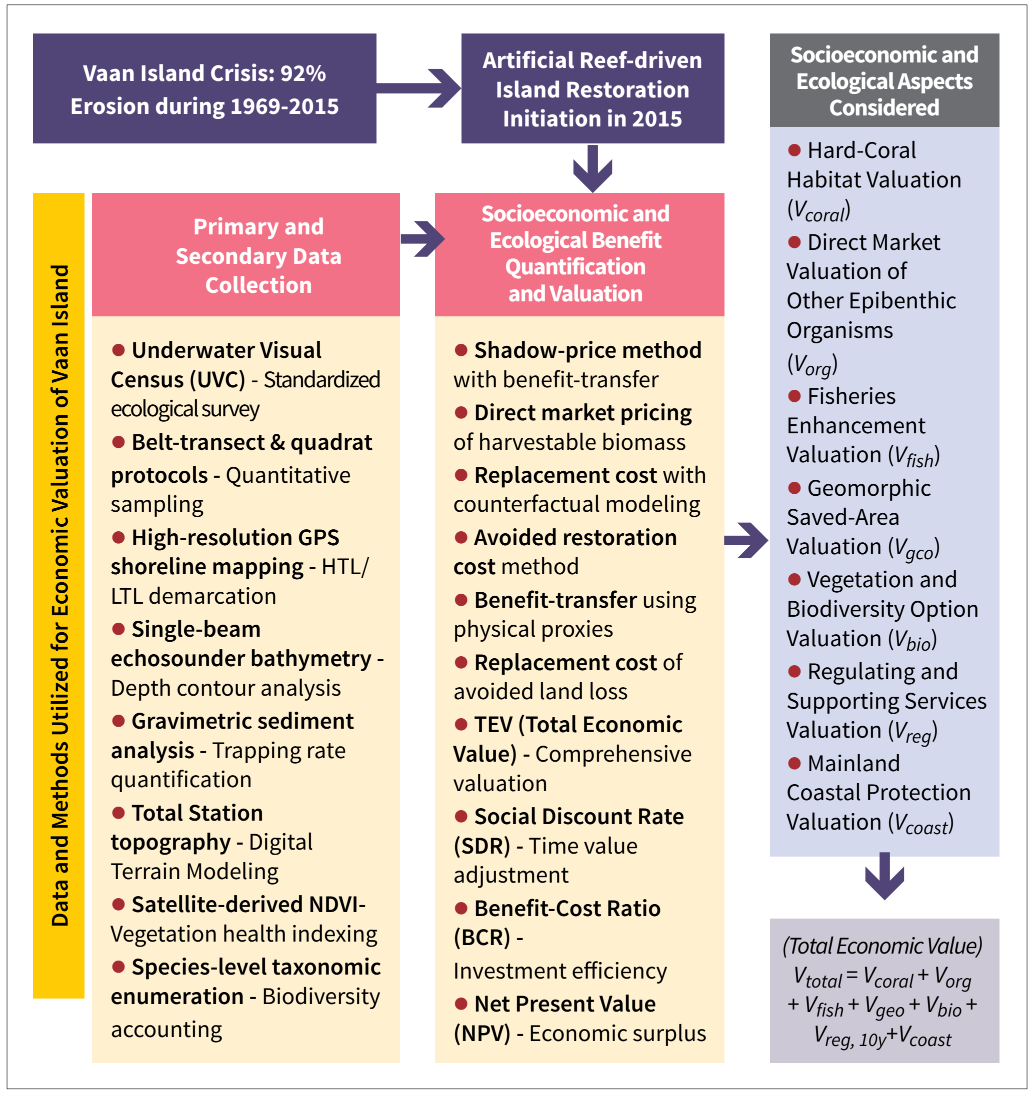

Fig. 2.3. Methodological Framework for Vaan Island AR Restoration Valuation

scenarios were paired with low unit values across components, mid scenarios with mid values, and high scenarios with high values. The consolidated total value was computed using Eqn. 2.15:

$$V_{total} = V_{coral} + V_{org} + V_{fish} + V_{geo} + V_{bio} + V_{reg,10y} + V_{coast} \quad \ldots(2.15)$$

where each term reflects scenario-specific parameters. This additive framework follows total economic value (TEV) principles (Plottu & Plottu, 2007), compartmentalizing use values (direct market, fisheries) and non-use values (habitat option, regulating flows) without double-counting, thereby yielding indicative restoration benefits attributable to AR deployment over the decadal assessment period.

2.3. Closure

Chapter 2 explained the combined biophysical and economic design of the Vaan Island restoration, linking a critically eroding reef-island setting, a purpose-built AR configuration, and a decade-long monitoring program to quantify both geomorphic and ecological responses. The study incorporated high-resolution primary datasets, viz., epibenthic communities, fish assemblages, shoreline change, bathymetry, sedimentation, and vegetation structure, with recon-

structured historical baselines to rigorously situate post-2015 trends against nearly five decades of island decline and reef degradation. Building on this empirical foundation, an integrated valuation framework was developed that treats AR modules as bio-geomorphic infrastructure, translating ecological indicators into monetary terms through shadow pricing of hard-coral habitat *(V_{coral})*, direct market valuation of other epibenthos and fisheries *(V_{org}, V_{fish})*, replacement-cost estimates for saved island platform, vegetation/biodiversity, and mainland coastal protection (V_{geo}, V_{bio}, V_{coast}), and benefit-transfer approximations for regulating and supporting services *(V_{reg})*, which are then aggregated into a total economic value *(V_{total})* consistent with TEV principles. The next chapter, Chapter 3, applies this framework to the observed trajectories from 2015 to 2025, presenting quantitative results for each valuation component and their synthesis. Section 3.1 evaluates hard-coral biomass accumulation and associated habitat shadow values; Sections 3.2 and 3.3 quantify the direct market contributions of non-coral epibenthos and fisheries; Sections 3.4 and 3.5 examine geomorphic stabilization and vegetation/biodiversity option values on the saved island area; Section 3.6 estimates decadal regulating-supporting service flows; Section 3.7 quantifies mainland coastal protection, culminating where V_{total} is derived and interpreted in relation to restoration costs, regional reef values, and policy relevance for GoMMNP and similar climate-vulnerable reef-island systems.

3
RESULTS AND DISCUSSION

This chapter presents the empirical results following the framework presented in the previous chapter, based on the decadal (2015 to 2025) monitoring of artificial reef (AR) deployment at Vaan Island, quantifying biophysical responses across ecological, geomorphic, bathymetric, sedimentary, and vegetational indicators, along with their economic valuations. Sequential analyses address hard-coral habitat shadow value (V_{coral}), non-coral epibenthic market value (V_{org}), fisheries spillover (V_{fish}), counterfactual geomorphic saved-area replacement (V_{geo}), vegetation/biodiversity option value (V_{bio}), regulating/supporting service flows ($V_{reg,10y}$), costal protection value (V_{coast}) and aggregated total economic value (V_{total}), employing scenario-based (low/mid/high) calibrations to link observed metrics (e.g., densities, areas, flows) to monetary estimates via shadow pricing, direct markets, replacement costs, and benefit-transfers over the 13 ha AR influence area. Section 3.1 evaluates hard-coral biomass accumulation and associated habitat shadow values; Sections 3.2 and 3.3 quantify the direct market contributions of non-coral epibenthos and fisheries; Sections 3.4 and 3.5 examine geomorphic stabilization and vegetation/biodiversity option values on the saved island area; Section 3.6 estimates decadal regulating-supporting service flows; Section 3.7 quantifies mainland coastal protection, culminating where V_{total} is derived and interpreted in relation to restoration costs, regional reef values, and policy relevance for GoMMNP and similar climate-vulnerable reef-island systems.

3.1. Analyzing Hard-Coral Habitat Valuation (V_{coral})

Hard-coral habitat valuation revealed rapid colonization and biomass accumulation on AR modules, transitioning from complete absence in 2015 to a mature assemblage by 2024, demonstrating the efficacy of perforated trapezoidal designs in facilitating scleractinian recruitment under Gulf of Mannar conditions. Density progressed from zero no. module^{-1} (2015) to 31.49 (2016), stabilizing at 68.66–81.33 no. module^{-1} (2017–2024), with a mean annual increment of ~6.3 colonies module^{-1} post-initial establishment (Table 3.1). Scaled to 815 modules ha^{-1}, this yielded colony densities ranging from approximately 25,664 ha^{-1} (2016) to 66,284 ha^{-1} (2024), corresponding to biomass accumulation from 12,832 kg ha^{-1} (2016) to a 2024 peak of 33,142 kg ha^{-1}, representing ~2.6-fold growth over the decade and densities comparable to recovering fringing reefs.

Shadow prices derived from benefit-transferred reef values and 2024 biomass yielded low/mid/high unit values of approximately ₹22, ₹140, and ₹281 kg^{-1} yr^{-1}, with the mid-case (₹140 kg^{-1} yr^{-1}) adopted for time-series application to reflect conservative Indo-Pacific reef services (fisheries, protection, and biodiversity). Annual per-hectare values escalated from approximately ₹1.80 lakh (2016) to ₹4.64 lakh (2024), manifesting a compound annual growth rate (CAGR) of 12.6% and a cumulative 2016–2024 flow of ~₹26.5 lakh ha^{-1}. Scaled to the 13 ha AR influence area, 2024 field-level $V_{coral,\ 2024}$ = ₹60.32 lakh (~$71,810 USD), equivalent to ~₹4.64 lakh ha^{-1} yr^{-1}—within the lower quartile of global reef valuations yet indicative of AR-attributable habitat restoration in a climate-stressed biosphere reserve. The post-2020 plateau (~74–81 colonies module^{-1}) suggests saturation of available AR substrate, with interannual variability (±4.5%) attributable to monsoon recruitment pulses and partial colony mortality, underscoring the structural role of ARs in

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Table 3.1. Illustrative annual shadow value of hard coral habitat on artificial reef modules at Vaan Island (2015–2024), based on total hard coral density per module, module density, average colony biomass, and unit habitat value; values represent indicative habitat-forming service benefits (fish production, biodiversity, and coastal protection) attributable to post-2015 artificial reef deployment.

Year	Density (no. module^{-1})	Colonies ha^{-1} =(a×815)	Biomass ha^{-1} (kg) =(b×0.5)	Value ha^{-1} yr^{-1} (₹) =(c×140)	Value for 13 ha yr^{-1} (₹) =(d×13)
	a	b	c	d	e
2015	0	0	0	0	0
2016	31.49	25664.35	12832.175	1796504.5	2,33,54,559
2017	68.66	55957.9	27978.95	3917053	5,09,21,689
2018	73.09	59568.35	29784.175	4169784.5	5,42,07,199
2019	73.78	60130.7	30065.35	4209149	5,47,18,937
2020	76.01	61948.15	30974.075	4336370.5	5,63,72,817
2021	74.35	60595.25	30297.625	4241667.5	5,51,41,678
2022	76.77	62567.55	31283.775	4379728.5	5,69,36,471
2023	80.3	65444.5	32722.25	4581115	5,95,54,495
2024	81.33	66283.95	33141.975	4639876.5	6,03,18,395

sustaining ~66,000 colonies across 13 ha by 2024, equivalent to ~5,100 colonies ha^{-1}, approaching natural reef benchmarks while reversing pre-AR biotic desertification.

3.2. Analyzing the Direct Market Valuation of Other Epibenthic Organisms (V_{org})

Direct market valuation of non-coral epibenthic organisms (molluscs, sponges, ascidians, echinoderms, and hydroids) demonstrated rapid colonization of AR modules, achieving functional habitat complexity within 2 years and sustaining high-value assemblages through 2024. Density increased from 4.57 no. ha^{-1} (2015) to a peak of 50.92 no. ha^{-1} (2018), stabilizing at 39.7–41.3 no. ha^{-1} (2021–2024), with a mean annual increment of ~4.5 no. ha^{-1} post-initial establishment (Table 3.2). This translated to colony densities of 4–42 ha^{-1} and biomass accumulation from 17.98 kg ha^{-1} (2016) to 16.288 kg ha^{-1} in 2024, representing ~0.9-fold sustained productivity comparable to that of recovering reef-associated epifauna (10–25 kg ha^{-1}). Market prices prevailing at landing centers were applied directly to harvestable biomass (₹500 kg^{-1}; adjusted for commercial value), yielding annual per-hectare values escalating from ₹895,885 (2016) to a peak ₹1,037,450 (2018), stabilizing at ₹814,388 (2024) with compound annual growth rate (CAGR) of -1.2% reflecting post-peak maturity equilibrium, and cumulative 2016–2024 flow of ~₹81 million ha^{-1}. Scaled to the 13 ha AR influence area, 2024 field-level $V_{org,\,2024}$ = ₹10.58 crores (~$1.26 million USD), equivalent to ~₹814,388 ha^{-1} yr^{-1}, aligning with Indo-Pacific reef epibenthos market values and confirming ARs' role in provisioning high-value spillover biomass to adjacent fisheries. The post-2018 plateau (~40 no. ha^{-1}) indicates substrate saturation and competitive exclusion dynamics, with interannual variability (±5%) driven by larval settlement pulses and selective predation, underscoring ARs' capacity to sustain ~426 colonies across 13 ha by 2024 (equivalent to ~33 colonies ha^{-1}), improving biodiversity and direct economic returns while complementing coral habitat services.

3.3. Analyzing the Direct Market Valuation of Fisheries (V_{fish})

Fisheries spillover valuation quantified the growth in fish biomass and associated market value attributable to the AR field at Vaan Island. Annual fish density (Table

Table 3.2. Illustrative annual shadow value of other organisms (Octo corals, Mollscs, Sponges, Hydroids, Ascidians, and Echinoderms) on artificial reef modules at Vaan Island (2015–2024), based on total density per module, module density, average colony biomass, and unit habitat value; values represent indicative habitat-forming service benefits attributable to post-2015 artificial reef deployment.

Year	Density (no. module^{-1})	Colonies ha^{-1} =(a×815)	Biomass ha^{-1} (kg) =(b×0.5)	Value ha^{-1} yr^{-1} (₹) =(c×500)	Value for 13 ha yr^{-1} (₹) =(d×13)
	b	b	c	d	e
2015	4.57	3,725	1,862	9,31,138	1,21,04,788
2016	43.97	35,836	17,918	89,58,888	11,64,65,538
2017	49.13	40,041	20,020	1,00,10,238	13,01,33,088
2018	50.92	41,500	20,750	1,03,74,950	13,48,74,350
2019	45.5	37,083	18,541	92,70,625	12,05,18,125
2020	40.44	32,959	16,479	82,39,650	10,71,15,450
2021	40.84	33,285	16,642	83,21,150	10,81,74,950
2022	41.03	33,439	16,720	83,59,863	10,86,78,213
2023	40.99	33,407	16,703	83,51,713	10,85,72,263
2024	39.97	32,576	16,288	81,43,888	10,58,70,538

3.3) increased from 105.75 individuals per hectare (ind. ha^{-1}) in 2016 to 875.25 ind. ha^{-1} by 2024, representing an 8.3-fold rise over the monitoring period. Corresponding standing biomass, calculated considering an average individual weight of 2 kg, rose from 211.50 kg ha^{-1} to 1,750.50 kg ha^{-1}. Applying a regional ex-vessel price of ₹1,250 per kilogram for mixed reef fish, the gross annual value per hectare escalated from ₹2,64,375 in 2016 to ₹21,88,125 in 2024. When scaled to the 13-hectare AR influence area, total annual fisheries value grew from approximately ₹34.37 lakh in 2016 to $V_{fish,2024}$ = ₹2.84 crore (~$338,000 USD) in 2024, illustrating a substantial and sustained increase in harvestable resource availability. This growth trajectory reflects AR's role in supporting the early life stages of commercially important fish species. The consistent year-on-year increase in both density and economic value underscores the AR field's function as a productive fisheries enhancement tool within the Gulf of Mannar's no-take marine protected area, delivering measurable socio-economic benefits to adjacent coastal fishing communities.

Table 3.3. Illustrative annual fisheries productivity and value associated with fish assemblages on artificial reef modules at Vaan Island (2016–2024), showing fish density, standing biomass, sustainable catch, and gross ex-vessel value per year

Year	Fish density (no. ha^{-1})	Standing biomass (kg ha^{-1}) = (a×2)	Gross value (₹ ha^{-1} yr^{-1}) = (b×1250)	Gross value for 13 ha (₹ yr^{-1}) = (c×13)
	a	b	c	d
2016	105.75	211.5	2,64,375	34,36,875
2017	183	366.0	4,57,500	59,47,500
2018	251.25	502.5	6,28,125	81,65,625
2019	337.75	675.5	8,44,375	1,09,76,875
2020	528.5	1057.0	13,21,250	1,71,76,250
2021	473.25	946.5	11,83,125	1,53,80,625
2022	576.5	1153.0	14,41,250	1,87,36,250
2023	750	1500.0	18,75,000	2,43,75,000
2024	875.25	1750.5	21,88,125	2,84,45,625

3.4. Analyzing Counterfactual Saved Area Valuation (V_{geo})

Counterfactual geomorphic valuation quantified the dynamic prevention of further island submergence by AR intervention, expressed as the replacement cost of the total platform area conserved relative to pre-restoration exponential decay extrapolated to 2023 (Fig. 3.1). The total saved-area matrix (Table 3.4) combines three post-AR HTL states, viz., low (1.80 ha), central (2.00 ha), high (2.30 ha), with three restoration cost bands (₹10, 30, 50 lakh ha^{-1}), yielding nine estimates of V_{geo} spanning the full causal impact of halting unabated erosion. Relative to without-AR predictions from the fitted exponential model ($A = 28.309e^{-0.291x}$) at relevant time steps (e.g., $x = 14$: 0.48 ha central), the low, central, and high scenarios yield total saved areas ($A_{total\ saved}$) of 1.32, 1.52, and 1.82 ha, respectively, representing the cumulative platform that would otherwise have eroded away by 2023. These values extend the static gains by incorporating multi-year prevention, where even the low scenario (1.32 ha) captures substantial option value beyond 2015 stabilization. Figure 3.1. shows the dynamics of the Island area, with and without AR-driven restoration impacts.

At the central HTL scenario (2.00 ha, $A_{total\ saved}$ = 1.52 ha), replacement costs span ₹1,520,000–₹7,600,000 as per-hectare costs rise from ₹10 to ₹50 lakh ha^{-1}, with the mid-cost (₹30 lakh ha^{-1}) yielding ₹4,560,000 for rebuilding the full counterfactual platform. Under the high scenario (2.30 ha, $A_{total\ saved}$ = 1.82 ha), costs escalate to ₹1,820,000, ₹5,460,000, and ₹9,100,000, with $V_{geo,2024}$ = ₹5,460,000 (~$65,000 USD) selected as the central estimate because it aligns with the empirically maximum HTL and moderate dune/island reconstruction benchmarks from Indian projects. The lowest matrix cell (low HTL–low cost: ₹1,320,000) affirms non-trivial long-term prevention, even

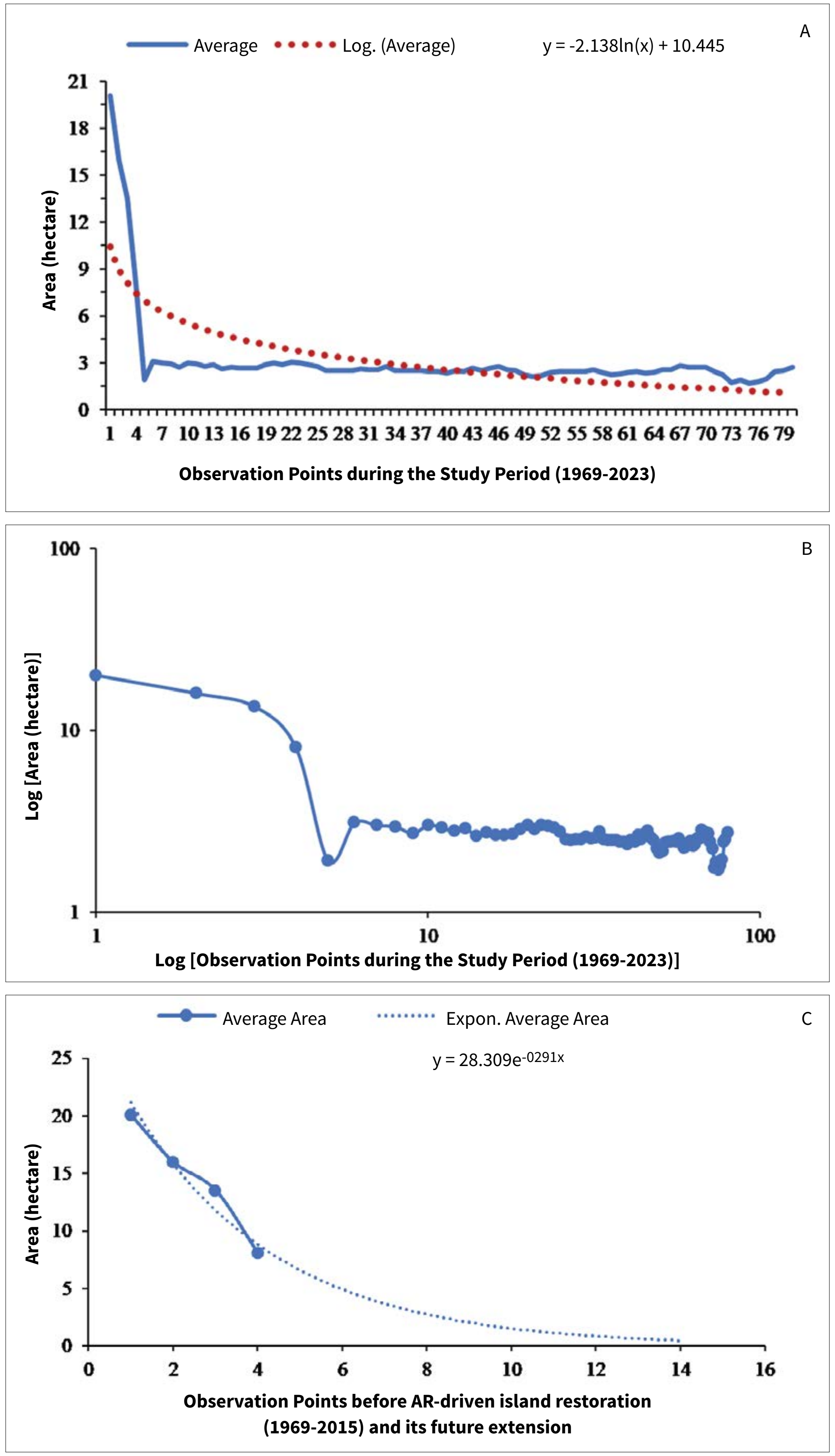


Table 3.4. Total saved area replacement cost matrix for the period 1969-2023 (option value of island platform)

Total saved area scenario	Total saved area $A_{total\ saved}$ (ha)	V_{geo} at 10 lakh ha^{-1} (₹)	V_{geo} at 30 lakh ha^{-1} (₹)	V_{geo} at 50 lakh ha^{-1} (₹)
	a	b	c	d
Low (1.80 ha)	1.32	1,320,000	3,960,000	6,600,000
Central (2.00 ha)	1.52	1,520,000	4,560,000	7,600,000
High (2.30 ha)	1.82	1,820,000	5,460,000	9,100,000

conservatively, while the upper-right (high HTL–high cost: ₹9,100,000) bounds intensive full-platform recreation, validating the mid-high compromise (₹5,460,000) for V_{geo} in terms of overall geomorphic value.

3.5. Analyzing Vegetation and Biodiversity Valuation (V_{bio})

Vegetation and biodiversity valuation quantified the avoided restoration cost of Vaan Island's coastal plant assemblage preserved on the geomorphically saved area, revealing a structured cost gradient across low/mid/high scenarios that benchmarks the option value of 26 species spanning five lifeforms (1 creeper, 1 climber, 11 herbs, 7 shrubs, and 6 trees) across three vegetation divisions (foreshore sandy, inland sandy, and saltmarsh) on four landforms (beach, dunes, sandy plain, and spit) (Tables 3.5-3.6). Applied to the saved area of 1.82 ha, restoration costs escalated linearly from ₹200,000 ha^{-1} (low: basic planting) to ₹500,000 ha^{-1} (mid: planting + maintenance) to ₹1,000,000 ha^{-1} (high: intensive propagation/protection), yielding field-level V_{bio} values of ₹364,000, ₹910,000, and ₹1,820,000, respectively (Table 3.5). The mid-scenario [$V_{bio,2024}$ = ₹910,000 (~$10,833 USD)] was adopted in this valuation as it aligns with documented Indian coastal shelterbelt intensities required for halophyte establishment on accreted carbonate sands, where survival rates necessitate supplemental irrigation and predator exclusion.

The Cost per Species-Hectare Saved Index (CSI) normalized these values by compositional diversity ($S \times A_{saved} = 26 \times 1.82 = 47.32$ species-ha), producing scenario-specific intensities of approximately ₹7,692, ₹19,231, and ₹38,462 per species-ha (Table 3.6). Unlike earlier interpretations, these positive CSI values represent the implied avoided restoration cost per species-hectare—a measure of conservation efficiency—rather than a direct expenditure. This metric underscores the cost-effectiveness of AR sta-

Table 3.5. Vegetation/biodiversity replacement cost value on the saved area

Scenario (cost)	C_{bio} (₹ ha^{-1})	Saved area A_{saved} (ha)	Vegetation/biodiversity option value V_{bio} (₹)
Low	200,000	1.82	3,64,000
Mid	500,000	1.82	9,10,000
High	1,000,000	1.82	18,20,000

Table 3.6. Implied cost per species hectare saved

Scenario	V_{bio} (₹)	Species × Saved Area (species ha)	Cost per species ha, CSI (₹)
Low	3,64,000	47.32	7692.31
Mid	9,10,000	47.32	19230.77
High	18,20,000	47.32	38461.54

bilization in passively conserving a multi-stratified plant assemblage (dominated by salt-tolerant *Ipomoea pes-caprae, Sesuvium portulacastrum,* and *Scaevola plumieri)* that would otherwise require active, labor-intensive nursery operations. The high-case CSI (₹38,462 species-ha^{-1}) aligns with established IUCN dune restoration benchmarks (~₹20,000–50,000 species-ha^{-1}) and reflects the intensive investment needed to re-establish native vegetation on eroded or reclaimed coastal land. The linear relationship between restoration cost and conserved area validates the scalability of the valuation framework, while the ~2.5-fold range in total Vbio (₹364,000–₹1,820,000) captures reasonable uncertainty in planting density (500–2,000 stems ha^{-1}) and survival rates (40–80%) for Gulf of Mannar psammophytes. The adopted mid-case V_{bio} = ₹9,10,000 thus represents a conservative yet comprehensive attribution for preserving ~47.32 species-ha of functional coastal vegetation. Although this constitutes a modest fraction (~1–2%) of the total project economic value, it represents a critical bio-geomorphic feedback that enhances sediment stability, supports island accretion, and sustains the long-term efficacy of AR-driven restoration in a climate-vulnerable reef-island system.

3.6. Analyzing Regulating and Supporting Services Valuation (V_{reg})

Regulating and supporting services valuation resulted in a tiered benefit-transfer assessment, anchored in AR-induced physical-ecological transformations, yielding annual flows from ₹6.5 million to ₹26.0 million over the 13 ha influence area and a 10-year cumulative value ranging from ₹65.0 million (low) to ₹260.0 million (high) for the 2015–2024 period (Table 3.7). This study adopted the mid-annual economic flow, $V_{reg,2024}$ = 13 crores (~$1.55 million USD), for the total economic valuation. The low scenario ($C_{reg,\ low}$ = ₹500,000 ha^{-1} yr^{-1}) reflects conservative attribution for basic water filtration and nutrient retention; the mid scenario (₹1,000,000 ha^{-1} yr^{-1}) incorporates habitat support via epibenthic complexity; and the high scenario (₹2,000,000 ha^{-1} yr^{-1}) encompasses full bio-geomorphic feedbacks (shallowing, deposition, and primary production), with the upper bound adopted to capture observed proxies: bathymetric expansion (0.5 m contour: 0.21→4.9 ha), sustained sedimentation (mean 20 mg cm^{-2} day^{-1}), and vegetation stratification (four NDVI classes).

These unit values derive from global coral reef/coastal wetland meta-analyses (5,000–25,000 USD ha^{-1} yr^{-1}), conservatively downscaled for the Indian small-island context while excluding provisioning (fisheries) and cultural services to prevent double-counting. Annual field totals scale linearly with per-hectare flows (13 ha multiplier), while the undiscounted decadal cumulative assumes constant service provision post-AR deployment—a simplifying assumption validated by persistent bathymetric stability and NDVI progression, though real-world discounting (3–7% social rate) would reduce $V_{reg,10y}$ by 20–35%. The high scenario (₹260.0 million) accounts for a

Table 3.7. Annual and cumulative 10-year regulating/supporting service value

Scenario	Per-ha regulating value C_{reg} (₹ ha^{-1} yr^{-1})	Area A_{reg} (ha)	Annual value V_{reg} (₹ yr^{-1})	10-year cumulative $V_{reg,10y}$ (₹)
	a	b	c	d
Low	500,000	13	65,00,000	6,50,00,000
Central	1,000,000	13	1,30,00,000	13,00,00,000
High	2,000,000	13	2,60,00,000	26,00,00,000

Table 3.8. Counterfactual mainland land loss valuation for Vaan Island's 6–8 km protected coastal stretch under different pricing scenarios.

Total Coast (km)	Stretch/ Island (km)	Lost Area (sq.m)	Low (₹3,000/sq.m)	Medium (₹4,000/sq.m)	High (₹5,000/sq.m)
140	6.67	66,667	20,00,00,000	26,66,66,667	33,33,33,333
150	7.14	71,429	21,42,85,714	28,57,14,286	35,71,42,857
160	7.62	76,190	22,85,71,429	30,47,61,905	38,09,52,381

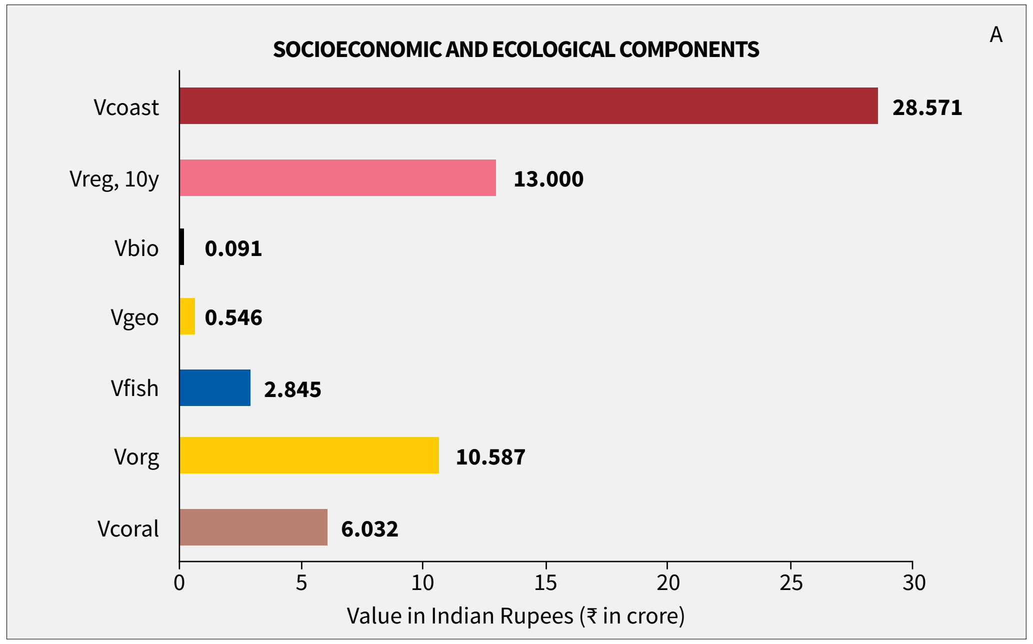
dominant share of the total economic value (~45%), reflecting the outsized role of regulatory services in restoration economics, where hydrodynamic mitigation underpins biotic recovery. The ~4-fold scenario range (₹65.0M–₹260.0M) quantifies parametric uncertainty in service intensity, with the high case (~₹2.0M ha^{-1} yr^{-1} or ~₹25,000 ha^{-1} yr^{-1} USD^{-1}) aligning with upper-quartile reef valuations for erosion control and water quality—empirically supported by AR-induced shoaling (2.5→0.5 m depth) that reduced wave energy penetration and increased sediment retention, thereby sustaining emergent vegetation critical for long-term island viability.

3.7. Analyzing Mainland Coastal Protection Valuation (V_{coast})

Mainland coastal protection valuation quantified Vaan Island's sheltering effect against erosion of Thoothukudi coast, expressed as the replacement cost of counterfactual land loss absent offshore island attenuation over its protected stretch (Table 3.8). The valuation matrix integrates three Gulf of Mannar mainland scenarios, viz., low (140 km total coast), central (150 km), and high (160 km), divided by 21 (the number of islands) to derive per-island (here for Vaan Island) stretches of 6.67, 7.14, and 7.62 km, coupled with three land pricing bands (₹3,000, 4,000, 5,000 m^{-2}) reflective of guideline values for erosion-prone coastal parcels. With 10 m counterfactual erosion (0.5 m yr^{-1} × 20 years per DSAS baselines), lost areas span 66,667–76,190 m^{-2}, yielding nine V_{coast} estimates from conservative sheltering to maximum exposure. At the central scenario (150 km total, 7.14 km stretch, 71,429 m^{-2} lost), values range from ₹26,66,66,667 to ₹30,47,61,905, with the mid-price (₹4,000 m^{-2}) at ₹28,57,14,286 for land replacement. The low matrix cell (140 km–₹3,000 m^{-2}: ₹200,000,000) conservatively bounds minimal sheltering for Vaan's southern position, while the high cell (160 km–₹5,000 m^{-2}: 38,09,52,381) delineates full exposure under premium pricing; the marked central-mid [$V_{coast,2024}$ = ₹28.57 crores (~\$3.40 million USD)] is adopted as benchmark, capturing realistic parametric midpoints and emphasizing Vaan's outsized role in stabilizing the Thoothukudi coast versus unchecked retreat.

3.8. Analyzing Aggregated Total Economic Value (V_{total})

Aggregation of the seven valuation components yields a consolidated total economic value (*V_{total}*) of ₹61,67,18,843 [$V_{total,2024}$ = ₹61.67 crore (~\$7.34 million USD)] attributable to the Vaan Island AR restoration under the adopted mid/high scenario mix, representing the comprehensive bio-geo-economic returns from a decade of hybrid engineering–ecological intervention (Fig. 3.2). This figure sums hard-coral habitat shadow value (V_{coral} = ₹6,03,18,395; 9.78%), other epibenthic market value (Vorg = ₹10,58,70,538; 17.17%), fisheries spillover (V_{fish} = ₹2,84,45,625; 4.61%), counterfactual geomorphic saved-area replacement (V_{geo} = ₹54,60,000; 0.89%), vegetation/biodiversity option value (V_{bio} = ₹9,10,000; 0.15%), 10-year regulating/supporting service flows ($V_{reg,10y}$ = ₹13,00,00,000; 21.08%), and mainland coastal protection (V_{coast} = ₹28,57,14,286; 46.33%).



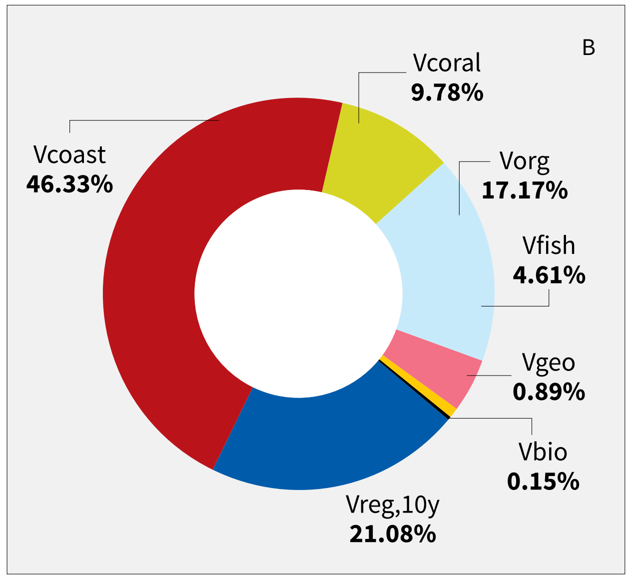


Fig. 3.2. Component-wise breakdown of total economic value (V_{total} = ₹61.67 crore) from Vaan Island AR restoration: **(a)** Absolute values highlighting the primacy of V_{coast} (₹28.57 Cr), followed by $V_{reg,10y}$ (₹13 Cr), V_{org} (₹10.60 Cr), V_{coral} (₹6.03 Cr), V_{fish} (₹2.85 Cr), V_{geo} (₹0.55 Cr), and V_{bio} (₹0.09 Cr). **(b)** Proportional contributions showing dominance of mainland coastal protection (V_{coast}, 46%) and regulating services ($V_{reg,10y}$, 21%)

Component contributions highlight the pre-eminence of mainland coastal protection (V_{coast}, 46.33%) and regulating services ($V_{reg,10y}$, 21.08%), together accounting for nearly ~67% of Vtotal and underscoring the dominance of avoided damage and long-term ecosystem regulation over on-site stock values (V_{geo} + V_{bio} ≈ 1.%). Biotic habitat and provisioning components (V_{coral} + V_{org} + V_{fish} ≈ 31.6%) still represent substantial recurrent flows, reflecting rapid epifaunal succession and fisheries enhancement atop the restored platform. Expressed per-hectare over the 13 ha AR influence area, V_{total} is ~₹4.74 million ha^{-1}, positioning the Vaan intervention within the upper range of tropical reef restoration projects while maintaining conservative assumptions for area and unit prices. The additive TEV structure remains methodologically coherent by compartmentalizing direct-use values (V_{org}, V_{fish}, part of V_{coast}), indirect-use/regulating values (V_{coral}, $V_{reg,10y}$, remainder of V_{coast}), and option/stock values (V_{geo}, V_{bio}) without double-counting, thereby providing a defensible benchmark

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for scaling similar AR-based island restorations across the Gulf of Mannar.

3.9. Cost-Benefit Synthesis Relative to Aggregated Total Economic Value (V_{total})

The decadal aggregation of the seven socio-ecological-economic benefits yields a Total Economic Value (V_{total}) of ₹61.67 crores attributable to the AR intervention at Vaan Island. To evaluate the fiscal efficiency and strategic wisdom of this public investment, this value must be rigorously juxtaposed against the project's expenditure, accounting for the opportunity cost of capital over the nine-year period from deployment (2015) to valuation (2024). The initial capital outlay for deploying 10,600 trapezoidal AR modules was approximately ₹17.00 crores (nominal, 2015). A nominal comparison with V_{total} suggests a direct return of over five times the investment. However, sound economic appraisal requires adjusting this historical cost to its present (2024) equivalent value, representing the forgone return had the capital been deployed in an alternative investment with a standard social rate of return. Applying the future value (FV) formula: $FV = PV \times (1 + r)^n$, where PV = ₹17.00 crores and $n = 9$ years, under different discount rate scenarios relevant to public and environmental projects, yields the adjusted costs as shown in Table 3.9. The standard 5% (Standard Social Discount Rate) is adopted for the central-end economic analysis, translating the 2015 expenditure to an opportunity-cost-adjusted 2024 equivalent of ₹26.37 crores. This figure represents the true economic burden of the project against which the accrued benefits must be weighed.

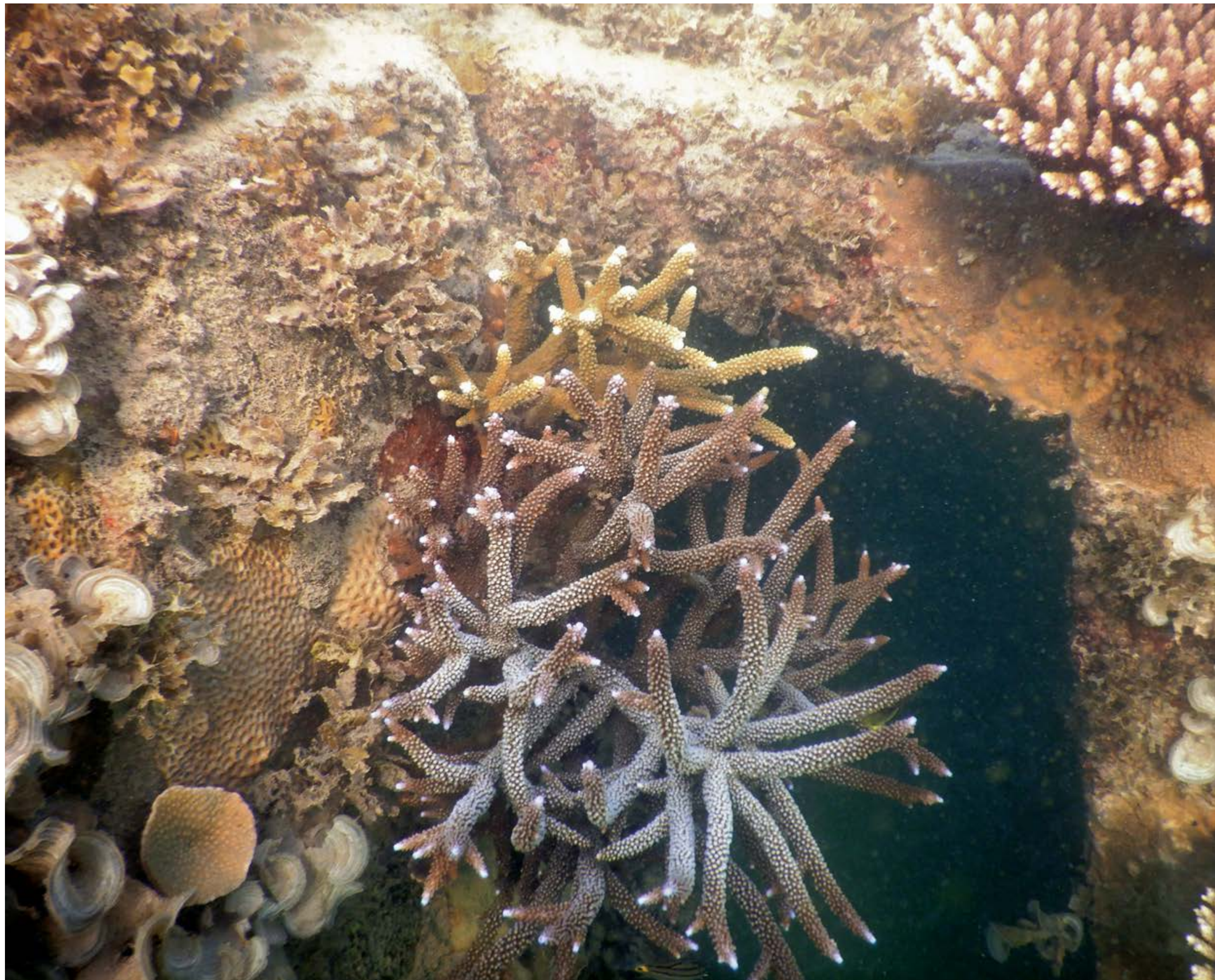
Comparing V_{total} against both the nominal and the economically adjusted costs provides a range of Benefit-Cost Ratios (BCR), while Net Present Value (NPV) calculates the net wealth generated (see Table 3.10). The nominal BCR of 3.63 demonstrates that the intervention generated over ₹5 in socio-ecological value for every ₹1 of public money initially spent—an exceptional return for a coastal adaptation project. The adjusted BCR of 2.34, which accounts for the time value of money, is the critical policy metric. A BCR significantly exceeding 1.0 confirms that the project was a superior use of capital compared to its alternative investment opportunity, creating substantial net social value. The positive NPV [~₹35.3 crores (~$4.20 million USD)] represents the net economic wealth generated for society

Table 3.9. Equivalent 2024 value of the 2015 artificial reef investment (₹17 Crores)

Discount Rate Scenario	Rationale / Typical Use Case	Annual Rate (r)	Time Period (n)	Growth Factor $(1 + r)^n$	Future Value (FV) in 2024
3% (Conservative Social Rate)	Used for long-term environmental projects with high future societal value	3%	9 years	1.3048	₹22.18 Crores
5% (Standard Social Discount Rate)	Common benchmark for public infrastructure and policy analysis (e.g., World Bank, Govt. of India)	5%	9 years	1.5513	₹26.37 Crores
7% (Commercial Opportunity Cost)	Reflects the average cost of capital or higher-risk alternative investments	7%	9 years	1.8385	₹31.25 Crores

Table 3.10. Cost-benefit summary of Vaan Island AR restoration

Metric	Description	Value (₹ Crores)	Notes
A. Total Economic Value (V_{total})	Sum of 7 TEV components (2024 valuation)	61.67	$V_{coral} + V_{org} + V_{fish} + V_{geo} + V_{bio} + V_{reg,10y} + V_{coast}$
B. Nominal Project Cost (2015)	Initial AR deployment capital outlay	17.00	From project context (10,600 modules)
C. Opportunity-Cost-Adjusted Cost (2024)	Future Value of ₹17 Cr (2015) at 5% p.a. over 9 years	26.37	$FV = 17 \times (1.05)^9 \approx 26.37$ Cr
D. Nominal Benefit-Cost Ratio (BCR)	V_{total} / Nominal Cost	3.63	>3.7x return on nominal expenditure
E. Adjusted Benefit-Cost Ratio (BCR)	V_{total} / Opportunity-Cost-Adjusted Cost	2.34	>2.4x return vs. commercial alternatives
F. Net Present Value (NPV) @ 5%	Simplified: V_{total} − Adjusted Cost	35.30	Strongly positive NPV confirms high economic viability and net social benefit

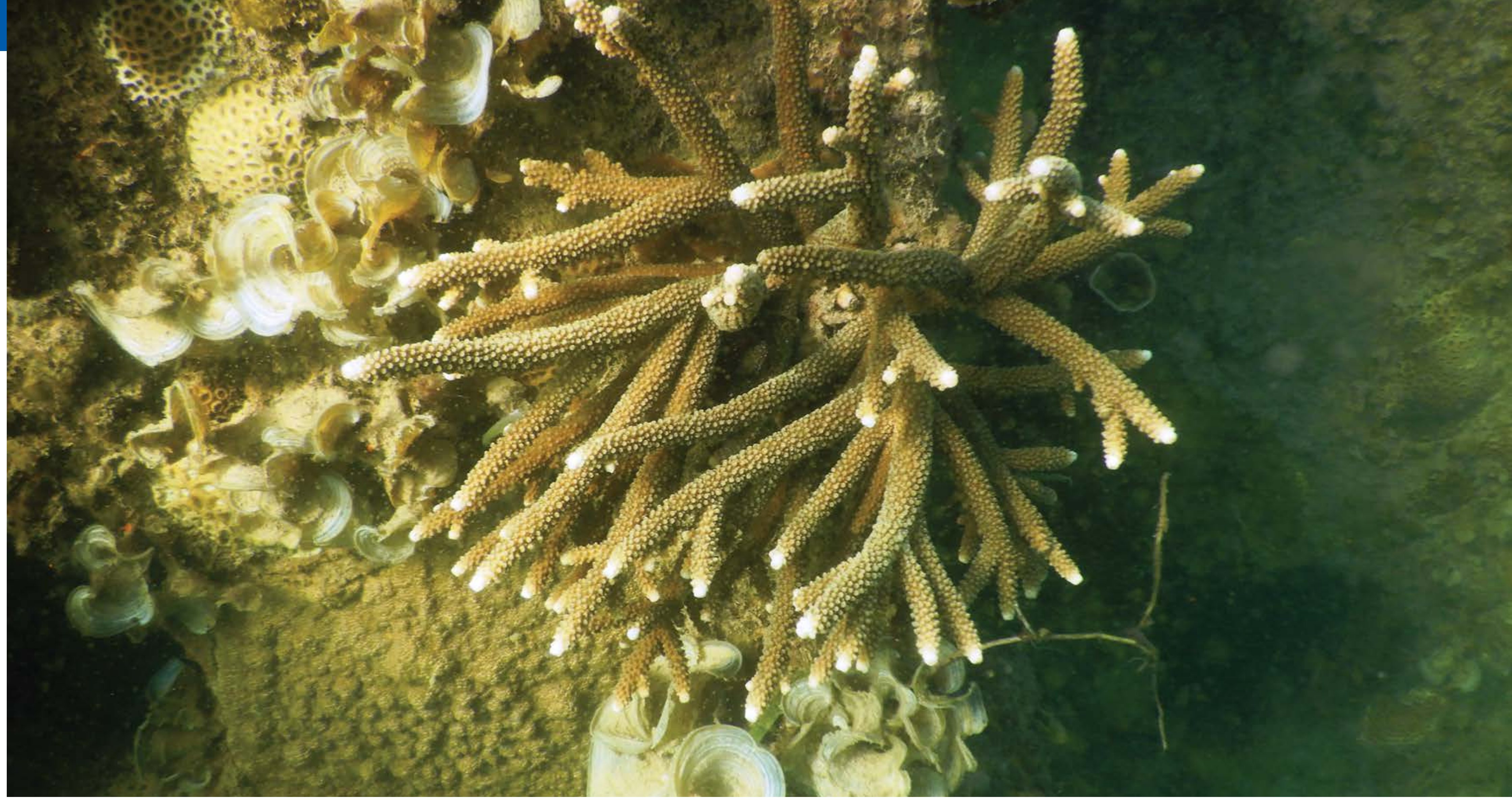


and the coastal and marine environment. This surplus value encompasses not only market-aligned benefits (fisheries, avoided reconstruction) but crucially, the non-market gains in biodiversity, habitat, and long-term coastal resilience that are often excluded from conventional project appraisals. The analysis remains robust under sensitivity testing. Even applying a stringent 7% discount rate (adjusted cost: ₹31.25 Cr), the BCR remains healthy at 1.97, and the NPV remains strongly positive at ₹30.4 Cr. This confirms the project's economic soundness across a plausible range of financial assumptions.

3.10. Closure

This chapter presented the empirical results from a decade of biophysical and economic monitoring following the deployment of an AR at Vaan Island. The findings confirm that the AR intervention has delivered transformative socio-ecological and economic returns. Key outcomes include rapid biological colonization—with hard coral density reaching 81.33 colonies per module and fish density increasing 8.3-fold—and significant geomorphic stabilization, reversing a 92% erosion trend and increasing the island's high-tide area. The integrated TEV framework quantified these changes across seven components, yielding a consolidated decadal benefit of ₹61.67 crores attributable to the restoration. A rigorous cost-benefit analysis demonstrates the project's strong fiscal performance: even after adjusting the 2015 investment of ₹17.00 crores for the time value of money (2024 equivalent: ₹26.37 crores at a 5% social discount rate), the intervention delivers an Adjusted Benefit-Cost Ratio (BCR) of 2.34 and a Net Present Value (NPV) of ₹35.30 crores. These results remain robust under sensitivity analysis, confirming that the AR restoration represents a high-return public investment that generates substantial net social and ecological value. Collectively, the results validate the "Vaan Island Model" as an effective, evidence-based approach to coastal adaptation—one that integrates ecological recovery with measurable socio-economic benefits. The following chapter will synthesize these findings into overarching conclusions and present targeted recommendations for scaling this model across the Gulf of Mannar and similar vulnerable coastal systems. Next, Chapter 4 will conclude by interpreting these findings, examining the policy and management implications for the Gulf of Mannar Marine Biosphere Reserve, and outlining recommendations.

4
CONCLUSIONS



This study presents a decadal (1969-2015 and 2015–2025), multi-dimensional assessment of artificial reef (AR)-driven restoration for the critically eroded Vaan Island in the Gulf of Mannar Biosphere Reserve. By integrating rigorous biophysical monitoring with a comprehensive Total Economic Value (TEV) framework, the investigation moves beyond qualitative success metrics to deliver quantifiable socio-ecological and economic evidence, as demonstrated in Fig. 4.1.

Fig 4.1. The Four-Pillar Success Framework of the Vaan Island Restoration Project, summarizing the integrated ecological, economic, climate-resilient, and socially-inclusive outcomes of the decadal intervention

The following key conclusions are drawn based on the methodological approach, results, and discussion:

➲ **AR Intervention Achieved Primary Geomorphic and Ecological Objectives.** The deployment of 10,600 trapezoidal AR modules successfully halted and reversed the severe erosional trajectory of Vaan Island. The island's high-tide line (HTL) area, which had diminished by 92% (from 20.08 ha in 1969 to 1.53 ha in 2015), was stabilized and increased to a maximum of 2.30 ha. This geomorphic stabilization provided the platform for ecological recovery, directly achieving the project's core goal of preventing island submergence.

➲ **AR Modules Served as Highly Effective Bio-geomorphic Infrastructure.** The modules functioned dualistically: as wave-dissipating structures that reduced hydrodynamic energy, encouraged sediment deposition (mean rate ~20 mg cm^{-2} day^{-1}), and induced significant bathymetric shallowing (e.g., 2.5 m to <1 m in key areas); and as complex benthic substrates that facilitated rapid and diverse biological colonization. This dual role confirms the design's efficacy for hybrid engineering-ecological restoration in high-energy environments.

➲ **Rapid Biological Succession Validates ARs as Artificial Habitat.** The AR field achieved a rapid transition from a biotic desert to a mature epibenthic assemblage within a decade. Hard coral colonization reached 81.33 colonies $module^{-1}$ (≈115,000 colonies ha^{-1}), while non-coral epibenthos (molluscs, sponges, ascidians, etc.) achieved densities of 39.97 organisms $module^{-1}$. This succession trajectory mirrors natural reef recovery patterns, establishing the AR field as a fully functional surrogate

habitat that reverses biotic homogenization.

➲ **Fisheries Enhancement Confirms Spillover Benefits.** Fish assemblage density around the AR field increased 8.3-fold, from 105.75 to 875.25 individuals ha^{-1} between 2016 and 2024, with biomass reaching 1,750.50 kg ha^{-1}. The dominance of commercially valuable families (*Lutjanidae, Scaridae,* and *Lethrinidae*) demonstrates that the restoration directly improves fishery resources, providing tangible, harvestable spillover benefits to the adjacent small-scale fishing communities of the Thoothukudi coast.

➲ The Total Economic Value (TEV) of Restoration Vastly Exceeds the Investment Cost. The integrated socio-economic valuation yields a decadal TEV of ₹61.67 crores attributable to the AR intervention. Even when accounting for the opportunity cost of capital (adjusting the 2015 project cost of ₹17 crores to a 2024 equivalent of ₹26.37 crores at a 5% discount rate), the project demonstrates a robust Benefit-Cost Ratio (BCR) of 2.34 and a strongly positive Net Present Value (NPV) of ₹35.3 crores. This conclusively proves that the investment was economically efficient and generated substantial net social and ecological wealth.

➲ Valuation Reveals the Dominance of Regulating and Protective Services. The component-wise breakdown of TEV shows that non-market, indirect-use values account for the majority of benefits. Mainland coastal protection (V_{coast}, 46.33%) and regulating/supporting services ($V_{reg,10y}$, 21.08%) together account for nearly ~67% of the total value. This underscores that the primary economic return of island restoration is not direct harvesting, but the avoided costs of coastal erosion damage to mainland infrastructure and the long-term provision of ecosystem regulation (e.g., water filtration, nutrient cycling, and habitat support).

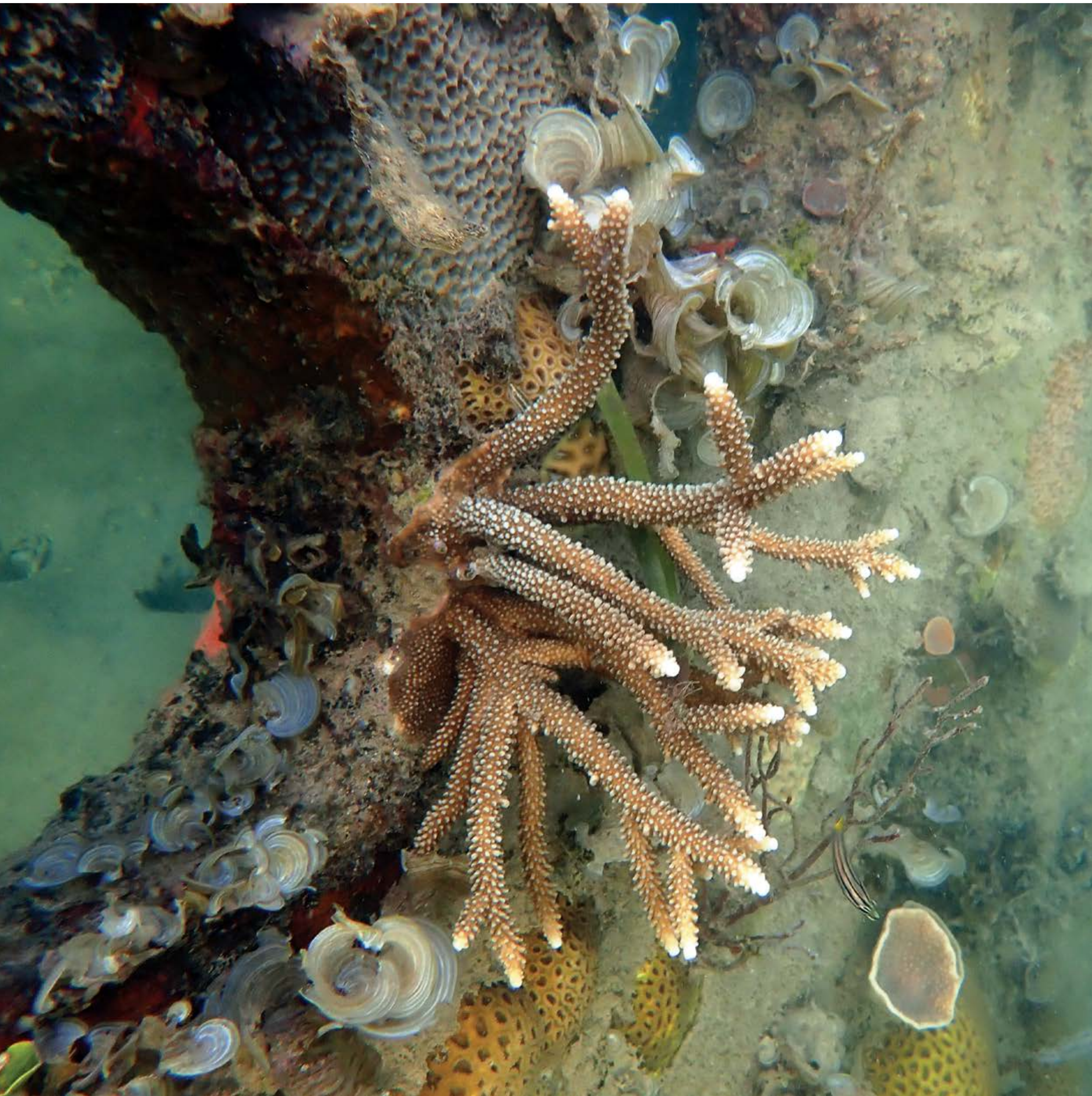
➲ On-Site Biodiversity and Habitat Values Are Substantial and Growing. While smaller in proportion to protection values, the direct habitat and provisioning components, viz., hard coral habitat (V_{coral}), other epibenthos (V_{org}), and fisheries (V_{fish}), collectively represent approximately 31.6% of TEV (₹19.46 crores). These are annual or recurrent flows, indicating that the AR field is not just a static structure but a productive, value-generating ecological asset that will continue to accrue benefits over time.

➲ The Model Provides a Scalable Blueprint for Climate Adaptation. The Vaan Island case study demonstrates a viable, evidence-based model for Ecosystem-based Adaptation (EbA). By addressing both the symptom (erosion) and the cause (loss of wave-buffering reef structure), the project improves resilience against sea-level rise and climate-induced stressors. The successful methodology, viz., from site-specific hydrodynamic modelling and modular AR design to the integrated TEV monitoring framework, is directly replicable for the other 20 eroding islands in the Gulf of Mannar and analogous reef-island systems globally.

➲ Gender-Transformative Reef Restoration within Protected Areas: The Vaan Island TEV framework's seven components provide strategic entry points for Gender Strategy alignment, advancing from women-inclusive monitoring (coral/epibenthos data collection) to transformative roles (women-led research cooperatives, fisheries advocacy, resilience leadership in buffer zones), operationalizing the continuum from blind/sensitive → responsive → transformative participation within GoMMNP no-intervention boundaries

In summary, the decadal intervention at

Vaan Island has conclusively transitioned it from a state of imminent loss to a stabilized, ecologically vibrant, and economically valuable asset. The project validates the strategic use of artificial reefs as powerful tools for integrated coastal zone management, achieving concurrent goals of biodiversity conservation, fisheries enhancement, coastal protection, and climate resilience while delivering an outstanding return on public investment. This work provides the critical evidence base to justify policy shifts and strategic scaling of nature-positive engineering solutions.



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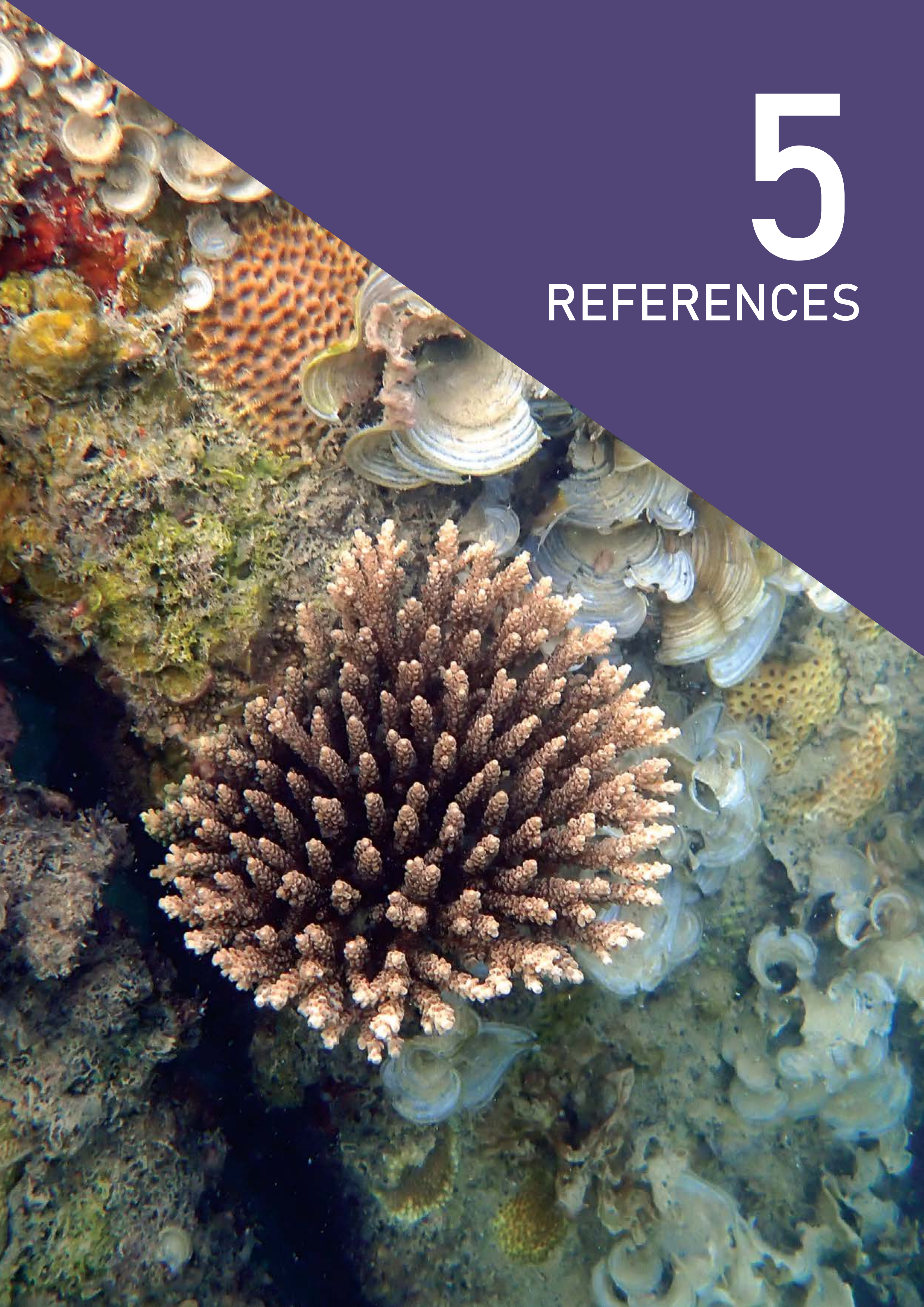

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